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Optimum Design of CHP Network in Smart Grid from Cost and GHG Reduction Aspects

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Abstract- *Smart-grid system is consisting of variety of small power plants including combined heat and power (CHP or CGS), and the each component is controlled optimally with exchanging electricity through network. The author and his colleagues have analyzed the effect of reducing greenhouse gas and cost of CGS network system for variety types of buildings. Networking electricity though grids has great effect to extract the potential of CGS. The paper introduces a simple evaluation method to identify the optimum capacity of CGS and the effect of cost and CO_2 reduction for different kinds of demand conditions. The paper also presents an example of evaluation result for the CGS network system applied to a specific area in Japan, showing importance of cooperative operation of the networking CGS's. Finally comparison is made between CGS network and heat pump system for the condition of improved efficiencies of power plants, CGS and heat pumps in the future.*

Keywords: CHP, Cogeneration, Smart Grid, Network, Greenhouse Gas

1. INTRODUCTION

Cogeneration system (CGS), which is sometimes called combined heat and power (CHP), is expected as one of the most prospective system for the reduction of greenhouse gases (GHG). However, depending on the building types and operating conditions of the system, the effect varies significantly. The author and his colleagues have analyzed the effect of reducing greenhouse gas and cost of CGS network system for variety types of buildings. Most of the work was published in Japanese, whose major papers are listed in the reference [1-10]. This paper is the summary of the major results of the research for a keynote speech.

The buildings analyzed here are limited to social buildings in Japan (not industry), because the energy demand patterns can be specified. The analysis was made on the conditions to maximize economy and to minimize greenhouse gases (CO_2 in the paper). The emission from power plants for the electric demand is included in the analysis. This kind of analysis generally depends on the energy demand patterns, and it is difficult to obtain general conclusions. The paper introduces a simple evaluation method to identify the effect of CGS for different kinds of demand conditions. The paper also presents the effect of networking CGS system through the grid, showing importance of cooperative operation in the limit of voltage fluctuation in the grid.

2. ANALYTICAL METHOD AND BASIC DATA

The following indexes of cost and CO_2 reduction rates are introduced:

$$S_{\$} = \frac{\$_{\mathrm{CV}} - \$_{\mathrm{CG}}}{\$_{\mathrm{CV}}} \tag{1}$$

$$S_{CO_2} = \frac{(CO_2)_{\mathrm{CV}} - (CO_2)_{\mathrm{CG}}}{(CO_2)_{\mathrm{CV}}} \tag{2}$$

where $\$_{CV}$ and $\$_{CG}$ represent annual costs of conventional and cogeneration systems respectively. The cost includes initial investment costs as well as running cost by means of their payback time. The conventional system receives electricity from power grid and heat from a boiler. Similarly, S_{CO2} is defined as an index of CO_2 reduction rate in a year.

In this analysis, five types of buildings (house, office, hotel, store, and hospital) were analyzed. Hourly rate patterns of energy demand of each building are given for three seasons. The annual energy demand for a unit floor area are decomposed to monthly energy demand, and the hourly energy demand is determined from the monthly demand and the above hourly rate patterns. Hourly pattern of the peak energy demand is used for determining the system capacity.

The power of the CGS is controlled to match either for the heat demand (heat-demand operation) or electric demand (electric-demand operation), and the backup boiler is operated when the CGS heat output is insufficient for the heat demand. The heat demand consists of the heat for utility and for heating. The capacity of the backup boiler was set equal to the peak heat demand for security reason. The excessive electric power is returned to the grid with the price of 23% of

Table 1: Annual energy demand in Tokyo [8]

[kWh/m^2-year]

	House	Office	Hotel	Store	Hospital
Electricity	21	156	200	226	170
Utility	35	3	93	27	93
Heating	23	36	93	41	86
Cooling	9	81	116	145	93

Table 2: Analysis conditions [8]

CGS	Ele. Efficiency		
	100%Load	33	[%]
	25%Load	22	[%]
	Heat Efficiency		
	100%Load	53	[%]
	25%Load	52	[%]
	CO_2 Emission	205	[g-CO_2/kWh fuel]
	Gas Fuel Price	54	[\/m^3]
Power Plant	Efficiency	39	[%]
	CO_2 Emission	528	[g-CO_2/kWh ele.]
	Price (Buy)	20	[\/kWh ele.]
	Price (Sell)	45	[\/kWh]
Boiler	Efficiency	80	[%]
	CO_2 Emission	205	[g-CO_2/kWh fuel]
	Gas Fuel Price	54	[\/m^3]
Electric Air Conditioner	COP	33	[-]

Table 3: Rated reduction ratio, s_σ [8]

CO_2 Emission	0.34	[-]
Running Cost	0.52	[-]

buying cost in the analysis. When reversed grid connection is not accepted, the CGS is operated to match for the electric demand.

Table 1 is the annual energy demand in a unit floor area for the buildings in Tokyo climate. Table 2 is efficiency and cost conditions of the system. All the systems including power plant and boiler are assumed to run with natural gas to evaluate the best choice of the utilization of natural gas in the view point of CO_2. The data used in the analysis is detailed in Ref. [6, 8].

3. MAPPING METHOD FOR GENERALIZATION

As the analysis depends on the energy demand patterns, it was attempted to develop a generalization method to identify the effect of CGS. In this section only running cost is evaluated in the form of Eq. (1).

Defining x as the running cost and CO_2 emission in a unit time, Eqs. (1) and (2) can be written as:

$$S = \int \frac{x_{\mathrm{CV}} - x_{\mathrm{CG}}}{X_0} \cdot \frac{dt}{T} \tag{3}$$

where the integration period is one year, x_{CV} is for the conventional system, x_{CG} is for cogeneration system, X_0 is the averaged value of x_{CV} in a year, and T is the total time in a year, i.e. 365x24h. As the x_{CV} and x_{CG} are a function of electric demand $E(t)$ and heat demand $Q(t)$ at a time, Eq. (3) can be modified to the integration by operating conditions instead of time:

$$S = \iint \frac{x_{\mathrm{CV}} - x_{\mathrm{CG}}}{X_0} \cdot f(E,Q)\,dEdQ \tag{4}$$

where $f(E, Q)$ is the probability density of the operating conditions of E and Q in a year. Expressing the instantaneous reduction rate of cost and CO_2 in s, i.e. $s=(x_{CV}-x_{CG})/x_{CV}$, the annual reduction rate S becomes:

$$S = s_\sigma \iint \frac{s}{s_\sigma} \cdot \frac{x_{\mathrm{CV}}}{X_0} \cdot f(E,Q)\,dEdQ \tag{5}$$

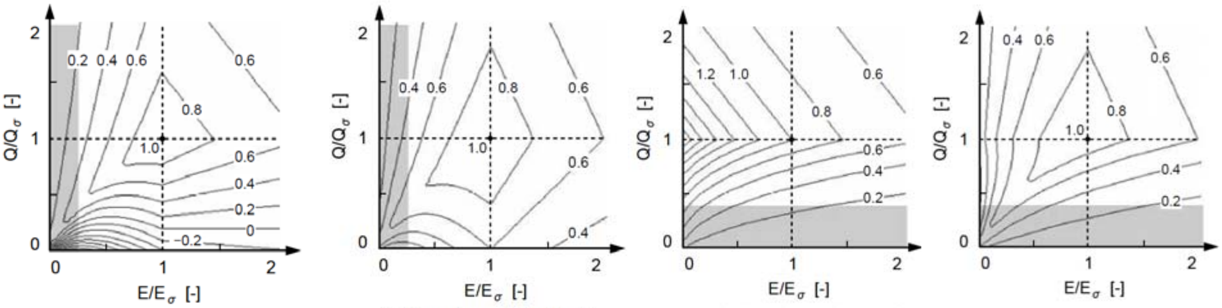
where s_σ is the reduction rate at rated power condition and it corresponds to the basic performance of the CGS. This s_σ value is independent of the building types and demand patterns, and the value used in the analysis is shown in Table 3. The integration term in Eq. (5) has the meaning of the effectiveness of the system relative to the rated reduction rate, s_σ. It is expressed in ζ and termed "effectiveness" in the paper:

$$\zeta = \iint \frac{s}{s_\sigma} \cdot \frac{x_{\mathrm{CV}}}{X_0} \cdot f(E,Q)\,dEdQ \tag{6}$$

The s/s_σ is normalized reduction rate by the rated performance. The value becomes unity when the energy demand matches to the rated power, and it decreases at the different conditions. The x_{CV}/X_0 is the weight of the operating load relative to the average value, and it is a simple linear function of the load. The normalized reduction rate, s/s_σ, can be plotted as in Fig. 1, and the probability rate of the operating condition, $f(E, Q)$, can be mapped as in Fig. 2. Thus the effectiveness, ζ, can be roughly estimated from the two figures; which is demonstrated in the following:

Figure 1 shows the normalized reduction rates at the operating condition relative to the rated power. The ordinate is the heating demand relative to the heat output of CGS at rated power, and the abscissa is the electric demand in the same manner. The maps are deferent between electric-demand control and heat-demand control operations. They have similar trends of the maximum value at the rated condition except for the CO_2 map in heat-demand operation. In the heat demand operation the CO_2 reduction rate is even greater than unity at the lower electric demand region. This is due to the fact that excessive electricity is reversed to the grid and it contributes to the reduction of CO_2 in the grid, i.e. negative CO_2 emission.

Figure 2 is the demand maps for the 5 types of buildings. The coordinates are normalized by annual average of the electricity and heat demands. The lines in the figures are the rated power lines of the CGS. The inclination of the line varies depending on the annual heat/electric demand ratio (Q_m/E_m), which is determined by the local climate. From the maps we can understand the CGS is suited to hotels and hospitals, in which the demand distributes close to the rated point. Offices and stores are not suited for the CGS, as the demand scatters away from the rated line. In the houses the demand



(a) CO_2 in electric demand operation (b) Running cost in electric demand operation (c) CO_2 in heat demand operation (d) Running cost in heat demand operation

Fig. 1: Relative reduction ratio maps, s/s_σ [8]

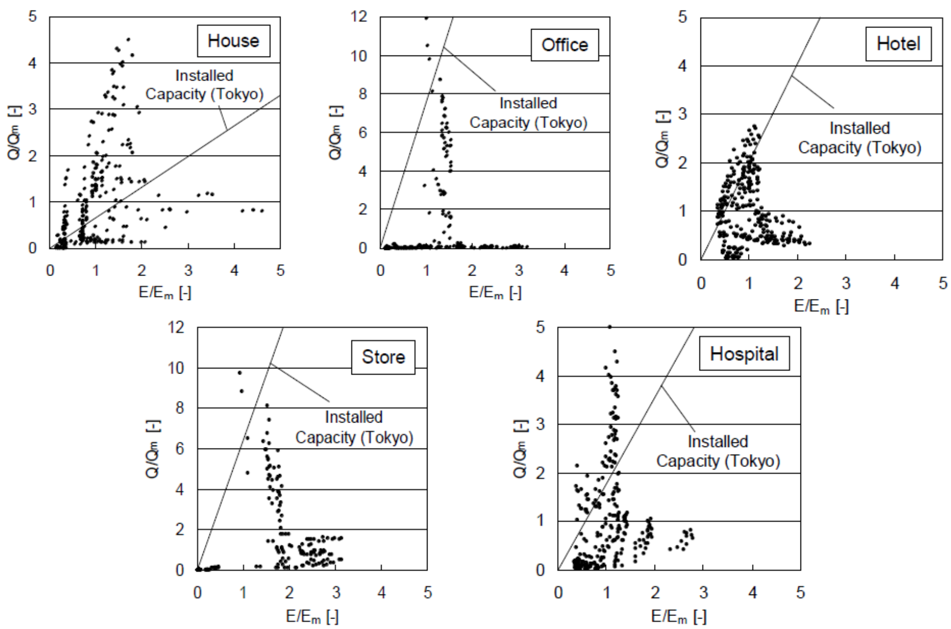


Fig. 2: Demand repetition maps and installed capacity lines of each building [8]

points scatter and the CGS is not very effective when CGS is operated according to electric demand. However the points distribute in the high CO_2-reduction-rate region shown in Fig. 1 (c), when it is operated for heat demand. This indicates that the houses should be connected to the grid in heat-demand operation; this has the important meaning of networking CGS.

Figure 3 shows the effective CO_2 reduction coefficient, ζ, for the CGS power-size relative to the demand. The figure indicates that the optimum CGS power should be ca. 0.8 of the average electric demand for hotels and hospitals. The CGS size is larger for houses and the effectiveness becomes significantly high for the heat demand operation, indicating the importance of grid networking. It can be seen that CGS is not effective in stores and offices, in which CO_2 reduction rate can be even negative in electric-demand operation.

Figure 4 shows the effective cost reduction coefficient in electric-demand operation. The abscissa is heat/electricity demand ratio in a year (Q_m/E_m). The data arrange on a curve except for office, and they have the maximum value at the Q_m/E_m ratio in the range 0.8-1.5.

Figure 5 is the effective CO_2 reduction coefficient in heat-demand operation. The data arrange on a curve regardless of the building types and the value becomes high at the Q_m/E_m ratio greater than 2.0. This indicates that the CGS is effective for the buildings with large heat demand, when reversed electric connection to the grid is accepted. In Japan most of the buildings have Q_m/E_m ratio less than 2.0, and only houses have greater values than 2.0.

4. EFFECT OF NETWERKING CGS TO GRID

As seen in the previous section, using excessive electricity from CGS by connecting it to the grid is significant for the reduction of CO_2. In general, particularly in present Japan, it is limited to connect and reverse the excessive electricity to the grid. This is because power companies dislike the fluctuation of the voltage and, more than that, decreased electric demand. Thus author proposed a concept of cooperative cogeneration network system [5], which is similar to the smart grid. In the concept a power company leases CGS systems to users and controls the operation through information line. The system equips heat-storage-devices and operates cooperatively to the grid. With this

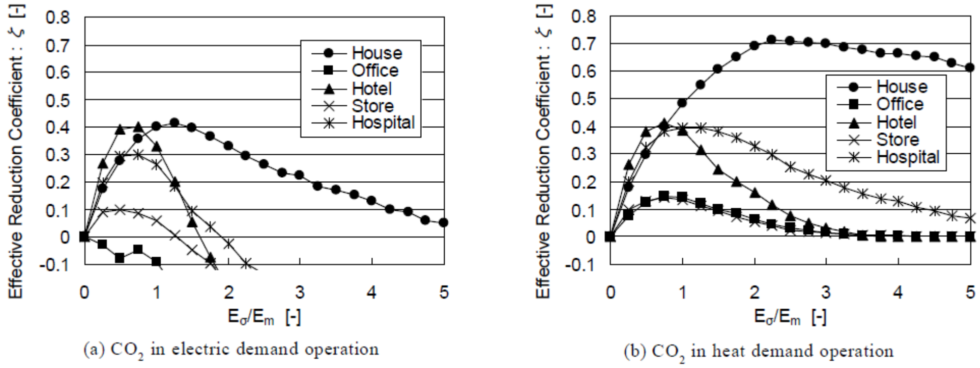


Fig. 3: Effective reduction coefficient changes for the ratio of (CGS electric power)/(average electric demand) [8]

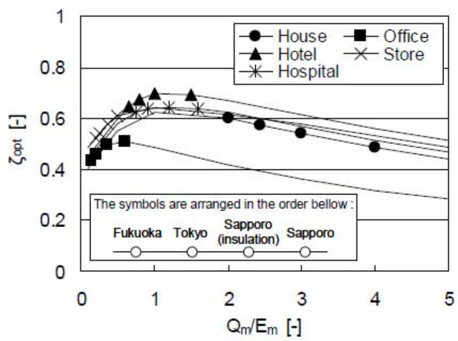


Fig. 4: Effective reduction coefficient of running cost with optimal installed capacity for electric demand operation. The symbols indicate the values for the four major city conditions [8].

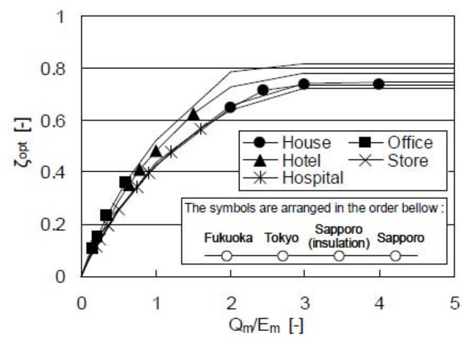


Fig. 5: Effective reduction coefficient of CO_2 with optimal installed capacity for heat demand operation [8]

system voltage fluctuation can be controlled flat and the security potential of the society is increased significantly for disasters.

Analysis was made for an area involving large numbers of residential houses in Sapporo city, as the networking is effective for houses as seen in the previous section [7]. The operation was limited to keep the grid voltage variation within the regulated values. Additionally the excessive electricity is consumed in the feeder line and further reverse flow over the transformer substation is prohibited. In the analysis most of the houses are assumed large apartment buildings, and cooling in summer time is made by absorption heat pump using the heat from CGS. The capacity of the CGS systems is optimized to be cost minimum including initial cost for the each operation case.

Figure 6 is the annual cost and CO_2 reduction rates of the total buildings in the area by the CGS introduction, comparing four operating patterns: (1) switching heat and electric demand operation to avoid wasting heat without grid connection, (2) electric demand operation with no reverse flow of electricity to the grid, (3) heat demand operation with the limitation from the grid as explained above, and (4) cooperative operation to the grid with the heat storage device in the limitation from the grid. In the last case the heat storage capacity is set at

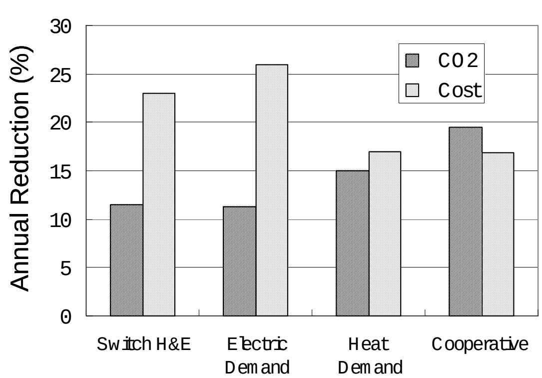


Fig. 6: Annual CO_2 emission and cost for the 4 cases of grid connection and operation patterns [7]

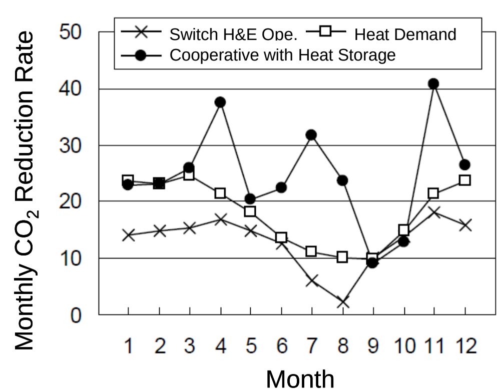


Fig. 7: CO_2 reduction rates in each month [7]

	Load pattern	Network of heat utilization	Interconnection with power grid
Case0	Constant	Available	Available
Case1	Variable	Non	Non
Case2	Variable	Non	Available
Case3	Variable	Available	Available

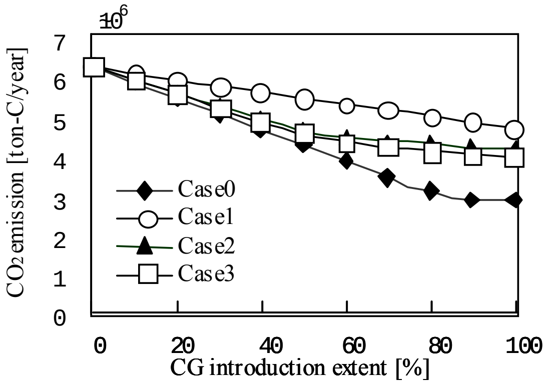


Fig. 8: Comparison of CO_2 emissions from public buildings in all Hokkaido area for the different network conditions: the abscissa is the floor area percentage of CG introduction [5]

one-day need. The result shows that the CO_2 reduction rate becomes 20% by the cooperative networking; this value is almost identical to the ideal value at rated point as shown in Table 3 multiplied by 0.75, the maximum value in Fig. 5. The rate is 15% with heat-demand operation without heat storage, and it is 11% with electric-demand operation, which is equivalent to the present system with no grid connection. The cost reduction rate is the maximum with the electric-demand operation. This is due to the cheap price of the reversed electricity as shown in Table 2. To promote the networking for CO_2 reduction, it is necessary to raise the reversed electricity price.

Figure 7 is the monthly CO_2 reduction rates for the three operations. It shows significant difference between the cooperative operation and the other two operations, particularly in April, July and November. This is due to the fact that electric demand and heat demand does not match well in April and November, and heat storage system effectively compensates the time difference of the two demands. In August the heat demand for absorption heat pump contributes to the improved reduction rate in the cooperative system.

In the next effect of CGS networking was evaluated for the public buildings in Hokkaido area in Japan, including 212 cities and towns. In Fig. 8 the abscissa is the percentage of the floor area with CGS relative to the whole floor area. The case 0 assumes constant electric and heat demand with averaged annual values, showing ideal case for the maximum CGS potential. Case 1 has no networking and CGS works independently in each building. Case 3 has heat network with pipe lines as in European cities as well as electric network. The figure shows that networking of electricity significantly decreases CO_2 emission compared to the case 1, which is no network. Additionally the simple electric network in Case 2 has the equivalent effect with the system with heat network, Case 3. This suggests that heat network with hot water piping is not necessary if the electric network is available for CGS. When the CGS floor area exceeds 50%, the CO_2 reduction effect starts saturating due to the limitation by nuclear power plant. The figure shows that the yearly CO_2 reduction rate for the installation of 1 kW of CGS corresponds to 880kg-C/(year*kW) in the case of grid connection, whereas it is 350kg-C/(year*kW) without grid connection.

5. COMPARISON WITH HEAT PUMPS

Establishment of large networks of CGS in the society is a big project and it must be evaluated comparing with heat pumps, which can exhibit their maximum performance without networking. In this section effect of CO_2 reduction rate is compared between CGS networks and heat pumps with the condition of improved efficiency: the improved system in the future is termed "prospective" in the paper. Prospective power plant efficiency is set 50% and CGS efficiency is 45%. The COP dependency of heat pump on ambient temperature

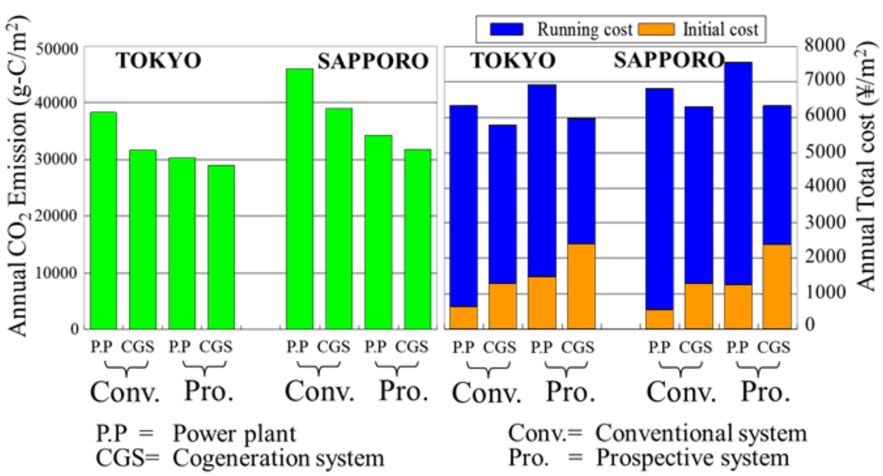


Fig. 9: Comparison of annual CO_2 emissions and cost between conventional and prospective systems (Hotel, Tokyo & Sapporo) [10]

Table 1: Annual energy demand in Tokyo

and demands was calculated. Approximate COP of heat pump was about 4.5 in Tokyo and 3.2 in Sapporo in winter. If heat pumps can't supply heat for the demand sufficiently, electrical heater backs up the heat pump and boiler backs up in the prospective CGS.

Figure 9 is the results of the analysis for Tokyo (warmer climate) and for Sapporo (colder climate). It shows the annual CO_2 emissions and costs in heat demand operation for hotels in each system. The "Conv. P.P" and "Conv. CGS" indicates the conventional system with the condition shown previously. The "Pro. P.P" is the prospective electric system with heat from improved heat pump and electric heater, whose electricity is supplied from the efficient power plant. The result shows that CGS emits smaller amount of CO_2 than heat pump system in the two regions, but the difference is smaller in Tokyo area. Although the initial costs of the prospective CGS are higher than heat pump, its running cost is lower and the total benefit is larger than heat pump. It should be noted that CGS must also have good efficiency of electric generation to be competitive to the prospective heat pumps.

5. CONCLUSIONS

(1) Generalized evaluation-method was proposed for cost and CO_2 reduction with CGS compared to the conventional system. It showed that the cost and CO_2 reduction rates roughly become a simple function of heat/electricity ratio (*Qm/Em*) of annual demand. Cost reduction becomes the maximum at the ratio of ca. 0.8-1.5, and its value is 0.65 times the value in Table 3, which is the ideal maximum value for the rated power point. When reversed grid connection is possible, CO_2 reduction becomes the maximum at the *Qm/Em* ratio of ca. over 2.0, and the value becomes 0.7 times the value in Table 3.

(2) Introduction of CGS must be made in appropriate buildings with right operation patterns in order to have effective reduction of CO_2. In some cases it is possible to even increase CO_2 when economic advantage is only concerned.

(3) Houses have the great potential of reducing CO_2, and reversed electric connection to the power grid is essential to maximize the potential. In the large number of connections cooperative operation with heat storage system increases the CO_2 reduction rate to the maximum ideal vale, and it contributes to the flattening of the electric demand in the grid.

(4) When CGS is networked to the grid, heat is effectively used and hot water line is unnecessary. In the case of introducing CGS network in Hokkaido area, CO_2 reduction rate becomes 880kg-C/(year*kW), whereas it is 350kg-C/(year*kW) without grid connection.

(5) In the improved efficiency of power plants and heat pumps in the future, heat pumps have large CO_2 reduction effect, but cogenerations still have greater effect particularly in the cold climate regions. In this case CGS must also have good efficiency of electric generation to be competitive to heat pumps.

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7. REFERENCES

[1] G. Georgiades, T. Chikahisa, Y. Hishinuma, and Y. Fujiwara, *Proc. of Int. Joint Power Generation Conference (IJPGC'99)*, pp153-160, 1999

[2] T. Chikahisa, C. Georgiades, Y. Hishinuma, and Y. Fujiwara, "A Method for Determining Location and Optimum Service Area of a District Heating Network with Cogeneration and Application Results", *Trans. of JSME Series B*, vol. 66, no. 642, pp. 539-546, 2000 (in Japanese)

[3] K. Kawakami, T. Chikahisa and Y. Hishinuma, "Analysis of Cogeneration Network Systems Effective for Reducing Greenhouse Gases", *Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies*: vol. I: pp. 1713-1716, 2002

[4] T. Chikahisa and Y. Hishinuma, "Basic Characteristics of Performance and Strategy to Maximize CO_2 Reduction Extent of Cogeneration Systems", *Proceedings of International Conference on Power Engineering –03*, pp. 2.43-49, 2003

[5] T. Chikahisa and Y. Iwasa, "Concept of Cooperative Cogeneration Network System and CO_2 Reduction Potential", *Proceedings of the Thermal Engineering Division Conference, Japan Society of Mechanical Engineers*, 2003 (in Japanese)

[6] T. Chikahisa, Y. Hishinuma, and T. Nanba, "Evaluation of Cogenerations on Carbon Dioxide Reduction and Economy (Comparison for Building Types, Districts, and Cooling Systems)", *Trans. of Japan Society of Mechanical Engineers, Series B*, vol. 71, no. 706, pp. 1671-1677, 2005 (in Japanese)

[7] Y. Iwasa, Y. Tabe, and T. Chikahsa, "Carbon Dioxide Reduction an Load Leveling Effect of Distributed Cooperative Cogeneration Network System with Considering Power Limitations in Distribution Grids", *Transaction of the Society of Heating, Air-Conditioning Sanitary Engineers of Japan*, no.104, pp19-27, 2005 (in Japanese)

[8] Y. Iwasa, K. Kawakami, Y. Tabe, and T. Chikahisa, "MAPPING Method to Evaluate CO_2 Reduction and Economy of Cogeneration Systems", *Transaction of Japan Society f Mechanical Engineers, Series B*, vol. 71. No. 714, pp. 469-475, 2006 (in Japanese)

[9] T. Chikahisa, "Dependence of CO_2 Reduction Potential of Cogeneration Systems on Operating Conditions and Its Optimal Design", *Proceedings of Third Symposium on Environment and Energy in National Institute of Advanced Industrial Science and Technology of Japan*, pp.3-14, 2006 (in Japanese)

[10] K.S.S. Naing, Y. Tabe and T. Chikahisa, "Analysis of CO_2 Emission in Prospective Distributed Energy Systems with CGS and Heat Pump", *Proceedings of the Thermal Engineering Division Conference, Japan Society of Mechanical Engineers*, 2007