Investigation and Evaluation on District Energy System at Kitakyushu Science and Research Park - Field Study on Running Situation during 2002

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Abstract
A district energy system in Kitakyushu Science and Research Park (KSRP) has been introduced. In this paper, the system’s running situation was analyzed by using the recorded data in 2002. Generating electricity, heat recovery efficiency and recovery heat utilization efficiency for gas engine and fuel cell were calculated. On the basis of the above study, energy saving and CO₂ reduction were evaluated.

The results can be summarized as follows: 1) The on-site generating electricity equipments provided 51.2% of the total electricity demand, including fuel cell with 34.5%, gas engine with 13.4% and PV system with 3.3%. In total heat energy demand, 70% of hot water load, 30.9% of cooling load and 14.3% of heating load were provided by recovering the heat energy from fuel cell and gas engine system. 2) Fuel cell was running 8572 hours with constant generating electricity efficiencies, about 30.8%. Gas engine only run 4281 hours with higher generating electricity efficiencies, about 24.5%. PV system achieved over 8% module conversion efficiencies in 83% of generating electricity time. 3) Fuel cell had lower heat recovery efficiency, but this heat energy recovered almost was utilized by the heat exchanger or absorption chiller. Gas engine had higher heat recovery efficiency, but only 70% of them were utilized by heat recovery equipments. 4) Compared with the conventional energy supply system, the district energy system achieved 56% primary energy utilization efficiency, 10.9% saving energy ratio and 1.32% CO₂ reduction ratio.

Keywords: district energy system; fuel cell; gas engine; PV; efficiency; evaluation

1. Introduction
Distributed energy resources hold great potential for meeting future energy needs. This is especially important when aspects of sustainable development and environmental compatibility are considered. Currently there are many distributed generation sources in operation. Distributed generation is the utilization of an on-site power source to provide electricity and other energy to one or more buildings or facilities. Distributed generation can utilize a wide range of power generators including: combustion turbines; PV systems; fuel cells; micro-turbines; and so on.

In Japan, which depends on imports for most of its primary energy supply, distributed 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. Co-generation system (CGS) as a kind of distributed generation has been developed rapidly during the last 20 years, in Japan. The number of CGS systems has increased from 67 in 1986 to 4515 in 2003, and the total generation capacity has amounted from 200kW in 1986 to 6,504MW as of March 2003. The annual capacity of CGS installed is increasing by the constant 400-450 MW every year since 1986[1][2]. CGS system is expected to reach 1,002MW output scale by the year 2010[3]. On the other hand, in the last five years, the production of photovoltaic cells has increased steadily by an average of 30% per year. In 2002, the total PV production capacity in the world has reached 520.15MW, among of which Japan shared of 274MW, more than 52% [4].

At Kitakyushu Science and Research Park (KSPR) in Japan, a new district energy system including fuel cell, gas engine and PV system has been introduced since April 2001. Currently, some research [4][5] on the system has been carried out. LIU[4] examined the PV system in the district energy system. GAO[5] evaluated the energy and environmental performance of the system in summer. However, in order to grasp the system’s running situation, it is need to evaluate comprehensively the system. In this research, an analysis has been conducted on the district energy system by using the recorded data in 2002. Generating electricity system and heat recovery system were analyzed respectively. Also an

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(Received November 8, 2004; accepted March 22, 2005)
environmental and energy saving impact evaluation has been reported.

2. Outline of research system

Figure 1 is the schematic illustration of energy supply system installed at Kitakyushu Science and Research Park. In this system, 153kW PV system, 200kW fuel cell and 160kW gas engine had been installed to supply the electricity of the end-use at KSRP and the insufficient electricity was provided by the utility electricity. The heat discarded from the fuel cell and gas engine was utilized to supply the heat load for heating, cooling and hot water. The insufficient loads, including space heating or cooling and hot water, are provided by gas boiler.

Table 1 shows details and the nominal power generation and heat recovery efficiencies of the fuel cell and gas engine. Gas engine capacity is 160kW with a nominal generating electricity efficiency of 28.7% and a heat recovery efficiency of 47.7% for one circuit with high temperature of 90°C. Fuel cell capacity is 200kW with a nominal electrical power production efficiency of 40% and a heat recovery efficiency of 20% for both circuits, one at a high temperature of 90°C and another at 50°C. Fuel cell was running for 24 hours except for some special period, such as maintenance and repair of equipments or national holiday. Gas engine was designed to run during 8:00–22:00 generally, but it changed with the demand of electricity consumption.

Table 2 is the nominal performance of this PV system. The PV system has been installed with 156 double-sides glass single-crystal silicon solar modules and 912 multicrystal silicon solar modules. The total capacity of this PV system is 153kW, including 21kW from single-crystal and 132kW from multi-crystal silicon solar cell. The module conversion efficiencies (Rated conversion efficiency is measured at 25°C) for the single-crystal and multi-crystals silicon solar cell are 7.2% and 13.3%, respectively.

3. Investigation methodology

During the research investigation, generating electricity data were recorded hourly using an electricity meter. In order to analyze the heat release utilization efficiency, the difference between the input and output hot water temperatures and the hot water flow rates were measured for each system at hourly intervals. Consequently, generating electricity amount and the heat utilized by the systems could be quantified.

For the purposes of comparison a conventional energy-supply system is shown in figure 2. In the conventional system, a boiler is used to supply heating energy and a steam absorption chiller is used to supply cooling energy by a district heating/cooling system. The basic parameters of the equipments and the emission of CO₂ are assumed as in Table 3[5].

In order to evaluate the system, the following expressions were defined:

![Diagram 1: Schematic Illustration of Energy Supply System](image1)

![Diagram 2: The Conventional Energy Supply System](image2)

![Table 1: Details of Cogeneration System](image3)

| Item                  | Fuel cell | Gas engine |
|-----------------------|-----------|------------|
| Generating capacity   | 200       | 160        |
| Generating efficiency | 40%       | 28.7%      |
| Heat recovery efficiency | 20% (at high temperature) | 47.7% (at 90°C high temperature) |
| Operational mode*     | Running for 24 hours | Running during 8:00-22:00 |

*NOTE: Fuel cell was running for 24 hours except for some special period, such as maintenance and repair of equipments or national holiday. Gas engine was designed to run during 8:00–22:00 generally, but it changed with the demand of electricity consumption.

![Table 2: Nominal Details of PV System](image4)

| Item                  | Multi-crystal module | Single-crystal module |
|-----------------------|----------------------|-----------------------|
| Equipment capacity    | 21                   | 132                   |
| Module maximum output | 135                  | 145                   |
| Module conversion efficiency | 7.2%   | 13.3%                |
| Effective area of generating electricity (m²) | 1.008 | 1.006 |
| Number of module (unit) | 156               | 912                   |

![Table 3: The Basic Parameters of the Equipments](image5)

| Equipment of the utility generating electricity | Gas boiler | Absorption chiller | Electricity for the utility(Kg/CkWh) | Natural gas(Kg/Chm³) |
|-------------------------------------------------|------------|--------------------|-------------------------------------|----------------------|
| Efficiency                                      | 35%        | 80%                | 118%                                | 0.104                | 0.584                |
Generating electricity efficiency:
\[ \eta_E^i = \frac{Q_{E^i}}{Q_{E^i,\text{opt}}} = \frac{E_x^i \times k}{Q_{E^i,\text{opt}}} \quad (i=0,1,2) \] (1)

For PV system:
\[ Q_{E^0,\text{opt}} = Q_{E^0,\text{opt}}^\text{PV} = \sum Q_{E^0} \times F_i \] (2)

For gas engine and fuel cell:
\[ Q_{E^1,\text{opt}} = Q_{E^1,\text{opt}}^\text{GE} = \frac{V_{E^1,\text{opt}} \times k}{\eta_{E^1,\text{opt}}} \] (3)
\[ Q_{E^2,\text{opt}} = Q_{E^2,\text{opt}}^\text{FC} = \frac{V_{E^2,\text{opt}} \times s}{\eta_{E^2,\text{opt}}} \] (4)

Heat recovery efficiency:
\[ \eta_{HR}^i = \frac{Q_{HR}}{Q_{E^i,\text{opt}}} \quad (i=1,2) \] (5)

Recovery heat utilization efficiency:
\[ \eta_{HV}^i = \frac{Q_{HV}}{Q_{E^i,\text{opt}}} \quad (i=1,2) \] (6)

Primary energy utilization efficiency for fuel cell and gas engine:
\[ \eta_{\text{total}}^i = \frac{Q_{E^i,\text{opt}} + Q_E^i \times k}{Q_{E^i,\text{opt}}} = \frac{E_x^i \times k}{Q_{E^i,\text{opt}}} \quad (i=1,2) \] (7)

Primary energy utilization efficiency for present system and conventional system:
\[ \eta = \frac{Q_{E^i,\text{opt}} + Q_E^i \times k}{Q_{E^i,\text{opt}}} \] (8)

For present system:
\[ Q_{E^0,\text{opt}}^\text{PV} = \sum Q_{E^0}^\text{PV} + E_{\text{Recover}}^\text{PV} \times k + \eta_{E^0,\text{opt}}^{\text{HV}} \times (V_{E^0,\text{opt}}^{\text{Heat}} + V_{E^0,\text{opt}}^{\text{Recover}} + V_{E^0,\text{opt}}^{\text{Cooling}}) \times s \] (9)
\[ Q_{E^1,\text{opt}}^\text{GE} = \sum Q_{E^1}^\text{GE} + \sum Q_{E^1}^\text{GE} \times k + (V_{E^1,\text{opt}}^{\text{Heat}} + V_{E^1,\text{opt}}^{\text{Recover}} + V_{E^1,\text{opt}}^{\text{Cooling}}) \times s \times \eta_{E^1} \] (10)

For conventional system:
\[ Q_{E^1,\text{opt}}^\text{Conv} = E_{\text{Recover}}^\text{Conv} \times k + (V_{E^1,\text{opt}}^{\text{Heat}} + V_{E^1,\text{opt}}^{\text{Recover}} + V_{E^1,\text{opt}}^{\text{Cooling}}) \times s \times \eta_{E^1,\text{Conv}} \] (11)
\[ Q_{E^2,\text{opt}}^\text{Conv} = E_{\text{Recover}}^\text{Conv} \times k + (V_{E^2,\text{opt}}^{\text{Heat}} + V_{E^2,\text{opt}}^{\text{Recover}} + V_{E^2,\text{opt}}^{\text{Cooling}}) \times s \times \eta_{E^2} \] (12)

CO2 reduction ratio:
\[ \eta_{\text{CO2}} = \frac{E_{\text{CO2}} - E_{\text{CO2}}}{E_{\text{CO2}}} \] (13)
\[ E_{\text{CO2}} = E_{\text{CO2}}^\text{Conv} \times V_{\text{CO2}} + E_{\text{CO2}}^\text{Conv} \times V_{\text{CO2}} \] (14)
\[ E_{\text{CO2}} = E_{\text{CO2}}^\text{Conv} \times V_{\text{CO2}} + E_{\text{CO2}}^\text{Conv} \times V_{\text{CO2}} \] (15)

4. Investigation result and discussion

4.1 Electricity system

Daily electricity loads from various systems were calculated and their variation is shown in Figure 3. From the profiles, it can be concluded that the total electricity consumption in 2002 reached 4599.15Gwh. And the cooling period (during May 27 – Oct.15) consumed more electricity than other periods. Electricity consumptions in cooling and heating (during Jan.1~ Apr.21 and Nov.5~ Dec.31) periods were 2076.36Gwh and 1908.45Gwh respectively, accounting for about 45% and 41% of the total annual electricity consumption respectively. The fluctuation of the daily electricity consumption is dramatic with weekday and weekend (including national holiday), the peak load occurs at 18th July with 18.13Mwh/Day and New Year’s Day has the minimum electricity consumption only with 5.87Mwh/Day. The average is 12.60Mwh/Day.

The total electricity was provided by four parts, fuel cell, gas engine, PV system and the utility electricity. Fuel cell contributed 34.5% of the electricity load with 1587.16Gwh, followed by gas engine 13.4% with 616.01Gwh and PV system 3.3% with 153.26Gwh. On-site equipments including fuel cell, gas engine and PV
system provided 2356.50Gwh electricity for the consumer, accounting for 51.2%. The insufficient part came from the utility electricity and reached 2242.66Gwh, about 48.8%.

Fuel cell almost provided stably about 4.35Mwh electricity for the consumer every day except for the maintenance and repair of equipments (during Mar.22~28, Jul.27~28 and Sep.29~Oct.1). The generating electricity amount of gas engine fluctuated sensitively with the load demand of consumer between 0-3.789Gwh/Day. The generating electricity amount of PV system and the irradiance are almost fluctuating synchronism [4]. It ranged between 0~0.808Gwh/Day. And the electricity amount from the utility electricity also changed with the load demand of consumer.

Figure 4 is electricity load over 24 hours in the whole year. From the chart, it can be found that PV system generated electricity from 7:00 am to 6:00 pm. And the generating electricity amount during 9:00 am to 4:00 pm shared the total generating electricity of 95%. The generating electricity of PV system at 12:00 reached to the maximum and accounted for 8.72% of the total electricity demand. Gas engine was designed to running during 8:00~22:00 generally. And in this period, gas engine contributed 17% of the total electricity for the consumer. Fuel cell was running with constant generating electricity amount. During 23:00~24:00 and 1:00~8:00 am, fuel cell contributed the half of the total electricity. Anytime in one day, the electricity amount from the utility electricity almost reached to the half of the total electricity consumption.

Generating electricity efficiency is an important evaluation index for various systems. Generating electricity efficiency for different generating electricity modes (PV system, gas engine and fuel cell system) can be calculated by using these expressions as mentioned previously and their accumulation curve were shown in figure 5. From the profiles, it can be concluded that fuel cell had longer generating electricity hours, reaching to 8572 hours throughout the year with constant generating electricity efficiency. There was 45 hours that generating electricity efficiency was larger than 35%, accounting for 4% of overall generating electricity hours. There was 8541 hours that generating electricity efficiency was larger than 28%, accounting for 99.6% of overall generating electricity hours. Gas engine was running 4281 hours throughout the year with higher generating electricity efficiency. 90% generating electricity hours achieved more than 23% generating electricity efficiency, 5.7% lower than the designated value of 28.7%. Considered PV system, the hours of generating electricity only was 2813 hours. It was 2340 hours that the hourly module conversion efficiency was larger than 8% throughout the year.

4.2 Heat system

In CGS system, heat recovery system is a decisive factor to energy saving and environmental effective. In order to evaluate the heat recovery system, in this paper, at first, the present situation of heat energy consumption was analyzed, and then the heat recovery efficiency was evaluated by using these expressions as mentioned previously.

Figure 6 is daily variation of heating and cooling load. The total heating load reached 9068.47GJ and only 14.3%, about 1297.72GJ came from heat recovery system. The insufficient heating load demand, about 7770.37GJ was provided by the gas boiler, accounting for 85.7% of the total load demand. In the heating period during Jan.1 ~Apr.21, recovery heat for heating accounted for 21.7% of the heating demand in the period. However, in another heating period from Nov.5 to Dec.31, more than 98% of heating load was provided by the gas boiler because of the heat exchanger for heating being bad. The total cooling load reached 7978.70GJ and only 2463.23GJ, about 30.9% came from heat
recovery system. The insufficient heating load demand, about 5515.43 GJ was provided by the gas boiler. The daily cooling peak was 102.20 GJ and occurred at July 23. Compared with cooling/heating load, hot water load in every day was little and relatively stable, the average is 6.90 GJ/Day (see Figure 7). The annual total hot water load reached 2513.43 GJ and more than 70% of the total load came from the heat recovery system, about 1783.94 GJ. More than 90% of hot water load demand during the heating and no-cooling-heating period came from the recovery heat. However, the recovery heat for hot water only accounted for 50% of the total hot water load in cooling period. This is because the recovery heat from cogeneration system was utilized fully by the absorption chiller in the cooling period.

Heat release energy to be used comprised two parts, one is the recovery heat from fuel cell and another is from gas engine. The total heat release energy to be used reached to 5544.90 GJ and about 44.7% with 2478.57 GJ came from the gas engine; the remainder part, about 55.3% was provided by fuel cell (see Figure 8). In cooling period (May.27~Oct.15), gas engine and fuel cell system contributed the half of heat release to be used for the consumer respectively. In no-cooling-heating period, the heat release to be used mainly came from fuel cell, more than 93% of the utilized energy. In the heating period from Jan.1 to Apr. 21, the heat energy utilized from fuel gas reached 56% of the total utilized energy in this period. While in another heating period from Nov. 5 to Dec. 31, fuel cell contributed 76% of the total heat energy utilized.

Figure 9 is accumulation curve of heat recovery efficiency and recovery heat utilization efficiency for difference mode. From these profiles, it can be concluded that fuel cell had stable heat recovery efficiency. There are 3633 hours that heat recovery efficiency was more than 20%. And it can be found the curve of heat recovery efficiency was identical with the one of recovery heat utilization efficiency. This implied that in fuel cell system, the recovery heat was utilized fully. Gas engine had higher heat recovery efficiency; in overall 4281 operating hours, there was 3894 hours that heat recovery efficiency was over 30%. Comparing these two efficiency curves of gas engine, it can be found that although the waste heat from gas engine was larger, it was not utilized fully.

The electrical power was generated by the fuel cell and gas engine. The heat release collected from the fuel cell and gas engine can be divided two parts. One is defined as utilization recovery heat that is used by the absorption chiller and heat exchanger, while the other is defined as the no-utilization recovery heat that was not used in the absorption chiller or heat exchanger and which was emitted to atmosphere as waste heat through the cooling tower. No-recovery heat is defined as energy that was not recovered by the system and it was also emitted to atmosphere as waste heat through the cooling tower. Figure 10 shows the balance of energy
consumption for gas engine. In gas engine system, the proportion of the generating electricity energy comprised 24.5% of the total energy. The proportion of the heat recovery energy was 39.2% of the total energy, with the heat recovery actually utilized being about half of this. The total primary energy efficiency of the gas engine varied with time between 19%~68%. And during Jan.1~Apr.21 and Jun.1~Sep.1, more than 95% recovery heat energy was utilized fully. In the other period, there was 5% recovery heat to be utilized. Therefore, the proportion of the waste heat energy (including no-utilization recovery heat energy and no-recovery energy) was between 40% and 70% of the total energy. Similarly, Figure 11 is the balance of energy consumption for fuel cell. In fuel cell system, the proportion of the energy utilized was 47.2% of the total input energy; among of which comprised 30.8% generating electricity energy and 16.4% utilization recovery heat energy. Waste heat energy accounted for 52.8% of the total energy and all almost was No-recovery heat energy.

5. Evaluation of the district energy system

According to the expressions defined in section 3, the primary energy utilization for present system and the conventional system can be calculated respectively and their variation is described in Figure 12. In this district energy system, the maximum primary energy utilization efficiency was 73.3% and 12.7% higher than the conventional system. In no-heating-cooling period, the two systems have almost same primary energy utilization. However, during the cooling and heating period, the primary energy utilization efficiency for the present system was 5.3%~13.3% higher for the conventional energy system.

Figure 13 shows comparison of primary energy input for the two systems. The primary energy input was 10.9% lower for the conventional energy system at Kitakyushu Science and Research Park. And the total energy input in 2002 reduced 7628.5GJ, including 1571.68GJ (about 2.2%) from PV system and 6056.82GJ from CGS system (8.7%).

Figure 14 is the variation of CO₂ reduction ratio. Although the district energy system in the heating period achieves CO₂ reduction ratio of 10%, the average value of CO₂ reduction ratio only was 1.32% because the system discharged more CO₂ than conventional system in no-cooling-heating period. The district energy system reduced 10.13 ton CO₂ emission. This demonstrates that the system expected CO₂ reduction from the district energy system were not achieved.

6. Summary

In Kitakyushu Science and Research Park, a new district energy system has been introduced. In the paper, this system running situation was analyzed by using recorded data. On the basis of the above study, energy saving and CO₂ reduction were evaluated. The results can be summarized as follows.
1) 51.2% of the total electricity demand was provided by the on-site generating electricity equipments, including fell cell with 34.5%, gas engine with 13.4% and PV system with 3.3%. The insufficient part, about 48.8%, came from the utility electricity. PV system generated electricity during 8:00 am to 6:00 pm and shared of about 9% of the total electricity in this period. Gas engine contributed 17% of the total electricity during 9:00-22:00. Fuel cell was running with almost constant generating electricity amount. And fuel cell contributed the half of the electricity demand during the pervious 23:00-next day 8:00 am for the consumer. Anytime, about half of electricity demand came from the utility electricity.

2) Fuel cell was running 8572 hours with constant generating electricity efficiencies. In mostly time, its generating electricity efficiencies is less than 32%, which is 8% lower than the designated value of 40%. Gas engine only run 4281 hours with higher generating electricity efficiencies; 90% time had more than 23% generating electricity efficiencies, which is 5.7% lower than rated value of 28.7%. PV system achieved over 8% module conversion efficiencies in 83% of generating electricity time.

3) In all heat energy demand, about 70% of hot water load, 30.9% of cooling load and 14.3% of heating load were provided by the recovery heat from fuel cell and gas engine system. Among all the heat energy from the recovery heat, 44.7% came from gas engine, 55.3% from fuel cell.

4) Fuel cell had lower heat recovery efficiency; its value is about 20% and this recovery heat almost was utilized by the heat exchanger or absorption chiller. Gas engine had higher heat recovery efficiency. In 90% of running time, it achieved over 30% heat recovery efficiency. And in all recovery heat, about 70% was utilized by recovery equipments.

5) The district energy system achieved 56% primary energy utilization efficiency, 6% higher than the conventional system. The primary energy input was 10.9% lower for the conventional energy system at Kitakyushu Science and Research Park. And the total energy input in 2002 reduced 7628.5GJ, including 1571.68GJ (about 2.2%) from PV system and 6056.82GJ from CGS system (8.7%). In the heating period, this district energy system achieved CO2 reduction ratio of 10% and the average value of CO2 reduction ratio only was 1.32%.

In summary, compared with the conventional system, the district energy system at KSRP had reduced the primary energy input of 10.9% and the 10.13 ton CO2 emission and achieved 56% primary energy utilization efficiency during 2002. However, it could not reach the expected advantage. Particularly, the reduced environmental impact was not observed. The average value of CO2 reduction ratio only was 1.32%. The main reason is that the recovery heat from fuel cell and gas engine can not be used fully. It is necessary to improve the heat recovery efficiency and recovery heat utilization efficiency for the district energy system. This will be studied further in the future.

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