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Effect of load following strategies, hardware, and thermal load distribution on stand-alone hybrid CCHP systems

Barun K. Das*, Yasir M. Al-Abdeli, Ganesh Kothapalli

School of Engineering, Edith Cowan University, Joondalup, WA 6027, Australia

HIGHLIGHTS

- Hybridised stand-alone CCHP systems meeting electric, heating and cooling demand.
- Multi-objective (COE, \$/kWh; $\eta_{CHP/CCHP}$, %) GA optimisation for target LPSP.
- Integrates heating, cooling, prime mover (ICE, MGT) and other device specifications.
- Studies the effects of power management strategies and relative load distribution.
- Adding absorption chillers in CHP systems raises the COE (+11%) compared to CCHP.

ARTICLE INFO

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CHP
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ABSTRACT

This study investigates the effects of two types supplementary prime movers (internal combustion engines and micro gas turbines) when integrated with photovoltaic modules into hybrid energy systems (PV/Batt/ICE, PV/Batt/MGT). All systems analysed meet highly dynamic electric, heating, and cooling demands to a specified reliability (Loss of Power Supply Probability). The effects of adding absorption chiller, thereby fundamentally transforming the systems from Combined Heat and Power to Combined Cooling, Heating, and Power (CCHP) is studied. This is done in the context of two different load following strategies (Following Electric to Thermal Load–FEL/FTL vs Following Electric Load–FEL). The Multi-objective Genetic Algorithm (GA) is implemented to optimise these systems based on both Cost of Energy and overall efficiency, the consequential outcomes of the simulations are also reported in terms of several key operational indicators.

Results indicate that if operating under an FEL/FTL type PMS, both PV/Batt/ICE and PV/Batt/MGT–based CHP systems have marginal differences in terms of Cost of Energy (0.25 \$/kWh, 0.28 \$/kWh, respectively) compared to the CCHP systems (0.28 \$/kWh, 0.31 \$/kWh, respectively). However, the overall efficiency in CCHP systems is higher with FEL/FTL (65% for PV/Batt/ICE, 43% for PV/Batt/MGT) compared to FEL (57% for PV/Batt/ICE, 37% for PV/Batt/MGT). In terms of load following strategies, the FEL leads to higher environmental benefits compared to the FEL/FTL for both PV/Batt/ICE and PV/Batt/MGT–based CCHP systems. The results also indicate that relative magnitude of heating ($P_{ther,h}$) and cooling ($P_{ther,c}$) has insignificant effects on the Cost of Energy for the PV/Batt/ICE–based CCHP systems; however, this significantly increases with $P_{ther,h}$:$P_{ther,c}$ for the PV/Batt/MGT.

1. Introduction

Combined Cooling, Heating, and Power (CCHP) systems utilise the waste heat from prime movers to satisfy cooling loads whilst also meeting heating and power demands. The merits of trigeneration include potentially improving overall system efficiency and reducing environmental emissions, and hence these systems have attracted attention globally [1]. Although CCHP systems are featured in large scale commercial and industrial applications (> 1 MW), small–medium scale CCHP systems (< 1 MW) are considered for remote communities, hospitals, and households especially where grid electricity is not readily available. In CCHP technologies, which integrate combustion–based prime movers, a proportion of the waste heat in the flue gases, 30% of fuel input energy in Internal Combustion Engines (ICEs) or 66–73% of fuel input energy in Micro Gas Turbines (MGTs), is recovered. Alternatively up to 30% of the fuel energy input may be recovered from the water jacket in ICEs [2]. When larger scale trigeneration systems are connected to a national grid [3], any deficit of heating and cooling load

* Corresponding author at: School of Engineering, Edith Cowan University, 270 Joondalup Drive, WA 6027, Australia.
E-mail address: bdas@our.ecu.edu.au (B.K. Das).

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Nomenclature

B_{SOC}	battery state of charge (%)
$B_{SOC,\ max}$	maximum battery state of charge (%)
$B_{SOC,\ min}$	minimum battery state of charge (%)
C_{A_cap}	annualised capital cost ($)
C_{A_fuel}	annualised fuel cost ($)
$C_{A\_O\&M}$	annualised operation and maintenance cost ($)
C_{pg}	specific heat of exhaust gas (kJ/kg-K)
COP_{AC}	coefficient of performance of absorption chiller
COP_{EC}	coefficient of performance of electric chiller
d	discount rate (%)
E_L	energy load demand (kWh)
EC_{cool}	cooling energy output from electric chiller (kW)
E_s	useful energy production from the system (kWh)
E_{sup}	energy generation by supplementary prime movers (kWh)
E_{cool}	cooling energy demand (kWh)
E_{elec}	electrical energy demand (kWh)
E_{heat}	heating energy demand (kWh)
EWH_{heat}	heating energy output from electric water heater (kW)
E_{ther}	thermal energy demand (kW)
F_{ICE}	fuel energy to ICE (kW)
F_{MGT}	fuel energy to MGT (kW)
LPS_{elec}	Loss of Power Supply, i.e. reliability of meeting electric load (kWh)
LPS_{heat}	Loss of Power Supply, i.e. reliability of meeting heating load (kWh)
LPS_{cool}	Loss of Power Supply, i.e. reliability of meeting cooling load (kWh)
$LPSP_{comp}$	computed loss of power supply probability
$\dot{M}_{ExhICE}$	exhaust gas mass flow rate for ICE (kg/h)
$\dot{M}_{ExhMGT}$	exhaust gas mass flow rate for MGT (kg/h)
N_{batt}	number of lead acid batteries
N_{PV}	number of PV modules
N_{sup}	number of supplementary prime movers (ICE or MGT)
$N_{s/s}$	number of start-stop for supplementary prime movers after N_{sup}
n	components life time (yr)
P_{cool}	cooling load met by absorption chiller (kW)
P_{elec}	electric load demand (kW)
P_{ICE}	power generation by ICE (kW)
P_L	total load demand (kW)
P_{MGT}	power generation by MGT (kW)
P_{NET}	net power generation (kW)
P_{PV}	power generation by PV (kW)
P_{sup}	power generation by supplementary prime movers (kW)
$P_{sup,min}$	minimum starting threshold of supplementary prime movers (kW)
P_{ther}	thermal load demand (kW)
$P_{ther,c}$	cooling load demand (kW)
$P_{ther,h}$	heating load demand (kW)
P_{heat}	heating load met by heat exchanger (kW)
$Q_{Exh,avl}$	available heat energy from exhaust gas (kW)
Q_{Exh}	recoverable heat energy from exhaust gas (kW)
Q_{jw}	recoverable heat energy from jacket water (kW)
Q_T	total recovered heat energy (kW)
T_{ExhMGT}	exhaust outlet temperature from MGT (K)
T_{HEin} η_{CCHP}	exhaust inlet temperature to heat exchanger (K)
T_{HEout}	exhaust outlet temperature from heat exchanger (K)
$\dot{WH}_{MGT}$	available heat energy from MGT (kW)
$\dot{WH}_{sup}$	available heat energy from supplementary prime movers (kW)

Greek symbols

β	lifetime equivalent CO_2 emission (kg CO_2-eq/kWh)
η_{CHP}	overall CHP efficiency (%)
η_{CCHP}	overall CCHP efficiency (%)
η_{inv}	inverter efficiency (%)
$\eta_{wh,sys}$	overall process heater efficiency (%)

Abbreviations

CCHP	combined cooling, heating, and power
CHP	combined heating and power
COE	cost of energy ($/kWh)
FEL	following electric load
FTL	following thermal load
GA	genetic algorithm
ICE	internal combustion engine
LCE	life cycle emissions
LHV	lower heating value
LPS	loss of power supply (kWh)
LPSP	loss of power supply probability
MGT	micro gas turbine
PV	photovoltaic
PMS	power management strategy
RP	renewable penetration (%)

can be met by a boiler (either electric or combustion driven) as well as electric chiller, respectively. On the other hand, in relation to small scale stand-alone hybridised CCHP systems, limited research is available in the literature [4,5], particularly if these systems are hybridised by the addition of renewables. Hybridisation of CCHP applications is beneficial in three ways. Firstly, integrating renewable sources reduces reliance on fossil fuels; secondly, capturing the waste heat from supplementary prime movers substantially improves the overall efficiency; and thirdly, the availability of supplementary prime movers (i.e. ICE, MGT) helps increase system reliability when insufficient renewable power exists. In this regard, integrating renewable energy (e.g. PV, wind, biomass etc.) with the conventional sources (e.g. ICE, MGT etc) also reduces dependency on fossil fuels and has the potential to improve the overall system efficiency up to 90% [6] by using waste heat from supplementary prime movers to meet heating and cooling load.

Prime movers such as Internal Combustion Engines, Micro Gas Turbines, gas turbines, steam turbines, Stirling engines, and high temperature fuel cells (FCs) are used extensively in the CCHP applications [7–9]. However, where stand–alone hybrid energy systems are concerned, most of the research to date focuses on meeting electric (utility) the power demand only [10–13]. Although some studies biomass [14], integrated solar collectors [15,16] for meeting the heating and cooling demand, very few research have studied CCHP systems where PV with the supplementary prime movers are considered [17,18]. In this context, Basrawi et al. [17] analysed a hybrid PV/MGT-based CCHP system with the economic (Net Present Value-NPV) and the environmental (CO_2, NOx, and CO) consideration. They used life cycle cost analysis to assess the economic performance and environmental impact from operational emissions for MGT. However, the system was not optimised using intelligent techniques and only considered an hourly averaged (single) day load profile (not a dynamic load profile). Their study also did not have any details power management strategy. In a recent study, Yousefi et al. [18] carried out multi-objective optimisation of a hybrid ICE/PV-T driven CCHP system using dynamic load profiles and hourly resolved solar irradiation data, but did not present their load meeting reliability or the PMS. Additionally, their research was not based on stand-alone systems which gives merit for the present study.