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LCA Environmental Load Minimization for Operating Different Cogeneration Systems

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ABSTRACT To estimate environmental impacts through the entire life cycle of any industrial activity like co-generation system (CGS) operation, Life Cycle Assessment (LCA) has been found to be a powerful tool. Therefore the authors have first proposed a standardized method called the LCA-NETS scheme (NETS: Numerical Eco-load Total Standard) based on objective data, in which a new unit of [NETS] is used for the standardized numerical value of eco-load, and second developed a new version software of the LCA-NETS scheme for analyzing numerically the eco-loads from a specified CGS and then minimizing the impacts due to the CGS operation. As a result, the LCA-NETS eco-load evaluation scheme constructed here is found to be an attractive and powerful tool to analyze the quantitative LCA environmental loads for any type of co-generation system and to predict its most ecologically and economically optimized operation scheme, resulting in compromising compatibility between eco and cost performance.

Keywords: Co-generation, LCA (Life Cycle Assessment), NETS, Optimization, Eco-Operation

1. Introduction

To estimate environmental impacts (eco-loads) through the entire life cycle of any industrial activity like co-generation system (CGS) operation, Life Cycle Assessment (LCA) has been found to be a powerful tool. In evaluating the LCA environmental impact due to co-generation operation, an identified standard measure is to be introduced, as there are various causes for the environmental loads. Consequently, the authors have proposed a standardized method called the LCA-NETS scheme (NETS: Numerical Eco-load Total Standard) based on objective data, in which a new unit of [NETS] is used for the standardized numerical value of eco-load.

The aim of this paper is first to develop a new version software of the LCA-NETS scheme for analyzing numerically the eco-loads from a specified CGS and then minimizing the impacts due to the CGS operation. This LCA-NETS scheme also calculates the cost performance for the CGS operation and then predicts its economically optimized operation scheme. In evaluating the eco-load and the cost, we can select an arbitrary type of co-generation system from different type CGS units consisting of gas turbine (GT), gas engine (GE), diesel engine (DE), and Fuel cell (FC) in which peripheral elements of waste-heat recovery boilers, auxiliary boilers, steam turbines, electricity operated turbo refrigerators, steam absorption refrigerators, heat exchangers, etc are also optional. Fuel is also optional from kerosene, light and heavy oils, natural gas, coal and coal reformed gas, and another types of fuels. The efficiencies of the respective machines are to be inputted as functions of energy balances. As a case study, the developed software is applied to energy demands of the Mie University including the university hospital. The electricity and heat hourly demands are specified from the

statistical data of university living energy demands depending mainly on the floor spaces. The LCA items for purchase electricity, fuels and CGS elements can be calculated from the inventory database constructed by the authors. The Environmental impacts resulting from the specified CGS including fossil fuel depletion and natural resources depletion, global warming, ozone layer depletion, water and air pollution, rain acidification, waste processing, and recycling effects. As a result, the LCA-NETS eco-load evaluation scheme constructed here is found to be an attractive and powerful tool to analyze the quantitative LCA environmental loads for any type of co-generation system and to predict its most ecologically and economically optimized operation scheme, resulting in compromising between eco and cost performance.

2. Environmental load Evaluation Method

2.1 "LCA-NETS"

We developed "LCA-NETS", environmental load evaluation method to consolidate and evaluate quantitatively various environmental loads with different causes using the same standard [1-3]. The method standardizes the objective indices, for example various statistical data and regulation values, published by public organizations such as the United Nations and the Japanese Government. We often observe examples of standardization using subjective factors such as weight coefficients. The first feature of our method is that we employ objective standardization and exclude subjective operating parameters as much as possible. Table 1 indicates the types of environmental loads that "LCA-NETS" can handle at present and the basis of the standard values for the consolidation.

Table 1 Environmental Load Factors Handled by LCA-NETS and Standard Values for the Consolidation

	Environmental load factors	Consolidated standardization values	Number of substances	Data Sources
Global Scale	1. Depletion of fossil fuel	Proven energy reserve	4	MITI United Nations statistic materials and others
	2. Depletion of natural resources	Proven mineral reserve	42	United Nation, USGS published materials and others
	3. Global warming	GHG emissions, GWP	43	IPCC report, environmental white paper and others
	4. Ozoneosphere destruction	Emission of CFCs, ODP	24	Material from related industries, environmental statistical materials and other sources
	5. Atmospherically pollution	Environment Agency, WHO regulation values	11	Tables published by the Environment Agency, Chronological Scientific Tables and other sources
	6. Hydrosphere pollution	Environment Agency, WHO regulation values	28	Tables published by the Environment Agency, Chronological Scientific Tables and other sources
District scale	7. Acid rain	[H ⁺] concentration in rainwater	7	Environmental white paper, Chronological Scientific Table, Tables published by academic magazines
	8. Waste processing	Amount of residuals in the final disposal	2	Materials from related industries, Environmental white paper, and UN statistics
	9. Recycling effect	Factor classified statistical materials	Many	Material from related industries, academic papers, statistics, and other sources

The basic idea of “LCA-NETS” is as follows. When analyzing an environmental load (for example, global warming due to CO₂ emission), it is expressed by standardizing on the basis of the L-R Tolerance Balance Theory, that balances the maximum tolerable value that the “Loader” (power plant, etc.) can emit (CO₂, NO_x, SO_x, etc.) or consume (fossil fuel or natural resources), and the maximum tolerable value that the “Receiver” (primarily human and other ecosystem) affected by the load can tolerate [2]. This approach has an additional feature of allowing a quantitative evaluation of the various environmental loads completely in the new units [NETS].

The L-R Balance Theory defines, first of all, the Maximum Permissible Eco-load Value (MEV_i) [NETS] for given environmental load (i) tolerable by the ecosystem on the Receiver side. For example, MEV_i for Global Environmental Load (G) that the world population can tolerate is defined as follows:

$$MEV_i^G = 6.0 \times 10^{11} \text{ [NETS]} \quad (1)$$

here, the total population of the world in 1999 is 6.0×10^9 , assuming that the basic tolerable value for a man is 100 [NETS]. The reason why the tolerable value for a person is determined as 100 [NETS], is that the tolerance level has reached the 100% level, and unless some measure is taken, the standard of living we have continued so far cannot be maintained. The superscripted G means the global scale environmental load, and the subscripted i is the environmental load factor class “ i ”.

When the maximum tolerance value is P_i [ton, kWh, m³, etc], according to the L-R Tolerance Balance Theory,

$$P_i \times ELM_i = MEV_i \quad (2)$$

here, ELM_i [NETS/ton, kWh, m³, etc](Environmental Load Module) is the conversion coefficient connecting P_i [ton, kWh, m³, etc] and MEV_i [NETS], and also refers to the environmental load consolidated basic value for unit emission or unit consumption. The method of calculation is described in the following section. As the LCA has to be summarized along all stages of the life cycle, the total life

cycles environmental load consolidated value EcL [NETS] is calculated using the following formula.

$$EcL = \sum_{i=1}^n (ELM_i \cdot x_i) \quad (3)$$

here, x_i (tons, kWh, m³) is the emission or the consumed amount of the related environmental load factor class “ i ”.

2.2 Calculation of P_i and ELM_i

As a example of calculation of P_i and ELM_i , fossil fuel depletion is described here. If this massive consumption of fossil fuel in thermal power generating stations continues, the fuel will finally be depleted. As fossil fuel is a precious resource for the entire human race, depletion of the fuel will certainly impose a global scale environmental load. Some people do not give enough consideration to the serious global environmental load caused by the depletion of the fossil fuel.

With the global environmental load for fossil fuel depletion, “LCA-NETS” employs the newest proved energy reserves as consolidated standard for the maximum tolerable P_i^{FD} that the “Loader” side can consume. Table 2 shows classified proved reserves of fuel consumed by commercial power generating stations and the maximum consumable value P_i^{FD} , and the individual environmental load consolidated standard values ELM_i^{FD} calculated using Eq. (1) and Eq. (2). As the table 2 shows, the global environmental load for fossil fuel depletion, as observed from ELM_i^{FD} for the consumption of 1 kg of each of the fuels are: coal (1.0) < petroleum (6.9) < natural gas (9.3) < uranium (2.3×10^5). The reason why uranium gives very large value is that its proven reserves are much smaller than for the other fuels. However, as the calorific value per unit volume for the total thermal generation value, calculated from the total calorific value of the proved reserves is also great, the unit calorific value 1 kJ calculated from the total calorific value of the proved reserves (Table 2. ELM_i^{FD} lower line) gives coal (1.0) < petroleum (4.3) nearly = natural gas (4.5) < uranium (10). Some of selected P_i and ELM_i in other environmental category is shown in table 3.

Table 2 P_i^{FD} and Standard Value ELM_i^{FD} for the Depletion of Fossil Fuels (1999)

Types of fuel	Proven reserves	P_i^{FD}	ELM_i^{FD}
Coal	$9.84 \times 10^{11} [\text{ton}]$	$9.84 \times 10^{14} [\text{kg}]$	$6.1 \times 10^{-4} [\text{NETS/kg}]$ $2.3 \times 10^{-8} [\text{NETS/kJ}]$
Petroleum	$1.65 \times 10^8 [\text{m}^3]$	$1.42 \times 10^{14} [\text{kg}]$	$4.2 \times 10^{-3} [\text{NETS/kg}]$ $1.0 \times 10^{-7} [\text{NETS/kJ}]$
Natural gas	$1.41 \times 10^{14} [\text{m}^3]$	$1.05 \times 10^{14} [\text{kg}]$	$5.7 \times 10^{-3} [\text{NETS/kg}]$ $1.1 \times 10^{-7} [\text{NETS/kJ}]$
Uranium	$4.36 \times 10^6 [\text{ton}]$	$4.36 \times 10^9 [\text{kg}]$	$1.4 \times 10^2 [\text{NETS/kg}]$ $2.5 \times 10^{-7} [\text{NETS/kJ}]$

Table 3 Selected Respective P_i and ELM_i

Category	Substance	P_i [ton]	ELM_i [NETS/ton]
Natural resources depletion	Iron ore	6.61×10^{10}	8.77×10^0
	Bauxite	2.80×10^{10}	2.07×10^1
	Zinc ore	4.30×10^8	1.35×10^3
Global warming	CO_2	2.05×10^{12}	2.83×10^{-1}
	CH_4	1.06×10^{11}	5.46×10^0
	CFC-11	9.95×10^7	5.83×10^3
	HCFC-22	1.24×10^8	4.69×10^3
Ozone layer Depletion	CFC-11	7.22×10^7	8.03×10^3
	CFC-113	9.03×10^7	6.42×10^3
	HCFC-22	1.32×10^9	4.41×10^2
Water pollution	Pb	7.22×10^8	8.03×10^2
	Cr	3.60×10^9	1.61×10^2
	Hg	7.18×10^7	8.08×10^3
Air pollution	Carbon tetrachloride	5.09×10^6	1.14×10^5
	Tetrachloro-ethylene	2.04×10^7	2.85×10^4
	Vinyl chloride	2.54×10^9	2.28×10^2
Acid rain	NO_2	5.64×10^6	2.98×10^3
	NO	3.68×10^6	4.56×10^3
	SO_2	3.93×10^6	4.27×10^3
Waste processing	Industrial waste	2.08×10^8	6.06×10^1
	General waste	1.51×10^8	8.34×10^1

3. Eco-operation of Co-generation Systems

3.1 Environmental Load Evaluation for Grid Electricity

First of all, we have to calculate the ELM and EcL values throughout the lifecycle "from cradle to grave" due to the average grid electricity generation in Japan. The total electricity generation from Japanese grid systems (comprising 10 Japan's electric power companies) reaches to $E_{total} = 9.18 \times 10^8$ [MWh/year] in fiscal year 2000, and the distribution ratio " r_i " of oil fired-, coal fired-, natural gas fired-, nuclear, and hydro power station, are 8%, 12%, 32%, 38% and 8%, respectively [4]. The environmental loads for purchase electricity from Japanese grid electricity are calculated by the following equations;

$$EcL_i^{Elec.} = \sum_{j=1}^n ELM_j \times G_j \quad (4)$$

$$EcL_{Total}^{Elec.} = \sum_i EcL_i^{Elec.} \quad (5)$$

$$ELM_{Average}^{Elec.} = \sum_i \frac{EcL_i^{Elec.}}{E_{total} \times r_i} \quad (6)$$

where the superscript "Elec." is concerned with the purchase electricity from Japanese grid electricity system, and the subscript "i" denotes oil fired-, coal fired-, natural gas fired-, nuclear, and hydro power stations, respectively. Notation "Average" denotes the average value for Japanese electricity. Table 4 shows the values of $ELM_{Elec.}$ that is

Table 4 ELM values for grid electricity in Japan (2002)

[NETS/kWh]	Hydro	Oil-Fired	Coal-Fired	LNG Fired	Nuclear	Total
Fossil Fuel Depletion	2.6E-05	1.0E-03	3.0E-04	1.1E-03	3.2E-03	1.7E-03
Natural Resources Depletion	2.2E-06	9.7E-06	1.3E-05	2.0E-05	1.2E-05	1.4E-05
Global Warming	5.1E-06	2.1E-04	2.7E-04	1.7E-04	5.8E-06	1.1E-04
Rain Acidification	3.4E-07	1.3E-04	2.4E-04	9.3E-06	5.0E-06	4.4E-05
Total	3.4E-05	1.3E-03	8.2E-04	1.3E-03	3.2E-03	1.9E-03
Distribution Ratio [%]	8.4	7.7	12.1	32.2	38.1	100.0

resulted from Japanese grid electricity system by type of power plant [5]. For nuclear energy, high-grade uranium ores can supply conventional nuclear power plants for 60-75 years. However, provided the breeder and reprocessing technology will be ready for its commercialization within the next 2-5 decades, which then, will greatly enhance the natural resources of fissionable uranium by the factor over than 100 times of the current known world resources.

3.2 Co-generation Model

Co-generation also called combined heat and power (CHP) is considered to be a very cost-efficient means of generating both electricity and thermal energy from the same fuel source. The cost efficiency comes not only from the generation of electricity, which can be used to reduce the expense of purchased utility power, but also from the fact that the generated steam is used twice. Another attractive element of co-generation is that a variety of fuel types may be used, ranging from natural gas to fuels such as wood or agricultural waste. In this paper we evaluate two

Fig 1 Co-generation system model

Table 5 Configuration of System Performance

(a) Gas Turbine Combined Cycle Model		
Component	Number of Unit	Performance
Gas Turbine	3 X 1 MW	Max. thermal efficiency: 25% Min. power Output: 0.5 MW
Wasted Heat Recovery Boiler	4 units	Max. steam conversion efficiency: 80%
Steam Turbine	1 X 1 MW	Max. thermal efficiency: 10% Air ration (intake/outtake): 9
Auxiliary Boiler	4 units	Max. steam output: 10 GJ/h Min. steam output: 0.05 GJ/h
Steam Absorption Refrigerator	5 units	Coefficient of performance: 1.2 Max. capacity: 14 GJ/h
Electric Turbo Refrigerator	5 units	Coefficient of performance: 4.0
Heat Exchanger	1 unit	Conversion efficiency from steam to hot water: 90%

(b) Gas Engine Model		
Component	Number of Unit	Performance
Gas Engine	3 X 1 MW	Max. thermal efficiency: 30% Min. power Output: 50 kW
Gas Refrigerator	5 units	Space Heating: Max. output: 10 GJ/h Space Cooling: Max. output: 12 GJ/h
Gas Heat Pump	5 units	Space Heating: Max. capacity: 10 GJ/h Space Cooling: Max. capacity: 12 GJ/h
Gas Boiler	5 units	Max. output: 10 GJ/h
Electric Heat Pump	5 units	Space Heating: COP: 2.3 Max. capacity: 7.2 GJ/h Space Cooling: COP: 4.0 Max. capacity: 12.5 GJ/h
Hot-water absorption Refrigerator	5 units	Max. capacity: 12.5 GJ/h Coefficient of performance: 0.8
Heat Exchanger	2 unit	Conversion efficiency from steam to hot water: 90%

types of co-generation systems fueled by natural gas including gas turbine combined cycle system (GTCC) and gas engine system (GE).

Figure 1 (a) shows the GTCC system employed here, where GT denotes gas turbine, BW (wasted heat recovery boiler), ST (steam turbine), BA (auxiliary boiler), RE (electric turbo refrigerator), RS (steam absorption refrigerator) and HE (heat exchanger). Figure 1 (b) also shows the GE system, where GE denotes gas engine, GR (gas refrigerator), GH (gas heat pump), GB (gas boiler), EH (electric heat pump), WR (hot-water absorption refrigerator), HEX (heat exchanger) and CT (cooling tower). The energy and mass balances of electricity, fuel, steam, hot water, hot water, and cold water derive many balance equations for the respective machines composing the entire co-generation unit. Table 5 (a) and (b) indicate configuration of system performance for GTCC and GE model, respectively.

3.3 LCA Optimization for Eco-Operation

The algorithms applied here as the first steps are the well-known simplex and branch-bound methods to seek optimized solutions of objective functions in linear programming. In this work, all the elemental machines composing the co-generation unit to be estimated are assumed to have a linear function between the output y_i (generated electricity, steam, etc.) and input x_i (fossil fuel, etc.) as expressed in Eq. (7).

$$y_i = a \cdot x_i + b \cdot \delta \quad (7)$$

where a and b are constants that express the performance of

Fig. 2 Software using GUI and Q & A style

each machine, and δ is a one-zero variable to express ON-OFF of the machine; $\delta = 1$ when the machine is operated and $\delta = 0$ when stopped.

Equation (7) should be formulated for all the components shown in Fig. 1 so well as to express its performance in advance, and obtained equations are inputted in the computer. The energy balance conditions for each energy demand have also to be formulated for the respective components.

For instance, in order to optimize the operation of GT co-generation system, for instance the operation for n -th of gas turbine, it is convenient to introduce the 1-0 variable of δ_{GTn} that can define the relationship between the input (fuel supply F_{GTn}) and the output (electricity E_{GTn} and excess/wasted heat Q_{GTn}), and can be expressed as following equations,

$$E_{GTn} = p_{GTn} \cdot F_{GTn} + q_{GTn} \cdot \delta_{GTn} \quad (8)$$

$$Q_{GTn} = r_{GTn} \cdot F_{GTn} + s_{GTn} \cdot \delta_{GTn} \quad (9)$$

$$E_{GTn} \cdot \delta_{GTn} \leq F_{GTn} \leq \bar{F}_{GTn} \cdot \delta_{GTn} \quad (10)$$

where, and E_{GTn} and $\bar{F}_{GTn}$ are the minimum and the maximum limit of the fuels' flow, respectively, and the value of coefficient p_{GTn} , q_{GTn} , r_{GTn} , s_{GTn} depends on the type and the efficiency of gas turbine.

To formulate the optimization, it is necessary to satisfy the boundary conditions such as the demand of the electricity, air heating, air cooling, hot water, and also must be met the balance of energy. For instance, as for the demand and supply of electricity, the formula meet conditions mentioned above can be written as following equations.

$$\sum_{n=1}^{N_{GT}} E_{GTn} + \sum_{n=1}^{N_{ST}} E_{STn} + E_{Buy} = E^a + E_{Demand} \quad (11)$$

$$E^a = \sum_{n=1}^{N_{GT}} E_{GTn}^a + \sum_{n=1}^{N_{ST}} E_{STn}^a + \sum_{n=1}^{N_{BA}} E_{BA_n}^a + \sum_{n=1}^{N_{RS}} E_{RS_n}^a + \sum_{n=1}^{N_{RE}} E_{RE_n}^a \quad (12)$$

where, attaching character "a" shows the electric power which is used for the equipments operation. The operation of the actual system is done not only single turbine but also keep mutual relation with the electric power, the flow of steam, etc., complicatedly. In order to optimize operation of GE co-generation system, the equations are also derived as well the GT system.

Figure 2 shows the software to set up the co-generation unit to be estimated, on which we can easily operate using GUI (Graphical User Interface) and Q & A

style. Since various kinds of numerical values required be asked on the display in Q & A style, their inputs are easily completed and confirmed before calculations. The branch and bound method is used here to obtain with high efficiency the optimum solutions of objective functions including the eight environmental loads under the many constraint conditions. The solving scheme is programmed, and the optimum solutions can be obtained in very short time.

4. Results and discussion

4.1 Electricity and Heat Analysis

Figure 3 shows enegy demand of Mie University in a winter day in January (Fig. 3 (a)) and a summer day in August (Fig. 3 (b)), where Elec. is electricity, Q_c is air cooling, Q_h is air heating, and Q_{hw} is hot water. Figures 4 and 5 show the hourly changing of each co-generation system operation optimized by the combined simplex and branch-bound method. These curves correspond to the results of energy demands on summer and winter days shown in Fig. 3. The hourly optimum operation scheme for each component is also obtained to minimize the cost and the total Eco-load. In the co-generation system, the electricity demand is supplied by the co-generation system and purchase electricity, and then the space heating, hot water and space cooling are mostly supplied by the waste heat from the co-generation unit. In ordinary method, the electricity demand is supplied only from the purchase electricity, and the fossil fuel and the purchase electricity supply the heat demands. The natural gas is used for both the system as a fuel.

Figures 4 (a) and (b) show eco-operation of gas turbine combined cycles (GTCC) system. In here the

Fig.3 Hourly energy demands in Mie University

maximum electric generation efficiency is set to be 35% from gas and steam turbine system (25% for gas turbine single system), with the power output GT 1000 [kW] $\times$ 3 units, ST $\times$ 1 unit. Steam turbine in here is used for adjusted the generation ratio of power and heat to satisfy the energy demand. It can be seen from Fig. 4 (a) that one of gas turbine and steam turbine is to be operated for almost 24 hours (except from 2:00 to 4:00), and that the 2nd and 3rd of gas turbine are to be operated from 8:00 to 17:00. On the other hand, from Fig. 4 (b), one of gas turbine and steam turbine are to be operated for 24 hours, and the 2nd and 3rd of gas turbine are to be operated from 8:00 to 18:00. Almost of the base load of heat and power can be covered by this

(a) Eco-operation for GT systems in

(b) Eco-Operation for GT system in summer

Fig. 4 Eco operation for GT system

(a) Eco-Operation for GE system in

(b) Eco-Operation for GE system in summer

Fig. 5 Eco operation for GE system

system. In the daytime, generated electricity and grid electricity are larger than electricity demands; it means electric turbo refrigerators (RE) are operated to supply air cooling.

Figures 5 (a) and (b) show eco-operation of GE co-generation systems. Gas engine designed here is a system composed of gas generator with the maximum power output GE 1000 [kW] $\times$ 3 units. In here the efficiency of power generation set to be maximum 30%. As the results, from Fig. 5 (b) it can be observed that one unit of gas engine is to be operated for 24 hours, and that the 2nd and 3rd of gas engines are to be operated during the daytime. However, from Fig. 5 (a), gas engine is not to be operated during the nighttime; it means that using electricity from grid electricity is environmentally friendlier than to generate by the co-generation unit.

4.2 Environmentally and Cost Analysis

Figure 6 shows the hourly changing of the Eco-load values under optimization in summer and winter days. In this figure also includes the Environmental load evaluated using only purchase electricity (ordinary method) in order to compare with the data from the co-generation system proposed in this work. The hourly optimum operation scheme for each system is also obtained to minimize the total Eco-Load. As the result, GE system is almost the same as GT system, and both of them are ecological system compared with ordinary system. In all cases, the electricity generated by co-generation units is much friendlier to the environment than purchase electricity, particularly for the energy demand in the daytime. The environmental load value integrated over the whole day may be reduced in comparison with the case without the optimization. Consequently, it can be concluded that the NETS estimation and its optimization described in this paper contribute well to reducing the environmental loads and also to propose the eco-operation scheme of co-generation energy systems.

Figure 7 indicates the hourly operation cost during eco-optimized operation of co-generation. As the result, in the operation cost viewpoint, the both system is also economically compared with only purchase electricity, and combined cycle co-generation unit is shown as the most economically system. Other case study did by this software for 4 hotels and 8 offices building in the reference [3].

5. Concluding Remarks

In this paper we have introduced the LCA scheme with the aid of the LCA-NETS scheme as a numerical measure to estimate the quantitative load of any industrial activity on environment due to resources' depletions, global warming, ozone layer depletion, water and air pollution, rain acidification, and waste processing. This LCA-NETS scheme has been applied to co-generation energy systems because of their direct connection with energy and environment issues. The computer programmed algorithm and software using the combined simplex and branch-bound technique have been developed and accomplished to give us the numerical *ELM* in the unit of NETS and its optimization. The optimization has been calculated corresponding to the hourly energy demands of Mie University for electricity, space cooling, space heating, and hot water. The co-generation eco-operation schemes employed in this paper give advantageous methods from

Fig. 6 Hourly Environmental load of each system

Fig. 7 Hourly Cost of each system

environmentally and economically eco-operation of view points. As a result, the gas turbine combined cycle co-generation system is recommended as the ecologically and economically best selection.

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