Design Methodology for Ecologically and Economically Optimizing Scheme for Introduction of Co-generation Systems

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Abstract

A life cycle impact assessment methodology is applied to specific co-generation energy systems consisting of gas turbines or gas engines, and then used to minimize the CO_2 emissions and environmental impacts during system operations. The operating costs of the system are estimated, too. These results are compared with those of ordinary energy systems. First, the energy demands of various facilities, including hotels, hospitals, office buildings and houses are analyzed. The hourly electricity and heat demands such as space cooling, space heating and hot water are estimated from the statistical data of living energy demands, depending mainly on the floor space for each case study. Second, the energy balances for each energy demand are formulated about whole system and respective system components. The algorithms applied here are the well-known simplex and branch-bound methods to seek optimized eco-operation solutions from objective functions in linear programming. The life cycle assessment-numerical eco-load total standard (LCA-*NETS*) evaluation method proposed by the authors is applied in this paper. The environmental impacts resulting from the specified co-generation systems are then evaluated. In this paper, the advantages and disadvantages of the introduction of co-generation systems are examined from the standpoints of ecological awareness and cost-effectiveness. By introducing the co-generation system to energy supply, the estimation result is 3-19% for environmental impact, 7-22% for CO_2 emission, and 4-22% for Operating cost reductions. The results of this study provide a basis for useful recommendations for distributed power supply systems and further development of sustainable eco-energy supply systems.

1. Introduction

A mass of 11.7×10^8 ton-CO_2 was exhausted in year 2005 in Japan [1]. The amount of CO_2 emitted from electric power plants accounts for 40% of overall CO_2 emissions. Moreover, the input of primary energy to the power sector is approximately 40%, and the resulting environmental impact becomes large. However, the thermal efficiency of the thermal power plant is about 40%, resulting in a very high loss. This loss is exhausted into atmosphere and sea as heat. A co-generation system has been introduced in a facility as an energy conservation system that can make up for the loss and contribute to environmental impact reduction. However, the adoption rate of the co-generation system accounts for only about 2.5% of the total power generation capacity, 2.74×10^8 kW. Therefore, the use of such co-generation systems has not yet become widespread. In ordinary energy systems, a large amount of gas that influences the environmental impact such as CO_2 is exhausted. The reason is that fossil fuels are used for energy demands such as electricity, cooling, heating and hot-water supply in low thermal efficiency. However, if a co-generation system, which makes the most of waste heat from power generator and boiler, is applied to meet the heat demands, CO_2 emission and fossil fuel consumption can be dramatically reduced. The heat demands of the home and business sectors in year 2005 were about 2.72×10^{12} MJ. If these heat demands are met by commercial electricity, 2.86×10^8 ton-CO_2 is exhausted, which represents approximately 24% of total yearly CO_2 emissions. If these heat demands are assumed to be covered by waste heat from the co-generation system, CO_2 emissions can be reduced. Energy conservation is greatly influenced by the heat demand in the operation of the co-generation system. Moreover, the system is operated alone or together with commercial electricity. Therefore, the optimum system configuration and operation of the co-generation system corresponding to electrothermal demand are important. A life cycle assessment (LCA) methodology is applied in this study for the evaluation of the environmental impact of such a co-generation system. In order to determine the optimum operational condition for the electrothermal demands, the multivariable optimization problem is solved. In addition, a method for evaluation of the environmental impact that uses LCA has been developed. Additionally, cost-effectiveness has been considered along with the environmental impact. Moreover, the availability of the introduction of this new co-generation system over a year has been examined.

2. Optimization Method

To obtain optimum operation of a co-generation system from the standpoint of minimizing CO_2 emissions, environmental impacts and operating costs, an optimization technique for electricity and heat flows is introduced. The algorithms applied here are the well-known simplex and branch-bound methods to seek optimized solutions of objective functions in linear programming. In this study, the co-generation systems of the gas turbine or the gas engine are examined.

The gas turbine co-generation system employed here is shown in Figure 1. The symbol *GT* denotes a gas turbine unit, and *BW* denotes a waste heat recovery boiler. *BA*, *RE*, *RS* and *HE* symbolize an auxiliary boiler, an electric turbo refrigerator, a steam absorption refrigerator and a heat exchanger, respectively. A gas turbine is selected here as the main electricity generation equipment. Electricity demand is supplied by commercial electricity and generated electricity. Space cooling is supplied by an electric turbo refrigerator and a steam absorption refrigerator that is driven by waste heat from gas turbines and auxiliary boilers. Space heating and hot water are supplied by a heat exchanger that is driven by waste heat from gas turbines and auxiliary boilers. The commercial electricity and *GT* generator capacity should be able to handle the overall electricity demand and electricity consumption of each type of the above equipments used. Then, Equation (1) is derived for the electricity balance:

$$E_{buy} + E_{GT} = E_{RE} + \sum_i E_i^a + E_{dem} \tag{1}$$

where E_i^a is the electricity required for the operation of elemental machine i. The balance equations of cooling, heating and hot-water supply are derived according to the energy balance. All of the elemental machines composing the co-generation unit are assumed to have a linear function between output and input as expressed by Equation (2):

$$y_i = a \cdot x_i + b \cdot \delta \tag{2}$$

where y_i and x_i are the generated output and the input (e.g., amount of fuel consumption), respectively; a and b are the constants that show the performance of the equipment, and δ is a 0-1 variable that characterizes the on-off state of the equipment. The output of the nth gas turbine, E_{GTn}, is formulated in Equation (3) as an example:

$$E_{GTn} = \frac{E_{GTn,\max} - E_{GTn,\min}}{F_{GTn,\max} - F_{GTn,\min}} \sum_{n=1}^{n=n_{GT}} \left(F_{GTn} - F_{GTn,min}\delta_{GTn} \right) + E_{GTn,min} \sum_{n=1}^{n=n_{GT}} \delta_{GTn} \tag{3}$$

where F is the fuel consumption, and *max* and *min* are the values at maximum and minimum outputs of the equipment, respectively. The equations for other equipment and the gas engine system are not shown for conciseness.

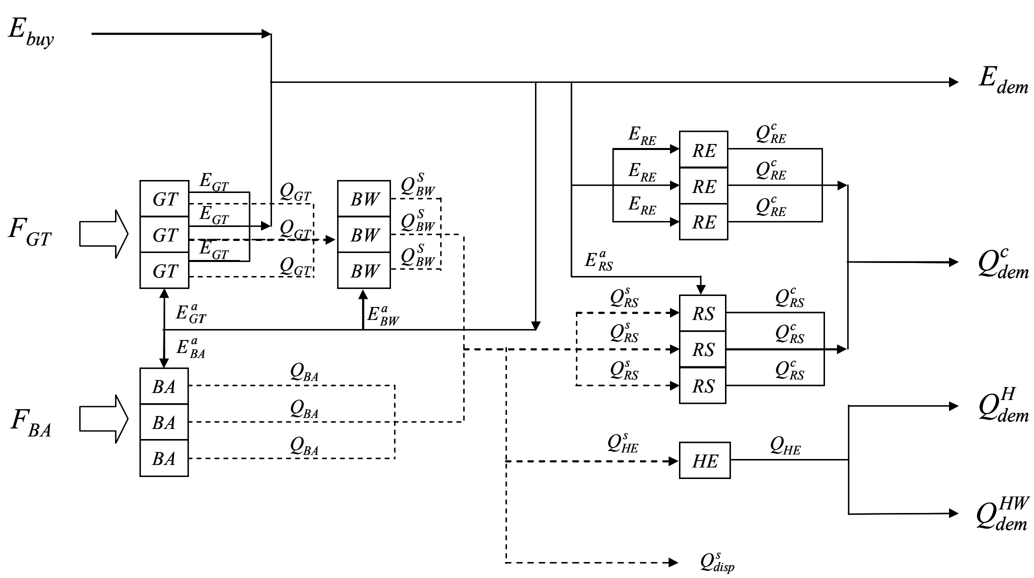

Figure 1. Co-generation system using gas turbine.

3. Evaluation of Co-generation System and Discussion

Prior to evaluating the environmental impact and operating cost, the electricity and heat demands are estimated. The demand per unit floor space is estimated from statistical data from hotels, hospitals, office buildings and houses in the various seasons [2]. The features of energy consumption of each facility can be recognized. In the multiplication of floor space to meet these demands, the energy demands of the facility can be estimated in terms of various scales. Therefore, various evaluations can be carried out under several conditions. In LCA of the co-generation system, the boundary for evaluation is defined for calculating CO_2, NO_X and SO_X emissions, along with resource consumption. The environmental impacts of exhaust gas emission and fuel consumption during the operation are extremely large compared with that of construction and abolition of the system. Thus, only the operating stage is evaluated in this paper.

Since environmental impacts involve various factors, a comprehensive evaluation is important. Therefore, a method proposed by the authors for the integration of environmental impacts, "LCA-*NETS*", is applied in carrying out LCA. By using this method, various environmental impacts are shown by a new consolidated unit, "NETS." For the details of this methodology, see [3] and [4]. The environmental impact factors of fuel consumptions and emissions are estimated in Tables 1 and 2, where *ELM* refers to the environmental load module, that is, the conversion coefficient of environmental impact.

Table 1. *ELM* for fuel consumption and gas emission.

Resource	Coal	LNG	Oil	Uranium	CO_2	NOx
ELM [NETS/kg]	6.12E-04	5.49E-03	4.22E-03	1.53E+02	1.20E-03	1.79E-01

Table 2. *ELM* for commercial electricity and co-generation system.

***ELM* for commercial electricity**				
NO_X emission of commercial electricity			Environmental impact by NO_X emission of commercial electricity	
7.13E-05 [kg/kWh]		=>	1.28E-05 [NETS/kWh]	
SO_X emission of commercial electricity			Environmental impact by SO_X emission of commercial electricity	
1.18E-04 [kg/kWh]			2.72E-05 [NETS/kWh]	
Breakdown of fuel consumption of commercial electricity			Environmental impacts by fuel consumption of commercial electricity	
Coal	5.96E-02 [kg/kWh]		Coal	3.65E-05 [NETS/kWh]
Oil	1.98E-02 [kg/kWh]	=>	Oil	8.35E-05 [NETS/kWh]
LNG	5.91E-02 [kg/kWh]		LNG	3.24E-04 [NETS/kWh]
Uranium	1.13E-06 [kg/kWh]		Uranium	1.74E-04 [NETS/kWh]
			overall	6.18E-04 [NETS/kWh]
CO_2 emission of commercial electricity		=>	Environmental impact by CO_2 emission of commercial electricity.	
3.78E-01 [kg-CO_2/kWh]			4.54E-04 [NETS/kWh]	
***ELM* for cogeneration system**				
Emission factor of CO_2 for use of natural gas		=>	Environmental impact by CO_2 emission by use of natural gas	
2.6923 [kg-CO_2/kg-NG]			3.24E-03 [NETS/kg-NG]	
Emission factor of NO_X for use of natural gas		=>	Environmental impact by NO_X emission by use of natural gas	
5.57E-05 [kg-NOx/kg-NG]			6.12E-05 [NETS/kg-NG]	
			Environmental impact by natural gas use	
			5.49E-03 [NETS/kg-NG]	

***ELM* for commercial electricity**
1.11E-03 [NETS/kWh]
***ELM* for cogeneration system**
8.79E-03 [NETS/kg-NG]

Commercial electricity is assumed to be supplied by thermal, nuclear and hydroelectric power plants. Impacts during the operation stage are evaluated in this study. Only the environmental impact concerning fuel consumption is taken into account for nuclear plants. Hydroelectric power plants are assumed not to have an environmental impact. For the fuel used in the co-generation system, CO_2, NO_X and SO_X emissions, and fuel consumption in operating stage are estimated. Natural gas is assumed to be the fuel for the co-generation system. The numerical value published by the Ministry of the Environment in Japan for CO_2 emissions per 1 kWh of commercial electricity is employed. For economic evaluation, the prices of commercial electricity and natural gas are estimated based on those of electric power companies and town gas, respectively.

A co-generation system evaluation software has been previously developed for environmental impact and economical estimation [5]. This software can automatically determine system configurations by considering the energy demand, equipment capacity, thermal efficiency, etc. Additionally, it can derive the best operating scheme corresponding to the demand only by input of the floor space of a facility. Environmental impact is indicated in consolidated units of NETS, and then CO_2 emissions and operating costs are estimated by this software. The capacity of each elemental machine in the system is set to be one third of the maximum value of each demand, and then the number of equipment units is set at three except for the heat exchanger. The thermal efficiency and coefficient of performance of equipments are set in reference to the average value of actual machines [6]. The floor space of each facility is taken as 20,000 m^2 for this case study. The capacity and the number of equipment units of the co-generation system introduced into a hotel are listed in Table 3.

CO_2 emissions, environmental impacts, and operating costs for a day corresponding to the seasons in the hotel are shown in Figure 2, while those for each month are shown in Figure 3. The results are shown only for the hotel for conciness. The evaluation results over one year for all facilities are listed in Table 4. The result for the ordinary energy system, where the gas turbine generator must be stopped, is also listed for reference.

By introducing the co-generation system to meet the above energy demands, a reduction of 3 to 19% in environmental impacts, 7 to 22% in CO_2 emissions, and 4 to 22% in operating costs is feasible. Thus a co-generation system has a direct advantage over commercial electricity and fuels in this case. As the thermal efficiency of the gas engine is higher than that of the gas turbine in small or medium-scale systems, the superiority of a gas engine co-generation system will be shown. The thermal efficiency of a gas turbine becomes higher in large-scale systems.

In order to show the advantage of the co-generation system, a high heat demand, particularly space heating or hot water, is necessary. The heat demands in a hotel or hospital are relatively higher than those of office buildings over a given year. Therefore the effectiveness and significance of introducing the co-generation system are quite considerable. The advantage of the co-generation systems is shown even in summer from the environmental impacts viewpoint. However, these values depend heavily on the performance of the elemental system components, especially thermal efficiency, although the component performance is set with reference to actual machines in this case study. The thermal efficiency of a gas turbine or a refrigerator depend greatly on their capacity. Therefore, it is very important to tailor the thermal efficiency to the capacity of the machine.

Table 3. Evaluation conditions of co-generation systems for a hotel.

		Capacity of equipments	Efficiency *min*, *max*	Number of equipments
Gas turbine system				
	Gas turbine	200 [kW]	0.28,0.22	3
	Waste heat recovery boiler	1400 [MJ/h]	0.80	3
	Auxiliary boiler	1500 [MJ/h]	0.75,0.85	3
	Electric turbo refrigerator	1500 [MJ/h]	4.0	3
	Steam absorption refrigerator	1500 [MJ/h]	1.2	3
	Heat exchanger		0.90	1
Gas engine system				
	Gas engine	200 [kW]	0.41,0.33	3
	Gas refrigerator	1500 [MJ]	1.18	3
	Gas heating system	1000 [MJ/h]	0.95	3
	Gas boiler	1300 [MJ/h]	0.85,0.95	3
	Hot water absorption refrigerator	1500 [MJ/h]	0.70	3

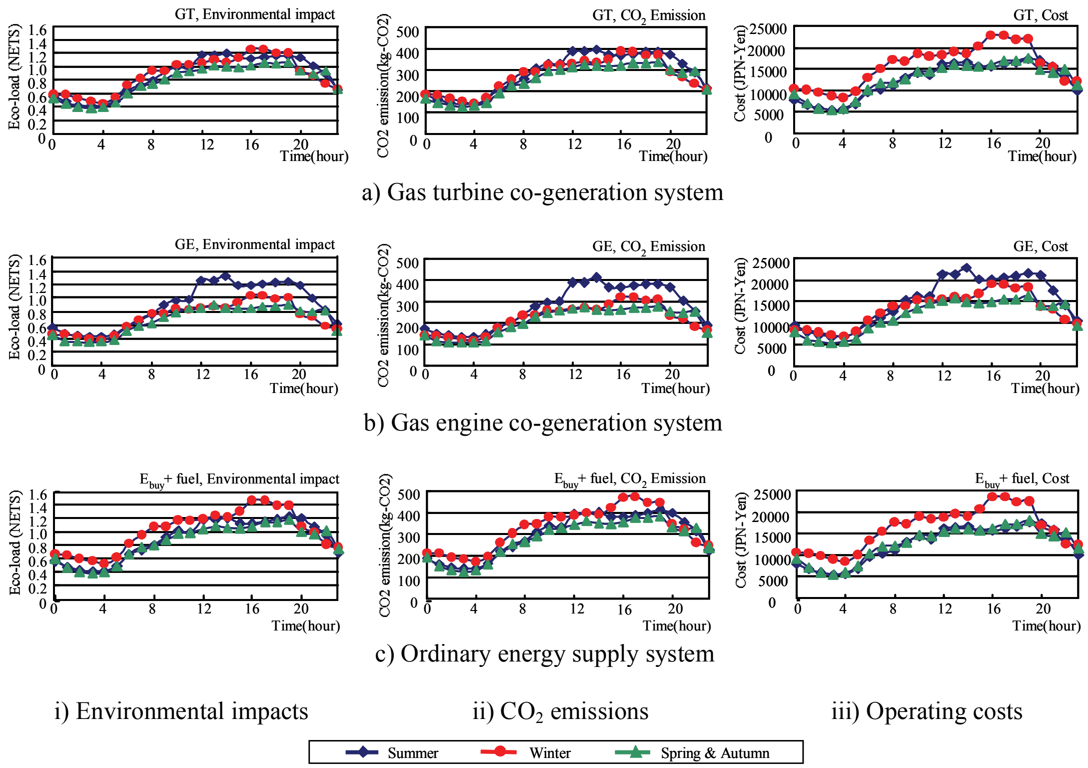

Figure 2. Comparison of environmental impacts and operating costs for a hotel (20,000 m^2).

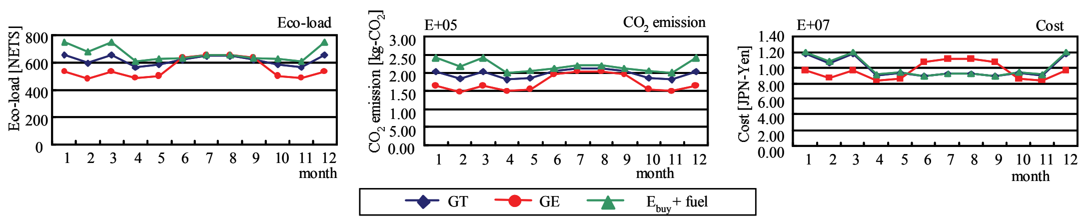

Figure 3. Comparison of monthly environmental impacts and operating costs for a hotel (20,000 m^2).

Table 4. Estimated values of the facilities for one year.

	Gas turbine co-generation system	Gas engine co-generation system	Ordinary energy supply system
Hotel			
CO_2 emission [ton-CO_2]	2,360	2,050	2,620
Environmental impact [NETS]	7,390	6,630	7,980
Operating cost [Million JPN-yen]	119	115	120
Office building			
CO_2 emission [ton-CO_2]	1,480	1,420	1,520
Environmental impact [NETS]	4,420	4,430	4,530
Operating cost [Million JPN-yen]	63	69	63
Hospital			
CO_2 emission [ton-CO_2]	2,100	1,840	2,320
Environmental impact [NETS]	6,580	5,920	7,100
Operating cost [Million JPN-yen]	107	102	108
Condominium			
CO_2 emission [ton-CO_2]	340	290	370
Environmental impact [NETS]	1,070	930	1,160
Operating cost [Million JPN-yen]	18	16	18

In this case study, the introduction of the co-generation system is considered very effective for reducing environmental impacts, CO_2 emissions and operating costs, especially by means of the gas engine co-generation system. If the energy demand becomes higher, the gas turbine co-generation system will have an advantage, because the thermal efficiency of a gas turbine is higher than that of a gas engine in a large-scale system.

Next, a co-generation system with another configuration is evaluated. Here the basic electricity demand in a day is met by a gas turbine or gas engine generator, and the rest of the electricity demand is supplied by commercial electricity. The basic electricity demand is approximately one third of the maximum electric demand. The right hand side of Table 5 shows the results in this case, compared with the previous results shown on the left hand side of the table. In this case, the gas turbine or gas engine generator runs the system. This means that the generator reduces the environmental impact even when a small generator is used. However, the impact and cost to construct the co-generation system are not included in this evaluation. If the advantage of introducing the co-generation system is small, these impacts should be taken into account in the exact evaluation.

Table 5. Comparison of results investigated on the effect of the number of power units between gas turbine and gas engine co-generation systems.

	Gas turbine co-generation system (3 x 1/3)	Gas engine co-generation system (3 x 1/3)		Gas turbine co-generation system (1 x 1/3)	Gas engine co-generation system (1 x 1/3)
CO_2 emission [ton-CO_2]	2,360	2,050	=>	2,430	2,300
Environmental impact [NETS]	7,390	6,630	=>	7,560	7,210
Operating cost [Million JPN-yen]	119	115	=>	119	118

4. Conclusions

The software to propose a system configuration and to evaluate environmental impacts, CO_2 emissions and operating costs of co-generation operation has been established based on a LCA methodology. This software can evaluate the gas turbine and gas engine co-generation systems, and can compare the results with that of an ordinary energy supply system. The validity of this software is examined by a case study of the energy demand of a hotel. The demands are estimated from the statistical data on living energy demands and floor space. The results show the advantages and disadvantages of the co-generation system. This estimation methodology will be useful for the introduction of a co-generation system to meet an arbitrary energy demand. The results of this study may well prove useful for recommendations on distributed power supply systems and further development of sustainable eco-energy supply systems.

5. References

1. The Energy Data and Modeling Center, EDMC Handbook of Energy & Economic Statistics in Japan, 2007, The Energy Conservation Center, Japan.
2. The Society of Heating, Air-conditioning and Sanitary Engineers of Japan, Plan, Design and Evaluation of Co-generation System, (in Japanese), Maruzen, Tokyo, Japan.
3. Kato, S., Nomura, N. and Maruyama, N., Eco-operation of Co-generation Systems Optimized by Environmental Load Value, *Proc. of 1998 Int. Joint Power Generation Conf.*, *ASME*, 1998, Vol. 1, pp. 417-421.
4. Maruyama, N., Kato, S., Kojima, Y., Widiyanto, A. and Takai, H., LCA Estimation Scheme of Co-generation System Reconcile Environmentally and Economically Eco-operations with a NETS Concept, *Proc. of International Conference on Efficiency, Costs, Optimization, Simulation and Environmental Aspects of Energy Systems*, 2000, Vol. 2, pp. 1093-1104.
5. Maruyama, N., Sadamichi, Y., Nakanishi, S. and Kato, S., Design Methodology for Energy Supply System from Ecologically and Economically Conscious Standpoints, *4th International Energy Conversion Engineering Conference*, 2006, Paper No. AIAA 2006-4081, CD-ROM.
6. Japan Co-generation Center, Co-generation Synthesis Manual (in Japanese), 2003, Tusanshiryou-shuppankai, Tokyo, Japan.

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