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# Thermo-Economic Study of Cooling, Heating and Power System Implemented for Indonesian Power Plants

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***Abstract***

*Most highly efficient Indonesian power plants operate with a combined cycle. Other cycles such as Rankine cycle, Brayton cycle and Diesel cycle are still operated in many power plants. One-half to two-thirds of the energy input to a typical generation system is wasted as heat, rather than turned into electricity. It motivates for developing cooling, heating and power systems. Electric power generating systems are located near a heat load that utilizes the heat rejected from the generation equipment to improve their efficiency. Gas turbines are a great machines producing electric power. Their power output increases when ambient temperature decreases. This gives opportunity to sell more electric power when the air before entering compressor is cooled. High temperature of exhaust gas from the gas turbine also gives recovery opportunity by using heat recovery steam generator (HRSG) for running steam power plant and also as waste heat from HRSG for generator of an absorption chiller.*

*Simulation was conducted based on data near to main data of the new power plant PT Bekasi Power Jababeka Cikarang. The results confirm that cooling of air before entering compressor in a combined cycle power plant causes the net power and thermal efficiency of the power plant increase. These advantages should be paid with more investment such chiller unit and energy consumption for the chiller unit. The HRSG without additional firing will give better efficiency even though the net power generation from the power plant decreases. An analysis involving thermo-economic criteria also proven that implementation of air inlet cooling in gas turbine system gives financial benefit. The best alternative chiller system is that using combination of vapor compression chiller and single-effect vapor absorption chiller to give highest financial benefit. All vapor compression chiller system is more convenient in their implementation, besides it gives high financial benefit. All vapor absorption chiller system is not competitive alternative, additionally it need wider space. This study result confirms that the cooling, heating and power system is applicable for other existing Indonesian power plant from thermodynamic and economic aspects.*

*Key words: cooling, heating, power, thermodynamic, cycle*

## 1. Introduction

Growth of industrial activities and increasing human life style will influence in increasing of energy consumption either electrical energy or fossil fuels. Growth of electric infrastructure is lower than electric energy consumption have caused electric energy crisis in Indonesia. As shown in Figure 1, electric energy consumption has an increasing trend. National electric situation in 2008 has shortcomings due to the power plant backup is inadequate when peak load time. Consequently, this enforces to shut down partial electric utilities. Besides a plan for establishing new power plant until year 2010 around 10,000 MWe, any shorten strategies have also been conducted by Indonesian government such as energy saving program and time usage diversity of industrial energy consumption by shifting working days. Recently, total nationally installed electric generator capacities are more 22,000 MWe. Among of them, 6300 MWe power plant capacity work with base of combine cycle, 6900 MWe power plant capacity works with base of Rankine cycle, 2700 MWe power plant capacity works with Brayton cycle, and 3000 MW power plant capacity works with Diesel cycle. The other power plants are working with bases of geothermal system and hydro system [Statistics Indonesia: Statistics Energy, 2008].

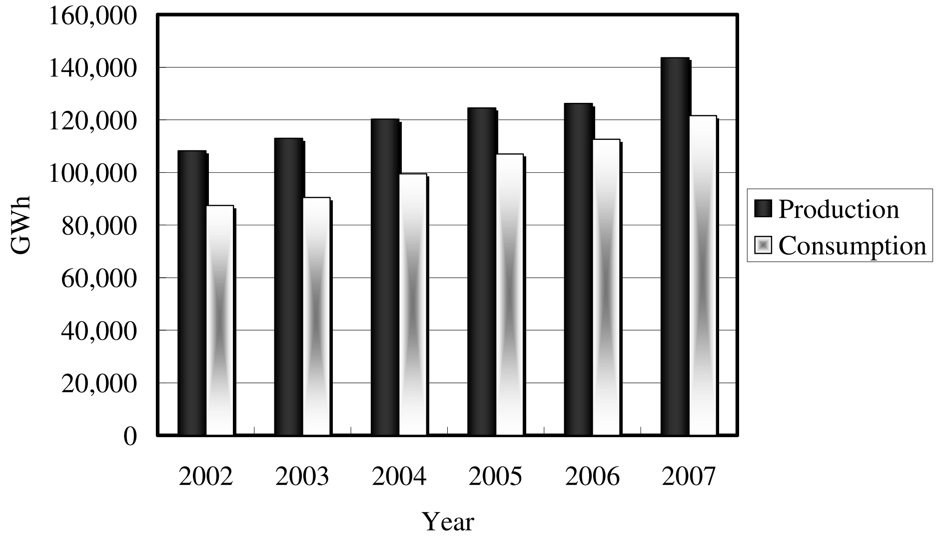



Figure 1. Indonesian Electric Energy Situation [Datawarehouse ESDM, 2008]

Since the compressor work is more proportional to volumetric airflow rate and decreasing inlet air temperature will increase net power of the gas turbine, this gives opportunity to sell more electric power when the air before entering compressor is cooled. High temperature of exhaust gas from the gas turbine also gives recovery opportunity by using heat recovery steam generator (HRSG) for running steam power plant and also as waste heat from HRSG for generator of an absorption chiller. This situation gives great opportunities for improving the performance of most thermal power plant especially for Brayton and Rankine cycles based power plant as concern of this study. Therefore, this paper will conduct thermo-economic analysis for implementation of cooling, heating and power (CHP) systems for Indonesian power plant.

## 2. Power-Plant System

Any variance of combined cycle based power plant may be established in accordance with recent technology. The combined cycle power plant uses natural gas only, i.e. gas turbine system and then exhaust gas is recovered by HRSG. HRSG may be without additional firing or with additional firing. It depends on steam condition produced and exhaust-gas condition from gas turbine and net power interests. The power plant usually one gas turbine with paired with a HRSG. Two or three HRSGs may be connected with a steam turbine system.

A combined cycle based power plant with 130 MWe of total power plant capacity, i.e. gas turbine generator 2 X 40 MWe and steam turbine generator 1 x 50 MWe are used as main data in this study. This main data close to new Bekasi Power Plant being established in Jababeka Cikarang. Schematic of the system is shown in Figure 2. On the other hand, the cooling system is investigated from economic aspect. Additional net power from the power plant can be afforded, but parasitic power and investment cost besides other expenses will occur.

Cooling, Heating and power systems may incorporate some combination of technologies, such as gas turbines, steam power plant and mechanical and absorption chillers. A system can be optimized for a specific plant based on the power demand and electricity prices and the availability of thermal energy. Understanding of thermodynamic properties and their implementation in thermal system and thermodynamic cycle is very useful to support our efforts to perform high efficiency thermal system. Additionally, any equipment in an existing system will increase a capital cost of the installation. Therefore, thermodynamic simulation only will give inadequate results. It should be expanded to consider economic parameters.

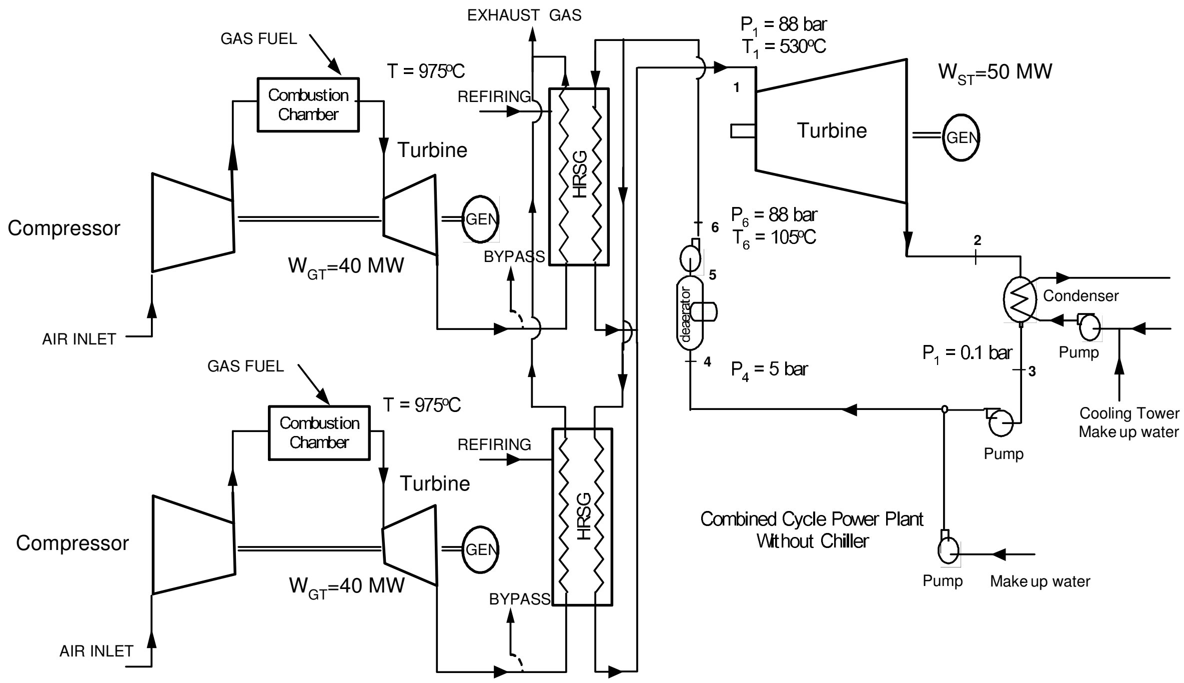


Figure 2. Schematic of combined cycle based power plant

## 3. Thermodynamic Analysis of CHP System

Thermodynamic calculation is based on thermodynamic data as shown in Figure 2. Two possibilities of HRSG operation condition are simulated. One condition is that HRSG operating without additional firing (re-firing) and other is that HRSG operated with additional firing. Isentropic efficiencies of compressor, gas turbine, pump and steam turbine are 80%, 95%, 70% and 85% respectively. Generator efficiency is assumed as 98% and pressure ratio of the two compressors is 4. Gas temperature before entering the gas turbine is 975°C and exiting from the gas turbine is 558°C. On the other hand, main conditions for the steam power system are 88 bars and 530°C of steam entering into the steam turbine, 0.1 bar of two-phase exiting form the steam turbine. Pressure drop of fluid through the heat exchangers is neglected. Total electric power generated by three generators is 130 MWe, i.e. gas turbine generator 2 X 40 MWe and steam turbine generator 1 x 50 MWe are used as main data. This power generation is set at 1 bar and 25°C of ambient air condition. This air condition is used as standard based calculation of the main power data. Air properties are assumed in accordance with ideal gas.

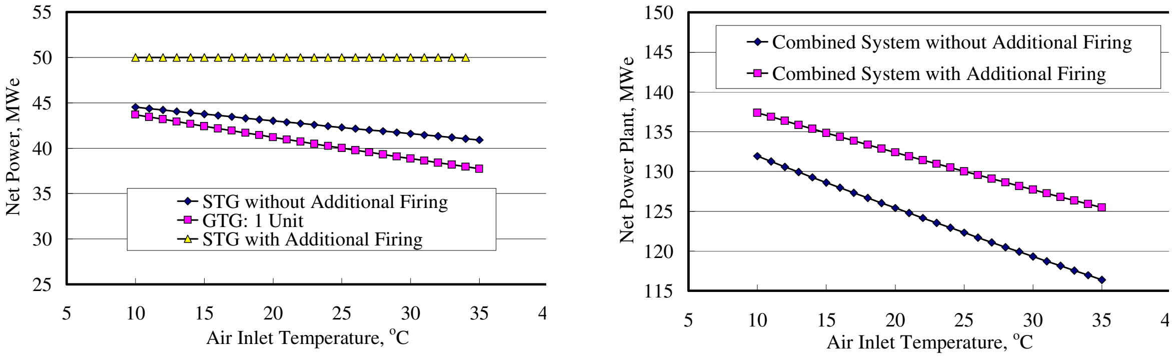
Efficiency of the combined cycle system is calculated in accordance with equation (1).

$$\eta_{system} = \frac{W_{net,GTG} + W_{net,STG}}{Q_{comb} + Q_{HRSG}} \quad (1)$$

Where $W_{net,GTG}$ is total net output power produced by two gas turbine generators after it is subtracted by the compressor works, $W_{net,STG}$ is total net output electric power produced by a steam turbine generator after it is subtracted by the pump works. $Q_{comb}$ is input heat rate into combustor as combustion result, $Q_{HRSG}$ is additional input heat rate in case of additional firing occurring in HRSG.. This value will be zero when without additional firing in HRSG. Parasitic load for air-cooling system and water-cooled condenser system is still not included in this analysis. It will be included in thermo-economic analysis for selecting cooling system.

Influence of air inlet temperature in power generated by gas turbine generator (GTG) and steam turbine generator (STG) with different condition for HRSG i.e., two HRSGs without additional firing and both without additional firing are shown in Figure 3 (a). The powers generated by GTG and

STG without additional firing significantly decrease when air-inlet temperatures increase. This result confirms that the additional firing in HRSG just has function for practical interest to satisfy power load.



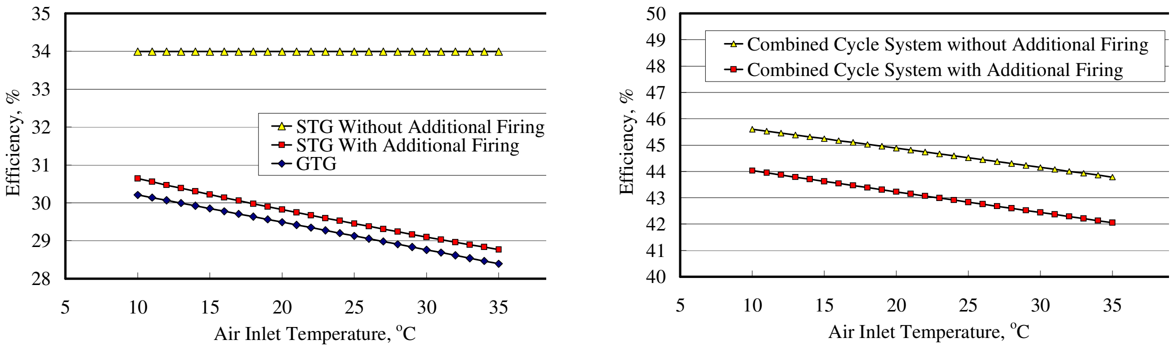

(a). Net output power of gas turbine and steam turbine-generators

(b). Net output power combined cycle system

Figure 3. Influence of air inlet temperature into compressor on net output power

Influence of air inlet temperature in power generated by GTG and STG with different condition for HRSG, i.e. both HRSGs with additional firing and both HRSGs without additional firing are shown in Figure 3(b). The powers generated by GTG and STG without additional firing significantly decrease when the air inlet temperature increases. Decreasing of the combined system with additional firing is larger than the system without additional firing. Practical interest in performing larger power capacity makes the additional firing in HRSG to be a choice, but this way still needs to be accessed from energy conservation aspect.

Figure 4(a) shows influence of the air inlet temperature on efficiencies of GTG and STG with different condition for both HRSGs, i.e. the HRSGs without additional firing and the HRSGs with additional firing. The efficiencies performed by GTG and STG without additional firing significantly decrease when the air inlet temperature increases. This means that the additional firing in HRSG causes inefficiency of fuel.




(a). Efficiency system of each gas turbine generator and steam turbine-generator

(b). Efficiency system of combined cycle system

*Figure 4. Influence of air inlet temperature into compressor on efficiency system*

Influence of the air inlet temperature on efficiencies of GTG and STG with HRSG different condition, i.e., two HRSGs with additional firing and both HRSGs without additional firing is shown in Figure 4(b). The efficiency performed by GTG and STG without additional firing significantly decreases when the air inlet temperature increases. This result confirms that the combined cycle system without additional firing in HRSG will save fuel, and finally produce cheaper electric power than additional firing in HRSG.

*In addition to reducing or preventing the loss of gas turbine power output, the air inlet cooling also reduces or prevents the loss of steam produced in cogeneration systems and the loss of power output of steam turbines in combined cycle systems when the ambient air temperature rises above 15°C. The power output of a gas turbine falls with a rise in the ambient temperature because the mass flow rate of the inlet air decreases. This decreased mass flow rate also causes decreased total energy in the gas turbine exhaust gases, which in turn leads to reduced steam production in the HRSGs. The reduced steam generation in the HRSGs results in lower output of steam turbines in the combined cycle systems. The advantage of this system is that it has much less parasitic load. The big advantage offered by the air inlet cooling is that it enables the gas turbine to produce increased output power, and ensures that the output power can be maintained at a high level when the ambient temperature is high.*

## 4. Cooling Load and Alternative Cooling System

A significant benefit of air inlet cooling entering compressor is that it prevents a decrease of fuel efficiency of the gas turbine compared to gas turbine operated in tropical air condition. In this analysis three alternatives are considered, i.e. all vapor compression chiller (VCC), all-vapor-absorption system (VAC), and combined vapor compression chiller and vapor compression chiller (VCC+VAC). The cooling load estimated by equation (2).

$$q_{cooling} = \dot{m}_{air}\left(h_i^* - h_e^*\right) \qquad (2)$$

where $q_{cooling}$ is cooling load, $\dot{m}_{air}$ is mass flow rate in kg/s, $h_i^*$ is enthalpy of inlet air in kJ/kg dry air, and $h_e^*$ is enthalpy of exit air in kJ/kg dry air.

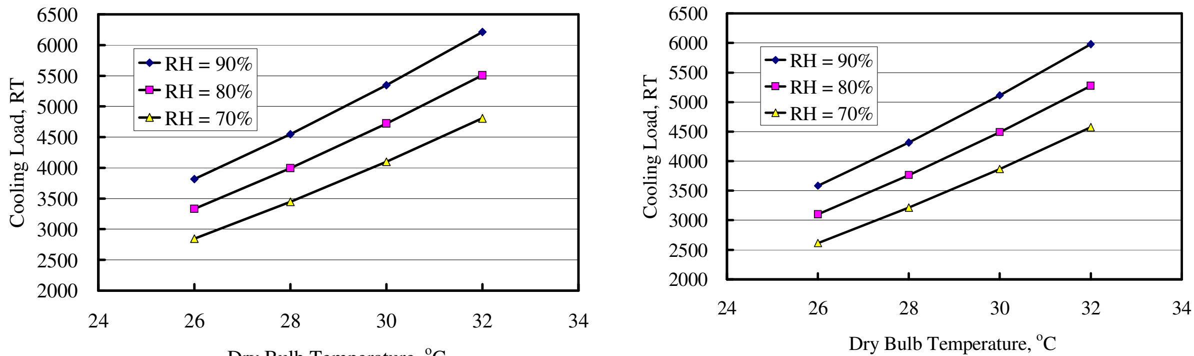
Effect of air inlet cooling for compressor on additional power produced and cooling load, which influenced by ambient air, are shown in Table 1. The additional net power in this result is not still reduced by parasitic power yet for driving chiller. This result shows that cooling load for chiller is significantly influenced by ambient air condition. Higher energy level of the ambient air should be more energy transported by chiller in order to keep the air condition. The RH of the ambient air also significantly affects on the cooling load. This effect does not occur for additional net energy generated by the power plant. Table 1 summarizes effect of ambient air condition on additional net power and cooling load. The additional net power produced by decreasing temperature of inlet air is still not including parasitic power for chiller. Ambient air in a power plant site is taken for several conditions, air inlet cooling into the both compressors down to 15$^o$C and RH 70%.

Table 1. Additional power generated and cooling load

| Ambient Conditions | Additional Net Power MWe* | | Cooling Load, RT |
|---|---|---|---|
| | No Additional Firing | Additional Firing | |
| 32°C, RH 90% | 10.488 | 8.050 | 5980 |
| 32°C, RH 70% | | | 4575 |
| 30°C, RH 90% | 9.311 | 7.146 | 5114 |
| 30°C, RH 80% | | | 4491 |
| 28°C, RH 90% | 8.120 | 6.231 | 4317 |
| 28°C, RH 70% | | | 3215 |
| 26°C, RH 90% | 6.913 | 5.304 | 3586 |
| 26°C, RH 70% | | | 2615 |

* Excluding parasitic power for driving chiller

Figure 5 shows effects of ambient air condition on the cooling load for the air entering both compressors. In case of the air inlet cooling down to 15°C and RH 60% is shown in Figure 5(a) and for the air inlet cooling down to 15°C and RH 70% is shown in Figure 5(b). As ambient condition always changes along time, determining cooling load should be suitable with the actual cooling load. Over chiller size will bring much capital cost and smaller chiller size will cause the conditioned air unable down to a desired condition. Therefore, chiller size should be judged so that optimal operation and design can be performed. This needs more experimental data of ambient air condition a long year. The chiller size significantly influences in economic analysis result. The chiller size is chosen based on maximum cooling load so that the chiller size is 6000 RT.




(a). Air condition at 15°C, RH=60%

(b). Air condition at 15°C, RH = 70%

Figure 5. Effect of air condition on cooling load

## 5. Economic Analysis of Chillers and Discussions

Economic analysis needs both thermodynamic and economic parameters. Energy in heat or power forms is needed to drive the cooling system. Table 2 shows the energy needed for any component of the alternative systems [Punwani et al. 2000]. These data agree with recent technology. Centrifugal compression chiller represents the vapor-compression chiller. This also agrees with recent technology that centrifugal type is most suitable for large chiller capacity. No heat is need for the centrifugal compression chiller. Absorption chiller needs a heat source for its generator. The coefficient of performance is 4.3 for centrifugal compression chiller, 0.7 for single effect absorption chiller, and 1.2 for double effect absorption chiller. Since our concern on fuel saving, the system analyzed is that the combined cycle without additional firing. Average additional net power excluding parasitic power of chiller is taken as 9,000 kW (see this value among values in Table 1). Waste heat may use from two HRSGs as much as 4,700 kW. This waste heat is suitable for the single-effect vapor absorption chiller, which absorbing heat from 125$^0$C down to 110$^o$C at 313.9 kg/s of gas flow rate. Lower heating value of natural gas is taken as 42,000 kJ/kg.

Table 2. Empirical parasitic power

| Components | Centrifugal Chiller* kW/RT | Single Effect Absorption Chiller* kW/RT | Double Effect Absorption Chiller* kW/RT |
|---|---|---|---|
| Chiller | 0.65 | 0.0217 | 0.0336 |
| Chiller Water Pump | 0.053 | 0.053 | 0.053 |
| Condenser Water Pump | 0.0618 | 0.1257 | 0.097 |
| Cooling Water Fan | 0.0451 | 0.0818 | 0.0655 |
| ***Total*** | 0.8099** | 0.2822 | 0.2491 |

*Water-cooled condenser, ** this value close to 4.3 of COP.

All parameters relating to parasitic cost of chillers should be considered so that accurate final economic results can be achieved. Table 3 represents the relating parameters including fuel rate and make-up water needed for chiller. VVC does not need fuel since the chiller use compressor and make-up water for cooling system of condenser. Hence VVC parasitic costs are derived from parasitic power Table 2 and added by make-up water cost, operation and maintenance (OM) costs. The alternative VAC also needs fuel for firing as heat source for generator besides parasitic power as represented in Table 2. Therefore, VAC parasitic costs are derived from parasitic power (Table 2) and added by fuel cost, make-up water cost, and OM costs. The last alternative VCC+VAC, the parasitic costs are derived from parasitic power in Table 2 and added by make-up water cost (condenser and absorber), operation and maintenance costs. The fuel cost in the third alternative is excluded since this system is set that VAC just used waste heat from the HRSG.

Table 3. Total power needed for chiller, fuel and make-up water

| Alternative | Parasitic Power, MWe | Ready Net Electric Power, MWe | Fuel, kg/s | Make-up water, lpm |
|---|---|---|---|---|
| VCC | 4.8594 | 4.1406 | - | 555 |
| VAC | 1.5244 | 7.4756 | 0.356 | 986 |
| VCC+VAC* | 4.3845 | 4.6155 | - | 645 |

*This alternative is designed for size of VAC agrees with waste heat from HRSG.

Engineering cost plays important role on finding the best alternative system. Since our concern on determining whether cooling system is effective for power plant and which is the best alternative system, the analysis is not conducted until the specific price of electric power produced (Rp./kWh), but it will be evaluated to judge benefit that will be resulted by using chiller. The analysis based on annual evaluation and the investment cost is paid annually by taking 12% of interest rate and economic life of the cooling system is 10 years. The natural gas price for the absorption chiller is assumed as Rp 55000,00/MMBtu. The electric price is assumed as Rp. 1000/kWh. Annual investment payment is calculated from equation (3). Water price for make-up water of cooling tower is assumed as Rp. 6,000.00/m$^3$.

$$A = \frac{iP}{1-(1+i)^{-n}} \tag{3}$$

where $A$ is annual payment, $P$ is investment cost, $i$ is interest rate in decimal (fraction, not percent) and $n$ is economic life (year). Any economic price is assumed such as Rp. 8,000,000.00/RT for VCC, Rp. 12,000,000.00/RT for VAC with single effect and Rp. 14,000,000.00/RT for VAC with double effect.

Comparative result of economic analysis for alternative chillers is represented in Table 4. It includes water cost, fuel cost, and OM costs, besides additional income will be got and investment payment should be paid as consequence of installation cost of chiller. Best financial benefit can be afforded when combination of VCC+VAC as cooling system. The next alternative is that using all VCC. All VAC is worst alternative among the three systems were analyzed. It is caused by COP of VAC is lower and direct firing for chiller makes a lot of heat losses into environment.

Table 4. Comparative result of economic analysis for alternative chillers

| Alternative | Additional Income, Rp./Year | Investment Payment, Rp./Year | Water Cost, Rp./Year | Fuel Cost, Rp./Year | OM, Rp./Year | Benefit, Rp./Year |
|---|---|---|---|---|---|---|
| VCC | 36.271 | 8.495 | 1.749 | - | 2.000 | 24.027 |
| VAC | 65.486 | 14.548 | 3.112 | 35.096 | 3.000 | 9.730 |
| VCC+VAC | 40,432 | 9.132 | 2.034 | - | 3.500 | 25.766 |

* Apparent number (Rp./Year) multiplied by 1000,000,000.

In order to see effect of electric price fluctuations, electric price is simulated for the three alternatives. Effect of the electric price on the financial benefit is represented in Table 5. VAC is not applicable when the electric price is lower than Rp. 1000.00/kWh. Taking assumption that the energy price increases a long time; CHP system will contribute much financial benefit besides fuel saving can be significantly achieved. Recently more than 13,000 MWe of Rankine cycle based power plants owned by electric state company are opportunities to be modified into CHP system. These results confirm that CHP system is possible to be implemented in Indonesia power plant and will give financial benefit and fuel saving.

Table 5. Effect of electric price on financial benefit per year*

| Price | VCC (Rp.) | VAC (Rp.) | VCC+VAC (Rp.) |
|---|---|---|---|
| Rp. 600.00/kWh | 9.518 | -16.464** | 9.593 |
| Rp. 800.00/kWh | 16.772 | -3.366** | 17.679 |
| Rp. 1200.00/kWh | 31.281 | 22.828 | 33.852 |
| Rp. 1400.00/kWh | 38.535 | 35.925 | 41.939 |

* Apparent number (Rp) multiplied by 1000,000,000. ** minus mean losses

## 6. Conclusion

An analysis involving thermo-economic criteria proven that implementation of air inlet cooling in gas turbine system gives energy saving and financial benefit. An increase in inlet air temperature from 15°C to 32°C increases heat rate, which causes a decrease in fuel efficiency by about three per cent for generating the same amount of the net power. CHP system can avoid this effect and it can even help increase fuel efficiency by cooling the inlet air to below 15°C. The biggest advantages accrue when ambient temperatures are high as a result CHP is most economic in hot locations. The advantage of CHP system is that it has much less parasitic load, but its major disadvantage is need more capital cost. Centrifugal vapor compression chiller is most convenient way to modify combined cycle system to be CHP system, however fuel saving and economic benefit can be yielded lower than combination of centrifugal vapor compression chiller and single-effect vapor absorption chiller (VCC+VAC). The all vapor absorption chiller (VAC) is worst alternative for the CHP system due to high fuel cost for driving the chiller. The CHP system is applicable for other existing Indonesian power plant from thermodynamic and economic aspects.

## References

Alhazmy, M. M., and Y.S.H. Najjar, 2004, Augmentation of gas turbine performance using air coolers, *Applied Thermal Engineering*, **24**, 415–429

Berry, J. B., Rod Schwass, James Teigen, Ron Fiskum, and Kevin J. Rhodes, 2005, Advanced Absorption Chiller Converts Turbine Exhaust to Air Conditionings, *International Sorption Heat Pump Conference*, June 22–24, Denver, CO, USA

Chacartegui, R., F. Jiménez-Espadafor, D. Sánchez, and T. Sánchez, 2008, Analysis of combustion turbine inlet air cooling systems applied to an operating cogeneration power plant, *Energy Conversion and Management*, **49**, 2130–2141.

Datawarehouse ESDM: Listrik (http://dtwh2.esdm.go.id/dw2007/index.php?mode=el), (access date: 11 Aug. 2008)

Hack, R. L., 2006, A Retrofit Integration of an Absorption Chiller with a Microturbine Array, *6th Microturbine Applications Workshop*, Jan 17-19, San Francisco, CA

Punwani, D.V., Tom Pierson, James W. Bagley, and William A. Ryan, 2001, A Hybrid System for Combustion Turbine Inlet Air Cooling at the Calpine Clear Lake Cogeneration Plant in Pasadena Texas, *ASHRAE winter meeting*, January, Atlanta.

Statistics Indonesia: Energy Statistics Capacity of Electric State Company, 1995 – 2006 (http://www.bps.go.id/sector/energy/table4.shtml), (access date: 14 Aug. 2008)

Wu D. W., and R. Z. Wang, 2006, Combined Cooling, Heating and Power: A Review, *Progress in Energy and Combustion Science*, **32**, 459-495.