

# 열병합 발전소의 구성안별 성능 평가 방안 - 플랜트 열성능 및 단순화 발전단가 분석

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## Performance Evaluation of Combined Heat and Power Plant Configurations - Thermodynamic Performance and Simplified Cost Analysis

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### ABSTRACT

Thermodynamic and economic analyses of various types of gas turbine combined cycle power plants have been performed to establish criteria for optimization of power plants. The concept of efficiency, in terms of the difference in energy levels of electricity and heat, was introduced. The efficiency of power and heat generation by power plants with other purposes was estimated, and power generation costs were figured out for various types of combined heat and power plants(i.e., fired and unfired, condensing and non-condensing modes, single or double pressure HRSG).

**Key Words** : Gas turbine combined cycle power plants, Combined heat and power, Thermal efficiency, Utilization factor, Generation costs

### 기 호 설 명

#### Alphabets

$C$  : Capacity factor  
 $I$  : Total construction costs  
 $I_c$  : Construction costs per kW  
 $Q$  : Heat  
 $W$  : Work  
 $Y_{El,yr}$  : Annual cost of electricity generation

$Y_{H,yr}$  : Annual cost of heat generation

#### Greeks

$\Phi$  : Heat generation rate  
 $\Psi$  : Fixed cost ratio  
 $\eta_{elec}$  : Efficiency of electricity generation

## 1. Introduction

For many industries, combined heat and power(CHP) systems offer higher efficiency than separate generation of heat and power using boilers and turbine generators. Prior to 1960, most combined heat and power systems were based on steam turbine cogeneration systems. Recently, however, because of the availability of high temperature exhaust gases caused by high operating temperatures in industry, and of the economic benefits resulting

from a high power to heat ratio, gas turbine cogeneration systems have become prime movers in many applications. Such systems, combined heat and power with gas engines and heat recovery boilers, can also be used for generating the heat used in buildings. The combined cycle power plant(CCPP), has drawn keen interest as an effective measure of energy utilization. The recent growth of the CCPP market has been caused by policies for regulation of emission gasses in the United States and Europe[1]. The combined cycle system(i.e., a combination of Brayton and Rankine cycles), can achieve high efficiency by utilizing hot flue gasses exhausted from gas turbines as the energy source for power genera-

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tion by steam turbines. A CCPP is composed of a gas turbine, a steam turbine, and a heat-recovery steam generator(HRSG) for generating high temperature steam. The HRSG is the key component of the CCPP, the role of which is to be a nexus of the Brayton and Rankine cycles. Until now, the focus of the CCPP design has been on steam cycle called bottoming cycle deciding the design of the steam turbine and HRSG, according to the operating conditions of the gas turbine, including such as capacity, gas turbine outlet temperature, and flue gas flow rate.

However, both power output and costs become important when considering the gas turbine performance and the HRSG design as elements influencing the total efficiency of CCPPs, because of the trade-offs among various purposes such as combined heat and power production or desalination[2]. Therefore, ways to optimize design of CCPPs are needed, considering the competing design criteria related to both efficiency and scale. Also, a set of evaluation criteria to determine whether a plant design has been optimized is needed. In this study, to suggest the performance evaluation criteria for CCPPs, various evaluation factors including thermal efficiency were applied to three different commercial power plants. Then, thermodynamic and economic analyses were conducted on six different cycle configurations of plants with fixed gas turbines and steam turbines.

Most of the previous studies on optimization of CCPPs have focused on HRSG design optimization with 1<sup>st</sup> and 2<sup>nd</sup> thermodynamic efficiencies for entire power plants [3-5]. In addition to this, some progress has occurred in the form of studies on the thermoeconomic optimization of HRSGs[6], and the determination of design according to steam generation rate and stack temperature of HRSGs[7]. There were also studies on economic

evaluation of the various configurations of plants[8,9] and design optimization focused on gas turbine cycles [10,11].

Considering the characteristic of CCPPs having not only power but also heat generation, the simple evaluation methods used before are insufficient to evaluate the performance of CCPPs properly. Especially, to compare different types of CCPPs having different objectives, it is necessary to suggest a performance evaluation method that would accommodate the different uses intended for CCPPs. The objective of this study was to suggest a methodology to evaluate different types of CCPPs and select the best one corresponding to the use purpose of a plant, through the proper performance evaluation. To determine the important design considerations, this study focused on thermodynamic performance of subject CCPPs having mixed purposes. The heat and electricity generation costs were derived from different combinations of system configurations with fixed gas and steam turbines.

## 2. Methodology

### 2.1. Target Plant Selection

#### 2.1.1. Target Power Plants

In this study, three types of plants selected for case study were subjected to analyses of efficiency, based on the first law of thermodynamics(see Fig. 1 and Table 1). Fig. 1 represents the schematic capacity and steam (or heat) use of the selected plants. Table 1 presents the purpose, steam condition, specific electricity and heat output and efficiency of power plants. The purposes and compositions of the case plants were varied: Type 1 plant generates electricity and steam for desalination plants, Type 2 plant generates electricity and heat for

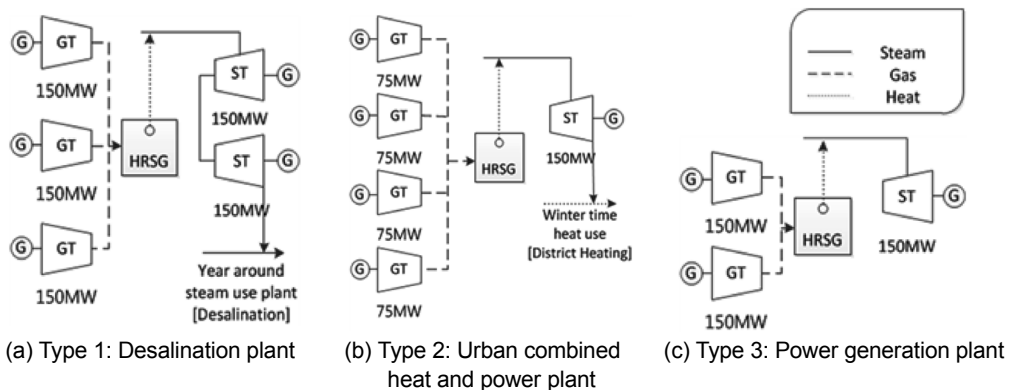


Fig. 1. Schematic diagram of subject power plants.

**Table 1.** Examples of combined cycle power plants cases

|                                       | Type 1                 | Type 2                  | Type 3           |
|---------------------------------------|------------------------|-------------------------|------------------|
| Firing                                | Fired                  | Unfired                 | Unfired          |
| Use purpose                           | Power and steam        | Combined heat and power | Electricity only |
| Year commercialized                   | 2007                   | 1992                    | 1997             |
| HP steam temp. (°C)/<br>press. (MPa)  | 544/9.04               | 492.3/6.15              | 523.7/5.39       |
| GT capacity (MW)                      | 166.0×3                | 85.9×4                  | 161.2×2          |
| ST capacity (MW)                      | 322.0                  | 160.8                   | 191.0            |
| Gross plant output (MW)               | 735.3                  | 427.7                   | 511.3            |
| Heat output (MW)                      | 564.1<br>(year-around) | 342.5<br>(winter only)  | -                |
| Electricity generation efficiency (%) | 49.2                   | 43.6                    | 52.9             |
| Utilization factor (%)                | 86.9                   | 78.5                    | 52.9             |

district heating, and Type 3 plant generates electricity only. The demand and usage of heat and steam by Type 1 and Type 2 plant are different. Type 1 plant uses steam year-around, but Type 2 plant uses heat in the winter only.

However, this method for evaluating performance by comparing the rates of power and heat generation of different types of CCPPs, is limited because of their different operating purposes and turbine models. Comparisons of electricity output alone cannot suggest optimal solutions for dealing with use demand. Also, the thermodynamic efficiency of the plants in Fig. 1 cannot be the criterion for evaluation of performance coincident with the demands of customers. To figure out specific impacts from selection of different equipment in plants, simple configurations of fixed gas and steam turbines were suggested in the next part.

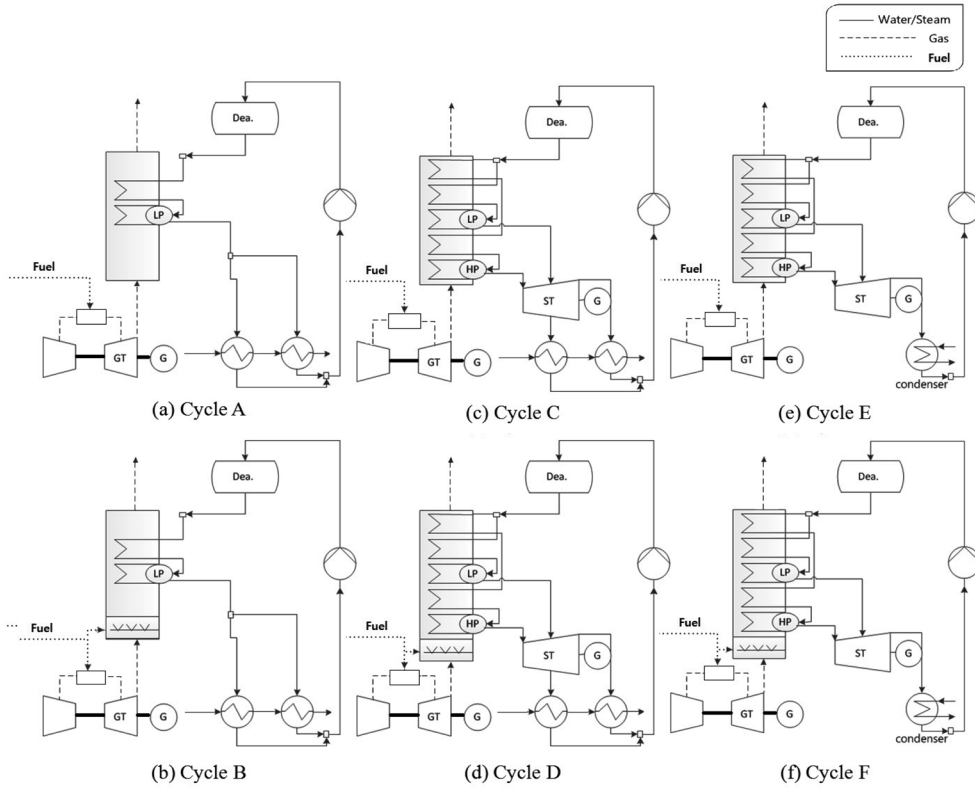
### 2.1.2. System Configuration

Unlike Type 1 and Type 3, as a combined heat and power plant, Type 2 has various modes of operation because of regional and seasonal differences in demand

for heat and electricity energy. The operation modes can be divided into back pressure mode(generating both electricity and heat; equipped with heat exchangers at the steam turbine outlet) and condensing mode(generating electricity only equipped with condensers instead of heat exchangers). These modes of operation are selected according to seasonal, regional, and customer demands. Since the operation mode of Type 2 is related to the cycle configurations, for a detailed analysis of this study, analysis in various operation modes(back pressure mode and condensing mode) should be additionally considered. Therefore, the analysis will include not only the three different types of power plants, but also different configuration cycles of the target CCPPs.

To figure out the effect of HRSG types and condensers, on total electricity and heat outputs in power plants with fixed gas and steam turbine models(Type 2 power plants in Fig. 1), combined heat and power plants, will be analyzed in six different cycle configurations. As shown in Fig. 2, various cycle configurations involve different equipment. Cycle A consists of a gas turbine, single-pressure HRSG, and heat exchangers. Cycle C consists of a gas turbine, steam turbine, double-pressure HRSG and heat exchangers. Cycle E consists of a gas turbine, steam turbine, double-pressure HRSG and condenser. In addition, to figure out the effect of duct burners supplying additional heat to exhaust gas from gas turbines, in order to increase the steam generation rate, heat and electricity generation rates are derived for cycles B, D, and F, which are configurations like A, C and E, but with additional duct burners(Fig. 2). Furthermore, the simple electricity and heat generation costs which could provide criteria for cycle selection, were also derived and evaluated.

- (a) Cycle A - Unfired HRSG LP process steam(0.685 MPa)
- (b) Cycle B - Supplementary fired(gas temperature at gas turbine outlet : 922 K) HRSG, LP process steam
- (c) Cycle C - Combined cycle, unfired, double-pressure level HRSG, HP at 6.149 MPa, 765 K(steam pressure and temperature), LP at 0.685 MPa, 437 K (saturated), noncondensing steam turbine-generator
- (d) Cycle D - Combined cycle, supplementary fired HRSG, HP at 6.149 MPa, 765 K. LP at 0.685 MPa, 437 K(saturated), noncondensing steam turbine-generator



**Fig. 2.** System configurations.

(e) Cycle E - Same as Cycle C, but with admission condensing steam turbine-generator

(f) Cycle F - Same as Cycle D, but with condensing steam turbine-generator

\* LP: Low pressure level, HP: High pressure level

\*\* Fired/unfired: with/without supplementary firing at duct burner with fixed gas and steam turbines.

## 2.2. Simulation

### 2.2.1. Thermodynamic Evaluation

One of the most representative of the performance evaluation criteria, is thermodynamic efficiency, representing the ratio of output energy to input energy. In this study, three efficiencies, shown as Eqs. (1)-(3), are used to evaluate performance of the different types of power plants in Fig. 1 and Table 1.

$$\eta = \frac{W_{output}}{Q_{input}} \quad (1)$$

$$UF = \frac{W_{output} + Q_{output}}{Q_{input}} \quad (2)$$

$$RI\ efficiency = \frac{2.6 \times W_{output} + 1.1 \times Q_{output}}{Q_{input}} \quad (3)$$

Eq. (1) represents electrical efficiency, and is generally used in performance evaluation of power plants by creating a ratio of the rates of electricity generation to heat consumption. Eq. (2) represents the fuel utilization factor, and creates a ratio of the rates of total heat and electricity generation, to heat consumption; in fuel units. Eq. (3) represents *RI* energy efficiency, which is used to compare combined generation of heat and power, with divided generation[12,13]. In *RI* energy efficiency, equivalence factors are multiplied to work and heat output which are derived from efficiency of divided generation of heat and power, respectively. The factor 2.6 for electricity can be calculated as the inverse number of electricity generation efficiency and an average European coefficient of coal plants, 38%, is used. Similarly, the factor 1.1 for generated heat can be obtained from the inverse number of heat generation efficiency and an average European coefficient of heat plants, 91%, is used. By multiplying these equivalence factors, *RI* energy efficiency represents ratio of heat consumption rate

between divided generation and combined generation of heat and power.

### 2.2.2. Economic Evaluation - Heat and Electricity Generation Costs per kWh

A balance between economic factors and design efficiency should be considered for power plant optimization. In general, when power plants are designed, if cost factor is the limiting condition among several designs, the optimized design is the plant with the highest efficiency, which does not go over the project budget. This study was focused on electricity and heat generation costs of six different cycle configurations of combined heat and power plants (Type 2) consuming relatively large amounts of steam, with fixed gas and steam turbines as shown in Fig. 2. The cost for generation of 1 kWh of electricity was figured out using Eq. (4), and the cost for heat generation was figured out using Eq. (5). Eq. (6) represents the possible revenue of power plant when electricity and heat are sold in generating their generating cost.

$$Y_{El,yr} = \frac{I_c \times \Psi}{8760} + \frac{I_{fuel} \times C}{\eta_{elec}} \quad (4)$$

$$Y_{H,yr} = \frac{\Psi}{8760} \times \left( \frac{I}{\Phi} - I_c \right) + \frac{I_{fuel} \times C \times \Phi_{BR}}{\Phi} \quad (5)$$

$$Possible\ Revenue = \frac{(Y_{El,yr} + Y_{H,yr} \times \frac{\Phi}{\Phi_{El}}) \times 8760}{I_c + I_{fuel} \times 0.25 \times 8760} \quad (6)$$

The unit generating cost as shown in Eq. (4) and Eq. (6) are sum of fixed cost and fuel cost.  $I_c$ ,  $\Psi$ , and  $I$  represents construction cost, fixed cost rate, and fuel cost at each. The operating hour of power plant is assumed as 8,760 hours and capacity factor  $C$  is assumed as 90%. In Eq. (5), the construction cost is subtracted to avoid the double counting, and also, the difference of efficiency and generation rate of heat and power is considered. In Eq. (6), the operating cost is considered with assumptions that operating cost is 25% of fuel cost in general.

Every power generation cycle in this study used natural gas as a fuel in gas turbines. The three subject power plants and six system configurations were simulated using Gate Cycle, a commercial software[14]. The properties needed in Eq. (1)-(6), such as fuel consumption rate, temperature and pressure profile, can be attained

by analyzing cycle. Using TPX in Excel[15], the thermodynamic properties of steam, such as enthalpy and entropy, can be obtained from pressure and temperature conditions. From the T-s diagram of each cycle, the power generation rate of the turbine, and the heat generation rate of the heat exchanger can be figured out.

## 3. Results

### 3.1. Efficiency

Fig. 3 represents the efficiency of three different types of gas turbine combined cycle power plants. The electricity generation efficiency was determined for each subject plant type (Type 1 54.74%, Type 2 44.92%, and Type 3 49.80%). Utilization factors considering both electricity and heat generation for each plant type were also calculated (Type 1 93.55%, Type 2 83.21%, and Type 3 with condensing steam turbine, does not generate heat). Last, equalized, or  $RI$ , energy efficiency representing the effect of gas turbine-CCPPs comparing to divided generation was calculated for each type (Type 1 185.0%, Type 2 158.9%, and Type 3 129.5%). The Type 3 plant had the lowest, and the Type 1 had the highest equalized efficiency. Because Type 1 plants had highest value in three points of view of performance efficiency, Type 2 plants and Type 3 plants can be compared to suggest the need of various efficiency factors. Type 2 plants can be interpreted as having a more effective combined cycle, because Type 3 plants, whose purpose is electricity generation had higher electricity generation efficiency, but lower equalized efficiency than did Type 2 plants. Therefore, it was showed that equalized efficiency, considering generation of electricity and heat separately, can usefully compare the effects of combined cycle configurations.

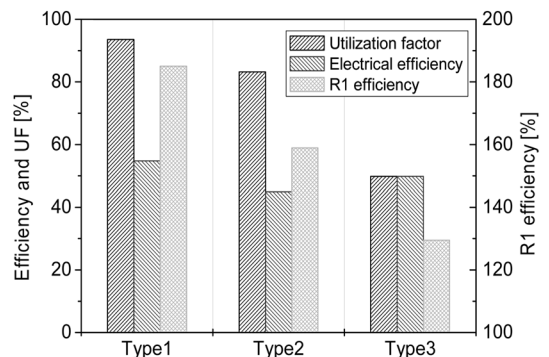


Fig. 3. Efficiency of various gas turbine combined cycle power plants.

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### 3.2. System Configuration

Fig. 4 represents the electricity and heat generation rates of six different cycle configurations of Type 2 combined heat and power plants. This result is similar to that of a technical report about gas turbine cogeneration system[16].

Fig. 4 displays the options available using a gas turbine in a combined heat and power system. In this study, the area of the heat exchanger units in the HRSG, gas turbine and steam turbine were fixed, and at the same time, the efficiency of each component was considered. Table 2 represents the electricity and heat generation cost of six cycle-configurations of combined heat and power plants with a 14% fixed charge rate,

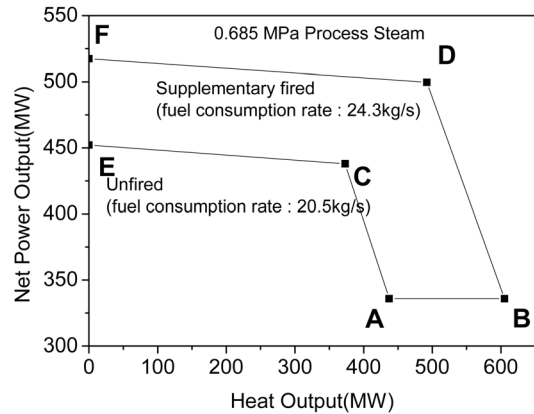


Fig. 4. Performance envelope for gas turbine combined heat and power system.

100% capacity use rate, and with operating and management costs included in fixed costs. As shown in Table 2, comparing A, C, and E configurations, although the construction costs increased when using double-pressure HRSG, the electricity generation costs decreased as the efficiency of the power plant increased. However, the heat generation costs increased because of a decline in the total heat generation rate. In addition, comparing the C and D configurations, the efficiency of the power plants increased as fuel was added to the boilers, and heat generation costs decreased as the total heat generation rate increased. The electricity generation cost increased because of increasing construction and fuel costs. Compared to unfired configurations (A, C, E) having same conditions, except fuel consumption, the electricity generation cost of every fired configurations (B, D, F) are increased. On the other hand, compared to unfired configuration (A, C), the heat generation cost of fired configurations (B, D) are decreased. Especially, in the case of the comparison of the A and B configurations, the additional combustion have only influence on net heat output. There are no steam turbine in the

Table 2. Economic Analysis of Various System Configurations

|                                      | A     | B     | C     | D     | E     | F     |
|--------------------------------------|-------|-------|-------|-------|-------|-------|
| Net power output (MW)                | 335.8 | 335.9 | 437.9 | 499.7 | 452.2 | 517.4 |
| Net heat output (MW)                 | 437.2 | 605.2 | 373.2 | 492.0 | 0     | 0     |
| Electricity efficiency (%)           | 34.45 | 29.08 | 44.92 | 43.26 | 46.39 | 44.80 |
| Fuel consumption (kg/s)              | 20.5  | 24.3  | 20.5  | 24.3  | 20.5  | 24.3  |
| Electricity generation costs (₩/kWh) | 234.5 | 287.5 | 191.0 | 199.7 | 189.4 | 197.5 |
| Heat generation costs (₩/kWh)        | 154.6 | 124.9 | 193.4 | 169.5 | 0     | 0     |
| Possible revenue (₩/₩)               | 1.86  | 1.91  | 1.37  | 1.31  | 0.67  | 0.65  |

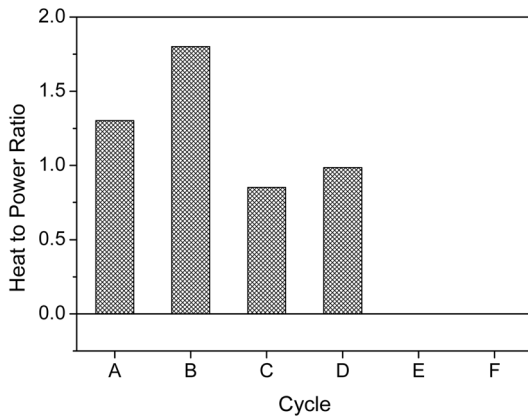


Fig. 5. Heat to power ratio

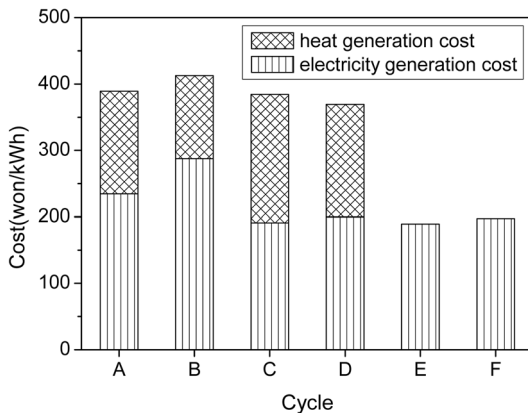


Fig. 6. Heat and electricity generation costs.

both configurations. It explains that the additional fuel in the B configuration can not generate additional electricity from supplementary firing and make more electricity generation than the case A. Looking at the possible revenue, supplementary firing of the double-pressure HRSG(D and F) has cost merit but there is no cost merit in supplementary firing of the single-pressure HRSG(B).

To figure out the effect of the different operation modes which are back pressure mode and condensing mode, comparison between the C and E, and also those between D and F, are necessary. As shown in the Table 2, regardless of supplementary firing, since the net power generation of condensing mode are slightly more than those of back pressure mode, electricity generation cost of condensing mode is slightly cheaper than the cost in the back pressure mode. However, considering the possible revenue, the possible revenue of the condensing mode is half the value of the back pressure mode.

Figs. 5 and 6 represent the result of cost estimation

in the form of graphs. As shown in Fig. 5 displaying the heat to power ratio, E and F cycles have zero value because they generate electricity only using condensing steam turbines. Fig. 6 displays the total generation costs, including heat and electricity generation. Also shown in Fig. 6, E and F cycles indicate the costs of electricity generation only.

#### 4. Conclusion

The thermodynamic analysis of different types of gas turbine combined cycle power plants was executed. Power and heat generation rates, and the generation costs of various cycle configurations were derived in order to determine a set of optimization criteria for design of gas turbine combined cycle power plants. The results including economic evaluation were derived for simpler models than real combined cycle power plants. The conclusions from this study are as follows.

- 1) The *RI* efficiency can be interpreted as a criterion to compare the effect of combined cycle plants with other power plants having different objectives.
- 2) Thermodynamic efficiency cannot be an absolute criterion for comparing the performance of combined cycle power plants with different purpose and configurations.
- 3) The different type of performance evaluation factors should be applied considering objectives of power plants.
- 4) The suggested method for design of combined cycle power plants is regarded as reasonable for application to commercial power plants.

To decide the optimal power plant configuration, project-planners of a power plant must know exactly what customers need. Depending on the requirements of customers, such as the amount of heat and power generation, project-planners have to select the proper evaluation methods, compare the performance of power plants, and then decide the optimal power plant satisfying the demands of customers. However, considering only the power plant efficiency is not sufficient to decide the cycle configuration. In this case, the cost factor can be one of the boundary factors in the final selection of the cycle. Parametric studies on these plants of interest, must proceed before optimization criteria can be suggested.

Consequently, the results of this study can be used as a first step to suggest performance evaluation method

of new type of power system. Also, it can be extended by being applied to new type of power plant such as power generation with carbon capture unit. This study suggested the need of different point of view to evaluate performance of power plant, and further study will proceed about suggestion of integrated process in power plant design considering objectives of system.

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