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Effect of operation strategies on the economic and environmental performance of a micro gas turbine trigeneration system in a tropical region

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ABSTRACT

This study investigates the effect of employment of different operation strategies on the economic and environmental performance of a micro gas turbine trigeneration system (MGT-TGS). The MGT-TGS covers power, heating and cooling load of a selected building in a tropical region. The prime movers used were MGTs with electrical output capacity of 30 kW and 65 kW. Four operation strategies; Power-Match, Heat-Match, Mix-Match, and Base-Load were examined. The Net Present Value and Emissions Reduction Index throughout the life cycle of the MGTs were calculated. It was found that MGT-TGS can only generate positive NPV (Net Present Value) at the end of 25 years life time under unsubsidized electricity price. Mix-Match and Power-Match operation strategies can generate positive NPV because the systems can generate more electricity. However, these operation strategies cannot reduce emissions especially CO_2 and CO when they were compared to a CCGT (Combined Cycle Gas Turbine). Base-Load is the only operation strategy that can reduce all emissions even when it is compared to a CCGT. When the economic and environmental performance is fairly considered using CPERI (Cost Per Emissions Reduction Index), Mix-Match is the optimum solution because it can generate CPERI of US$16.0–92,407, based on NPV.

1. Introduction

One sustainable solution to face energy depletion and environmental issues due to excessive utilization of fossil fuel is by utilizing energy efficiently. CGS (Cogeneration System) and TGS (Trigeneration System) are options available in the power generation sector. These types of distributed generation have an advantage in terms of utilizing exhaust heat for other purposes because they are operated close to the demand-site.

Reciprocating engines, MGTs (micro gas turbines) and fuel cells are commercially available prime movers for CGS and TGS applications. Every prime mover has its own characteristics. MGTs have less power generation efficiency as compared to reciprocating engines, but they emit less emissions especially NOx. They also operate with lower costs as compared to fuel cells. In addition, utilization of waste heat from MGTs are easier because the heat only needs to be recovered at the exhaust gas stage, and MGTs also produce high quality of heat with temperature exceeding 200 °C. Thus, MGTs are a good option if waste heat utilization, environment and cost factors are fairly considered. However, the claimed emissions and energy performance of MGTs are valid when it is operated at Full-Load. The efficiency and environmental performance usually decrease during Partial-Load operation. Thus, it is important to analyze their performance during the system design stage.

The need for Partial-Load operation depends on the operation strategy employed. Basic operation modes for CGS and TGS are Power-Match mode, Heat-Match mode, and mixed-match mode. Selection of the appropriate operation strategy will determine the CGS and TGS efficiency, economic and environmental performance. Thus, it is important to examine how operation strategies effect the performance of MGT-TGS in a particular condition.

There are many research conducted on the topic of MGT with CGS and TGS configuration. Some studies reported on the performance of MGT in various modifications, without considering its application in a specific building load. Ameri et al. utilized waste heat from 200 kW MGT for cooling purpose by integrating a steam

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Nomenclature

A	area, m^2
AUP	annual uniform payment, US$
C	cost, US$
Cap	capacity, kW or kWh or m^3
CPERI	cost per emissions reduction index, -
Em	emissions, kg
EF	emissions factor, kg/kWh
ERI	emissions reduction index, -
i	interest, -
LF	load factor, -
n	life time, year
NPV	net present value, US$
Pe	power, kW or kWh
Pr	profit, US$
PW	present worth, US$
PWF	present worth factor, -
Q	heat, kW
t	temperature, °C, K
η	efficiency, -

Subscript

AB.C	absorption chiller
AUP	annual uniform payment
boiler	boiler
battery	battery
conv.	conventional system
cool	cooling
ehr	exhaust heat recovery
eq	equipment
fuel	fuel
h.storage	heat storage
hm	heat medium of absorption chiller
ins	installation (cost)
i.p.c	inlet air pre-cooling
Pe	power
PL	partial-load
MGT	micro gas turbine
MGT-30	micro gas turbine with 30 kW power capacity
MGT-65	micro gas turbine with 65 kW power capacity
MGT-TGS	micro gas turbine trigeneration system
O&M	operation and maintenance
Pe	power
rep	replacement (cost)
sal	salvage value
SP@SR	single payment or single return

Abbreviation

In. P-C	inlet precooling
MGT	micro gas turbine
MGT-30	micro gas turbine with 30 kW power capacity
MGT-65	micro gas turbine with 65 kW power capacity
TGS	trigeneration system

ejector refrigeration. The integration can save fuel consumption in a range of 23–33% [1]. Energy and exergy analysis of Turbec-100 Model based MGT-CGS operated under fixed temperature and pressure was also carried out by Balli et al. under 298.15 K and 101 kPa, the energetic and exergetic efficiency of the MGT-CGS were found to be 76% and 36%, respectively [2]. A novel two stage MGT based on automotive turbocharger was developed and performance testing was examined by Al-Attab et al. Although the author successfully developed the MGT-CGS, the efficiency needs to be increased, and the emissions level also need to be reduced [3]. Biomass can also be utilized by MGT, but modification to the MGT is necessary. A novel integration of externally fired biomass to a recuperated MGT with CGS configuration was reported in Ref. [4]. Technoeconomic results on the performance show that 70% of biomass rate presented the highest profitability for the Italian scenario. For the Portugese scenario, economic performance optimization of a MGT-CGS by non-linear objective function method was studied by Ferreira et al. [5]. Similar to a large scale gas turbine, MGT performance is affected by the inlet air temperature. The effect of ambient temperature on the performance of a MGT with CGS and TGS was reported in Ref. [6]. Energetic performance for seasons in a cold region was also presented in the study. Analysis on the MGT-TGS with various configurations of absorption chillers was examined by a few researchers [7–11]. Moya et al. utilized waste heat from a 30 kW MGT for ammoni-water type absorption chiller [7]. The COP for the absorption chiller was in the range of 0.61–0.67. A similar study was reported in Ref. [10], but LiBr-water absorption chiller was used. Higher COP of absorption chiller, 1.04–1.44 was reported by Huicochea et al. when double effect absorption chiller was used [8]. Comparison of GT, MGT and SOFC based TGS was presented in Ref. [9]. Different configurations of chillers for MGT were examined using thermodynamics analysis in Ref. [11]. It was found that the optimum configuration was a two-stage compression chiller with an intercooler between two compressors and a subcooler at the condenser outlet.

An approach to use MGT to further generate electricity with Organic Rankine Cycle as bottoming cycle was also reported by a few researchers [12,13]. Organic Rankine Cycle coupled to a 100 kW MGT was tested in Ref. [12]. From six different working fluids tested, R245fa, isopetane and isobutene were found to be suitable working fluids for the MGT. In another study, MGT coupled with Organic Rankine Cycle with R113 as working fluid were studied [13]. The MGT with Organic Rankine Cycle was compared with MGT-CGS, and it was found that it is suitable for application with higher power-to-heat ratio.

They are also studies on the performance of MGT-TGS when it is employed with a specific building load. Sugiartha et al. reported that energy and environmental benefits can be obtained from the application of MGT-TGS for a supermarket application, and the Full-Load operation strategy was a better operation strategy as compared to the Heat-Match operation strategy [14]. The performance of a MGT-TGS and MGT-CGS in sewage treatment plants were reported in a few literature [15–18]. Bruno et al. presented results of different configurations of MGT with absorption chiller [15]. The effect of sizing on the efficiency of MGT-CGS for sewage treatment plant application was reported in Ref. [16]. The author compared the MGT-CGS with 30, 65 and 200 kW output in different regions and different plant scale. The effect of different climate on the performance of MGT-CGS was reported in Ref. [17]. It was found that the climate with low temperature can efficiently utilize the biogas produced, but lesser electricity can be obtained. The optimum configuration of MGT-CGS considering heat demand and characteristics of MGT-CGS was reported in Ref. [18]. Energy, economic and environmental analysis of various MGT-C/TGS configuration in an Iranian building load was also reported in Refs. [19,20]. Basrawi et al. compared the performance of separate system, MGT