PERFORMANCE OF MICRO GAS TURBINE TRI-GENERATION SYSTEM AND PHOTOVOLTAIC HYBRID BASED SYSTEM IN REMOTE AREA APPLICATIONS

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MASTER OF SCIENCE

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We hereby declare that we have checked this thesis and, in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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Thesis submitted in fulfillment of the requirements
for the award of the degree of
Master of Science

Faculty of Mechanical And Automative Engineering Technology

UNIVERSITI MALAYSIA PAHANG

JULY 2020

ACKNOWLEDGEMENTS

In the name of Allah, the Most Gracious and the Most Merciful.

Alhamdulillah, all praises to Allah for the strengths and His blessing in completing this thesis. Special appreciation goes to my supervisor, Dr Mohamad Firdaus Bin Basrawi, for his supervision and constant support. His invaluable help of constructive comments and suggestions throughout the data collection, experimental and thesis works have contributed to the success of this research. Not forgotten, my appreciation to my co-supervisor Professor Ir. Dr. Hassan Bin Ibrahim for his support and invaluable insights in completing this thesis. I would also like to extend my gratitude towards Malaysia Ministry of Education and University Malaysia Pahang for the research grant provided upon the funding provided for the research under grant RDU130133 (FGRS/2/2013/TK06/UMP/02/1) and RDU14011(FGRS/1/2014/TK06/UMP/01/1) respectively. My acknowledgement also goes to Dr. Daing Mohamad Nafiz bin Daing Idris, Dr. Azri bin Alias, Dr. Mohd Azri Hizami Bin Rasid, Dr. Ahmmad Shukrie Bin Md Yudin, Dr. Ahmed Nurye Oumer and Dr. Mohd Yusof bin Taib, Prof Dr. Shahrani Bin Anuar, Mr. Junaedi Irwan Bin Wan Abdul Halim, Mr. Aziha Bin Abdul Aziz , Mr. Mohd Fauzi Bin Mustafa ,Mr. Lee Giok Chui, Dr.Amir Bin Abdul Razak, Dr. Azim Bin Mohd Arshad, Dr. Luqman Hakim bin Ahmad Shah, Dr. Zulkifli bin Ahmad@Manap, Mrs.Norshalawati binti Mat Yusof , Mr. Mohamad Faizal bin Mohamed Zahri , Mrs. Nur Sufiah binti Jamaludin, Mrs. Suhaida binti Mohamad Salleh and to those who indirectly contributed in my research and postgraduate affairs.

All praises to Allah for the strengths and His blessing and mercy showered upon my parents. My deepest gratitude goes to my beloved parents Mr. Rashid Chand bin Abdullah and Mrs. Khadijah Bibi Binti Md Meerasa as well as my siblings Ms. Noor Jahan Binti Rashid Chand, Mr. Mohamad Nowfal Bin Rashid Chand, Mr. Mohamad Riyaz Bin Rashid Chand and Mr. Mohamad Fazil bin Rashid Chand. I express my sincere appreciation to them as encountering various obstacles, and challenges during this research is impossible without their endless love, prayers and encouragement, patients and sacrifices.

Last but not least, I would like to thanks all my friends especially Mr. Mohd Afzam, Mr. Nazani Nazri, Mr. Davindra Brabu Mathivanan, Ms. Siti Aisyah Safi, Mr. Muhamad Ridzuan Bin Hamdan, Mr. Hasrul Hanafi, Mr, Ali Elghool, Mr. Abdullah Al-Anati, Mr. Mohd Fahmi Othman, Md Mahmudul Hassan Roni, Mr. Mehedi Hassan, Dr. Mohd Yusri, Mr. Che Ku Ihsan, Mr. Hazwan Marzuki, Mr. Mohd Kamal, Mr. Ahmad Syazwan , Mr. Luqman, Ms. Nasrin Zafirah and Ms. Nur Munira Anwar and to those who assited me indirectly in completion of my thesis.

“It’s not about how hard you can hit, it’s about how hard you can get hit and keep moving forward”

Mohamad Rizdwan Bin Rashid Chand
(Wan Chand)

ABSTRAK

Antara tunjang utama bagi perkembangan teknologi di dalam bidang penjanaan kuasa (*Power Generation*) ialah untuk menambahbaikkan sistem penjanaan kuasa konventional sedia-ada dari segi prestasi pengunaan bahan bakar serta mengurangkan pembebasan gas berbahaya. Di samping itu, ia jugak bertujuan untuk mempelbagaikan sumber tenaga untuk memastikan kemampanan tenaga di dalam bidang penjanaan kuasa di masa hadapan. Antara alternatif yang telah dicadangkan adalah dengan membangunkan teknologi sistem hibrid yang mengintegerasikan sistem tri-generasi turbin gas mikro dan sistem fotovoltaik, PV- MGT(TGS). Sistem hibrid berikut berkemampuan untuk menghasilkan tenaga elektrik, air panas bagi tenaga haba serta udara sejuk bagi sitem penyaman udara dengan serentak. Sistem PV- MGT(TGS) berkemampuan untuk menghasilkan tenaga-tenaga berikut dengan mengabungkan komponen – komponen seperti turbin gas mikro, fotovoltaik, tangki simpanan air panas, tangki simpinan air sejuk, penukar haba, menara pendinginan, penghawa dingin penyerapan, dandang dan bateri. Terdapat banyak kajian telah dijalankan bagi menganalisa keupayaan sistem hibrid PV- MGT(TGS) untuk digunakan sebagai sistem penjanaan kuasa teragih (*Distributed Generation*). Namun, kajian-kajian yang telah dijalankan lebih bertumpu kepada aplikasi penjanaan kuasa di kawasan rumah kediaman, pejabat, pengilangan serta kawasan komersial yang hanya terletak di kawasan bandar. Walaupun, beberapa kajian telah mengambarkan prestasi yang positif,masih terdapat kekurangan di dalam kajian bagi aplikasi di luar bandar seperti perkampungan pendalaman dan pulau – pulau terperincil. Oleh yang demikian, kajian ini telah dijalankan untuk mengkaji potensi sistem hibrid PV-MGT(TGS) untuk diaplikasikan di kawasan – kawasan terperencil. Objektif utama penyelidikan ini ialah untuk menganalisis prestasi teknikal sistem hybrid PV-MGT(TGS) bagi aplikasi di kawasan terperincil untuk operasi tahunan dengan menjalankan simulasi. Penyelidikan ini jugak bertujuan untuk menilai sistem hibrid PV-MGT(TGS) dari segi faktor pengunaan tenaga, ekonomi dan kesan terhahap pesekitaran berdasarkan operasi di kawasan terperencil. Sebuah kawasan yang terletak di Pulau Tioman telah dipilih sebagai tapak kajian. Data - data pengunaan tenaga elektrik, bilangan pelancong dan data cuaca di kawasan tersebut telah diperolehi melalui tinjauan tapak, kaedah anggaran dan sistem pemantauan. Bagi tujuan simulasi, komponen – komponen sistem hibrid PV-MGT(TGS) telah dimodelkan dengan mengunakan data -data pengilang, penerbitan dan model termodinamik sediaada. Simulasi tersebut dijalankan mengunakan perisian Simulink® di mana model matematik bagi komponen sistem hibrid PV-MGT(TGS) dan data-data pengunaan tenaga telah disusun (compiled) bagi tujuan simulasi. Untuk mereplikasikan operasi sistem hibrid PV-MGT(TGS), algoritma bagi strategi operasi telah dinyahkodkan di dalam perisian tersebut. Simulasi operasi sistem hibrid PV-MGT(TGS) untuk penjanaan kuasa di resort tersebut dijalankan bagi operasi selama 8760 jam (1 Tahun). Seterusnya, berdasarkan prestasi sistem hibrid tersebut dinilai dari segi factor pengunaan bahan tenaga mentah m, kos Kitaran Hidup serta dan kadar perlepasan gas- gas berbahaya. Melalui penyelidikan ini, ia didapati bahawa sistem hibrid PV-MGT (TGS) dapat mencapai 21.08% penjimatan dalam pengunaan tenaga bahan mentah jika dibandingkan dengan sistem konvensional. Sistem hybrid berkemampuan untuk pengurangan pelepasan gas oksida Nitrogen (NO_x) sebanyak 81.00%, karbon monoksida (CO) sebanyak 57.00% dan karbon dioksida (CO_2) sebanyak 75.60% jika dibandingkan dengan sistem konvensional. Walau bagaimanapun, sistem hibrid PV-MGT (TGS) gagal mencapai keuntungan bersih (Net Profit) melalui analisis kos kitaran hidup.

ABSTRACT

The technological advancements in power generation are primarily undertaken to overcome the drawbacks of conventional energy system while diversifying energy sources to ensure sustainability in future power generation. One of the alternatives proposed is to implement a hybrid system combining both photovoltaic and micro gas turbine in a trigeneration scheme, the PV-MGT(TGS) hybrid system. Basically, it is a distributed energy system that is capable of producing electricity, hot water and cooling air simultaneously. The system integrates various components including micro gas turbine, photovoltaic, heat exchanger, hot and chilled water storage, absorption chiller and auxiliaries' components such as boiler and batteries. Although there were several studies conducted on analyzing the performances of PV-MGT(TGS) hybrid system for urban residential and office application, however, there is lack of existing studies describing performances of the respective system for remote area application. Thus, this research intended to analyze the performance of PV-MGT(TGS) hybrid system for remote area applications to ensure its feasibility for such applications. The main objectives of the research are to investigate the technical performances of PV-MGT(TGS) hybrid system for annual operation in remote area through simulations.as well as to analyze the energetic, economic and environmental performances of the hybrid system in a remote area application. The system is analyzed based on the performances obtained from an application-based simulation. Whereby, a resort located on Tioman Island is selected as the demand site. The energy data and weather data of the demand site are acquired through site visit survey, estimation tool and real-time monitoring system respectively. The mathematical model of each component in the hybrid system is derived from manufacturer's data sheets, published experimental data and thermodynamic modeling. The simulations are performed in the Simulink® environment where the mathematical models, operation algorithms of the proposed dispatch strategy and collected data are integrated. The simulations are carried out on an hourly basis for 8760-hour period (1 Year). Subsequently, based on the simulation result, the energetic, economic and environmental performances of the hybrid system are evaluated through primary energy analysis, life cycle cost analysis and emission reduction index. The outcome of the research demonstrates that the PV-MGT(TGS) hybrid system are able to achieve 21.08% of primary energy saving than the conventional system throughout the year. It can be observed that the hybrid system achieved 81%, 57%, 75.6% of emission reduction of oxide of Nitrogen (NO_x), carbon monoxide (CO) and carbon dioxide (CO_2). as compared to the conventional system. However, the PV-MGT(TGS) hybrid system failed to achieve positive net profit under Life Cycle Cost Analysis.

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LIST OF SYMBOLS

A_{CWS}	Surface Area of Chilled Water Storage [m^2]
A_{HWS}	Surface Area of Hot Water Storage [m^2]
C_{Bat}	The Capacity of Battery [AH]
A_{HW}	Surface Area of Hot Water Storage Tank [m^2]
A_{PV}	Effective Surface Area of a Single Photovoltaic Module [m^2]
$\mathrm{C_{AB.C}}$	Capital Cost of Absorption Chiller [US$]
$\mathrm{C_{Batt}}$	Capital Cost of Battery [US$]
$\mathrm{C_{Boil}}$	Capital Cost of Boiler [US$]
C_c	Heat Capacity Rate of Cold Fluid in Heat Exchanger [kW/^{o}C]
C_{Cap}	Total Capital Cost [US$]
$\mathrm{C_{CT}}$	Capital Cost of Cooling Tower [US$]
C_E	Cost of Energy Consumed [US$]
C_{Ele}	Cost of Electricity per unit of kWh usage [US$/ kWh]
$\mathrm{C_{FCU}}$	Capital Cost of Fan Coil Unit US$]
C_h	Heat Capacity Rate of Hot Fluid in Heat Exchanger [kW/^{o}C]
$\mathrm{C_{Inv}}$	Capital Cost of Inverter [US$]
C_{Mar}	Market Cost of Equipment [US$]
$\mathrm{C_{MGT(CGS)}}$	Capital Cost of Micro Gas Turbine with Cogeneration System [US$]
C_{min}	Minimum Heat Capacity Rate in Heat Exchanger [kW/^{o}C]
C_{NG}	The Price of Natural Gas Per Unit Volume [$/m^3]
$C_{O\&M}$	Operation and Maintenance Cost [US$]
$\mathrm{C_{O\&M \cdot AB.C}}$	Operation and Maintenance Cost of Absorption Chiller [US$]
$\mathrm{C_{O\&M \cdot Bat}}$	Operation and Maintenance Cost of Battery [US$]
$\mathrm{C_{O\&M \cdot Boil}}$	Operation and Maintenance Cost of Boiler [US$]
$\mathrm{C_{O\&M \cdot CT}}$	Operation and Maintenance Cost of Cooling Tower [US$]
$\mathrm{C_{O\&M \cdot MGT(CGS)}}$	Operation and Maintenance Cost MGT- Cogeneration System [US$]
$\mathrm{C_{O\&M \cdot PV}}$	Operation and Maintenance Cost of Photovoltaic [US$]
$\mathrm{C_{O\&M \cdot Storage}}$	Operation and Maintenance Cost of Water Storage [US$]
COP	Coefficient of Performance [-]
$COP_{AB.C}$	Coefficient of Performance of Absorption Chiller [-]
$C_{p.Ex}$	Specific Heat Capacity of Exhaust Gases [kJ/kg.^{o}C]

$C_{p.W}$	Specific Heat Capacity of Water [kJ/kg.°C]
C_{Pipe}	Capital Cost of Piping [US$]
C_{PV}	Capital Cost of Photovoltaic [US$]
C_{Rep}	Replacement Cost [US$]
C_{Sal}	Salvage Cost [US$]
$C_{Storage}$	Capital Cost of Water Storage [US$]
$E_{.Cha}(t)$	Electric Consumption of a Single Chalet at Hour *t* [kWh]
E_{Avoid}	Total Annual Amount of Electricity Avoided from Grid [kWh]
E_{B}	Amount of Energy Available in Battery[kWh]
$E_{B.Chrg}$	Amount of Energy Charged into Battery [kWh]
$E_{B.Dchrg}$	Amount of Energy Discharged from Battery [kWh]
$E_{B.Max}$	Maximum Amount of Energy Stored/Charged in Battery [kWh]
$E_{B.Min}$	Minimum Amount of Energy Discharged from Battery [kWh]
E_{CT}	Electrical Energy Consumption of Cooling Tower [kWh]
$E_{D.demand}$	Average Daily Electrical Energy Demand [kWh/day]
E_{demand}	Electrical Energy Demand [kWh]
$E_{demand.Cha}(t)$	Electrical Energy Demand of Chalets at hour *t* [kWh]
$E_{demand.Res}(t)$	Electrical Energy Demand of Restaurant at hour *t* [kWh]
E_{Dump}	Excess Electrical Energy - Dump[kWh]
E_{MGT}	Energy Output of Micro Gas Turbine [kWh]
$E_{MGT.FL}$	Energy Output of Micro Gas Turbine at Full Load [kWh]
$E_{n.Conv}$	Total Amount of Emission by Conventional Energy System [kg]
$E_{n.Hybrid}$	Total Amount of Emission by PV-MGT (TGS) hybrid system [kg]
E_{P}	Parasitic Energy Consumption [kWh]
$E_{P.AB.C}$	Parasitic Energy Consumption by Absorption Chiller [kWh]
$E_{P.C}$	Parasitic Energy Consumption by Fuel Compressor [kWh]
$E_{P.HX}$	Parasitic Energy Consumption by Heat Exchanger [kWh]
$\boldsymbol{E_{penalty}}$	Amount of Electrical Energy Penalized due to Insufficiency [kWh]
E_{pump}	Parasitic Energy Consumption by Pumps [kWh]
E_{PV}	Energy Output of Photovoltaic Modules [kWh]
E_{rCT}	Rated Electric Consumption of Cooling Tower [kWh]
E_{Supply}	Electrical Energy Supplied to Meet Demand [kWh]
ε	Effectiveness of Heat Exchanger [-]

g	Gravitational Force [kg/ms^2]
H	Dynamic Head of Pump [m]
h_1	Convection Heat Transfer Coefficient of Pipe [W/m.^{o}C]
h_2	Convection Heat Transfer Coefficient of Surrounding [W/M.^{O}c]
i	Interest Rate [%]
$\bar{I}_B$	Direct Normal Solar Irradiation [kWh/m^2]
IC	Internal Combustion Engine
$\bar{I}_D$	Diffuse Solar Irradiation [kWh/m^2]
$\bar{I}_{EXT}$	Extraterrestrial Irradiation [kWh/m^2]
I_G.	Global Solar Irradiation [kWh/m^2]
$\bar{I}_{G.ave}$	Average Daily Global Solar Irradiation [kWh/m^2.day]
$\bar{I}_{G.STC}$	Global Solar Irradiation at Standard Testing Condition (STC) [kWh/m^2]
$\bar{I}_o$	Solar Constant [kWh/m^2]
K_{dirt}	Coefficient of Loses of Photovoltaic Module due to Dirt and Dust [-]
K_G	Coefficient of Solar Irradiation [-]
k_{Ins}	Thermal Conductivity of Insulation [W/m.^{o}C]
k_{Jacket}	Thermal Conductivity of Jacket [W/m.^{o}C]
$K_{mismatch}$	Coefficient of Loses of Photovoltaic Module due to Interconnection [-]
k_p	Thermal Conductivity of Pipe [W/m.^{o}C]
k_{soil}	Thermal Conductivity of Soil [W/m.^{o}C]
K_T	Clearness Index [-]
K_T	Coefficient of PV Module Temperature [-]
L	Length of Pipe [m]
$\dot{m}$	Mass Flow Rate of Pumps [kg/s]
$\dot{m}_{Ex}$.	Exhaust Mass Flow Rate of Micro Gas Turbine [kg/s]
$\dot{m}_{Ex.FL}$	Exhaust Mass Flow Rate of Micro Gas Turbine at Full Load [kg/s]
$\dot{m}_W$	Mass Flow Rate of Water [kg/s]
n	Number of Days
N	Life Cycle Period [year].
N_{Auto}	Number of Autonomy Days of Battery
NB	Nominal Bore of Pipe
N_{Chalet}	Number of Chalet Operating at Hour t

NH_3	Ammonia Solution
N_M	Number of Photovoltaic Module
NO_x	Oxide of Nitrogen
OD_{Ins}	Outside Diameter of Insulation [m]
OD_{Jacket}	Outside Diameter of Jacket [m]
OD_{Pipe}	Outside Diameter of Pipe [m]
PWF_{AUP}	Present Worth Factor for Annual Uniform Payment
PWF_S	Present Worth Factor for Single Payment
$Q_{AB.C}$	Amount Of Cooling Energy from Absorption Chiller [kWh]
Q_{AC}	Thermal Energy Demand for Air Conditioning [kWh]
$Q_{AC \cdot th}$	Thermal Energy Required by Absorption Chill [kWh]
Q_{boiler}	Thermal Energy Required from Boiler [kWh]
Q_{Chrg}	Thermal Energy Charged into Hot Water Storage [kWh]
Q_{CL}	Cooling Load for Air Conditioning [kWh]
$Q_{CW \cdot PG}$	Piping Heat Gain due to Surrounding Temperature [kWh]
$Q_{CWS.Max}$	Maximum Cooling Capacity of Chilled Water Storage [kWh]
$\boldsymbol{Q_{Dchrg}}$	Thermal Energy Discharged from Hot Water Storage [kWh]
Q_{demand}	Total Thermal Energy Demand [kWh]
$\boldsymbol{Q_{DHW}}$	Thermal Energy Demand for Domestic Hot Water [kWh]
$Q_{DHW \cdot PL}$	Piping Heat Loss due to Surrounding Temperature [kWh]
$\boldsymbol{Q_{dump}}$	Excess Thermal Energy – Dump [kWh]
Q_e	Thermal Energy Rejected to Cooling Tower [kWh]
Q_{ehr}	Thermal Energy from Exhaust Heat Recovery [kWh]
Q_{Ex}	Thermal Energy from Exhaust of Micro Gas Turbine [kWh]
$Q_{Ex \cdot FL}$	Thermal Energy from Exhaust of Micro Gas Turbine at Full Load [kWh]
$Q_{f.Boil}$	Fuel Energy Consumption of Boiler - LHV [kWh]
$Q_{f \cdot MGT}$	Fuel Energy Consumption of Micro Gas Turbine - LHV [kWh]
$Q_{f \cdot MGT \cdot FL}$	Fuel Energy Consumption of Micro Gas Turbine at Full Load - LHV [kWh]
Q_g	Thermal Energy Input Required by Absorption Chiller [kWh]
Q_{HWS}	Thermal Storage Capacity of Hot Water Storage [kWh]
$Q_{HWS \cdot Max}$	Maximum Thermal Storage Capacity of Hot Water Storage [kWh]

$Q_{L \cdot CWS}$	Cooling Energy Loss of Chilled Water Storage [kWh]
$Q_{L \cdot HWS}$	Thermal Energy Loss of Hot Water Storage [kWh]
Q_{Max}	Maximum Thermal Energy Transfer of Heat Exchanger [kWh]
$Q_{rAB.C}$	Rated Cooling Capacity of Absorption Chiller [kWh]
Q_{rg}	Rated Thermal Energy Input of Absorption Chiller [kWh]
$Q_{Tank \cdot}$	Thermal Energy Available in Hot Water Storage [kWh]
R_{Conv-1}	Convection at Pipe Inner Surface [W/m.^{o}C]
R_{Ins}	Conduction at Insulation Surface [W/m.^{o}C]
R_{Jacket}	Conduction at Jacket Surface [W/m.^{o}C]
R_{Pipe}	Conduction at Pipe Surface [W/m.^{o}C]
$R_{Total \cdot AG}$	Overall Thermal Resistance of Aboveground Piping [W/m.^{o}C]
$R_{Total \cdot UG}$	Overall Thermal Resistance of Underground Piping [W/m.^{o}C]
T_{amb}	Ambient Temperature [^{o}C]
T_C	Photovoltaic Module Cell Temperature [^{o}C]
T_{CW}	Design Chilled Water Temperature [^{o}C]
T_{CWS}	Temperature of Chilled Water in Cold Water Storage [^{o}C]
T_{DHW}	Design Hot Water Temperature [^{o}C]
T_{Ex}	Exhaust Temperature of Micro Gas Turbine [^{o}C]
$T_{Ex \cdot FL}$	Exhaust Temperature of Micro Gas Turbine at Full Load [^{o}C]
$T_{Ex.out}$	Exhaust Outlet Temperature in Heat Exchanger [^{o}C],
TGS	Trigeneration System
T_{HWS}	Temperature of Chilled Water in Hot Water Storage [^{o}C]
$T_{r.CW}$	Temperature of Return Water in Cold Water Storage [^{o}C]
T_{Soil}	Temperature of Grund Soil [^{o}C]
T_{STC}	PV module cell temperature at STC [^{o}C].
T_W	Initial Water Temperate of Storage [^{o}C],
$T_{W.i}$	Inlet Water Temperature of Domestic Pipe [^{o}C]
$T_{W.in}$	Exhaust Inlet Temperature in Heat Exchanger [^{o}C],
$T_{W.out}$	Water Outlet Temperature in Heat Exchanger [^{o}C]
U_{CWS}	Coefficient of Heat Loss of Chilled Water Storage [W/m^{2} ^{o}C]
U_{HWS}	Coefficient of Heat Loss of Hot Water Storage [W/m^{2} ^{o}C]
V_{Bat}	Nominal Voltage of Battery[v]
V_{CT}	Volume Flow Rate of Water Pumped into Cooling Tower [m^{3}/hr]

V_{CWS}	Volume of Chilled Water Storage [m^3]
$V_{demand \cdot HW}$	Volume of Hot Water Demand of Chalet [m^3]
V_{HW}	Volume of Hot Water Consumption in a Single Chalet [m^3]
V_{HWS}	Volume of Hot Water Storage [m^3]
$V_{NG.fuel}$	Natural Gas Calorific Value
V_{rCT}	Rated Volume Flow Rate of Water Pumped into Cooling Tower [m^3/hr]
z	Depth of Pipe in Ground Soil [m]
β	Temperature Coefficient of Photovoltaic Module [%/^{o}C],
η_{Bat}	Efficiency of Battery [-]
η_{cc}	Efficiency of Charge Controller [-]
η_{CWS}	Thermal Efficiency of Chilled Water Storage [-]
η_{el}	Electric Efficiency of Micro Gas Turbine [-]
η_{FCU}	Efficiency of Fan Coil Unit [-]
η_{inv}	Efficiency of Inverter [-]
η_{MGT}	Overall Efficiency of Micro Gas Turbine [-]
$\eta_{MGT \cdot FL}$	Electric Efficiency of Micro Gas Turbine at Full Load [-]
η_{mixed}	Storage Efficiency of Fully Mixed Hot and Chilled Water Storage [-]
η_{PV},	Efficiency of Photovoltaic Module [-]
η_V	Volumetric Efficiency of Hot and Chilled Water Storage [-]
ρ_W	Density of Water [kg/m^3]

LIST OF ABBREVIATIONS

a-Si	Amorphous Silicon
CCF	Cooling Capacity Factor of Absorption Chiller [-]
Cd-Te	Cadmium Telluride
CGS	Cogeneration System
CiGS	Copper Indium Gallium Selenide
CO	Carbon Monoxide
CT	Cooling Tower
CWS	Chilled Water Storage
d	Depreciation Rate
DBFC	Direct Borohyde Fuel Cell
DG	Distributed Generation
DMFC	Direct Methanol Fuel Cell
DOD	Depth of Discharge of Battery
EF	Emission Factor
EHX	Heat Exchanger
ERI	Emission Reduction Index
FC	Fuel Cell
HIF	Heat Input Factor
HMFCF	Heat Medium Flow Correction Factor
HRSG	Heat Recovery Steam Generator
HWS	Hot Water Storage
IEA	International Energy Agency
LCC	Life Cycle Cost Analysis
LF	Load Factor of Micro gas Turbine [-]
LHV	Lower Heating Value of Fuel
LiBr	Lithium-Bromide Solution
$LiBr\text{-}H_2O$	Lithium-Bromide and Water Solution
LT	Lifetime of Equipment
MGT	Micro Gas Turbine
Mono-PV	Monocrystalline Photovoltaic Module
NOCT	Nominal Operating Cell Temperature of Photovoltaic Module [^{o}C]

NTU	Number of Transfer Units of Heat Exchanger
PCFC	Protonic Fuel Cells
PEC	Primary Energy Consumption
PEC_{conv}	Primary Energy Consumption of Conventional Energy System
PER	Primary Energy Rate
PES	Primary Energy Saving
Poly-PV	Polycrystalline Photovoltaic Module
PV	Photovoltaic System/Module
PV-CGS	Photovoltaic Based Cogeneration System
PV-MGT(TGS)	Micro Gas Turbine Trigeneration and Photovoltaic Hybrid System
PV-TGS	Photovoltaic Based Trigeneration System
RTSM	Radiant Time Series Method
SE	Sterling Engine
SOC	State of Charge of Battery
SOFC	Solid oxide fuel cell
TCF	Photovoltaic Module Temperature Correction Factor
TNB	Tenaga National Berhad
WHRB	Waste Heat Recovery Boiler

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