Energetic and Economic Analysis of a Micro Gas Turbine Cogeneration System in Residential Buildings in a Tropical Region

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***Abstract*— The study clearifies the energetic and economic performances of a micro gas turbine cogeneration system (MGT-CGS) in residential buildings located in a tropical climate. Three different cases of MGT-CGS were investigated. The first case investigated an MGT with an exhaust heat exchanger (EHE), whereas the second case investigated an MGT with an EHE and absorption heat exchanger (AHE). The third case was similar to the second case but with the addition of inlet air pre-cooling equipment. It was found that Case 2 and Case 3 can utilize more exhaust heat from the MGT and had Energy recovered utilized efficiency $\eta_{ER,utilized}$ in the range of 0.36-0.38 during day time. While during night time the $\eta_{ER,utilized}$ was in the range 0.70-0.73. The MGT-CGS in Case 3 had higher Fuel energy saving index *FESI* while compared to a gas turbine with an air conditioner but a lower *FESI* in comparison to a combined cycle gas turbine. The shortest payback period for this case was 10 years.**

Keywords-Micro Gas Turbine; Cogeneration System; Distributed Generation; Energy, Economy

I. INTRODUCTION

The world is facing severe energy crisis which are mainly of two types: depletion of nonrenewable fossil fuels and the environmental pollution. Energy consumption in developing countries increase because of the development of the living standards of common people. In general, such countries comprise of tropical regions. For instance, power usage of the developing states of ASEAN-5 boosted up almost three times in just 20 years due to a 20-40% rise in population [1]. Per capita consumption of power of Malaysia which has a tropical climate grew 5.4 times during the years 1980 to 2008 [2]. Due to these indicated factors a cleaner, cheaper and more effective power generation system is needed.

Distributed generation (DG) with a cogeneration system (CGS) can productively utilize exhaust heat which can solve these crises to a great extent. DG has several advantages: (1) Can be easily installed and effectively operated in high-demand or rural areas, (2) Power can be distributed and transmitted with low losses and (3) Exhaust heat can be used efficiently.

Developed countries are quite interested in establishing DGs with CGS systems because of the advantages stated above. It was also reported that 38 CGSs are functioning at this time in Malaysia [3]. The reciprocating engines, fuel cells and micro gas turbines (MGTs) can be the sources of DGs. The reciprocating engines have high efficiency but they release high emissions. Fuel cells emit less emissions and this makes them the most favourable DG source but high costs and unreliable are some of the problems [4]. On the other hand, although the MGTs have lower power generation efficiency than reciprocating engines, the emissions are lower. Moreover, the advantages of MGTs are multi fuel compatibility, high power density and low maintenance requirements [5]. The price of MGTs have became more affordable due to the gradual development in power electronic and material science technology. Consequently, it can be expected that the use of MGTs will increase with time.

The studies on the energetic and economic performances of MGT-CGSs for the residential buildings in a tropical region are of vital importance because the energy consumption by this sector is high. For instance, energy consumption in residential buildings accounts for 13% of the total energy consumption and 48% of the total Malaysian power consumption [6]. The heat to power ratio of the MGTs is quite high but the cooling requirements can be met by using absorption heat exchanger (AHE) activated by exhaust heat. MGTs also have lower power generation efficiency in hot atmospheric conditions but an AHE can lower down inlet air temperature of the MGTs and therefore its power generation efficiency can be increased.

The main purpose of this research is to clearify the performances of an MGT-CGS for residential buildings in Malaysia and it particularly focuses on the energetic and economic characteristics of this system. Three different arrangements of MGT-CGSs were examined and compared. Firstly, the energy balance of the energy system and the buildings were studied. Then, the efficiencies of all three cases of this system were compared. The comparative analysis was done particularly on the basis of energy efficiencies, the Fuel energy saving index, and the payback period.

II. MATERIALS AND METHODS

A. Ambient Temperature Condition

The countries with tropical or mega thermal climates are belong to Group A in the Koppen Climate Classification. This group contains countries from South America to Asia such as Brazil ,Nigeria, Malaysia and Indonesia. The average ambient

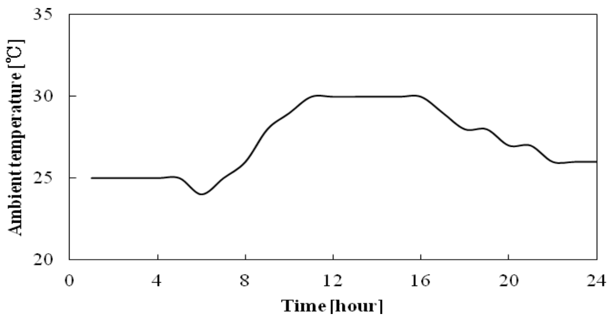

Fig. 1 Variation of average ambient temperature in a single day.

temperature of a tropical region varies throughout the day as shown in Fig. 1. During 12:00-14:00 the temperature was highest and found to be 30°C, whereas minimum temperature of 24°C was recorded at 06:00.

B. Analysis Model of Residential Buildings and Its Energy Demand

A group of double storey terraced houses situated at Shah Alam, Selangor was adopted as the model of the residential buildings. Each house is 6.5m long and 19.8m wide that cover an area of 133m^2. Each house has four rooms and four bathrooms. The illustration of the model residential buildings with an MGT-CGS is presented in Fig. 2.

A survey on the power requirements of a family of 6 people was performed in such a house in Malaysia [7]. It was reported that the demand for energy and water heating is almost constant because constant ambient temperature throughout the year, and power consumption by air conditioners is approximately 21% of the total energy demand. On the other hand, [8] reports the frequency of the air conditioner (AC) usage which can be used to estimate the pattern of an AC cooling demand as shown in Fig. 3. It can be seen that power demand P_{ed} increases during day hours whereas cooling demand $Q_{AC,load}$ increases during night hours.

III. MODEL OF MGT-CGS

A. MGT-CGSs and Their Arrangements

The system studied in the previous research [9] and [10] that consisted of a recuperated single shaft MGT, an EHE of

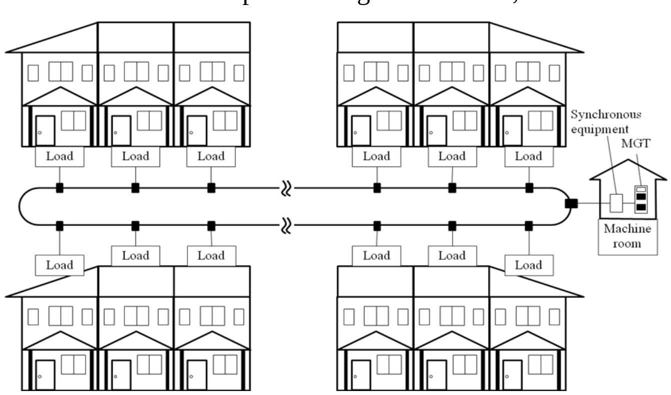

Fig. 2 Configuration of the MGT-connected terraced houses.

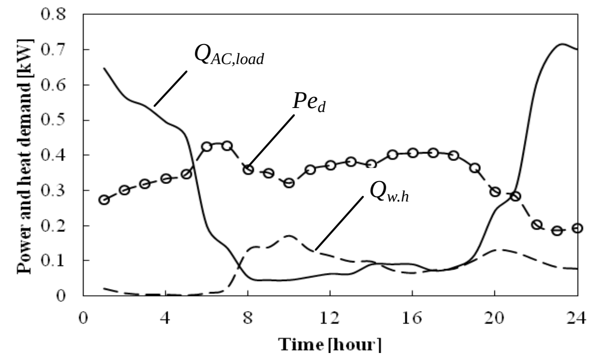

Fig. 3 Details of power and heat demand in a single day.

TABLE 1 BASIC SPECIFICATION OF THE MGT, EHE AND AHE.

Micro Gas Turbine (MGT)		
Exhaust temperature	ºC	273
Rated revolution speed	rpm	96300
Rated electrical power output	kW	30
Electrical power efficiency	-	0.26
Flow rate	m^3/h	~30
Exhaust Heat Exchanger (EHE)		
Effectiveness	-	0.80
Cold water inlet temperature	ºC	80
Cold water mass flow rate	kg/s	1.616
Capacity ratio	-	0.054-0.063
Absorption Heat Exchanger (AHE)		
Cooling outlet temperature	ºC	7
Rated heat medium temperature	ºC	88
Standard cooling capacity	kW	70
Standard heat rejection to cooling tower	kW	171
Standard heat medium input capacity	kW	100

tube-shell type and a H_2O-LiBr AHE was used in this study. Table 1 represents the basic specifications of all main components used in this system.

Each of the three MGT-CGS cases had different arrangement. However, all MGT-CGS operated in power matched mode. There are two ways to operate the system with an all-day changing power load, either operating it at partial load which will result in less power generation efficiency or operating at full load by installing a battery as the power storage. In this study first approach was used because it will have low initial and O&M costs, and the MGT is also good at operation under rapid changing load.

Comparison of all MGT-CGS arrangements are shown in Fig. 4. As shown in Fig. 4, electrical power grid covers all power demands including air conditioning, water heating, washing machine and other electrical appliances in the conventional system, but natural gas grid covers the demand in all MGT-CGS cases. For Case 1, exhaust heat was used to provide hot water only while other demands were covered by power generated by the MGT. Air conditioning and water heating both were covered by exhaust heat in Case 2, making it

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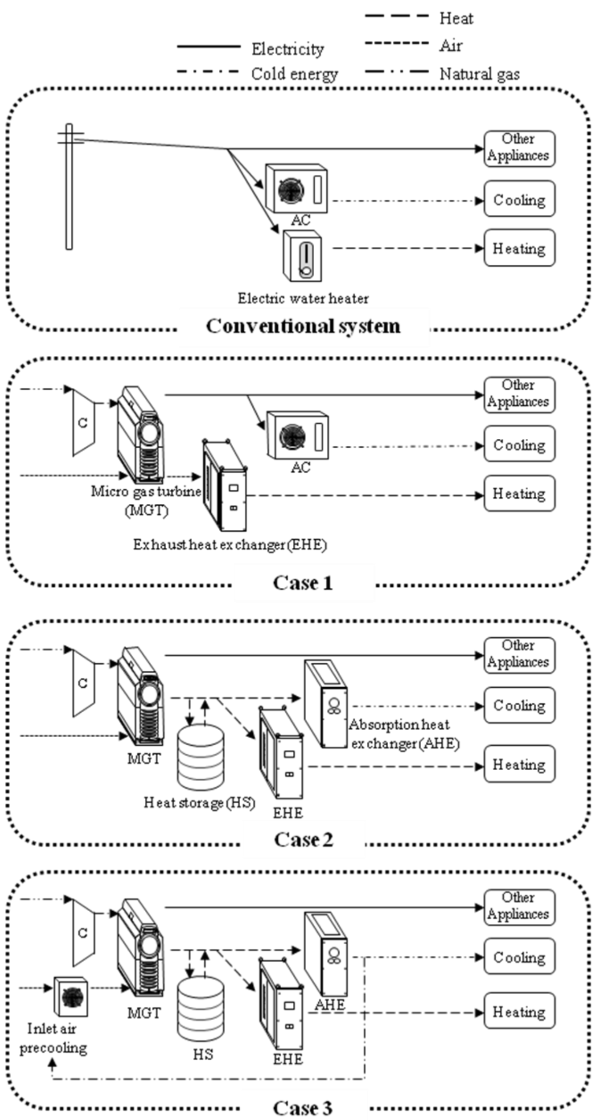


Fig. 4 Configuration of the energy system in all cases.

more efficient. Case 3 is expected to have the highest efficiency because inlet air temperature of the MGT was also cooled by exhaust heat which can also increased the power generation efficiency of the MGT. In addition, a heat storage equipment was also considered in Case 2 and Case 3. From the relation on energy demand power produced from the MGT, the units of houses for the three difference cases were assumed to be 52, 60 and 66, respectively.

B. Energy Balance of Energy System

Power balance of the energy systems can be calculated by the following equation:

$$Pe_{MGT} = Pe_{o.a} + Pe_{AC} + Pe_{g.c} + Pe_{w.p}, \qquad (1)$$

where Pe_{MGT} is power generated by the MGT [kW], $Pe_{o.a}$ is power demand for other appliances [kW], Pe_{AC} is power demand for air conditioning [kW], $Pe_{g.c}$ is power demand for a gas compressor of the MGT, and $Pe_{w.p}$ is power demand for pumping hot water to all houses [kW].

Heat energy balance of the system can be calculated by the following equation:

$$Q_{ehr} = Q_{w.h} + Q_{w.h,loss} + Q_{AC,AHE} + Q_{c.w,loss} + Q_{i.p.c,AHE} + Q_{unutilized}, \qquad (2)$$

where $Q_{w.h}$ is water heating demand [kW], $Q_{w.h,loss}$ is loss at the hot water pipeline [kW], $Q_{AC,AHE}$ is heat demand for cooling by AHE [kW], $Q_{c.w,loss}$ is heat loss at cold water pipeline [kW], $Q_{i.p.c,AHE}$ is heat needed for inlet air precooling equipment of the MGT [kW], and $Q_{unutilized}$ is unutilized heat [kW]. $Q_{AC,AHE}$, $Q_{c.w,loss}$ and $Q_{i.p.c,AHE}$ were not considered in Case 1, whereas $Q_{i.p.c,AHE}$ was not considered in Case 2.

IV. EVALUATION METHOD OF MGT-CGS

A. Efficiency Analysis of MGT-CGS

It is important to evaluate the output of the MGT-CGS. Thus, power generation efficiency η_{Pe}, exhaust heat recovered utilized efficiency $\eta_{ehr,utilized}$ and energy recovered utilized efficiency $\eta_{ER,\ utilized}$ were calculated. They can be calculated by the following equations:

$$\eta_{Pe} = \frac{Pe}{Q_{fuel}}, \qquad (3)$$

$$\eta_{ehr,utilized} = \frac{Q_{ehr} - Q_{ehr,unutilized}}{Q_{fuel}}, \qquad (4)$$

$$\eta_{ER,utilized} = \frac{Pe + Q_{ehr} - Q_{ehr,unutilized}}{Q_{fuel}}, \qquad (5)$$

where $Q_{ehr,unutilized}$ is the exhaust heat which is recovered but not utilized [kW].

B. Economic Analysis of MGT-CGS

Firstly, a common economic analysis was carried out on how effectively the system can save fuel in comparison to conventional systems. For this, the power output by the conventional systems and the MGT-CGS was assumed to be the same. Fuel Energy Saving Index *FESI* was estimated by the following equation:

$$FESI = \frac{Q_{fuel,conv.} - Q_{fuel,CGS}}{Q_{fuel,Conv.}}, \qquad (6)$$

Two conventional systems: (1) an open cycle gas turbine (Conv.1) and (2) a combined cycle gas turbine (Conv.2) were compared to the MGT-CGS. The Energy commission of Malaysia reported the power generation efficiencies for Conv. 1 and Conv. 2 are 0.27 and 0.44, respectively [3]. Moreover, electricity transmission and distribution loss which is equal to 7% of the total power generated was also considered.

Payback period PBP can also be calculated by the relation between equipment cost C_{eq}, O&M cost $C_{O\&M}$ and Pay Back *PB* as shown below:

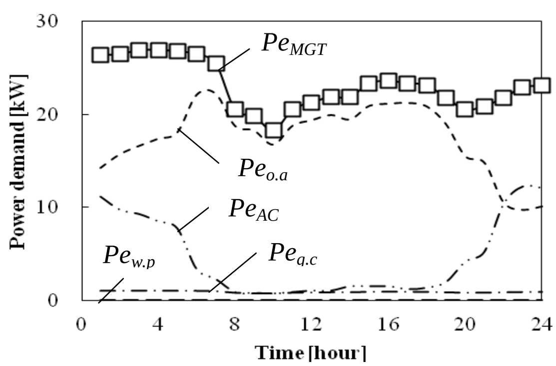
$$PBP = \frac{C_{eq.}}{PB - C_{O\&M}}. \qquad (7)$$

V. RESULTS AND DISCUSSION

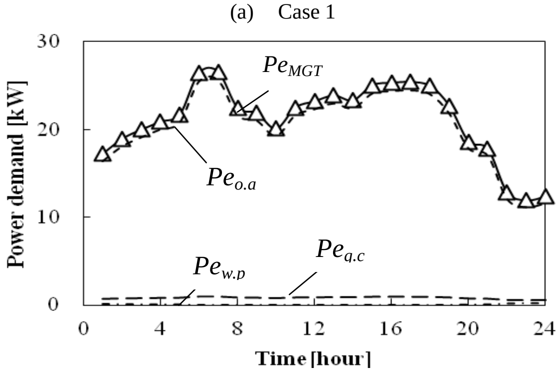
A. Power Supplied By MGT-CGS and Its Operation Condition

Fig. 5 represents the power supplied by the MGT in all cases. It should be noted that the power supplied Pe_{MGT} is equal to the total power demand Pe_d because the MGT-CGS was operated in a power demand matched mode.

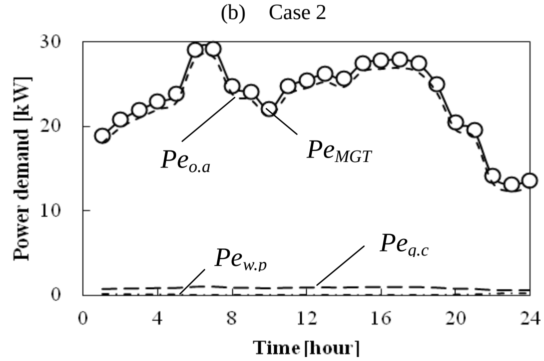
Case 1 shows that other appliances consumed more power during day hours (06:00-18:00), whereas the air conditioner consumed more power during night hours (18:00-06:00) because air conditioners in a tropical region were used mostly during sleeping. In addition, the total power demand varied throughout the day with minimum demand was found during 08:00-12:00 when fewer power-driven appliances were used. It was also found that pumping hot water and compressing gas required less power in all the cases.



(a) Case 1



(b) Case 2



(c) Case 3

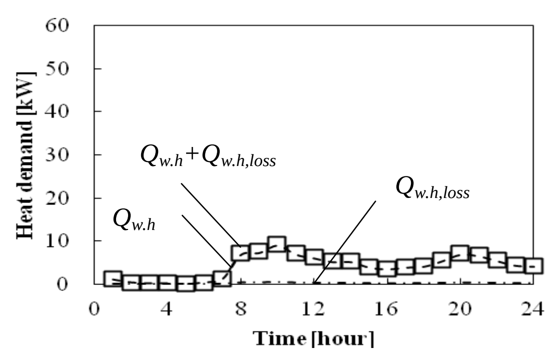
Fig. 5 Power supplied by the MGT-CGS and its break down for all cases.

For Case 2 and Case 3, due to the AHE used which fulfilled power demand of air conditioners, the power demand during night hours was comparatively lower than Case 1. The power demand was at peak around 07:00 in Case 2. It was also found that the result for Case 3 was found to be similar with Case 2 but the MGT-CGS in Case 3 has higher power. This was because inlet air pre-cooling increased the power output of the MGT.

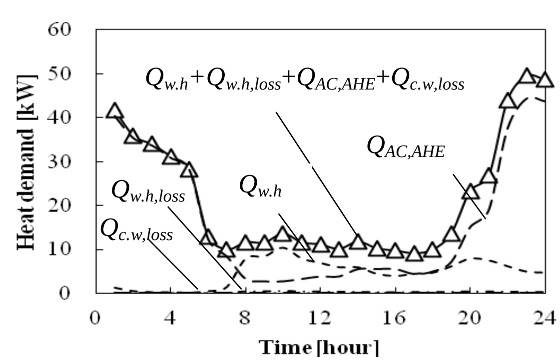
B. Heat Demand and Balance

Fig. 6 shows results for heat demand and balance for all cases. Fig. 6a shows result of Case 1 where water heating demand $Q_{w.h}$ varies throughout a day and reached its highest value of 9.4 kW. Furthermore, $Q_{w.h}$ was almost equal to the total heat demand because of the low hot water distribution losses $Q_{w.h,loss}$ of just 0.44kW. Fig. 6b for Case 2 and Fig. 6c for Case 3 also shows that the amount of hot and cold water distribution losses were small. Heat demands for Case 1 and Case 2 were different in term of amount of water heating demand $Q_{w.h}$ and Case 2 also had the heat for AHE for air conditioning $Q_{AC,AHE}$. Heat demand of AHE was in the range of 3-8 kW during 07:00-18:00 but the demand started to increase during 19:00-06:00 and reached as high as 44 kW at 23:00.

Case 3 had a similar heat demand pattern to Case 2 but was higher in amount. The increase in demand of $Q_{w.h}$ and $Q_{AC,AHE}$ was due to the ability of Case 3 to provide power to 6 more houses and the requirement of 1.8-3.6 kW for pre-cooling inlet air of MGT. The heat demand increased as high as 58 kW at 23:00.

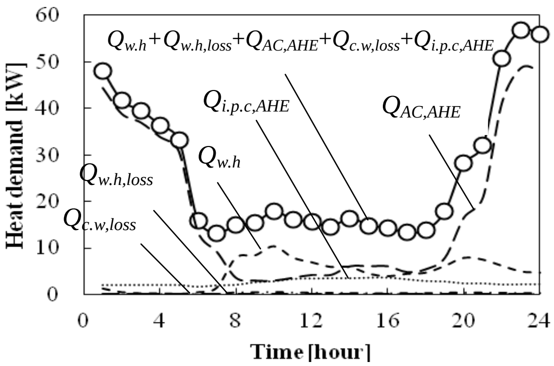


(a) Case 1



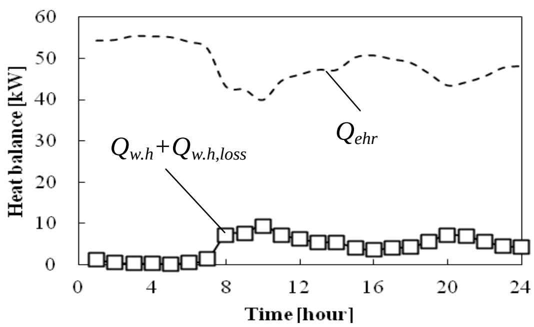
(b) Case 2

Fig. 6 Heat demand and its break down for all cases.

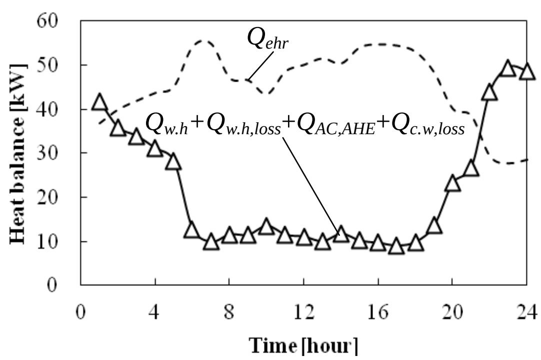


(c) Case 3

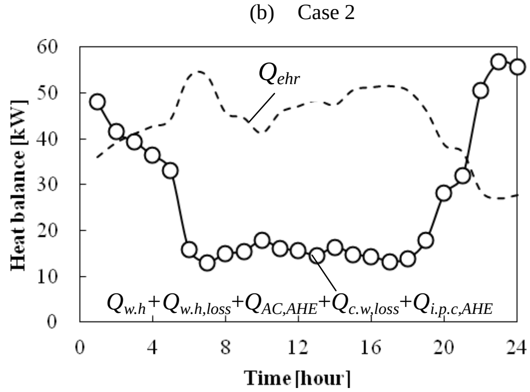
Fig. 6 Heat demand and its break down for all cases. *(Continued)*



(a) Case 1



(b) Case 2



(c) Case 3

Fig. 7 Relation between the total heat demand and the recovered exhaust heat for all cases.

Fig. 7 shows the relation between the total heat demand and exhaust heat recovered by the MGT-CGS. As shown in Fig. 7a, even though the system provides as high as 59 kW of heat, only 9.4 kW of heat can be utilized in Case 1. Case 2 and Case 3 show similar result in which although heat supply ability was high during day, heat demand was high during night. However, amount of unutilized heat during day time was sufficiently large to cover the remaining heat demand during night time. Thus, unutilized heat during day can be stored and be used during night.

VI. Evaluation Result of MGT-CGS

A. Energy Efficiency Comparison

Fig. 8 shows the power generation η_{Pe} and total energy utilized efficiency $\eta_{ER,utilized}$ for all cases. It was found that Case 2 and Case 3 were more efficient than Case 1. Power generation efficiency of the MGT-CGS varied in the range of 0.21-0.26. Case 2 and Case 3 had higher $\eta_{ER,utilized}$ because they can utilize a greater amount of exhaust heat and storing the unutilized heat during day to be used during night hours. This is also the reason $\eta_{ER,utilized}$ exceeded 1.0 during 23:00-24:00. Furthermore, Case 2 has an average $\eta_{ER,utilized}$ of 0.36 during day and of 0.70 during night time. Whereas Case 3 has an averaged $\eta_{ER,utilized}$ of 0.38 during day and 0.73 during night in Case 3 due to the installation of inlet air pre-cooling equipment. It can also be concluded that integration of a photovoltaic system to the MGT-CGS can be a good solution because efficiency of the MGT-CGS in residential sector of tropical regions is low during day time. This can help to improve the efficiency of the MGT-CGS during day time and enable the MGT-CGS to give its best possible output during night time. On top of that this system can help in developing renewable energy systems that have stable energy supply.

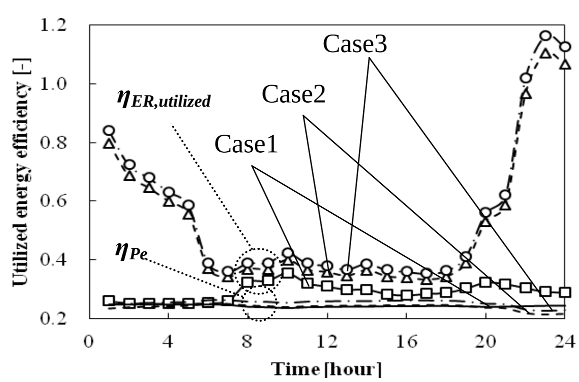
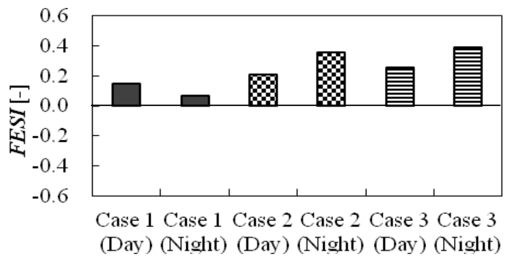


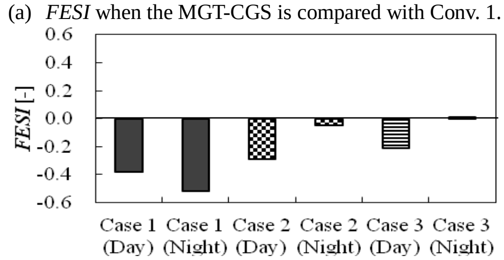
Fig. 8 Power generation and total energy utilized efficiency.

B. Economic Comparison

Fuel energy saving index *FESI* is a simple economic evaluation to compare the benefit of the MGT-CGS compared to conventional systems. Fig. 9 shows the result of *FESI* of the MGT-CGS for all cases. The MGT-CGSs for all cases were compared with two conventional systems as stated in section 4-B. Fig. 9a shows results when the MGT-CGS was compared with Conv.1, whereas Fig. 9b shows results when the MGT-CGS was compared with the Conv. 2. Fig. 9 shows that the MGT-CGS can save more than 10 % of fuel when it is compared with Conv.1. However, although the MGT-CGS had $\eta_{ER,utilized}$ as high as 0.73 compared to Conv.2 ($\eta_{ER,utilized} = \eta_{Pe}$ =0.44), Conv.2 was more economical. This is because even though Conv. 2 has lower $\eta_{ER,utilized}$, it has higher η_{Pe}, on top of that it was combined with an air conditioner that has COP as high as 3.0.



(a) *FESI* when the MGT-CGS is compared with Conv. 1.



(b) *FESI* when the MGT-CGS is compared with Conv. 2.

Fig. 9 *FESI* of MGT-CGS for all cases.

Fig. 10 presents results of the payback period for all cases of MGT-CGSs. In addition, initial and O&M costs are shown by symbols, and payback are shown by lines. The lowest initial cost of US$ 60 000 was found for Case 1, whereas the highest initial cost of US$ 123 500 was found for Case 3. It was also found that difference of cost between all cases were small throughout 20 years but difference of pay back between cases became larger. Payback of Case 3 increased more than other cases when time passes.

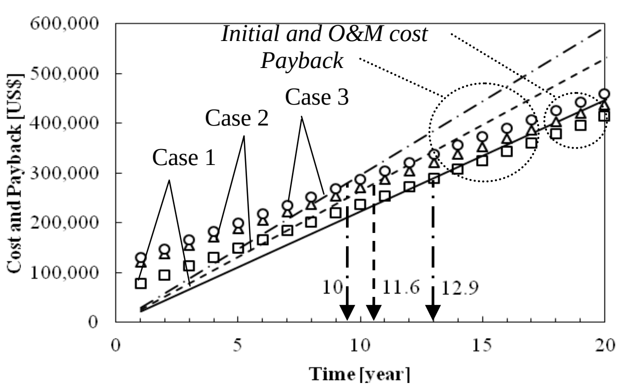


Fig. 10 Relationship of *PB* with initial and O&M cost.

The most complicated but the most efficient arrangement, Case 3 has the shortest PBP which was equal to 10 years. Energy Commission of Malaysia reported that 75% of the actual market price of electrical power is paid by Malaysian government who has subsidized it to a great extent. If the actual market price of electrical power is used in the estimation of PBP, the payback increased and then PBP decreased to a great degree. The new payback periods for Case 1, Case 2 and Case 3 are 1.2, 1.8, and 1.7 years, respectively.

VII. CONCLUSIONS

Energetic and economic performances of three arrangements of MGT-CGSs: (Case 1) an MGT and EHE; (Case 2) an MGT, EHE and AHE; (Case 3) an MGT, EHE, AHE and an inlet air pre-cooling equipment were investigated. Case 2 and Case 3 with an AHE can efficiently utilize exhaust heat for air conditioning. However, since an AC is usually used for sleeping during night time, energy efficiency is low during day time, and heat storage is also needed to store waste heat to be utilized during night time. Case 2 has an average energy recovered utilized efficiency $\eta_{ER,utilized}$ of 0.36 and 0.70 during day and night time, respectively. This efficiency further improves to be 0.38 during day and 0.73 during night in Case 3 due to the inlet air pre-cooling equipment. The inlet air pre-cooling equipment can increase power generation efficiency in the range of 1.2-1.6%. Since energy utilization during day is less than that during night, it can be concluded that operation of photovoltaic system during day hours can be more substantial. The analysis showed that the distributed generation of the MGT-CGS is better than a typical conventional system with a gas turbine (GT) but not as good as an ideal conventional system with a combined cycle gas turbine (CCGT). This is due to the CCGT has higher power generation efficiency and it can be combined with an air conditioner that has higher COP value. Case 3 has a payback period of just 10 years which is the shortest under highly subsidized fuel costs.

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