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Thermoeconomic Analysis of Chilled Water Production by Absorption Process

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ABSTRACT

Thermoeconomic approach has been used for energy system analysis. Among the method adopted is to use heat-power network starting with the input and ending with products as the outputs. This approach is adopted for energy cost analysis for a gas-fueled cogeneration plant with natural gas as an input while the outputs are power and chilled water. The energy balance principle is used for energy analysis. For economic analysis, the average annual cost analysis is used to evaluate the average power cost. The average annual cost is estimated based on the annualized capital equipment cost, cost of fuel, and operation and maintenance costs. The method is used to estimate the average power cost for a 8.4 MW cogeneration system. The system consists of 2 units Gas Turbines at 4.2MW each, 2 units Heat Recovery Steam Generators at 12 Tonne/hr each and 2 units of Steam Absorption Chillers at 1250RT each. The calculated average cost of RM0.15 per kWh for power generated and RM0.50 per RTh for chilled water respectively. This value does not cover fixed costs and distribution cost of power and chilled water to the user.

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INTRODUCTION

The energy system is a complex system as it normally consists of a number of integrating equipment. To analyze the system, various approaches are adopted. One of the systems that have been employed is thermoeconomic analysis. This analysis view the energy problem as a heat-power network starting with fuel as the input and ending with specified products (El-Sayed, Y. M., 2003). This approach is adopted in this study of a cogeneration system with natural gas as an input and power and chilled water as the outputs.

The applications of thermoeconomic for energy analysis have been done by various authors. FlavioGuarinello Jr. *et al*. have studied thermoeconomic evaluation of a gas turbine in cogeneration system (Guarinello Jr., 2000).The study applied thermoeconomic concepts to a projected steam injected of gas turbine cogeneration system. From the thermoeconomic analysis, the results show the higher of the monetary costs is electricity. However the lower cost for the productions is steam of the plant.

Related to gas turbine power plant, AlmasiA. *et al*. applied the optimum design approach is addressing the trade-off between thermodynamic and economy(Almasi A., 2011). Marc A. Rosen and Ibrahim Dincer reported the systematic correlation exists for capital cost and energy loss in a coal fired electrical generating system. The relative spread is large in thermodynamic loss rate to capital cost ratio when it is based on energy loss and smaller when it is based on exergy loss (Rosen M. A., L. Dincer, 2003). GalipTemir and Durrye Bilge suggested that investment and operation and maintenance costs have to be distributed evenly to the cost of the products for thermoeconomic analysis (Temir G. & Bilge D., 2004). In terms of biomass production, Lian *et al*. reported that the overall production cost decreased with steam pressure of the trigeneration plant and increased with steam temperature (Lian, Z. T., 2010). Other researcherswho had researched on economic optimization on power generating system are (Singh O. K., S. Kaushik, 2013;Zare, V., 2012;Najjar, Y. S., S. Al-Absi, 2013;Morandin, M., 2013;Sayyadi, H., M. Nejatolahi, 2011).

The benefit of using thermoeconomic for energy systems analysis is that it enables the allocation of costs to the individual products of output. This could be used to link the various input costs, namely the cost of fuel, the capital cost of equipments and the operation and maintenance cost. In this study, the cost of producing power and chilled water is analyzed with respect to input costs covering the annual cost of natural gas used for input to the system, the capital cost of Gas Turbine (GT), Heat Recovery Steam

Generator (HRSG) and Steam Absorption Chiller (SAC) and the operation and maintenance cost for the cogeneration system.

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Methodology:

The analysis consists of two parts; the energy analysis and the economic analysis. The energy analysis uses energy balance equations to evaluate the fuel requirements. The power and chilled water are the outputs of the system. The economic analysis is to evaluate the average annual production cost of the system taking into account the cost of GT, HRSG, and SAC.

Energy Snalysis:

The outputs of the cogeneration system are power and chilled water. To calculate the energy input to the system, Eq. (1) to Eq. (4) are applied;

$$Energyinput\ (fuel) = \dot{m} \times LHV (\text{kWh}) \quad (1)$$

$$AnnualEnergyoutput = AnnualPowergenerated\ + AnnualChilledwatergenerated \quad (2)$$

Where$\dot{m}$ is a mass flow rate of fuel (kg/s) and LHV is Low Heating Value (kJ/kg.K). For the power and chilled water energy output, the energy equations expressed as;

$$Energyoutput(power) = Powergenerated(kWh) \quad (3)$$

$$Energyoutput(chilledwater) = \dot{m}_{chw} C_{p(chw)}(\Delta T_{chw})(kWh) \quad (4)$$

Where$\dot{m}_{chw}$ is the mass flow rate of chilled water (kg/s), $C_{p(chw)}$ is the specific heat of chilled water (kJ/kg.K) in a ΔT_{chw} the different in temperature by chilled water out and return (K).

Economic Analysis:

The basis of the economic analysis is to evaluate the average annual cost of the power and chilled water.

Annual Cost:

For the analysis, the annual cost of the cogeneration system is consists of the following;

(i) Capital cost of equipment , C_I
(ii) Cost of fuel, C_{fuel}
(iii) Cost of operation and maintenance, $C_{O\&M}$

Annual cost input which is the total of the expenses can be defined as;

$$TotalAnnualCost = C_{I(annual\ )} + C_{fuel\ (annual\ )} + C_{O\&M(annual\ )} \quad (5)$$

WhereC_IIs the capital cost of equipment in the plant,C_{fuel} is cost of fuel and $C_{O\&M}$ is the annual expense items associated with the operation and maintenance phase.

From Eq. (5), the annual cost of fuel is calculated as;

$$C_{fuel\ (annual\ )} = (\dot{m}_f \times LHV \times n \times hoursrunning \times daysrunning) \times RC_f \quad (6)$$

Where$n$ is number of GT and RC_f is the cost of fuel per unit of energy (RM/kWh).

The total capital cost of equipment is calculated as;

$$C_I = \sum_{i=1}^{n} \sum_{j=1}^{m} C_{ij} \quad (7)$$

Where$i$=types of equipment, j = number ofequipment and C_j is the capital cost of $j$equipments. Whereas C_i is defined as;

$$C_i = I_i \times CRF \quad (8)$$

WhereI_j is the investment cost of j equipments in RM (Malaysia Ringgit) and Capital Recovery Factors (CRF) is evaluated by;

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (9)$$

where i is the interest rate and n is the operating period of the system in years.

The operation and maintenance cost is defined as;

$$C_{O\&M} = C_{operation\ (j)} + C_{repair\ (j)} + C_{maintenance\ \ (j)} \tag{10}$$

Where, $C_{operation\ (j)}$ is a labour cost, C_{repair} is refer to cost of repairing damage and $C_{maintenance}$ is refer to routine maintenance yearly.

Average Annual Production Cost:

The average annual production cost is defined as;

$$AverageAnnualproductioncost = \frac{TotalAnnualCost}{TotalAnnualEnergyOutput} \tag{11}$$

Case Study:

UniversitiTeknologiPetronas (UTP) cogeneration plant is taken as a case study. The plant operates on a 24 hour basis. The schematic diagram of the UTP cogeneration plant is shown in Fig. 1. The system consists of 2 units Gas Turbine at 4.2 MW each, 2 units HRSG at 12 Tonne/hr each and 2 units of SAC at 1250RT each.

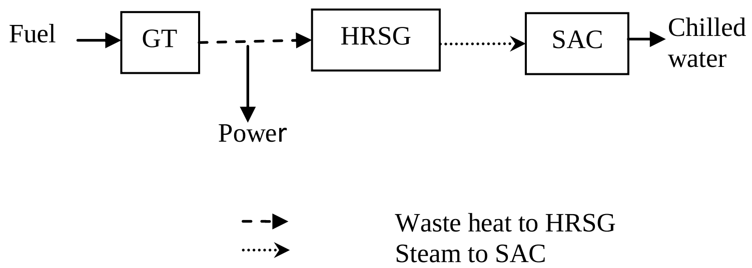

Fig. 1: UTP cogeneration plant.

The energy input is from fuel with the mass flow rate, $\dot{m}_f$ (kg/s). The compression ratio of the GT is 11.7 with the isentropic efficiency is 0.89 (Karim, Z. A. A., P. W. Yongo, 2011). The waste heat coming out from the GT at 600K to 700K will enter the HRSG to generate steam. The steam is taken as the input of SAC for chilled water production by absorption process. The chilled water supplies to the district cooling system is at 6ºC temperature and returns at 13.5ºC. The summary of operating data is shown in Table 1.

Table 1: Operating parameters for UTP cogeneration plant.

Component	Operating conditions	Value
GT	$\dot{m}_f$	0.26 kg/s
	LHV	41 000 kJ/kg.K
	Capacity	8.4 MW
	Isentropic efficiency	0.91
SAC	$EnergyCHW$	5051 kWh
	$C_{p(chw)}$	25.21 kJ/kg.K
	ΔT_{chw}	7.5ºC
	Capacity	1250 RT/h
	COP	0.65

Table 2: is the summary of economic parameters used for economic analysis.

Table 2: Economic parameters			
	GT	HRSG	SAC
No. of units	2	2	2
Operating hours	8hrs/unit	12hrs/unit	12hrs/unit
Days	360	360	360
I_j, Estimated price per unit rate (RM)	1.5M /MW	0.4M /Tonne steam	4000 /RT chilled water
RC_f, Estimated price of fuel (RM)	14/GJ		
$C_{O\&M}$, Estimated operation and maintenance costs (RM)	3.8M/year for the equipments		

(i) Energy of outputs:

- The data on power and chilled water production for both GT and SAC is based on the plant operating data as in Table 3.

Table 3: Annual operating data for power and chilled water production

The energy of:	Min	Max	Ave
Power (kWh)	30.8E6	139E6	48.5E6
Chilled water (kWh)	0	84.5E6	42.4E6
Total energy (kWh):	30.8E6	224E6	90.9E6

(ii) Annual cost:

- The cost of fuel is calculated by using Eq. (6). The value of the mass flow rate is assumed 0.26 kg/s for both GT.
- The capital cost for the equipment for 3 equipments ; GT, HRSG and SAC.
- From the Eq. (7), i =3 i.e GT, HRSG and SAC and j =2 for each components . The total capital cost of equipments is expressed as;

$$C_I = (2 \times C_{GT}) + (2 \times C_{HRSG}) + (2 \times C_{SAC}) \quad (12)$$

- In this study, it is assumed that *i=10%* and *n=20* years.
- Assuming the cost of operation and maintenance is constant as in Table 2.

RESULTS AND DISCUSSION

(i) Annual cost:

Using Eq. (6), Eq. (7) and Eq. (10), the estimated annual cost of the UTP cogeneration plant is shown in Table 4.

Table 4: Estimated annual costs equipments.

	C_{fuel}	C_{GT}	C_{HRSG}	C_{SAC}	$C_{O\&M}$
Annual costs (RM)	6.3M	1.5M	1.1M	1.2M	3.8M

From the results in Table 4 and assuming the price of fuel is RM0.05/kWh, the annual cost of fuel is estimated around RM6.3M while the total annual costs for the equipments is estimated about RM13.9M. The results of annual costs in percentage are shown in Fig. 2. It is shown the cost of fuel is higher than the annual cost of equipment. The annual cost of equipment and the operational and maintenance cost are 28% and 27% respectively.

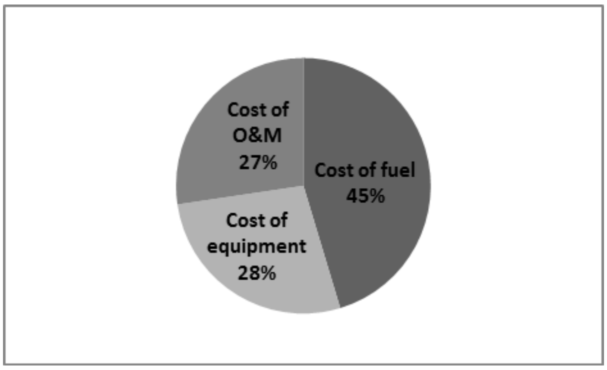

Fig. 2: Annual costs in percentage.

(iii) Average annual production cost:

Using Eq. (11), the average annual production cost of power is RM0.15 per kWh. While the production cost of chilled water is RM0.50 per RTh. These values do not iclude the fixed operating cost and distribution cost.

Conclusion:

The average power cost is estimated based on inputs and outputs. The input component covers the cost of fuel, the capital cost of equipments and operation and maintenance cost. While the output components are based on power and chilled water generated. The results obtained are RM0.15 per kWh for power generated and

RM0.50 per RTh for chilled water. However, the values do not cover the fixed cost and the distribution cost. The fixed cost and the distribution cost will be included in the future work.

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