Computational Study on Energy Savings and CO_2 Reduction from Combined Heat and Power with Chemical Heat Storage

Yoshikazu Shirai and Noriko Osaka

***Abstract*—The potential of chemical heat storage (CHS) for saving energy and reducing CO_2 emissions through more effective utilization of combined heat and power systems (CHP) was evaluated using a mathematical model based on linear programming. The mathematical model constructed in this study can be used to minimize the total cost in industrial factories by optimizing the capacity and operational performance of the energy supply equipment. CHP utilization, total primary energy consumption, and total CO_2 emissions were calculated from the optimized results. Optimization and calculation were conducted for selected food factory and automobile factory in Japan. It was assumed that their energy system consisted of a power grid, boiler, gas engines or gas turbines as CHP, along with CHS using MgO/H_2O materials. In the case of the food factory, the potential of CHS for saving energy and reducing CO_2 emissions could not be confirmed because the energy supply could be optimized without CHS, using only the power grid, CHP, and boiler. On the other hand, for the automobile factory, CHS improved CHP utilization by 2.1%, and reduced total primary energy consumption and total CO_2 emissions by 1.4% and 1.5%, respectively.**

***Index Terms*—Combined heat and power, chemical heat storage, linear programming.**

I. Introduction

The use of combined heat and power (CHP) devices (such as gas engines (GE) and gas turbines (GT)), also known as cogeneration, has been growing rapidly in response to efforts to save energy and prevent global warming [1]. CHP can simultaneously generate both electricity and heat from a single fuel source like natural gas, oil, or liquefied propane. Total energy efficiency of CHP reaches 70–85%. Moreover, it is estimated that CHP can potentially reduce primary energy consumption by 40% and CO_2 emissions by 30%, compared with the case in which electricity is purchased from the national power grid and heat is supplied by a gas boiler. This is because of lower transportation and distribution losses in the former case [2]. However, in factories, there are some cases where CHP are forced to operate at lower partial loads due to a lack of immediate demand for heating and cooling systems, hot-water supply, and industrial processes. This is because of shifts in hourly heat demand related to the business hours of offices and factories. If heat generated by CHP could be better managed temporally, there is a possibility that the utilization of CHP could be improved.

Heat storage systems are technological systems for managing heat through storage and release, and may be categorized as sensible heat storage, latent heat storage, and chemical heat storage (CHS) systems. CHS works on the principle of chemical reaction and has advantages of higher heat storage densities (~3,000 kJ/kg) and longer-term storage than other systems. The heat storage process involves a decomposition reaction with the aid of heat input, with heat energy converted into internal energy and simultaneously stored. On the other hand, the heat release process is promoted through a composition reaction, with reaction products stored separately. By selecting appropriate materials, heat energy can be stored at any temperature range. Table I shows the properties of typical CHS materials [3]-[6]. There have been several studies looking at improving material properties, such as heat storage speed and durability of materials [3]-[8]. However, studies of the potential for reducing energy consumption and CO_2 emissions are limited.

The objective of the present study was to evaluate the potential of CHS for saving energy and reducing CO_2 emissions through more effective utilization of CHP using a mathematical model. The mathematical model was constructed using linear programming, which is the simplest optimizing programming for an initial evaluation. The scope of this work was to optimize equipment capacity and operational performance to minimize the total cost in selected food and automobile factories in Japan. Based on the optimization results, CHP utilization, total primary energy consumption, and total CO_2 emissions in relation to CHS potential were calculated.

II. Method

A. Mathematical Model

To optimize capacity and operational performance of equipment in factories, the mathematical model was constructed based on linear programming. The numerical optimizer V16 [9] was used as a solver in the present study.

TABLE I: Chemical Heat Storage Properties

Materials	Storage temperature (℃)	Release temperature (℃))	Storage density (GJ/m3)	Ref.
Na_2S/H_2O	83	35	2.8	[3]
MgSO4/H_2O	122–150	122	1.5	[4]
MgO/H_2O	250–350	110	1.0–1.5	[5]
CaO/H_2O	500		1.0–1.5	[6]

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Table II shows the definitions of the symbols used. Fig. 1 shows the configurations of the industrial energy systems assumed in the model, including grid power, CHP, and boiler, both (a) without and (b) with CHS. In the model, grid power was generated at a power plant fueled by natural gas. CHP generated both power and heat from natural gas. The boiler generated heat from natural gas. In the case of (b), CHS was added to the system shown in (a) to control the heat generated by CHP. Natural gas, power, and heat represented the amount of energy, disregarding the heating media (steam or hot water) and temperature range.

TABLE II: DEFINITION OF SYMBOLS

Symbol	Unit	Definition
t	Hour	Time
n	Day	Payout time
$f1(t)$	kWh	Natural gas for power grid
$f2(t)$	kWh	Natural gas for CHP
$f3(t)$	kWh	Natural gas for boiler
$f4(t)$	kWh	Power generated by power plant (power grid)
$f5(t)$	kWh	Power generated by CHP
$f6(t)$	kWh	Heat generated by CHP
$f7(t)$	kWh	Heat generated by CHP and CHS
$f8(t)$	kWh	Heat generated by boiler
$d1(t)$	kWh	Power demand
$d2(t)$	kWh	Heat demand
$s1(t)$	kWh	Amount of heat storage
$\eta(t)$	%	Rate of part-load of CHP
$\eta(t)$_min	%	Minimum rate of part-load of CHP
$e1$	%	Power generation efficiency of power plant
$e2(\eta(t))$	%	Power generation efficiency of CHP
$e3(\eta(t))$	%	Heat generation efficiency of CHP
$e4$	%	Heat generation efficiency of boiler
$e5$	%	Heat storage efficiency of CHS
$e6$	%	Heat release efficiency of CHS
$p1$	kW	Capacity of CHP
$p2$	kW	Capacity of boiler
$p3$	kWh	Capacity of CHS
$c1$	JPY/kWh	Specific cost of power grid
$c2$	JPY/kWh	Specific cost of natural gas
$c3$	JPY/kWh	Base cost of power grid
$c4$	JPY	Base cost of natural gas (fixed)
$c5$	JPY/kW	Base cost of natural gas (depending on equipment capacity)
$c6$	JPY/kW	Investment cost per capacity of CHP
$c7$	JPY/kW	Maintenance cost per power generated by CHP
$CT1$	JPY	Total cost
$CT2$	JPY	Operation cost
$CT3$	JPY	Investment cost
$CT4$	JPY	Maintenance cost
$U1$	%	Average CHP utilization
$U2$	%	Average boiler utilization
$PE1$	MWh	Total primary energy
$PE2$	MWh	Primary energy for power grid
$PE3$	MWh	Primary energy for CHP
$PE4$	MWh	Primary energy for boiler
$o1$	kg/kWh	Specific CO_2 emissions of power grid
$o2$	kg/kWh	Specific CO_2 emissions of natural gas
$CE1$	ton	Total CO_2 emissions
$CE2$	ton	CO_2 emissions from power grid
$CE3$	ton	CO_2 emissions from CHP
$CE4$	ton	CO_2 emissions from boiler

To consider the energy balance of these systems, the output energy of each device was determined by multiplying its input energy by its energy efficiency as per Eq. (1)–(4):

$$f4(t) = e1 \times f1(t) \tag{1}$$

$$f5(t) = e2(\eta(t)) \times f2(t) \tag{2}$$

$$f6(t) = e3(\eta(t)) \times f2(t) \tag{3}$$

$$f8(t) = e4 \times f3(t) \tag{4}$$

Storage and radiation modes of CHS were defined as operational modes for considering actual operational conditions. The switch from storage mode to radiation mode was set to occur when the amount of heat stored was equal to heat storage capacity. On the other hand, the switch from radiation mode to storage mode was set to occur when the amount of heat stored was zero, as per Eq. (5):

$$\begin{cases} f7(t) = f6(t) & \text{for (a) without CHS} \\ f7(t) = (1 - e5) \times f6(t) & \text{for (b) with CHS at storage mode} \\ f7(t) = (1 + e6) \times f6(t) & \text{for (b) with CHS at release mode} \end{cases} \tag{5}$$

Power demand matched the sum of power grid and power-generated by CHP; and heat demand matched the sum of heat generated by CHP and boiler, as per Eq. (6)–(7):

$$d1(t) = f4(t) + f5(t) \tag{6}$$

$$d2(t) = f7(t) + f8(t) \tag{7}$$

The decrease in efficiency due to CHP partial-loading depends on a linear decrease in each section of the part-loads ($a < \eta(t)$ at $< a + 25$; $a = 0, 25, 50, 75$), as per Eq. (8)–(9):

$$e1(\eta(t)) = e1(a) + \frac{e1(a+25) - e1(a)}{25} \times (\eta(t) - a) \tag{8}$$

$$e2(\eta(t)) = e2(a) + \frac{e2(a+25) - e2(a)}{25} \times (\eta(t) - a) \tag{9}$$

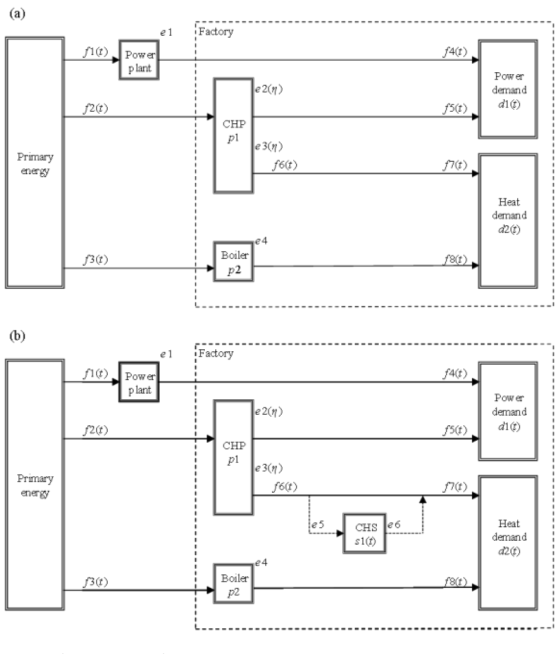

Fig. 1. Configuration of industrial energy system: (a) without CHS and (b) with CHS

The mathematical model consisting of Eq. (1)–(9) can be used to determine the optimal capacity and operational performance of the equipment used for energy supply, in relation to minimized total cost. Then, total cost was the sum of investment, operational, and maintenance costs, as shown in Eq. (10):

$$CT1 = CT2 + CT3 + CT4 \tag{10}$$

Operational costs included the cost of the power grid [10] and natural gas for the CHP and boiler [11], expressed by the calculation formulae shown in Eq. (11):

$$\begin{aligned} CT2 = & \sum(c1 \times f5(t) + c2 \times (f2(t) + f3(t)) \\ & + \left\{(c3 \times f5(t)_{\max}) + c4 + c5 \times \sum\left(\frac{p1}{e2(100)} + \frac{p2}{e4}\right)\right\} \times \frac{1}{30} \end{aligned} \tag{11}$$

Investment and maintenance costs of system were approximated using the optimized capacity of CHP and the power generated by CHP [12], as shown in Eq. (12)–(13):

$$CT3 = \frac{c6 \times p1}{n} \tag{12}$$

$$CT4 = c7 \times \sum(f5(t)) \tag{13}$$

The average utilization rates of CHP and boiler, power consumption, natural gas consumption, and CO_2 emissions were calculated using the optimized results, as shown in Eq. (14)–(15):

$$U1 = \frac{\sum f5(t)}{p1 \times 24} \tag{14}$$

$$U2 = \frac{\sum f8(t)}{p1 \times 24} \tag{15}$$

The primary energy consumption was calculated using the optimized results, as shown in Eq. (16)–(19):

$$PE1 = PE2 + PE3 + PE4 \tag{16}$$

$$PE2 = \frac{\sum(f1(t))}{1000} \tag{17}$$

$$PE3 = \frac{\sum(f2(t))}{1000} \tag{18}$$

$$PE4 = \frac{\sum(f3(t))}{1000} \tag{19}$$

The CO_2 emissions were calculated using the optimized results, as shown in Eq. (20)–(23):

$$CE1 = CE2 + CE3 + CE4 \tag{20}$$

$$CE2 = \sum(f4(t)) \times o1 \tag{21}$$

$$CE3 = \sum(f2(t)) \times o2 \tag{22}$$

$$CE4 = \sum(f3(t)) \times o2 \tag{23}$$

B. Calculation Conditions

The payout time was set to 3650 days (10 yr). The data from 62 GEs and 73 GTs commercialized in Japan were used to represent the capacity and energy efficiency of the CHP [2], and the minimum rate of the CHP partial-load was set to 50%. Power generation efficiency of the power plant and heat generation efficiency of the boiler were set to 36.9% and 90%, respectively. The CHS material was assumed to be MgO/H_2O because its heat storage temperature covers the temperature range of exhaust gas from the internal combustion engine of the CHP. Based on a previous study, heat storage and release efficiencies of the CHS were both set to 30% [7].

TABLE III: VALUE OF CONSTANT PARAMETERS

Symbol	Unit	Value	Ref.
$c1$	JPY/kWh	14.74	[10]
$c2$	JPY/kWh	7.27	[11]
$c3$	JPY/kWh	1576.8	[10]
$c4$	JPY	14256	[11]
$c5$	JPY/kW	38.95	[11]
$c6$	JPY/kW	150000 (GT), 200000 (GE)	[12]
$c7$	JPY/kWh	2 (GT), 3 (GE)	[12]
$o1$	kg/kWh	0.521	[13]
$o2$	kg/kWh	0.183	[14]

Table III shows the constant parameters of power grid and natural gas obtained from values published by the energy companies in Japan [10]-[14]. Investment cost per unit capacity of the CHP, and maintenance cost per unit power generated by CHP were used to average the interview values from industrial companies in Japan. Hourly trend data from selected food and automobile factories in Japan were used to represent power and heat demand, as shown Fig. 2 and Fig. 3.

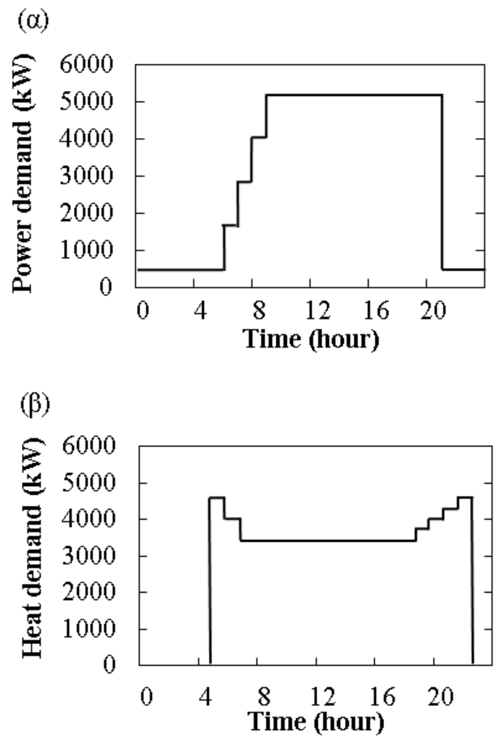

Fig. 2. Trends of (α) power and (β) heat demand of the food factory.

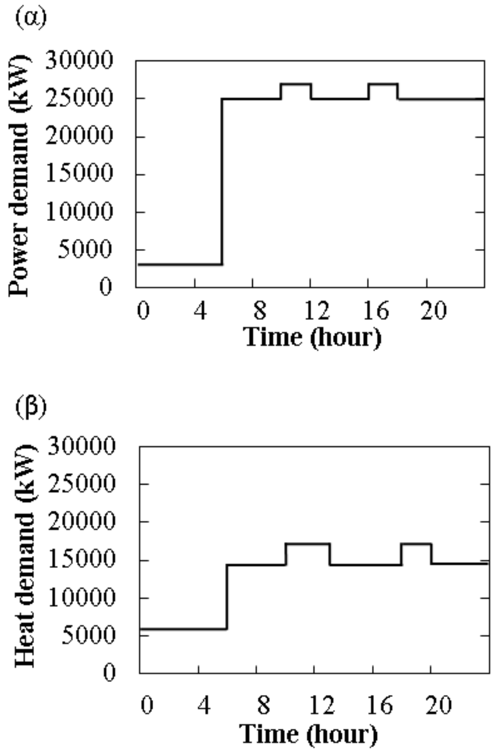

Fig. 3. Trends of (α) power and (β) heat demand of the automobile factory.

III. Results and Discussion

A. Food Factory

Fig. 4 shows the trend of optimized power and heat supply of the food factory. A GE of 3800 kW and a 4550 kW boiler were used to minimize total cost in both configurations (i.e., with and without CHS). Thus, no potential for energy savings and CO_2 reduction from use of a CHS was confirmed.

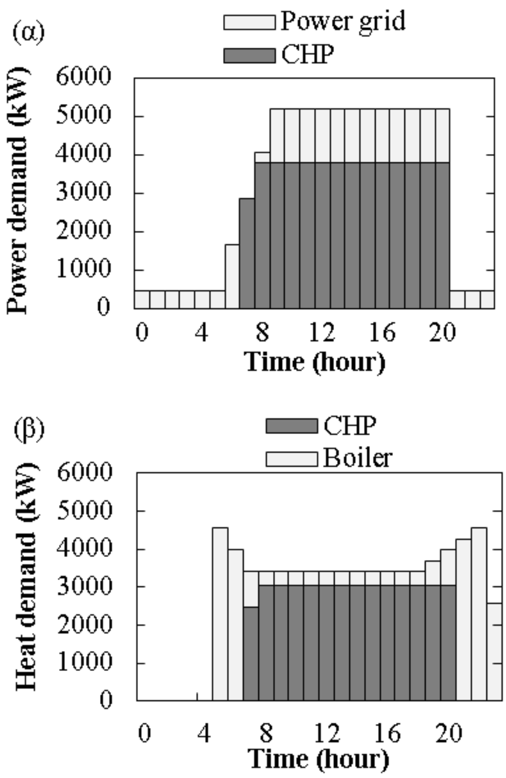

Fig. 4. Optimized trends of (α) power supply and (β) heat supply of the food factory in both configurations (i.e., with and without CHS).

TABLE IV: Summary of Food Factory Calculations

		Unit	Value
Utilization	CHP	%	57.3
	Boiler	%	24.1
Cost	Total	Million JPY/d	1.8
Primary energy consumption	Total	MWh/d	204.7
	Grid power	MWh/d	61.7
	CHP	MWh/d	113.8
	Boiler	MWh/d	29.2
CO_2 emissions	Total	t/d	38.0
	Grid power	t/d	11.9
	CHP	t/d	20.8
	Boiler	t/d	5.4

The GE supplied 3800 kW of power and 3057 kW of heat, corresponding to a rated load from 08.00 h to 20.00 h Moreover, the GE supplied 2850 kW of power and 2463 kW of heat, corresponding to 75% partial-load from 7.00 h to 8.00 h, depending on the heat demand of the food factory. On the other hand, the GE stopped operating from 20.00 h to 08.00 h because the demand for power and heat was lower than the GE energy supplied at 50% partial-load; operation of the GE would thus result in power and heat surplus. Average GE utilization was calculated to be 57.3%. The boiler operated from 05.00 h to 12.00 h and stopped operating from 00.00 h to 05.00 h, depending on the heat demand of the food factory. Average utilization of the boiler was calculated to be 24.1%. The power grid supply was constant, except between 07.00 h and 08.00 h.

Table IV summarizes the food-factory calculation results. Total cost, total primary energy consumption, and total CO_2 emissions were calculated to be 1.8 million JPY/d, 204.7 MWh/d, and 38.0 t/d, respectively.

B. Automobile Factory

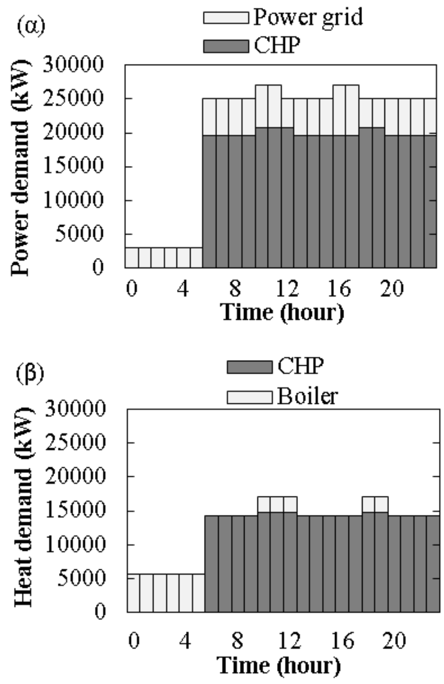

Fig. 5. Optimized trends of (α) power supply and (β) heat supply for automobile factory without CHS.

Figs. 5 and 6 show the trend of optimized power and heat supply of an automobile factory (a) without CHS and (b) with CHS. In the case of (a), four 5200-kW GEs and a 700-kW boiler were selected as the optimized CHP and boiler. The GEs supplied 20,800 kW of power and 14,815 kW of heat, corresponding to the rated load from 10.00 h to 13.00 h. Moreover, the GEs supplied 19,593 kW of power and 14,215 kW of heat, corresponding to 95% partial-load from 06.00 h to 10.00 h, from 13.00 h to 18.00 h, and from 20.00 h to 00.00 h, depending on the heat demand of the factory. On the other hand, the GEs stopped operating from 00.00 h to 06.00 h because power and heat demand were less than the GE energy supplied at 50% partial-load; power and heat surpluses would thus occur with GE operation. Average GE utilization was calculated to be 71.9%. The boiler operated from 00.00 h to 06.00 h, from 10.00 h to 13.00 h, and from 18.00 h to 20.00 h, depending on the heat demand of the automobile factory. Average boiler utilization was calculated to be 33.1%. Power grid supply was always provided. Total cost, total primary energy consumption, and total CO_2 emissions were 10.1 million JPY/d, 1102.9 MWh/d, and 204.8 t/d, respectively.

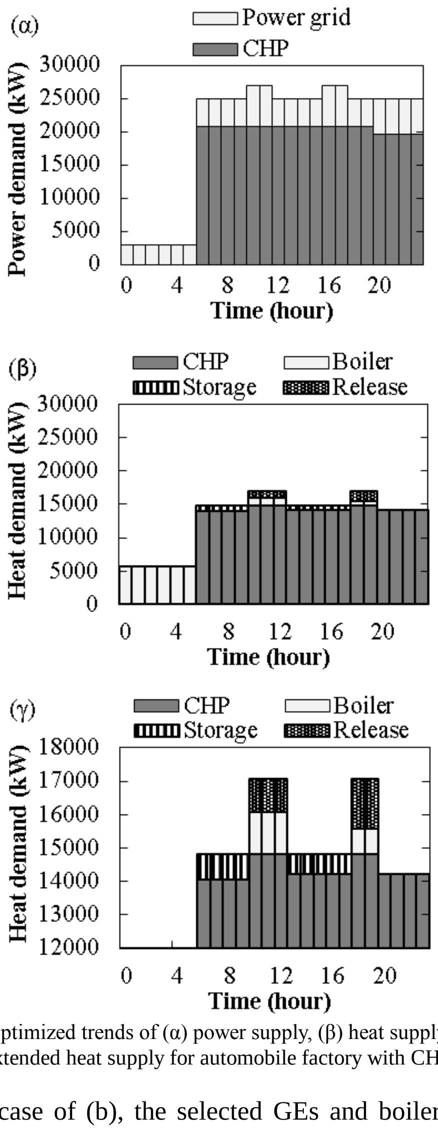

Fig. 6. Optimized trends of (α) power supply, (β) heat supply, and (γ) extended heat supply for automobile factory with CHS.

In the case of (b), the selected GEs and boiler were the same as in the case of (a). A 3000-kWh CHS was selected that stored 750 W of heat from 06.00 h to 10.00 h and 600 W of heat from 13.00 h to 18.00 h. On the other hand, the CHS released 1000 kW of heat from 10.00 h to 13.00 h, and 1500 kW of heat from 18.00 h to 20.00 h. Owing to the storage of heat by the GEs, the GE load improved to 100% from 06.00 h to 10.00 h and from 13.00 h to 18.00 h. The GEs started and stopped operating at the same times as in case (a). Average GE utilization was 74.0%. The boiler operated at the same time as in case (a) and the boiler load decreased, depending on the improvement in the GE operational load. Average boiler utilization was 29.2%. Total cost, total primary energy consumption, and total CO_2 emissions were 10.0 million JPY/d, 1087.8 MWh/d, and 201.7 t/d, respectively.

TABLE V: SUMMARY OF AUTOMOBILE FACTORY CALCULATIONS

		Unit	(a) Without CHS	(b) With CHS	CHS contribution
Utilization	CHP	%	71.9	74.0	2.1
	Boiler	%	33.1	29.2	-3.9
Cost	Total	Million JPY/d	10.1	10.0	-0.1
Primary energy consumption	Total	MWh/d	1102.9	1087.8	-15.1
	Grid power	MWh/d	317.8	288.4	-29.4
	CHP	MWh/d	734.7	755.0	20.3
	Boiler	MWh/d	50.4	44.4	-6.0
CO_2 emissions	Total	t/d	204.8	201.7	-3.0
	Grid power	t/d	61.1	55.4	-5.7
	CHP	t/d	134.4	138.2	3.7
	Boiler	t/d	9.2	8.1	-1.1

Table V summarizes the calculations for the automobile factory. CHS increased CHP utilization by 2.1%. Total cost was reduced by 0.9% because CHP had a lower energy cost (10.0 JPY/kWh power and 3.7 JPY/kWh heat) than the power grid (17.1 JPY/kWh power) and boiler (8.0JPY/kWh heat). In addition, total primary energy consumption and total CO_2 emissions were reduced by 1.4% and 1.5%, respectively, because the CHP had higher energy efficiency than both power grid and boiler.

IV. CONCLUSIONS

To evaluate the potential of CHS for saving energy, and for CO_2 reduction associated with more effective utilization of CHP, a computational study using a simple mathematical model was conducted for selected food and automobile factories in Japan. Based on this study, the following conclusions were drawn.

1) In the case of a selected food factory in Japan, no potential for energy savings and CO_2 reduction from use of a CHS was confirmed, because the energy supply could be optimized via the power grid, CHP, and boiler, without the use of a CHS.
2) In the case of a selected automobile factory in Japan, CHS could improve CHP utilization by 2.1% and reduce total primary energy consumption and total CO_2 emissions by 1.4% and 1.5%, respectively.

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