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Economic feasibility of waste heat to power conversion

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Abstract

With a high back-work ratio and a high exhaust-temperature, the simple cycle gas-turbine generation system usually has a low generation-efficiency especially when the ambient weather is hot. Among many technologies to improve the efficiency of a simple-cycle gas-turbine, inlet-air cooling, and steam reinjection are considered the best ways to modify an existing simple cycle unit without major destruction to its original integrity. To evaluate the individual effects after system modifications, a computer code for the simulation of the power-generation system was developed and validated in this study, and the ABSIM code developed by Oak Ridge National Laboratory was adopted to simulate the absorption refrigeration system. Based on the calculated improvement and the associated benefits, the estimated cost of refurbishment and other operational costs, economic analyses were performed under the current fuel and cost structures. Results indicate that the system with the steam reinjection feature has the highest generation-efficiency and thus the most potential profit on investment, while the system with both inlet-air cooling and steam reinjection features can generate the highest power-output and release the least exergy via the flue gases.

Keywords: Gas turbine; Waste heat-to-power; Absorption chiller; Economic analysis

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Nomenclature

C	cost (NT)
COP	coefficient of performance
$\dot{E}$	exergy rate (kW)
$\dot{E}_D$	exergy destruction-rate (kW)
e	unit exergy (kW/kg)
h	specific enthalpy (kJ/kg)
I	initial cost
LHV	lower heating-value (kJ/kg)
$\dot{m}$	mass flow-rate (kg/s)
NP	net profit (NT)
NT	New Taiwan dollar (exchange rate: 35 NT dollar equals 1US dollar)
PW	present worth (NT)
$\dot{Q}$	heat transfer (kW)
T	temperature (K)
TIT	turbine's inlet-temperature (K)
T_o	ambient temperature (K)
v	specific volume
$\dot{W}$	work rate (kW)
w	steam injection ratio

Subscript

1→20	state points in Fig. 1
a	air
cv	control volume
f	fuel
i	inlet
in	installation
k	kth component
o	outlet
O&M	operation and maintenance
q	heat transfer
v	vapor

Superscript

Ch	chemical
Ph	physical

Greek symbol

α	percentage of downpayment
η_g	power generation efficiency
λ	air–fuel ratio
ω	relative humidity

1. Introduction

Recently, oil prices repeatedly broke high records. People have regained their worry regarding energy resources. So, the U.S. Department of Energy has identified waste-heat recovery as a major priority in its 2005 Industrial Energy-Saving Roadmap [1].

The gas-turbine generation set (GENSET) is compact and possess an agile start-up feature: it is therefore suitable to be used as a load-follow unit. Unfortunately, the simple cycle GENSET has a low generation efficiency, especially when the ambient weather is hot (the time when electrical power is most needed). Therefore, gas-turbine GENSETs are mostly on standby unless there is a power-shortage problem or a black-out emergency.

Due to the unusual hot weather in the past summer, many simple cycle GENSETs that were originally designed to serve as peak-load units were forced to operate continuously during most of the summer. Retrofitting projects have been considered for converting these simple cycle units into more advanced cycle units with higher efficiencies and higher outputs.

From a fundamental thermodynamic analysis, we know the reasons that cause the simple cycle GENSET to have a low thermal efficiency. The first is that a large portion of the work generated by the turbine will be used to compress the inlet air (often called having a high back-work ratio). The other reason being the substantial amount of available energy loss along with the turbine exhaust due to the swift rotation of turbine and a relatively high back-pressure. An overview of advanced and future sustainable gas-turbine technologies has been described by Poullikkas [2]. In particular, the emphasis has been given to various advance cycles involving heat recovery from the gas-turbine's exhaust to improve the generation efficiency for simple cycle-units. The recovery of this otherwise wasted energy can be used to improve either the power generation capacity or/and the efficiency [3,4] via modifications to the basic cycle, such as gas-to-gas recuperation [5], steam injection [6], chemical recuperation [7], inlet-air cooling [8] and combined cycle [9,10].

Among many well-proven technologies, the combined cycle is perhaps the most popular way to recover the energy from the exhaust gas, and the recovered energy is actually used to boost the capacity and efficiency of power generation. However, its mobility (start up time) is relatively low and it's unsuitable for our projected unit, in which the daily on–off operation pattern is required. Some other promising technologies such as intercooling, reheat and regeneration, however, require altering the integrities of rotating machines and are also unsuitable for a retrofitting project.

The STIG method stands for steam injected gas-turbine, the steam generated from the heat-recovery steam generator (HRSG) is injected into the combustion chamber. Air from the compressor and steam from the HRSG both receive fuel energy in the combustion chamber and both expand inside the same turbine to boost the power output of the turbine. In fact, Saad and Cheng [11] reported that the STIG has become a well-established practice. The development of STIG technology including a list of turbines for conversion was also studied by Turzon [12]. In this study, a HRSG is used to fully recover the useful energy from the exhausted gases and generate steam at two different pressure-levels. The higher pressure steam is used for the STIG and the lower pressure steam is used for inlet-air cooling (IAC).

The IAC technology is simple to cool down the air entering the compressor, with a cooler inlet-air; the compressor consumes less work and can compress more air per cycle to increase the capacity of the gas turbine. The practice of IAC has been studied comprehensively by Lucia et al. [13]. His further study [14] has allowed the designer to recognize the benefits and limitations and to assist in the successful design and implementation of IAC systems.

Although many efforts have been devoted to either applying the STIG technology or the IAC method to enhance the gas-turbine's performance, little has ever integrated STIG and IAC for the same system. The integration of STIG and IAC was studied previously [15]. Some performance improvements have been simulated and evaluated especially on retrofitting systems as well [16,17]. Since the energy levels required by IAC and STIG are different, the recovered energy could be more fully utilized by a combined STIG and IAC system. In this study, we will focus on the economic feasibility of waste-heat to power conversion. Cost is always a primary factor in determining the feasibility of a new project. The cost of this retrofitting project is different from that of a turnkey project. The economic analysis is also evaluated in this study based on the overall expenditure for the existing plant, and the consideration of local energy and fuel cost-structures. Another important feature in this study is the heat recovery from the exhaust based on the exergy concept, which reveals the actual quality of energy recovery from the thermodynamic point of view.

2. System description

The integrated system with both IAC and STIG features are shown in Fig. 1. At the bottom side of Fig. 1 is the basic unit, which includes a compressor, a combustor, a gas turbine and a generator. In order to recover the energy from the exhausted gases, a heat-recovery steam generator (HRSG) was installed at the downstream exit of the turbine (state point 4). Two kinds of steam are generated from the HRSG, the higher pressure (at 14.1 bar) steam is used for the STIG (state point 9) and the lower pressure (at 9 bar) steam is used to heat the absorption chiller (state point 6). The absorption chiller will provide the chiller water (state point 15) and cool down the inlet air (state point 0) at the precooler. The heat received and absorbed at the absorption chiller will eventually be released to the ambient environment via a cooling tower, see state point 18 in Fig. 1.

In the process of inlet-air cooling, most of the vapor in the air will be condensed, the condensed water (at about 10 °C) will be added to the supply of cooling water, see point 17. The use of this cold condensed water can slightly improve the COP of the absorption chiller. The used cooling water (state point 14) will release its energy via a cooling tower and circulate back to the entrance of the cooling-water system (state point 19). In this study, a portion of used cooling water (state point 14) at a temperature about 37 °C will be used as the feed water to the HRSG (state point 8). This feed water in turn will be converted to high pressure steam (state point 9) at the HRSG. By this arrangement, more steam can be generated from the HRSG and less water plume will be evaporated into the ambient sink.

3. Computer simulation

A computer program was developed to simulate the power-generation system, in which the control volume model of each component was constructed using mass, energy, and

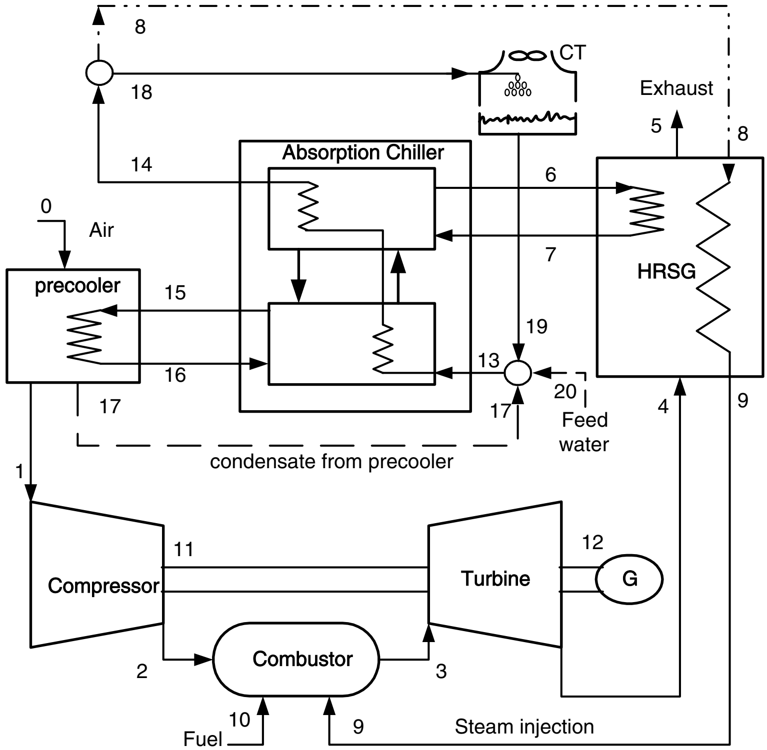

Fig. 1. The integrated system with IAC and STIG (0–1 precooler, 1–2 compressor, 2–3 combustion chamber, 3–4 turbine, 4–5 heat-recovery steam generator, 6–7 recovered heat to power absorption chiller, 8–9 recovered heat for steam injection, 12 generator, and 18–19 cooling tower).

exergy balances for determining the thermodynamic properties at every key position in Fig. 1. A set of governing equations for a particular component (k) is expressed as:

Mass balance

$$\sum \dot{m}_{i,k} = \sum \dot{m}_{o,k} \tag{1}$$

Energy balance

$$\dot{Q}_{cv,k} - \dot{W}_{cv,k} + \sum \dot{m}_{i,k} h_{i,k} - \sum \dot{m}_{o,k} h_{o,k} = 0 \tag{2}$$

Exergy balance

$$\sum \dot{E}_{q,k} - \dot{W}_{cv,k} + \sum E_{i,k} - \sum E_{o,k} - \dot{E}_{D,k} = 0 \tag{3}$$

where $\dot{E}_D$ denotes the rate of exergy destruction and $\dot{E}_q$ denotes the associated exergy transfer rate due to heat transfer.

If the effects of kinetic and potential energy are ignored, the total exergy rate $\dot{E}_k$ consisting of physical exergy and chemical exergy can be expressed as [16]

$$\dot{E}_k = \dot{E}_k^{PH} + \dot{E}_k^{CH} \tag{4}$$

where the physical exergy and chemical exergy of air , fuel and water can be found in the Appendix of Ref. [18]. The chemical exergy of the gases mixture is obtained by summing the overall compositions of air, that includes N_2, O_2, CO_2, $H_2O_{(g)}$ and other gases.

The equations of the combustion processes are

$$\begin{aligned}&\bar{\lambda}CH_4 + \left[x'_{N_2}N_2 + x'_{O_2}O_2 + x'_{CO_2}CO_2 + x'_{H_2O}H_2O\right] + \bar{w}H_2O \\ &\quad \rightarrow (1+\bar{\lambda}+\bar{w})\left[x''_{N_2}N_2 + x''_{O_2}O_2 + x''_{CO_2}CO_2 + x'_{H_2O}H_2O\right] \\ &x''_{N_2} = \frac{x'_{N_2}}{1+\bar{\lambda}+\bar{w}} \quad x''_{O_2} = \frac{x'_{O_2} - 2\bar{\lambda}}{1+\bar{\lambda}+\bar{w}} \\ &x''_{CO_2} = \frac{x'_{CO_2} + \bar{\lambda}}{1+\bar{\lambda}+\bar{w}} \quad x''_{H_2O} = \frac{x'_{H_2O} + 2\bar{\lambda} + \bar{w}}{1+\bar{\lambda}+\bar{w}}\end{aligned} \tag{5}$$

where x' and x'', respectively, represent the mole fraction before and after the combustion processes.

It was assumed that the retrofitted system operated in the steady state, and the ideal gas mixture models apply for air/steam and combustion products. The combustion in the combustor is complete. All components are adiabatic except that the combustor exhibits a heat loss at 2% of the LHV. The pressure losses are assumed to be 3% for the precooler, 1% for the compressor and turbine, and 5% for the combustor and HRSG.

The system of the absorption chiller driven by low-pressure steam of the HRSG was simulated by the ABSIM code, a modular code developed by ORNL under DOE sponsorship. The code has been employed successfully to simulate a variety of absorption chillers [19].

The generation efficiency was calculated as

$$\eta_g = \frac{\dot{W}_{net}}{\dot{m}_f(LHV)} \tag{6}$$

where $\dot{W}_{net}$ is the net power output of the GENSET.

The coefficient of performance of the absorption chiller can be defined as

$$COP = \frac{Q_{iac}}{Q_{gen}} \tag{7}$$

where Q_{gen} and Q_{iac} denote the generator's heat-load and inlet-air cooling evaporator capacity of the absorption chiller, respectively.

The accuracy of this developed computer program was validated by simulating the basic Frame 7B simple cycle generation set under ISO conditions (101 kPa, 288 K, and 60% RH). The performance data and conditions of this unit were provided by Taipower's Ta-Lin power plant. At the rated turbine's inlet-temperature (1264 K), exhaust temperature (783 K), compression ratio (9.0), and the flow rate of inlet air at 238.89 (kg/s), the calculated power output and power generation efficiency were 60.3 MW and 31.0%, which are very close to the rated values of 60.3 MW and 31.0%. In this simulation, the efficiencies of the compressor and turbine were adjusted to be 0.86 and 0.87, respectively. These values are quite reasonable and are used for the following calculations.

4. Economic analysis

Since the original system served as an emergency unit, the accumulated plant service period is very low even though the plant is more than 20 years old. The salvage value of the original system can be considered as zero because the entire system has been completed depreciated. However, the cost of refurbishment (overhaul) on the power generation system and the replacement of certain hot parts is relatively high and was estimated by the original vendor. The costs of new equipment were quoted from the literature, such as HRSG from the equation provided in Ref. [18], absorption chiller obtained from [20], and procooler given in Ref. [8].

The initial cost includes new equipment cost and refurbishment cost. The extra cost of STIG modifications such as special energy-storage (HRSG with two pressure levels), steam injection systems, dynamic control systems, and water-treatment equipment were quoted by the supplier [11] and added to the cost of the HRSG in the cost analysis. No land cost is considered, since the proposed new system (after retrofitting project) can be easily located at the current plant site.

Thirty percent of the initial (fixed) cost is considered as the downpayment, and the other 70% will be paid back annually during the expected plant-life (15 years) at the interest rate of 7.5%. The annual loan payment, C_{loan}, can then be written as

$$C_{\text{loan}} = (I_{\text{re}} + I_{\text{HRSG}} + I_{\text{ABS}} + I_{\text{prec}}) \cdot (1 - \alpha) \cdot \left[\frac{i \cdot (1+i)^n}{(1+i)^n - 1} \right] \tag{8}$$

where I is the initial cost of each new item of equipment, α the percentage downpayment, i the interest rate and n is the expected plant-life.

Besides the loan payment, the annual operation cost (C_{op}) consists fuel cost, water-consumption cost, and personnel and maintenance (O&M) costs. O&M costs were estimated by the Cheng Power System Company as 5% of total equipment cost. The fuel cost is the actual LNG price charged to Taipower (between 6.7 and 8.5 NT/m^3). The cost of the consumed water including the purification fee is estimated to be 1.5% of the fuel cost.

The annual income of this investment is the anticipated average price of electricity charged to customers during peak and semi-peak periods. Since the generation efficiency of the retrofitted system is higher than the mean of all Taipower's generation systems, the new system is expected to operate at full load during the entire peak and semi-peak time (about 4020 h per year).

The annual net profit (NP) is the difference between annual income and annual total cost. The present worth of total profit can then be calculated as

$$\text{PW} = \sum_{m=1}^{n} \frac{(\text{NP})_m}{(1+i)^n} \tag{9}$$

5. Results and discussion

The basic calculation is the simulation of a simple cycle GE MS7001B GENSET operating at an ambient temperature 305 K, relative humidity 80% (typical of local weather in the summer season). Point A in Fig. 2 shows the calculated power output is 52.1 MW and

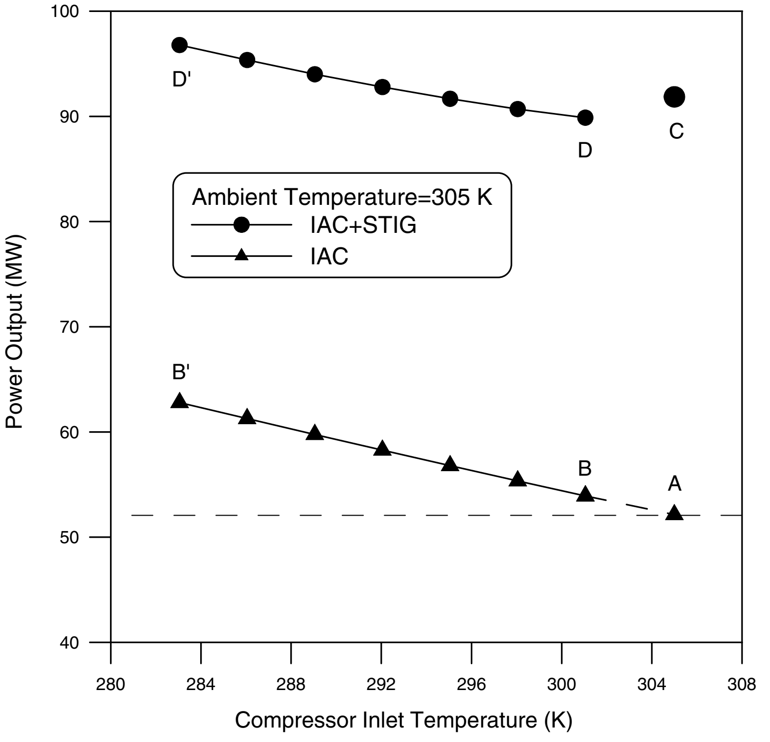

Fig. 2. Power output of different systems under different inlet-air temperature.

the efficiency is 29.3% (see Table 1) which are very close to the catalogue data (at 53 MW and 29.5%) provided by vender.

Since the compression work $= -\int v\,\mathrm{d}p$, where v is the specific volume of the inlet air, when the inlet air is cooled down, the compression work is thus reduced. At the same compression volume, the mass flow rate per compression is increased, therefore, the output is also increased, see the line BB′ in Fig. 1. At point B′, the inlet-air temperature is 283 K (the coldest temperature can be practically achieved by the absorption chiller with the LiBr+H_2O refrigerant), the output reaches 62.8 MW and the associated efficiency is 30.3%. At this point, the required steam to heat the absorption chiller is only 7.9 kg/s (at 9 bar). This represents only a small fraction of the energy, which can be recovered from the exhaust gases. The consumption rate of water shown in Table 1 for this case (11.1 kg/s) is the estimated loss rate from cooling tower.

Table 1
Comparison of simple cycle and other retrofitted systems

	Simple cycle	With IAC	With STIG	With IAC & STIG
Power output (MW)	52.14	62.79	91.85	96.78
Efficiency (%)	29.31	30.33	39.90	37.74
Water-consumption rate (kg/s)	–	11.1	46.5	46.9
Exergy loss to ambient environment (MW)	54.40	52.38	14.87	12.30
Exergy loss per MW output (MW/MW)	1.04	0.83	0.16	0.13

In the process of recovering energy from the exhaust gases via the HRSG, the temperature at the outlet of the stack (state point 5 in Fig. 1) is usually kept above 120 °C in order to prevent the vapor condensing. The effectiveness of the HRSG is assumed to be 0.8. Under these conditions, the maximum flow rate of generated superheat steam at 810 K and 14.1 bar is about 46.5 kg/s. If all the generated steam is injected into the combustor (STIG only), the injection ratio ($\dot{m}_{\text{steam}}/\dot{m}_{\text{gases}}$) is about 0.21, which is still below the maximum allowable injection ratio [21]. The calculated power-output for the case of full injection is shown as point C in Fig. 2, which shows the effect of the STIG is quite substantial. The power output is increased to 91.8 MW and the efficiency lifted to 39.9%. The profound effect from the STIG alone is because the required pressure of the injected steam is obtained from a pump. Since the pumping work is 2–3 orders of magnitude smaller than that of the compressor, the net power output produced by the steam is, thus, much higher than that of air per unit mass flow rate. In addition, the specific heat of superheated steam is almost double the value of air and the enthalpy of steam is higher than that of air at a certain temperature. Therefore, the STIG method is a very effective way to boost the net power output and increase the overall efficiency of the gas turbine.

If both the IAC and the STIG features are included in the system, the resulting output is depicted as the DD′ line in Fig. 2. Point D represents the minimum steam power output for the absorption chiller and point D′ is the state that the temperature of the inlet air at the limit (be same as that of point B′).

Table 1 shows at point D′ that the power output can be boosted to 96.8 MW but the efficiency is only about 37.7% (i.e. lower than that of STIG case). In this case, the higher-pressure steam is used for STIG injection, and the lower-pressure steam is used for inlet-air cooling. In fact, the HRSG two-pressure design can reduce the exergy loss. From Table 1, which shows the exergy loss via the stack is cut from 54.4 MW (simple cycle) to only 12.3 MW (IAC & STIG). Per MW power-output, the exergy loss for this case can even be reduced to 0.13 MW.

The fuel for this kind of power generation system can be either natural gas or distilled oil. The plant's operational condition can be well maintained and the impact on the neighboring environment can be minimized if natural gas is used as the fuel. The price of natural gas in the domestic market is relatively high and varied from 6.7 to 8.5 NT/m^3 (discounted rated for power generation purpose) during the past 10 years: in this study, the exchange rate is 35 NT equal to 1US dollar.

Fig. 3 shows the net profit for different unit electricity-prices if the current fuel price at 7.38 NT/m^3 is used in the calculations. With the highest generation efficiency, the system with the STIG can achieve a better profit, the system with both STIG and IAC can make a profit at the time when the electricity price exceeds 2.28 NT/kW h, and the system with IAC only can hardly break even under the electricity price expected in the near future. The results of Fig. 3 indicate the possible profit of a retrofitted project is closely releated to the system's generation efficiency. A higher efficient system can cut down the fuel cost, and the fuel cost is the dominant one among many costs, see Fig. 4.

Using LNG, the emission will be SO_x free since the sulfurs had been removed during the liquefying processes, and the emission of CO_2 (global-warming gas) will be only about a half of that using coal. In addition, the emission of NO_x can be lower than 25 ppm [11] if STIG technology is added to the generation system, because the injected superheated steam can smooth out the temperature distribution and mitigate the degree of local hot-spots inside the combusting chamber. These environmental benefits are not accounted

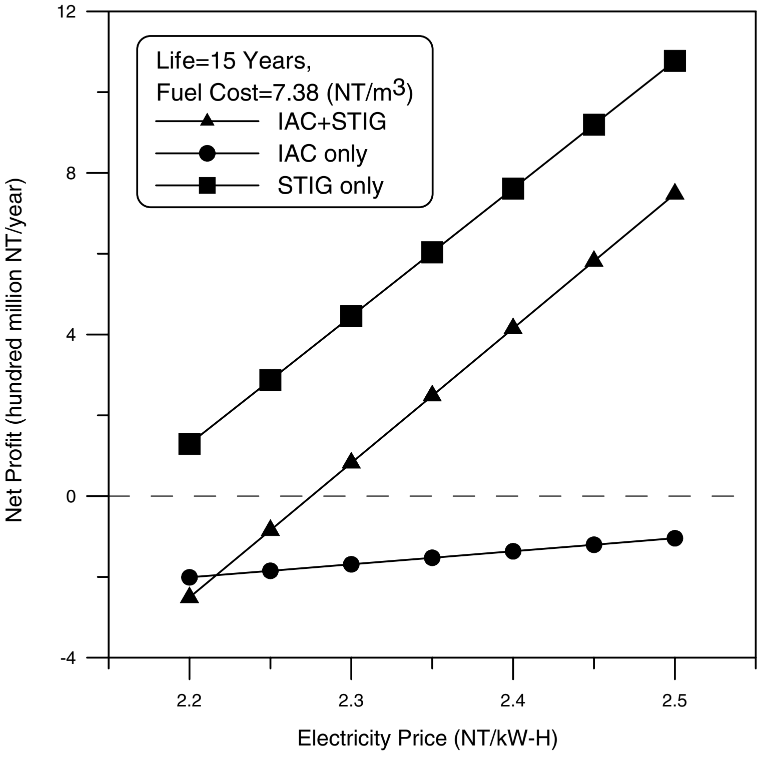

Fig. 3. Net profit at different unit electricity prices.

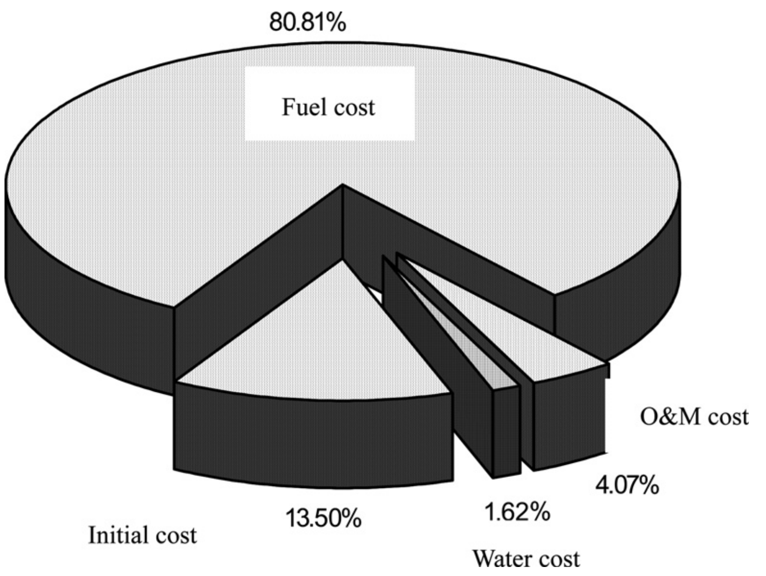

Fig. 4. Cost analysis of the system with IAC & STIG.

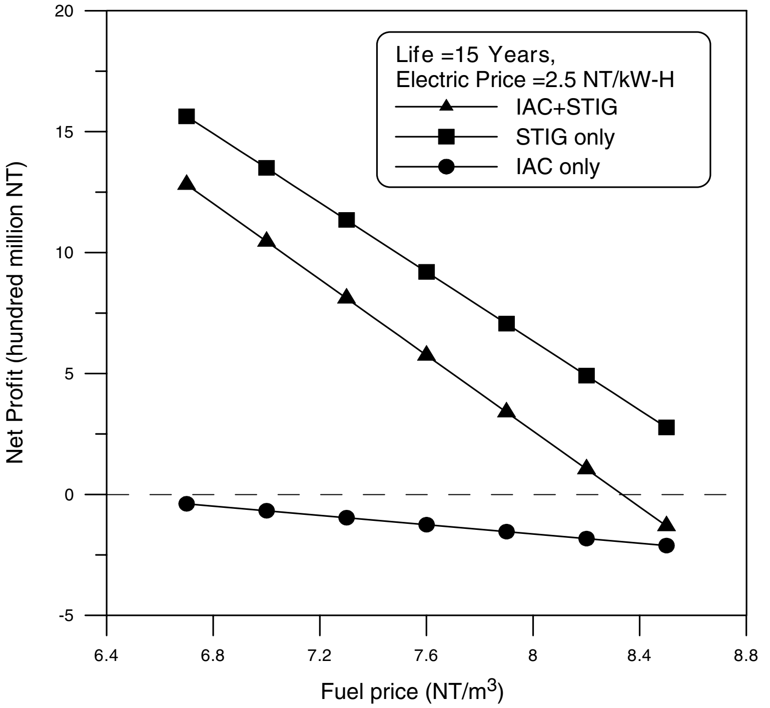

Fig. 5. Net profit for different fuel prices.

Table 2
Comparison of annual and cumulative profits and payback years

System	IAC	STIG	IAC & STIG
Annual profit	−0.06	1.67	1.36
Accumulative profit	–	14.24	11.63
Payback years	–	2.3	3.5

Unit: 10^8 NT.

for as monetary values in this analysis, but we know the electricity value obtained from burning LNG should be much higher than that from burning other fossil-fuels.

The unit price of electricity at 2.5 NT/kW-h was used to estimate the possible net profit under various fuel prices, see Fig. 5. Both the STIG only and STIG and IAC systems can gain profit if the unit fuel price is not over 8.3 NT/m^3. The annual profit, accumulated profit and payback years are listed in Table 2.

6. Conclusions

The reasons for having a low efficiency and a high exhausted temperature can be discerned from the fundamental thermodynamic analysis, and the methods used in the past to improve the efficiency were focused on either increasing the expansion work or decreasing the compression work. Among the many performance-improvement techniques, the steam-injection gas turbine (STIG) and the inlet-air cooling (IAC) are well suited for a retrofitting project without destroying to its original integrity. In this study, an existing simple cycle GE MS7001B generation-system was considered as the basic system and converted into the modified system with either IAC or/and STIG features. The calculated results indicate that the system with STIG can have the best generation efficiency (improved from 29.3% to 39.9%) and thus the shortest payback period, while the system with both STIG and IAC can achieve the greatest power capacity (increased from 52.1 MW to 96.8 MW). Since the energy used by the IAC or STIG to improve the system's performance is obtained via the recovery heat from the flue gases, additional environmental benefits can also be realized. The system with the STIG can further reduce the NO_x emissions below 25 ppm without the help of extra clean-up equipment, and the system with both IAC and STIG features can greatly reduce the exergy loss of the stack exhaust from 1.04 MW to 0.13 MW per MW output.

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