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Research Paper

Impact of heat recovery and thermal load control on combined heat and power (CHP) performance

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ABSTRACT

This research assesses the energy efficiency and techno-economic viability of a Combined Heat and Power (CHP) system designed for a typical building that meets both its electrical (97 kWh/d) and thermal (92 kWh/d) loads. The CHP system comprises wind turbines (WT), photovoltaic panels (PV), batteries, micro gas turbines (MGT), and boilers, which are evaluated for their techno-economic performance. To enhance the system's efficiency and minimize energy wastage in CHP, two strategies, namely heat recovery (HR) from MGT and Thermal Load Control (TLC) for converting surplus renewable power generation into thermal energy, are implemented. Four case studies are conducted to analyze the impact of each strategy on the CHP system's performance. The optimization of hybrid renewable energy systems, considering the overall system's economic performance, is achieved through the integration of MATLAB and HOMER PRO. The study reveals that the incorporation of TLC and HR results in significant reductions in the Cost of Energy (COE), Net Present Cost (NPC), CO2 emissions, loss of Power Supply (LPS), and energy sizing while increasing the renewable fraction in the CHP system. Sensitivity analysis is performed on the capital cost of components, TLC, and HR variations, demonstrating their substantial influence on the economic performance of CHP. The cash flow results show that the integration of these two components reduces the system cost by 25 %. It is also shown that almost 70 % of the CC of the system is related to PV and batteries. The proposed strategies and findings provide valuable insights for enhancing the reliability and techno-economic evaluations of hybrid renewable.

1. Introduction

Due to the urgency of mitigating global warming and reducing dependence on finite fossil fuel resources, the importance of alternative energy sources has significantly increased [1]. As the energy demand continues to rise, scientists need to identify environmentally friendly alternatives to fossil fuels. However, the availability of renewable energy systems is subject to unpredictability and intermittency due to factors such as climate change [2]. To address this challenge, integrating renewable energy into long-term growth strategies can help attract investment and ensure a sustainable future. Researchers worldwide are actively studying different sizes and configurations of energy systems to determine the most suitable options for specific locations and explore possibilities for their integration [3]. The use of hybrid systems analysis tools for technology-economic optimization studies has become increasingly prevalent in recent years [3,4]. One type of energy system that has garnered significant attention is CHP, also known as cogeneration systems. CHP systems offer an efficient and sustainable solution for meeting both electrical and thermal energy demands across various industries and buildings. These systems generate electricity and useful heat simultaneously from a single fuel source, leading to higher overall energy efficiency compared to separate electricity and heat generation methods. By harnessing the waste heat produced during electricity generation, CHP systems maximize the utilization of resources and minimize energy wastage [3,5].

The economic sizing of a CHP system plays a crucial role in determining its viability and optimal performance. The economic sizing of a CHP system involves evaluating several key factors. These factors include the facility's electrical and thermal energy requirements, the available fuel sources, energy pricing and tariffs, maintenance and operation costs, and the potential revenue from selling excess electricity

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Nomenclature

A	sectional area of wind, m^2
C_{bat}	capacity of the battery, kA
$C_{total,an}$	total annualized cost, $/yr
E	open-circuit voltage, V
F_t	fuel cost, $
f_{PV}	derating factor, %
$G_{.T}$	solar radiation W/m^2
$G_{T.\ S.T.C.}$	incident irradiation at the S.T.C., W/m^2
H_{HVhyd}	higher heating value of H_2, kJ/kg
$I_{\ bat}$	current rate of battery, A
I_t	investment expenditures, $
I_{FC}	current of F.C., A
M_t	Maintained cost, $
$n_{C,\ F.C.}$	number of cells in F.C.
$P_{inv,in}$	input power of the inverter, W
$P_{inv,out}$	output power of the inverter, W
$P_{WTG\ STP}$	output of wind turbine at S.T.C., W
Tc	temperature of the PV. cell, °C
Tc, $_{S.T.C.}$	temperature standard test condition,
$T_{.C.,NOCT}$	nominal operating cell temperature, °C
T_{α}	ambient temperature, °C
U	wind speed at anemometer height, m/s
$U_{.L.}$	heat loss coefficient, $W/m^2.°C$
V_{act}	activation polarization, V
Vc	average voltage of a cell, V
V_{conc}	concentration overpotential, V
V_{ohm}	ohmic polarization, V
$Y_{.P.V.}$	PV capacity rate, kW
Z_{hub}	wind turbine's hub, m
$\nu_{cut-out}$	cut-out velocity of the WT
ν_{cut-in}	cut-in velocity
$P_{WT}(t)$	power output from a WT
E_{Boiler}	energy output from the gas boiler
E_{TSS}	Thermal Energy Storage
EE_{excess}	surplus power generation
E_{HR}	usable heat energy
Q_{HR}	Heat recovery
V_{Fuel}	value of the fuel
F_{BG}	natural gas consumption (L/hr)
P_{MGT}	power micro gas turbine
NPC	net present cost, $
SOC	battery state of charge, %
ENS	energy not supplied, W
DOD	depth of discharge,%
O&M	operation and maintained cost, $/yr
CC	capital cost of the system $
LPS	loss of Power Supply, W
CRF	capital recovery coefficient, %
LCOE	level cost of energy $/kWh

Abbreviation

ESS	energy storage system,
FLC	fuzzy logic control
LF	load following
CC	charge cycle
DG	diesel Generator
RES	renewable Energies
HES	hybrid energy system
PV	photovoltaic
M.P.P.	maximum power point
PEMFC	proton exchange membrane fuel cell

Greek letters

ρ_0	air density, kg/m^3
σ	self-discharge rate, %/month
α_P	temperature coefficient, %
η_C	solar module efficiency, %
τα	solar transmittance, %

back to the grid. By considering these factors, a cost-effective and efficient CHP system can be designed and implemented [6–8]. It also improves overall energy efficiency, reduces greenhouse gas emissions, and enhances energy resiliency by providing a reliable on-site power generation solution. This involves identifying the most suitable installation configuration and rated capacity for different energy resources to ensure a continuous supply of electricity without capacity shortages. The objective is typically to minimize the COE, while also considering constraints such as minimizing GHG emissions and growing green energy penetration. A considerable amount of research has been conducted in the field of hybrid renewable energy system (HRES) modeling, employing various optimization techniques based on power supply reliability, energy balance, CO_2 emission, and AI-based approaches. Simulation tools have also been developed to facilitate HRES modeling, with notable examples including the HOMER microgrid software. HOMER allows for the modeling of hybrid energy systems which consist of a mix of renewable and conventional energy sources, catering to both autonomous and grid-connected configurations. It enables optimization and sensitivity analysis, and researchers worldwide have utilized it for techno-economic investigations of HRESs in different geographical locations, considering various combinations of resources, electrical demand levels, and specific objectives.

Several investigations have employed HOMER and other methodologies to conduct techno-economic analyses of CHP systems in developing nations around the world. It should be emphasized that conducting a techno-economic analysis of a CHP system can be highly dependent on the site or region under consideration. This is because factors such as cost parameters, electricity demand, and resource availability vary considerably across different geographical areas. These factors significantly influence the most appropriate configuration of CHP for a particular site. In the study conducted in [18], a techno-economic evaluation of a PV/WT/Battery-based HES for a remote standalone system was carried out. The researchers utilized the genetic algorithm optimization technique from the MATLAB optimization toolbox and compared the results with the HOMER but lack of study on surplus power generation. The study's main objective was to minimize the cost of electricity while maintaining a certain reliability index. The findings indicated that despite employing different sizing options, the GA and HOMER results were comparable. This implies that both optimization methods yielded similar outcomes in terms of minimizing the electricity cost for the given reliability requirements.

In [3] a study was conducted to optimize a HES based on PV-WT-DG as generation and -Battery and FC as backup, using the particle swarm optimization (PSO) algorithm. The results of their analysis were compared with those obtained from HOMER. The research findings demonstrated that there was a similarity in the COE between HOMER (0.277 $/kWh) and the PSO algorithm (0.280 $/kWh). Similarly, [9] also investigated the COE of a PV/WT/Batt-based HES optimized using a combination of the GA and PSO (GA-PSO) and compared the results with HOMER. They found that the COE values were comparable, with the GA-PSO optimization resulting in a COE of 0.508 $/kWh and HOMER yielding a COE of 0.51 $/kWh. In [10], the PSO method resulted in a slightly lower COE of 0.38 $/kWh. In comparison, when utilizing HOMER for optimization, the COE was slightly higher at 0.40 $/kWh.

Table 1
Overview of the recent study in the area of energy economic analysis.

System	Grid	Method/Tools	Storage	Objective Function	RF%	HR	TLC
PV-WT-DG[11]	Off	HOMER	Lead-acid, FZB, Lithium-ion	COE = 0.196$/kWh,NPC = $2.97 M	–	–	–
PV-WT-DG[10]	Off	HOMER	Lead-acid	NPC = $123851, COE = 0.192$/kWh	93	–	–
PV-WT-FC[12]	Off	HOMER	Hydrogen	Carbon dioxide emissions. Annual Production	100	–	–
PV-WT-DG[13]	On	MATLAB/HOMER	Lead-acid	COE = 0.128$/kWh,NPC = $75861; CO_2 emission	46	–	–
PV-WT-DG-Boiler	Off	HOMER	Hydrogen/BES	COE = 0.321$/kWh,NPC=$14.7 M; CO_2 emission	35.5	–	√
PV-WT-MGT[14]	Off	MATLAB	BES + TES	NPC = 0.166$/kWh; LPSP; Cabon footprint:2200 kg/yr	0.92	√	√
PV-DG[15]	On	HOMER	BES	↓ COE by 45 %; ↓ CO_2 emission by 32.09 %	24/53/64	–	–
PV*WT[16]	Off	HOMER	BES	COE;NPV;IRR; CO_2 emission	35	–	–
PV-FC-Boiler[17]	Off	HOMER	Hydrogen	COE:0.8$; NPV: $1006293	53	–	–
PV-WT-MGT-FC	OFF/On	HOMER-MATLAB	Hydrogen, BES	LPSP, NPC, CO2 emission; TOPSIS		√	–
PV-WT-Biog-Syngas [18]	Off	HOMER	BES	NPC, COE, CF	–	–	–
WT-PV-FC-Boiler-[19]	Off	ANSYS FLUENT, HOMER	BES-Hydrogen	CF,COE = 0.32, ↓ Emission,48 %	84	–	√

MGT: Mirco Gas Turbine; **BES**: Battery Energy Storage; **TES**: Thermal Energy Storage; ZFB: Flow-Zince-Bromine.

Table 1 shows the recent study conducted on hybrid energy systems.

Research on CHP for building energy applications has focused on various aspects including system design, optimization, control strategies, technology advancements, economic viability, and policy frameworks as shown in the above literature. By incorporating the state-of-the-art research on CHP for building energy applications, we can provide a more comprehensive analysis of the potential benefits, challenges, and future directions in this field, enabling a deeper understanding of how CHP can be effectively implemented and optimized to meet the specific energy needs of buildings while contributing to overall energy sustainability. The existing studies on CHP systems have made significant strides in comprehending their economic performance and sizing. However, there are still gaps that warrant attention in future research endeavors. One area that necessitates further investigation is understanding the impact of TLC strategies on the economic performance and optimal sizing of CHP systems. Gaining insights into how TLC strategies influence CHP systems' economic feasibility and size optimization is crucial for maximizing their efficiency and cost-effectiveness. Another aspect that requires scrutiny is the role of HR from MGT in CHP systems. Although studies have explored the influence of HR on CHP systems, further research is needed to ascertain how HR considerations can impact system sizing. By integrating HR technologies into the design and optimization process, it may be possible to enhance CHP systems' overall performance and efficiency. Moreover, a dearth of studies simultaneously investigates TLC and HR and their collective impact on CHP performance and sizing. Understanding the synergistic effects of TLC and HR can provide valuable insights into the design and operation of CHP systems. By considering both factors holistically, researchers can develop more comprehensive and accurate models for optimizing the size and configuration of CHP systems. This integrated approach will contribute to advancing CHP technology and its broader adoption as a sustainable energy solution.

The objective of this study is to explore the economic sizing of CHP systems in various contexts, with a focus on analyzing the impacts of TLC and HR strategies. The study focuses on a CHP system consisting of PV-WT-MGT-Boiler as an energy generation source and batteries and thermal energy storage as a backup. The analysis criteria encompass the goals of attaining the lowest Levelized COE and NPC, minimizing CO_2 emissions, LPSP, RF, optimizing component size, and maximizing the employability potential. The main goals of this research are to:

- Identify the optimal CHP sizing and configuration-based techno-economic performance
- Explore the synergistic effects of hybrid TLC and HR approaches in enhancing system performance.
- To investigate the impact of TLC and HR on techno-economic performance on sizing, COE, NPC, CO_2 emissions as well as LPSP.

The organization of the study is as follows: Section 2 presents a detailed overview of the research methodology utilized in this investigation. It encompasses aspects such as data collection, modeling techniques, and techno-economic analysis. Section 3 presents the expected results of the study, followed by a detailed discussion and comparison of the findings. This section aims to provide a deeper understanding of the results obtained and their implications within the context of the research objectives such as TLC and HR from techno-economic performance. Section 4 concludes the study by summarizing the key findings and their significance on CHP Performance. Additionally, it highlights potential avenues for future research that can build upon the current study's findings and contribute to advancing knowledge in the field.

One limitation of our study is that we collected load profile data for only one year and assumed it would remain constant throughout the entire project lifetime. This assumption may not account for potential changes in energy demand patterns and load variations over time, which could impact the performance and optimization of the CHP system. Additionally, we relied on two environmental data points obtained from HOMER's historical data. While this provides some insight into the environmental conditions, it may not capture the full range of variability and site-specific characteristics that could affect the system's operation and efficiency.

2. Methodology

This section provides a detailed explanation of the methodology employed to achieve the objectives of the study. It encompasses the mathematical model, simulation, optimization software, and the techno-economic concepts utilized in the research. The methodology was divided into four main phases: data collection, CHP modeling, and the techno-economic assessment strategy and energy management. In the data collection phase, environmental data such as irradiation, temperature, and wind speed, as well as component-related information, including initialization costs, operation and maintenance costs, replacement costs, and electrical and thermal load demand profiles, are collected. In the second phase, the CHP components are modeled based on HOMER Pro version 2021, which is utilized to model and find the CHP system's configuration. The third phase investigates and generates a set of hybrid system options that minimize NPC and COE within specified constraints. This phase aims to identify potential configurations that are economically feasible. In the last phase the control strategy will discuss in details. Four case studies were designed to investigate the impact of waste energy recovery on energy sizing, as shown in Table 2. In Case 1, the CHP was determined without any mitigation. In Case 2, the TLC was integrated with the CHP system to convert surplus power generation from renewables to supply the thermal load. In Case 3, HR from MGT was stored in thermal storage. Finally, Case 4 examined the hybrid TLC and HR on the CHP system.

Fig. 1 illustrates the schematic of the CHP system, which consists of two subsystems: the electrical and thermal subsystems. The CHP system utilizes two interconnection systems to convert wasted energy from the electrical subsystem into the thermal subsystem to meet the heating demand in the thermal system. These interconnection systems include the TLC and the HR system from the MGT. The paper introduces a novel approach to evaluating the costs and benefits of CHP systems through techno-economic evaluations based on the TLC concept and HR. The electrical subsystem comprises several components: a PV system, WT, MGT, battery energy storage, and an inverter. PV characteristics modules can be obtained from existing literature sources [12]. MGT units are interconnected with both the electrical and thermal subsystems. The waste heat generated by the MGTs is harnessed through an exhaust gas heat exchanger, providing hot water to fulfill heating requirements. The excess energy produced by PV systems and wind turbines is used to charge a battery bank. Batteries discharging takes place when PV generation is unavailable and the demand is below the minimum starting threshold for the MGT. The thermal subsystem, includes a gas boiler, electrical boiler, Thermal Energy Storage, and an exhaust heat exchanger.

2.1. Data collection

2.1.1. Environmental data

The environmental data for this study were collected at from a typical small-scale laboratory in Tehran based on HOMER Pro historical data by entering the latitude and longitude of the specific location [20]. Fig. 2 presents the average daily radiation levels throughout the year, showcasing a peak during June and July, while the lowest levels were observed in November. The daily solar radiation ranges between 470 and 950 W/m^2, with the highest values reaching between 770 and 1605 W/m^2. Over the monitoring period, a total of 3127.5 h of sunlight were recorded, equating to an average of 9.23 h of solar radiation received daily. The highest recorded solar radiation occurred on 19th June, measuring 1787 W/m^2. In contrast, the minimum solar radiation was observed on most days as early as 6:08 AM. Furthermore, the average monthly wind speed was recorded at 7.1 m/s, with a daily peak wind speed ranging between 8 and 12 m/s. Fig. 2 also illustrates the variations in wind speed across different months.

2.1.2. Load Demand Profile

The load profile consists of electrical and thermal components, which are recorded daily by the monitoring system. Fig. 3 provides an overview of the daily load demand throughout the year. The total electrical load demand is approximately 97 kWh per day, with a peak load of 9.56 kWh occurring in early July. On the other hand, the thermal load for this study is around 92 kWh per day, with a peak load of 6.04 kWh. It is important to note that the load is assumed to remain constant throughout the year. The electrical load in the laboratory includes power supply for electrical lab equipment and lighting, which contribute to the overall electricity demand. Meanwhile, the thermal load serves two main purposes. Firstly, it is required for the dry room, where the temperature needs to be maintained at around 62 degrees. Additionally, the thermal load is also used for the proposed water heater. In this project, a boiler is employed to supply thermal energy for both these loads.

Table 2
Designed a case study for the proposed system.

Case Study	CHP	TLC	HR
Case 1	√		
Case 2	√	√	
Case 3	√		√
Case 3	√	√	√

2.1.3. Components cost

Appendix 1 provides comprehensive technical specifications and details of the CHP components utilized in the research. In this particular research, fixed flat-plate PV arrays with a rated power capacity of 1 kW and an efficiency of 17.3 % were chosen. The wind turbine selected has a rated capacity of 1 kW and an initial cost of $14,00, with a lifespan of 25 years. Each battery is estimated to cost $200, with a life expectancy of 1400 cycles and a DOD (depth of discharge) of 30 %. The inverter is an off-grid device that converts electric power from DC to AC or from AC to DC. The selected inverter costs $200 and can convert 12 V input to 220 V output with a rated power of 1000 W. It is assumed that the inverter and rectifier will have a lifespan of 20 years with an efficiency of 93 %. The gas boiler was used to supply the thermal load demand, and its efficiency is considered to be 85 % for this case study. The MGT is used as a backup system during short energy generation from renewable energy sources.

2.2. Energy components modeling

Photovoltaic Modeling:

The PV power generation can be calculated as follows [20,21]:

$$P_{pv} = Y_{pv} f_{pv} \left(\frac{G_T(t)}{G_{T,STC}}\right)\left[1+\alpha_p\left(T_{cell}(t) - T_{cell,STC}\right)\right. \quad (1)$$

where y_{pv}, f_{pv}, refer to the PV system rated capacity, the PV system derating factor, and sun irradiation. $G_T(t)$, $G_{T,STC}$ are represent the sun irradiation at standard test conditions (STC). α_p is denote the power coefficient of power. $T_{cell,STC}$ and T_{cell} denote the temperature of solar cells under STC and the temperature of solar cells, respectively.

Wind system modeling:

The WT system power generation can be calculated as follows [21,22]:

$$P_{WT}(t) = \begin{cases} 0, \nu(t) \leq \nu_{cut-in} or \nu(t) \geq \nu_{cut-out} \\ P_r\left(\frac{\nu^3(t) - \nu^3_{cut-in}}{\nu^3_r - \nu^3_{cut-in}}\right), \nu_{cut-in} < \nu(t) < \nu_r \\ P_r, \nu_r \leq \nu(t) < \nu_{cut-out} \end{cases} \quad (2)$$

Where $P_{WT}(t)$ is the power output from a WT. P_r, ν_r, ν_{cut-in}, $\nu_{cut-out}$ are, respectively refer to the rated power, rated velocity, cut-in velocity, and cut-out velocity of the WT.

Battery energy storage Modelling:

The charging and discharging processes are simulated based on established models found in the literature [23]. HOMER calculates the maximum power that can be absorbed by the storage bank during each time step [20]. This value plays a crucial role in decision-making processes, such as evaluating if the storage bank has the capacity to store all excess renewable power or determining the necessary surplus power from a cycle charging generator. The maximum charge power is not constant and varies based on the storage bank's state of charge and its recent charging and discharging patterns. The determination of the capacity of a battery storage system involves assessing its ability to store surplus renewable energy during the charging phase and subsequently deliver that energy during periods of deficiency or high demand [24]. The battery charging formula is as follows [22]:

$$P_b(t) = \frac{kQ_s(t)e^{-k} + Q(t)kc(1 - e^{-k\Delta t})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \quad (3)$$

Where $P_b(t)$ refers to the maximum power that the battery can absorb

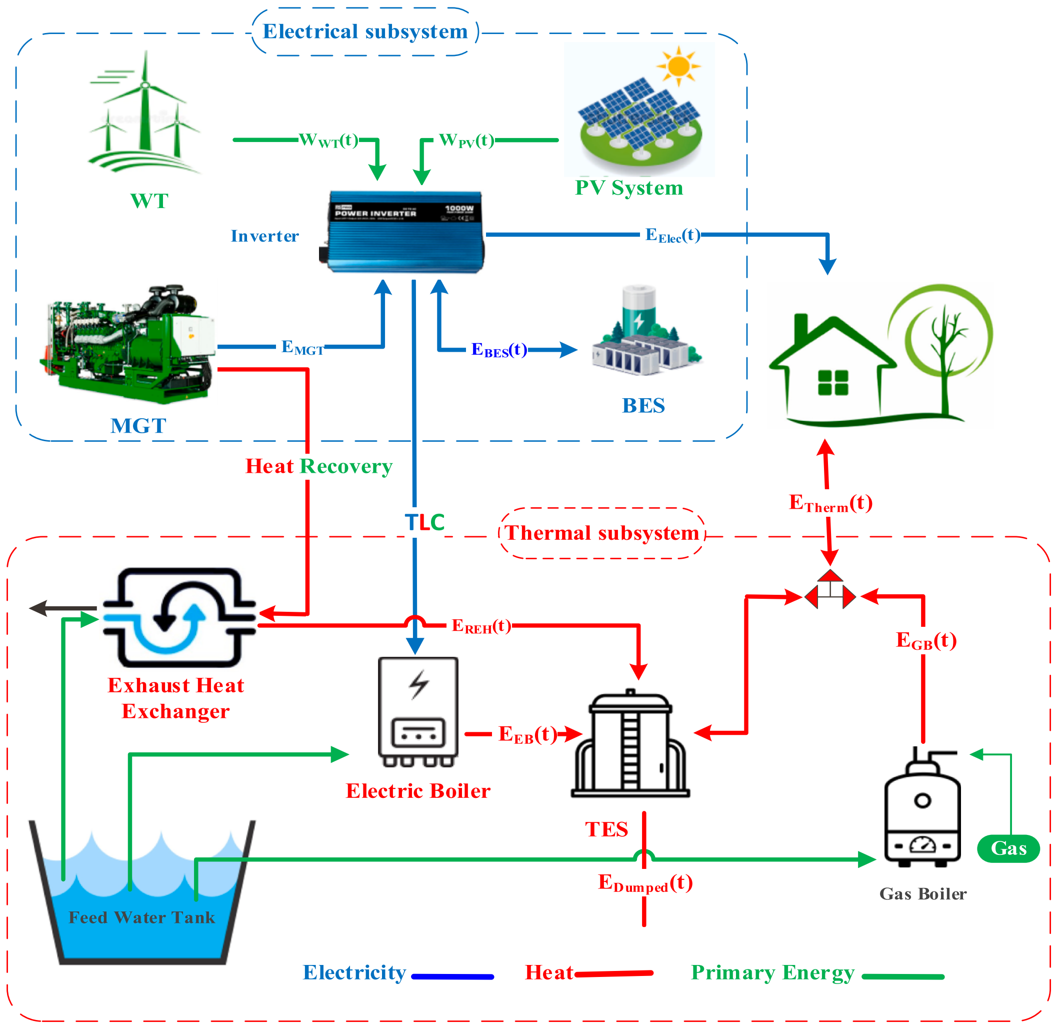

Fig. 1. The Schematic of the CHP system with input and output directions.

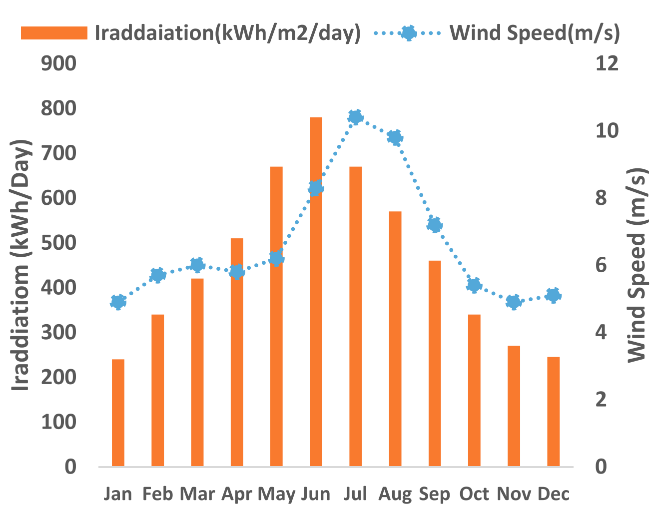

Fig. 2. Weather data for the lab location.

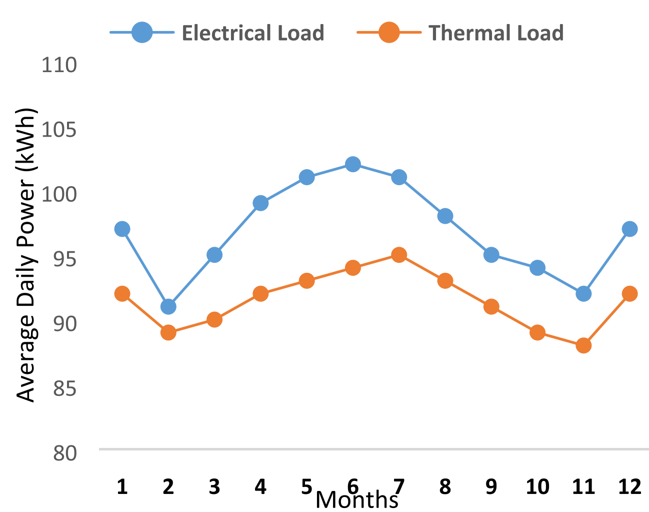

Fig. 3. Electrical and thermal Load profile.

during a specific time step, $Q_s(t)$ represents the available energy at the start of the time step and $Q(t)$ denotes the total energy available at the beginning of the time step, accounting for the minimum state of charge level (SOC_{min}), which is set at 20 % for a lead acid battery. c represents the storage capacity ratio, the storage rate constant, represented by k, and Δt is amount of time in the time step. HOMER determines the maximum power that the storage bank can discharge during each time step. This value is utilized in making decisions, such as evaluating if the storage bank can meet the load demand independently [20]. The maximum discharge power is not predetermined and remains dynamic, fluctuating across different time steps. It is calculated based on the storage bank's SOC and recent charging and discharging patterns, which are evaluated using the Kinetic storing model. This approach allows for an adaptive determination of the maximum discharge power, ensuring optimal utilization of the storage bank's capabilities throughout the simulation [22].

$$P_b(t) = \frac{-kcQ_s(t)^{-k\Delta t}(t)(1-e^{-k\Delta t})_{max}}{1-e^{-k\Delta t}+c(k\Delta t-1+e^{-k\Delta t})} \tag{4}$$

Where $P_b(t)$ refer to maximum battery discharge power, and Q_{max} is the total capacity of the storage.

Micro Gas Turbine(MGT) Modeling:

MGS generator can be calculated by the following formulation. The MGT aims to be used as a backup system whenever the solar PV panels, WT, and battery alone are insufficient to meet the building's energy demands, a generator is used as a backup means of power [20].

$$F_{MGT} = \alpha_0 \times Y_{RMGT} + \alpha_1 \times P_{MGT} \tag{5}$$

where F_{MGT} reparent the natural gas consumption (L/hr), The coefficient α_0 represents the intercept rate (L/hr per kW), while α_1 denotes the slope rate (L/hr per kW) for generator natural gas consumption. Y_{RMGT} is the generator generation rate (kW). In HOMER, we define the generator's electrical efficiency as the electrical energy coming out divided by the chemical energy of the fuel going in. The following equation gives this relationship [20]:

$$\eta_{MGT} = \frac{3.6 \times P_{MGT}}{\dot{m}_{fuel} \times LHV_{Fuel}} \tag{6}$$

Where $\dot{m}_{fuel}$ and LHV_{Fuel} are the mass flow rate of the fuel (kg/hr) and the lower heating value of the fuel. The factor of 3.6 arises because 1 kWh is equal to 3.6 MJ.

Exhaust Modeling for MGT Heat Recovery:

The HR determined in HOMER ranges from 20 to 30 % and it depends on energy dispatch strategies which will be discussed in the next section. The HR can be calculated based on the following [20,25]

$$Q_{HR} = -0.000003 \times P^2_{MGT}(t) + 1.3056 \times P_{MGT}(t) - 1.0554 \tag{7}$$

To determine the actual available heat energy, the following Eq. (8) is used. These formulas help account for any losses in the piping system and the efficiency of the heat exchanger when calculating the usable heat energy.

$$E_{HR}(t) = \varepsilon \times \xi \times Q_{HR} \tag{8}$$

Where $E_{HR}(t)$ is refer to heat energy, ε is donate the heat exchanger effectiveness, which is set to 0.8 and ξ is loss coefficient, which is set to 0.95

Thermal Loads Controller (TLC):

The operation of the system is sustained by utilizing excess generation from the electrical system. The output from the TLC is calculated, taking into account a conversion efficiency (η) of 90 %. This calculation enables the determination of the actual output generated by the TLC subsystem, considering the efficient conversion of excess electrical energy [22].

$$TLC_t = \eta \times EE_{excess} \tag{9}$$

where, EE_{excess} refers to the surplus power generation by renewable energy sources.

Thermal Storage System Modeling:

During the charging process of the TSS, there are two inputs: one from the TLC and the other from the HR system of the MGT. The control system, considering factors such as the thermal load demand and the SOC of both the TSS and the gas boiler, makes decisions to optimize the charging and discharging operations. The mathematical model for the charging and discharging of the TSS is outlined as follows [22]:

$$E_{TSS} = E_{TSS}(t-1) \times (1-\varphi) + [E_{Th,gen}(t) - E_{therm}(t) \tag{10}$$

During discharging:

$$E_{TSS}(t) = E_{TES}(t-1) \times (1-\varphi) - [E_{Termal}(t) - E_{thermal,gen}(t) \tag{11}$$

where, E_{Th}, gen is the thermal generation from excess energy through TLC and HR system. E_{Therm} is the energy thermal and φ is determined 0.07 as the rate at which heat is released within the system. $E_{TSS}(t)$ is the stored energy in the TSS.

Gas boiler modeling:

In order to meet the heat requirements at each time period and ensure that both the electric boiler and the natural gas boiler provide sufficient heat, the gas boiler acts as a supplement to the electric boiler. The gas boiler is responsible for addressing any deficit in thermal demands. The energy output from the gas boiler can be calculated using the following equation. This calculation ensures that both the electric boiler and gas boiler collectively meet the required thermal demand [22].

$$E_{Boiler}(t) = E_{thermal}(t) - \left[E_{BES} + E_{REH}(t) + (E_{TES}(t-1) \times (1-\varphi) - E_{TES,min}\right] \tag{12}$$

Where E_{Boiler}, E_{BES}, E_{TES} refer to the energy of the boiler, energy storage of the battery, and thermal energy storage..

2.3. Energy sizing and techno-economic assessment

HOMER Pro utilizes various formulas and calculations to perform energy sizing and assess the performance of hybrid energy systems. Key formulas used by the software include the energy balance equation to ensure energy supply meets demand, renewable energy resource calculations based on data and system configuration, component sizing formulas to optimize system component sizes, and economic evaluation formulas to assess financial viability. These formulas consider factors such as resource availability, load demand, system constraints, and economic indicators like LCOE and NPV [20]. HOMER Pro employs mathematical models, simulation techniques, and optimization algorithms to iteratively evaluate system designs and determine optimal sizing and configuration. To evaluate size of proposed system, the economic viability of the CHP system across various case studies, mathematical models are employed to analyze key variables such as NPC, COE, CO_2 emissions, LPSP, and renewable energy fraction [20]. The COE model assesses the cost per unit of energy generated, accounting for fuel consumption, conversion efficiency, and associated expenses. The CO_2 emissions model quantifies carbon dioxide released during system operation, incorporating factors like fuel consumption and emission rates. The REF model evaluates the proportion of renewable energy integrated into the system, comparing renewable energy output to total energy production. By utilizing these mathematical models, a comprehensive analysis can be conducted, aiding decision-making and facilitating comparisons among different CHP system implementations in terms of economic feasibility and environmental benefits. To be easy to evaluate the different variation on CHP system the MATLAB Version 2022b was use as controller to change the variation during HOMER simulation as it is shows in Fig. 4.

Net Present (NPC) Modeling:

The NPC model considers capital investments, operation and maintenance expenses, fuel costs, and discount rates to determine the present value of costs. The NPC can be calculated as follow [20]:

$$NPC = \sum C_{cap} + C_{O\&M} + C_{rep} + C_{fuel} + C_{salv} \tag{13}$$

Where C_{cap}, C_{rep}, $C_{O\&M}$ are the capital cost, the replacement cost, and the operation and maintenance costs of all components in the system. C_{fuel} is fuel cost and C_{salv} denotes the salvage value of components. The cost

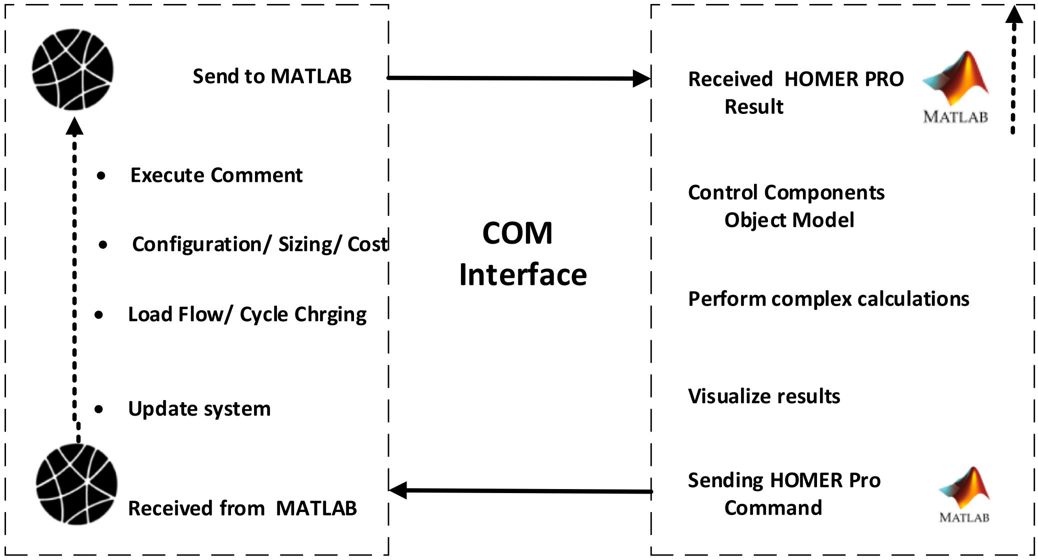

Fig. 4. Homer Pro and MATLAB integration structure.

calculation over the lifetime of the project can be calculated as follows.

$$C_{ANN} = NPC \times CRF(i, N) \tag{14}$$

Capital recovery factor of the system is determined by the following equation [20]:

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{15}$$

Where i denote the real annual interest rate and N refers to the project lifetime which is considered 25 years.

$$i = \frac{i' - f}{i' + f} \tag{16}$$

the variables *i* and *f* represent the interest rate and the yearly inflation rate, respectively.

Cost of Energy (COE) Model:

The COE is calculated as follows [20]:

$$COE = \frac{C_{ANN} - C_{G,boiler}}{E_{serve}} \tag{17}$$

Where E_{serve},. $C_{G,boiler}$ are refer to annualized energy served and the gas boiler marginal cost ($/kWh).

Renewable Energy Fraction (REF) Model

The Renewable Energy Fraction (REF) indicates the relative contribution of energy generated from renewable sources in comparison to the overall energy consumption or generation within a given system. It can be calculated based on the following equation [20]:

$$REF = 1 - \frac{Ren.EnergyGeneration}{Electric_{serve} + Thermal_{serve}} x100 \tag{18}$$

where renewable energy generation is the total energy generated from renewable sources. The total energy generation represents the system's overall energy consumption or generation, including both renewable and non-renewable sources.

Optimization framework

Objective functions

The CHP system is designed and optimized to meet the energy demand, both electrical and thermal subsystems, at the minimum possible cost, as determined by the COE. This optimization process takes into account various constraints to ensure the system operates efficiently and effectively. The objective function, expressed in Equation (19), captures the overarching goal of minimizing COE production while considering the specific optimization constraints. By formulating and solving this objective function, the CHP system can be optimized to provide cost-effective energy solutions that meet the required electrical and thermal demands [20].

$$Min\, COE = \frac{NPC \times CRF}{E_s} \tag{19}$$

Constraints

In the optimization process of sizing the CHP system, the decision variables are the number of components involved. To optimize efficiency in computations, the solution space is limited by predefined upper and lower bounds. These bounds set the range of acceptable values for each variable, ensuring that the optimization process remains focused and efficient within the specified limits. This allows for focused exploration of the most promising regions and facilitates the identification of an optimized CHP system size that meets the given constraints [20].

$$N_{min} \le N_m \le N_{max}, \tag{20}$$

In the context of the electrical energy balance in the system, N_m denotes the components size, while N_{min} and N_{max} denote the lower and upper limits, and allowable numbers of those components, respectively. The principle of electrical energy balance states that the cumulative generation from the components involved in delivering electrical energy must be equal to or greater than the hourly electric load demand [20].

$$P_{PV} + P_{WT} + P_{MGT} \mp P_{BAT} = P_{load} + P_{Exces} \tag{21}$$

P_{PV}, P_{MGT}, P_{WT}, and P_{BAT} are respectively denotes the power generation of PV, MGT, WT, and battery at a given time interval t. P_{load} and P_{Exces} is represents the electrical load demand and excess generation from renewable. The limitations on the energy storage capacity within the CHP system are dictated by the following constraints:

$$E_{min} \le E_{Store} \le E_{max} \tag{22}$$

where, E_{min} and E_{max} are represent the lower and upper limits of the storage system for both electrical and thermal subsystems.

LPSP represents the ratio of the total energy that is not supplied to the total load demand over the course of a year. It represents the probability of an interruption in power supply during that specific period.

$$LPSP = \frac{TotalUnmetEnergy}{TotalLoadDemand} x100 \quad (23)$$

Total Unmet Energy is the sum of energy not supplied to customers due to interruptions throughout the period of interest, Total load demand is the sum of the load demand from all customers over the same period.

$$LPSP = \frac{\sum_{t=1}^{T} (LPS_{Elec}(t) + LPS_{Ther}(t))}{\sum_{t=1}^{T} (E_{Elec}(t) + E_{Ther}(t))} \quad (24)$$

Where LPS_{Elec} and LPS_{Ther} are Loss of Power Supply (LPS) electrical and thermal and E_{Elec} and E_{Ther} are the energy electrical and thermal. The worst-case scenario for power supply, referred to as LPS, arises when the combined supplementary, renewables, and energy storage systems are unable to supply or deliver sufficient power to meet the load demand. LPS is calculated over a period of 8760 h as follows:

$$\sum_{t=1}^{T} LPS_{Elec}(t) = \sum_{t=1}^{T} \left(E_{Elec}(t) - \left[E_{Gen}(t) + E_{BES}(t-1) - E_{BES,min}\right] \times \eta_{inv}\right) \quad (25)$$

$$\sum_{t=1}^{T} LPS_{Ther}(t) = \sum_{t=1}^{T} \left(E_{Ther}(t) - \left[E_{EB}(t) + \left(E_{TES}(t-1) - E_{TES,min}\right) + E_{REH}(t) + E_{Gbolier}\right]\right) \quad (26)$$

The constraint is as follows:

$$LPSP \leq LPSP_{Desired} \quad (27)$$

where, $LPSP_{Desired}$ denotes that the predefined reliability of the CHP is measured to range from 0 % to 0.5 %. This value signifies the desired level of reliability that the system aims to achieve.

2.4. Energy management strategy

In this study, the focus is on utilizing the HOMER software tool to achieve optimization through various dispatch strategies. However, particular emphasis is placed on employing a load-following dispatch strategy due to its effectiveness in reducing excess energy and resulting in lower values of COE and NPC [20]. Fig. 5 illustrates the control strategy that governs the operation of the CHP. The power system configuration design was determined using a mathematical optimization method. The optimization method utilized in this study considers three crucial factors: the building's load profile, the capacity of renewable energy generation, and the system design constraints. These factors play a pivotal role in determining the optimal configuration and operation of the system. The search space in this context is determined by the sizing of various components in the power system. Simulations were conducted on various power system architectures. The power system was optimized according to the desired requirements (constraints). Each simulation involved 1276 data points per year and a time step of 60 min. The control algorithm begins by incorporating input parameters that

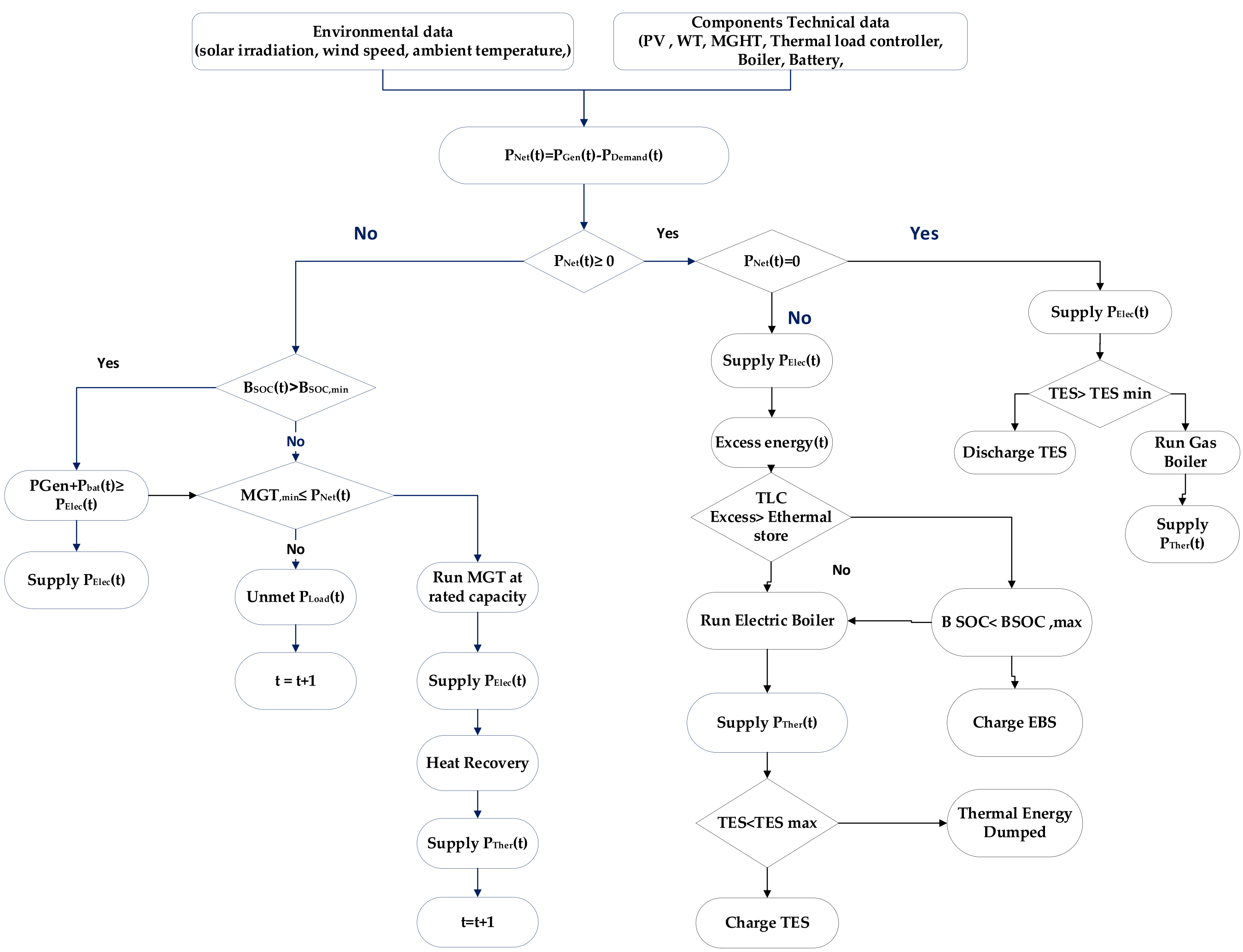

Fig. 5. CHP control strategy.

encompass electric and thermal loads, as well as meteorological data such as temperature, irradiance, and wind speed. These parameters are utilized to evaluate and determine the optimal energy generation and storing system behavior:

- when E_{NET} is larger than the load demand.*Itis* indicating that the energy generation exceeds the demand, there is an excess of energy available after fulfilling the electric demand. This excess generation is then stored in the batteries, up to its E_{max}. The remaining excess energy is directed towards the TLC to convert into thermal energy, In cases where the generated surpasses the demand, it is stored in the TSS system, up to its E_{max}, while any excess beyond the TSS capacity is discarded.
- When E_{NET} is equal to demand. It indicates that energy generation matches the demand, the renewable generation fulfills the electric load demand. Consequently, the thermal load demand is primarily met by the TSS. In scenarios where the primary thermal sources as well as the storage are unable to provide sufficient output, a Gas Boiler is triggered to supply the shortage of thermal demand. This ensures that the overall thermal demand is adequately met in such situations.
- when E_{NET} is less than the load demand, it indicates a deficit in CHP, resulting in no electric generation. To address this deficit, the controller discharges the batteries system to supply electrical load. In situations where the battery shortage persists, the MGT is utilized, provided it has reached the start-up threshold of 30 % of its rated power. The MGT not only helps meet the electrical deficit but also recovers some thermal energy from its exhaust. In such scenarios, the thermal demands are met through a combination of TLC and the TES system, ensuring the cumulative fulfillment of thermal requirements.

The following energy management flowchart calculates constraints and objective functions at each time step. The load-following strategy ensures that the generator meets the load demand without charging the battery, while the surplus power from renewable sources is used to charge the battery.

2.5. Results and discussion

This section primarily focuses on analyzing the energy costs associated with a hybrid system. The analysis begins with a technical energy analysis to determine the minimum number of components required for the CHP system. The main goal of the analysis is to investigate the impact of TLC and HR on CHP performance and to identify the weak points in the CHP system where energy is being wasted. By minimizing wasted energy, it is possible to reduce the number of PV modules, WT, and energy storage devices needed to ensure 100 % power availability. Furthermore, the section involves calculating the system's cost in terms of energy economics, taking into account both the energy and the associated costs. The aim is to determine the overall cost of the system, considering various factors and components.

Based on the information provided, Table 3 presents the energy sizing configurations based on the energy balance equation (Eq21) and the objectives mentioned earlier for different configurations. The results obtained from the HOMER software are sorted based on the case studies determined in Table 2. The table provides information on each case study, including component size, cost, fuel consumption, and renewable energy fraction (RF). Case studies 2 and 4 demonstrate the impact of TLC (presumably referring to a specific technology or strategy) on energy sizing, while case studies 3 and 4 highlight the impact of HR (presumably referring to waste heat recovery). Among the different case studies, Case Study 4, which incorporates both TLC and HR, achieved the highest performance with a renewable energy fraction of 46 %. It utilized a 19 kW PV array, a 6 kW wind WT, a 10 kW MGT, and 92 batteries. In terms of cost analysis, this configuration had a Net Present Cost (NPC) of $113,950 and a Cost of Energy (COE) of 0.215$, making it the most favorable choice among the considered configurations. Although Case Study 3 had a lower NPC compared to Case Study 4, other cost parameters such as COE, operating cost (OC), and fuel cost were higher, and the renewable energy fraction (RF) was lower than that of Case Study 4. Consequently, Case Study 3 was selected as the optimal choice for subsequent energy calculations in the following section. These results indicate that harvesting surplus energy generation from renewables and utilizing waste heat from the micro gas turbine (MGT) significantly reduces the system's cost.

Table 3
CHP Sizing based on control strategies.

System information	Configuration			
	CHP Base	CHP &TLC	CHP & HR	CHP & Hybrid TLC and HR
CHP COMPONENTS				
Solar PV(kW)	23	25	23	19
WT(kW)	–	7	4	6
Battery	89	121	94	92
Inverter (kW)	16	17	14	13
Boiler	1	1	1	1
MGT (kW)	10	10	10	10
TLC (kW)	–	15	–	15
SYSTEM COST				
NPC $	130,181	118,900	109,256	113,950
COE $	0.229	0.225	0.221	0.215
OC $/yr	5973	5074	5873	5174
IC $	54,740	75,500	60,540	57,103
Fuel Cost $/yr	1491	1002	1191	860
RF %	41	51	43	46
Carbon Dioxide kg/yr	16,980	14,589	15,382	13,175
ELECTRICAL SUBSYSTEM				
Renewable Generation (kWh/yr)	36,240	41,590	36,890	37,542
MGT (kWh/yr)	12,459	9785	11,494	8416
Electric Excess (kWh/yr)	8950	7541	8713	6875
THERMAL SUBSYSTEM				
Boiler Fuel Consumption m^3	2891	2690	2783	2583
TLC (kWh/yr)	0	7485	0	6785
HR (kWh/yr)	0	0	6890	5019

Fig. 6 illustrates the COE, NPC and initial cost (IC) of energy across different case studies. In Fig. 6a it is clear that in Case 1, which involves a system without any improvement, both COEs are high compared to others, with values of 0.229 $/kWh, while the IC compared to others is the lowest cost system. Case 2 and Case 3 incorporates TLC and HR, respectively, to minimize wasted energy. Among these two case studies, Case 2 with TLC integration shows the highest COE and IC, with values of 0.225 $/kWh and 75,500 $, respectively, while Case 3 with HR system has a slightly lower COE of 0.221 $/kWh and IC of 60,540 $. The optimum system is Case 4, which combines both TLC and HR systems, resulting in a minimum COE of 0.215 $/kWh and IC of 57,103 $. Although the base system has the lowest IC compared to the optimum system the COE generation is very high. It is observed that integrating the HR and TLC significantly impacts COE. Fig. 6b shows the comparison of COE and NPC among different case studies. Case study 1 (Base) has the highest COE and NPC compared to other cases. In addition, Case Study 3(with HR) has the lowest NPC in this system. However, the optimum system that integrated HR and TLC into the CHP system shows the COE and NPC with 0.215 $ kWh and 113950$, respectively.

Fig. 7 illustrates the impact of various parameters on the COE (a) and NPC (b) in the CHP system. The COE is expressed in $/kWh, with $0.215/kWh for the proposed system. Changes in CC of components, and gas fuel are examined to investigate changes in system cost. The

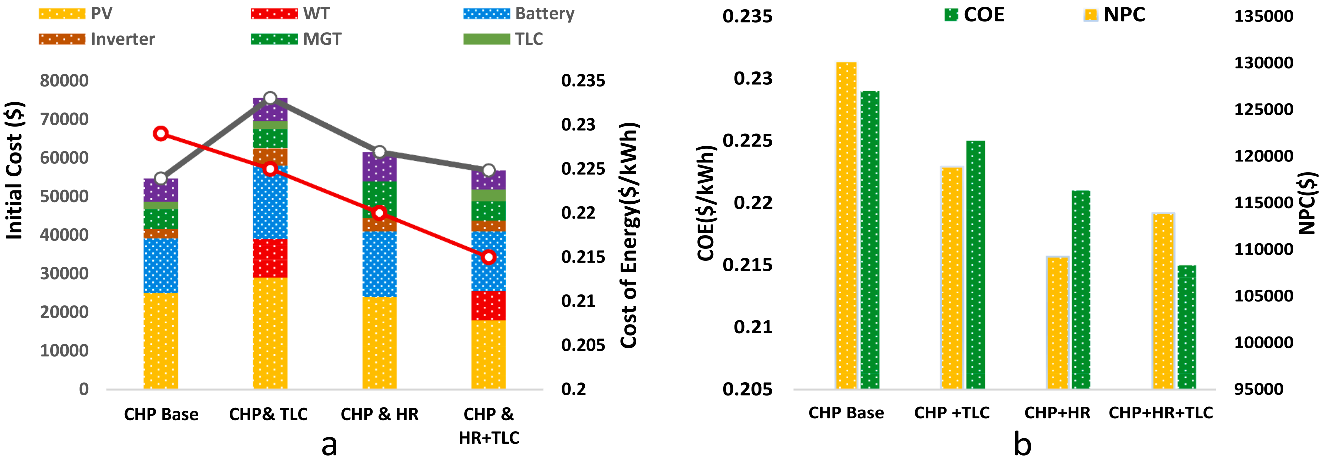

Fig. 6. The CHP configuration comparison based on IC/COE (a) and NPC/COE (b).

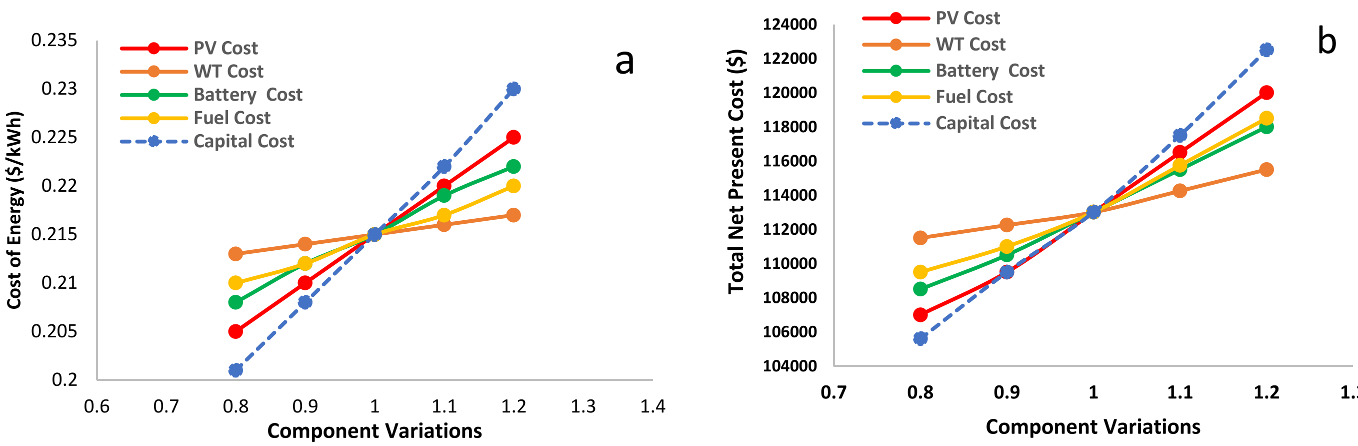

Fig. 7. The impact of CC components variations on COE (a) and NPC (b) for proposed system.

analysis indicates that changes in WT have an insignificant effect on the COE. The proposed system uses 6 kW WT and any changes in the price of WT have less impact on COE. However, reducing PV, battery and gas fuel costs cut by 20 % would substantially decrease COE. PV and batteries are the main source of CC of the system and any changes to this component impact COE. It is clear that almost 70 % of CC is related to these two components. Fig. 7b, shows the impact of component variations on NPC in the CHP system. PV and battery are the most important components in this hybrid energy system. Increasing and decreasing each of them significantly effects on NPC of the system. The 20 % reduction in CC and PV system CC reduce the 9 % and 8.5 % of NPC respectively. However, WT due to less CC has an insignificant impact on

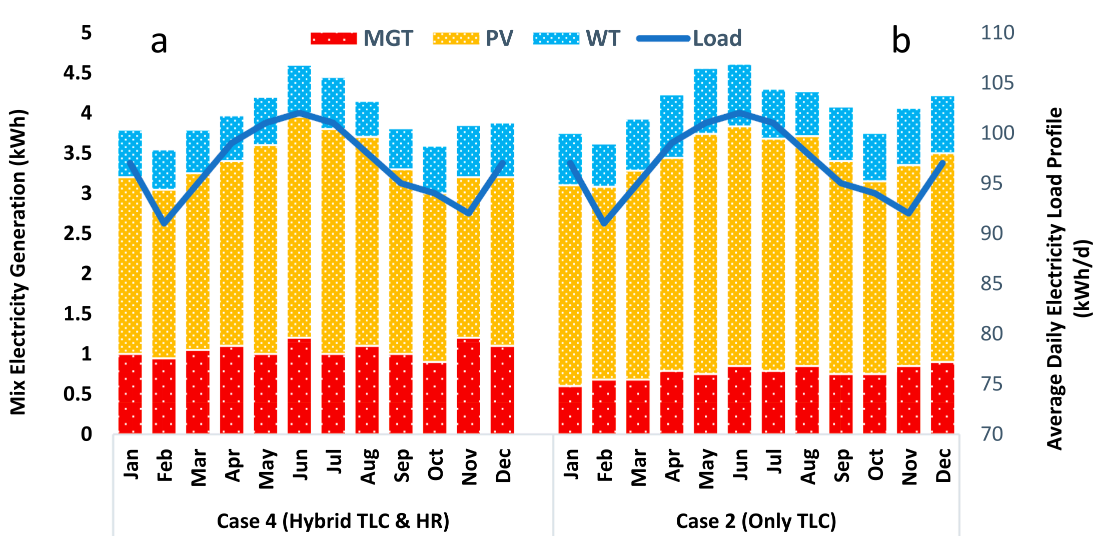

Fig. 8. CHP electrical subsystem generation based on case 4 (a), case 2 (b).

NPC.

Energy generation from resources is determined based on the dispatch strategy, as explained in section 2.4. In the electrical subsystem, the primary aim is to supply the electrical load generation mostly from renewable sources. If there is a deficit, the MGT will integrate, and any excess energy will be converted to thermal energy. According to the Table 3, the majority of the costs associated with this system are due to solar panels and batteries. Fig. 8 show the electrical subsystem power generation for case 4 and case 2(with TLC) based on LF control strategies. Fig. 8a displays the electric generation Case 4, where it is observed that 62 % of power generation comes from solar PV, and 29 % by MGT. This strategy's generation is close to the load profile, with minimum surplus power generation. Additionally, only 9 % of the generation is supplied by WT. On the other hand, in Fig. 8b, the surplus power generation is shown to be more than that case 4, leading to an increase in the system's cost. This figure clearly shows that the amount of solar and WT generators is significantly increased, and energy generation in this strategy is 65 % from PV and 13 % from WT. The renewable energy fraction from this system is high in this strategy.

Similarly, in the thermal subsystem, the aim is to use HR and TLC to minimize waste energy in the electrical subsystem and support boiler generation. TLC recovers surplus power generation from renewable energy sources, while HR recovers waste heat from the MGT. The impact of TLC and HR on minimizing boiler generation to supply the thermal load is shown in Fig. 9. The graph illustrates the rate of generation by integrating TLC and HR into the CHP system to supply the thermal load. This strategy ensures that the system generates a sufficient amount of thermal energy to meet the load requirements. The graph presents the thermal energy generation for both Case 4 and Case 3. It is observed that in Case 4 (a), more than 29 % of the generation comes from HR and TLC, significantly reducing the amount of gas boiler generation. TLC is represented by the blue color, and it is noted that the highest surplus power generation occurs from April to September, while HR system generation peaks in June and July. On the other hand, in Case Study 3 (b), HR generation is integrated into the system. It is evident that more than 80 % of the generation comes from the gas boiler, leading to a reduced renewable fraction rate in the system. These results support the objective of the study, which is to minimize component sizing with respect to the system's cost.

Minimizing wasted energy is always the main challenge in the CHP system and the above result shows how integration of TLC and HR significantly impacts energy generation. Fig. 10 illustrates how various TLC and HE affect the COE in the purpose system. Examining the impact of TLC and HR on the cost of the energy system is another objective of the study. Specifically, the study aims to determine which of these two integrations has a more significant effect on the overall cost. It is clear that a 20 % cut TLC significantly impacts the COE. It is increasing the 8 % COE (from 0.215 to 0.233). In addition, HR 20 % reduction can lead to increasing the 7 % COE (from 0.215 to 0.229). On the other hand, RF has an opposition direction, decreasing the RF leads to decreased COE and revised. However, Increasing the HR and TLC up to 20 % significantly reduces COE energy by 8 % and 6 % respectively. While the increasing RF increased the COE up to 10.5 %. By comparing the TLC and HR systems, it is observed that TLC has a more significant impact on the overall system. Reducing TLC and HR by 20 % in the Combined Heat and Power (CHP) system has a considerable effect on the Cost of Energy (COE). Furthermore, increasing TLC performance by an additional 20 % leads to even greater reductions in COE.

In this system, the main cost drivers are PV panels and batteries, which require in-depth investigation to determine the optimal number of each component. Oversizing or undersizing the capacity of PV panels and batteries can significantly impact the performance of the CHP system. Fig. 11 showcases an optimization surface plot that illustrates the relationship between the number of PV panels and batteries, focusing on two crucial metrics: the COE and the NPC. The plot demonstrates that the performance of batteries remains relatively similar within the range of 60 to 115 units. However, the determination of the optimal number of batteries is heavily influenced by the cost and number of PV panels. The plot clearly indicates a trend where increasing the number of PV panels beyond a certain threshold leads to a gradual escalation in NPC. Eventually, the NPC peaks at $135,000. Based on this analysis, the optimal configuration for this study involves integrating 19 kW PV panels and 90 batteries, which are highlighted by the dark blue region on the plot. This specific configuration results in a COE value of 0.215$, indicating a cost-effective and efficient solution. These results demonstrate the relationship between these components and the two cost indicators. It highlights the significant impact of incorrectly determining the size of these components on the overall system cost.

The dynamic simulation of the proposed system over time is shown in Fig. 12 for both the electrical subsystem (a) and thermal subsystem (b). The system was simulated for 25 years, and this figure illustrates the system's behavior by showing its operation for a week from January 1 till January 7. In the electrical subsystem, it is observed that the PV system has the highest generation, indicated by the green color. The battery energy storage was integrated into the system, shown in yellow color, to charge during surplus power generation and discharge during peak load. This strategy significantly reduces the COE and size of components. Battery plays an important part in the sizing of energy systems. A minimum number of batteries that minimize the mismatch between generation and load demand is the one of goals of the study. Load

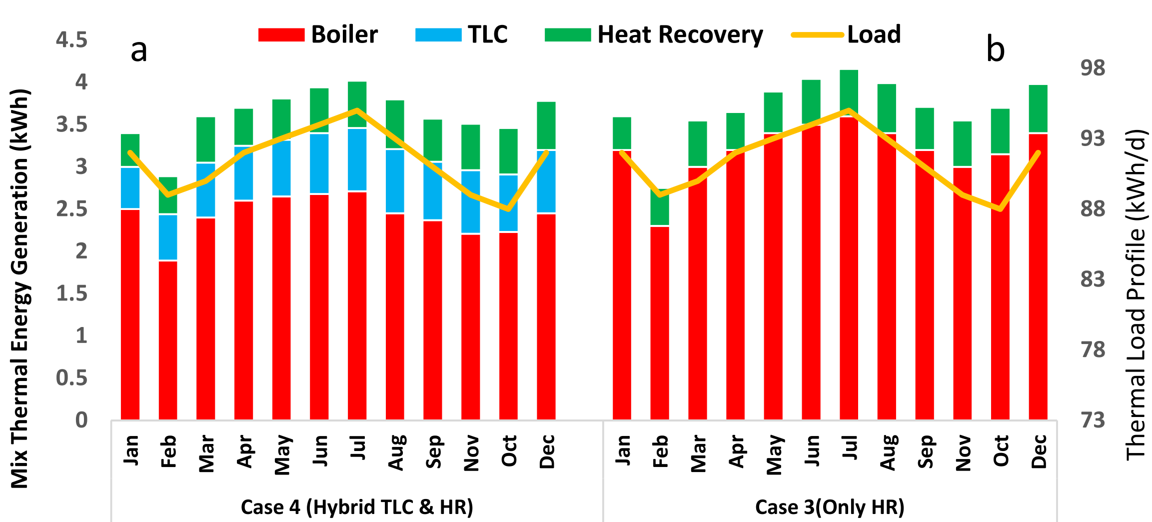

Fig. 9. Thermal subsystem mix generation for case 4 (a) and case 3 (b).

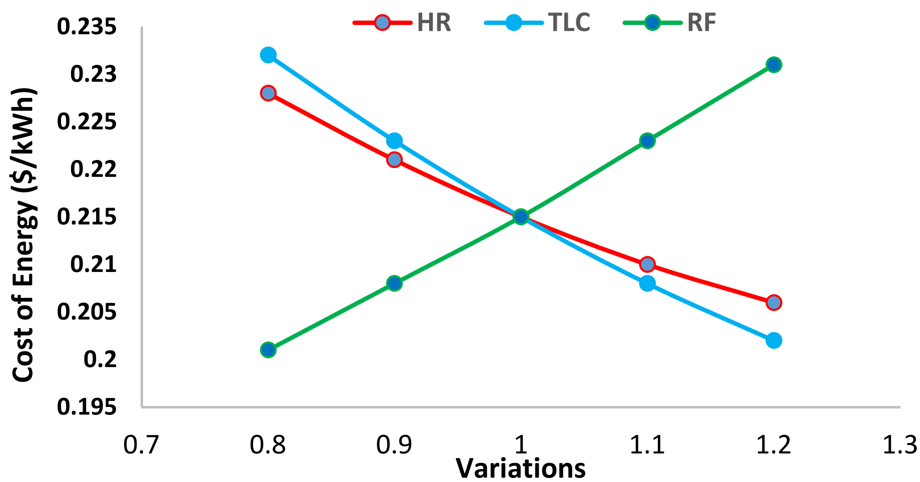

Fig. 10. Sensitive analysis on the impact of component size and variations on COE. The variation capacity of WT, PV, and BESS on COE was investigated.

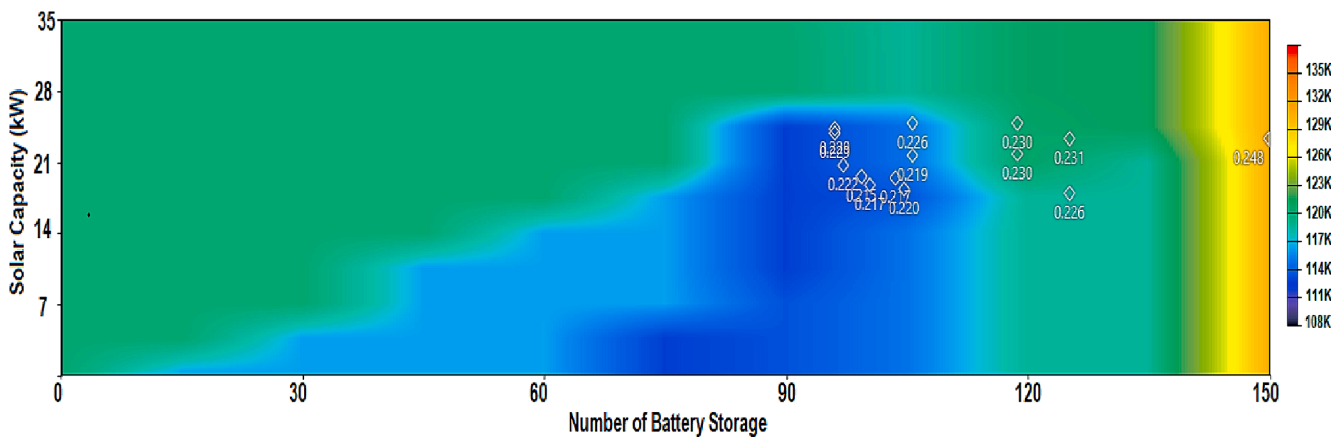

Fig. 11. Sensitive analysis of the proposed CHP. The solar and battery are a component that plays an important role in increasing and decreasing the CHP components.

demand during peak load conditions may face generation shortage as can be seen on 3rd January total power generation from renewable energy sources is less than the load demand. During these days, the weather conditions resulted in minimal sun irradiation due to the prevalence of rainy days. As a consequence, the available solar energy for PV panels would have been significantly reduced. This reduction in sun irradiation can have a direct impact on the energy generation capacity of the PV panels, potentially leading to lower energy production. Fig. 12b shows the thermal side of the system. The surplus power generation from the electrical side is converted through TLC to supply the thermal load and it is shown in green color. In addition, HR from MGT on the electrical side also converted through an exhaust system to the thermal energy to supply thermal load as it is shown by yellow colors. This amount reduces the boiler generation rate saves fuel and helps with CO_2 emission reduction.

The cash flow analysis provides a comprehensive view of the project's lifetime financial performance. In Fig. 13, a comparison is presented between the cash flow of the base system (case 1) and the proposed system (case 4), highlighting a significant reduction in system cost from $135,000 to $113,500, representing a nearly 25 % decrease. The blue line represents the base system, which has an initial cost of $57,103, while the orange line represents the proposed system with an initial cost of $54,740. This reduction in system cost can be attributed to the implementation of waste energy minimization techniques, such as HR and TLC, as well as a decrease in the number of components in case 4. Over the course of 25 years, the accumulated cash flow in case 4 is noticeably lower than in case 1. This outcome validates the effectiveness of waste energy reduction measures, HR, and TLC, as well as the optimization of system components. These strategies contribute to improved financial performance and cost savings over the project's lifetime.

The cost summary in this project was reported in Fig. 14, which shows the capital cost, replacement cost, operations and maintenance cost, gas (fuel) cost, as well as salvages in the CHP system. The optimum system has a capital cost of $57,103, where solar panels and batteries are the main components contributing to the capital cost. The replacement cost is mainly related to the batteries, which need to be replaced during the project's lifetime. The operation cost is around $5,174, primarily due to the boiler system. The fuel cost includes both the MGT and boiler, totaling $22,300, and the salvage represents the value of components at the end of the project's lifetime. Fig. 14b provides a detailed breakdown of the component costs. Batteries play an important role in this project, followed by the MGT and boiler. While the initial cost of the MGT and gas boiler is low, the operation cost is significantly higher due to fuel usage.

The validation process for the cost-effective CHP configuration presented in this study was conducted through a comprehensive techno-economic analysis, integrating MATLAB and HOMER Pro software. To ensure the reliability and robustness of the findings, it is essential to compare them with existing literature and validate against established research in the field. The integration of waste energy recovery techniques, including TLC and waste heat recovery, was aligned with similar studies focused on enhancing CHP system performance [26]. The

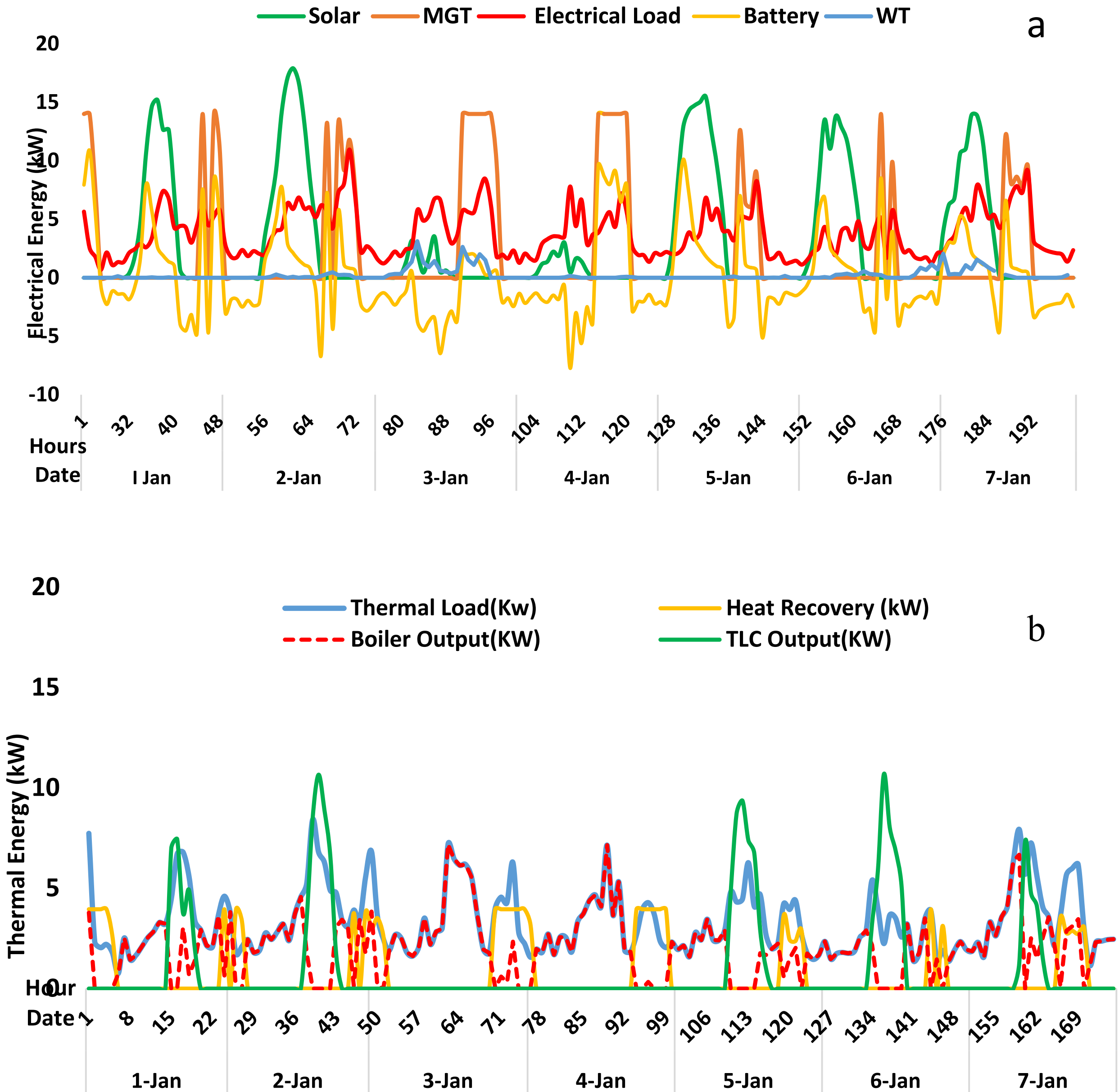

Fig. 12. Dynamic simulation of the proposed system for Electrical subsystem (a) and thermal subsystem (b).

observed reduction in system cost through waste energy minimization corroborated findings reported by [26,27]. Moreover, the sensitivity analysis conducted on capital costs of PV panels, batteries, and wind turbines was consistent with other studies in the field [28], reinforcing the established relationship between capital costs and COE and NPC. The optimal configuration identified in this study, integrating PV panels, wind turbines, micro gas turbines, a boiler, and batteries, was in line with the use of multiple energy sources and storage technologies for cost-effective CHP configurations [29]. The calculated NPC and COE for the proposed configuration could be compared with similar studies, while considering variations in system size, resource availability, and regional factors. The comprehensive validation process confirmed the reliability and validity of the study's findings, contributing to the knowledge base in energy systems analysis [29].These findings have significant implications for researchers, practitioners, and policymakers in the field, providing valuable insights for the development and deployment of cost-effective CHP configurations.

3. Conclusions and recommendation

This study aims to determine the most cost-effective CHP configuration for a typical building. The energy configurations are evaluated comprehensively from a techno-economic perspective by linking MATLAB to HOMER Pro. Energy assessment recognizes the impact of wasting energy on cost, which can provide feasible solutions to improve technical performance by identifying the sources. Energy cost calculations showed that PV panels and batteries were the major sources of energy cost. CHP configurations can be improved by minimizing waste energy. As novelty of study, TLC and HR were integrated to the CHP system to minimize waste energy as well as impact on energy sizing. A sensitivity analysis was conducted on the PV, battery, and wind turbine capital cost to investigate the optimum configuration. The best configuration was selected based on renewable fraction and the cost of energy being used. This project utilizes energy economics analysis to evaluate economic parameters, energy factors, and renewable energy sources, resulting in several significant findings:

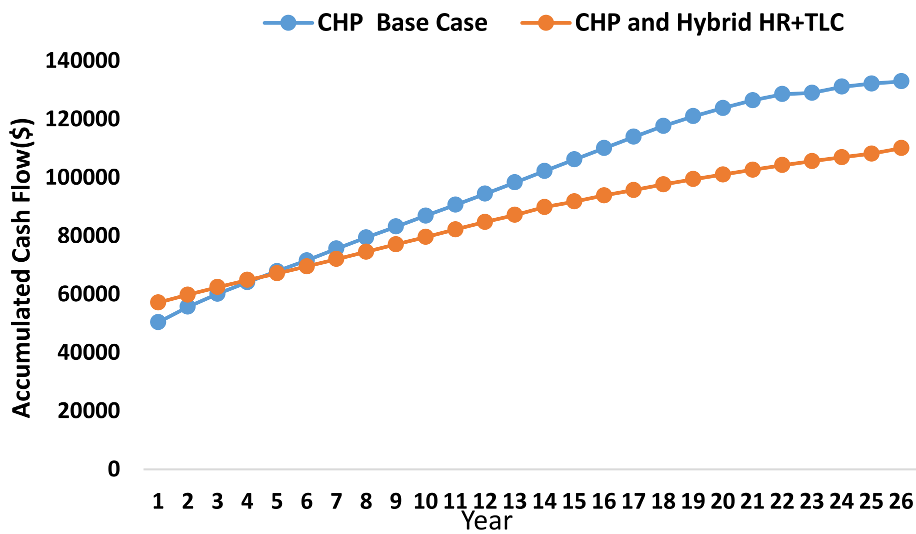

Fig. 13. Cumulative Cash flow summary over project lifetime.

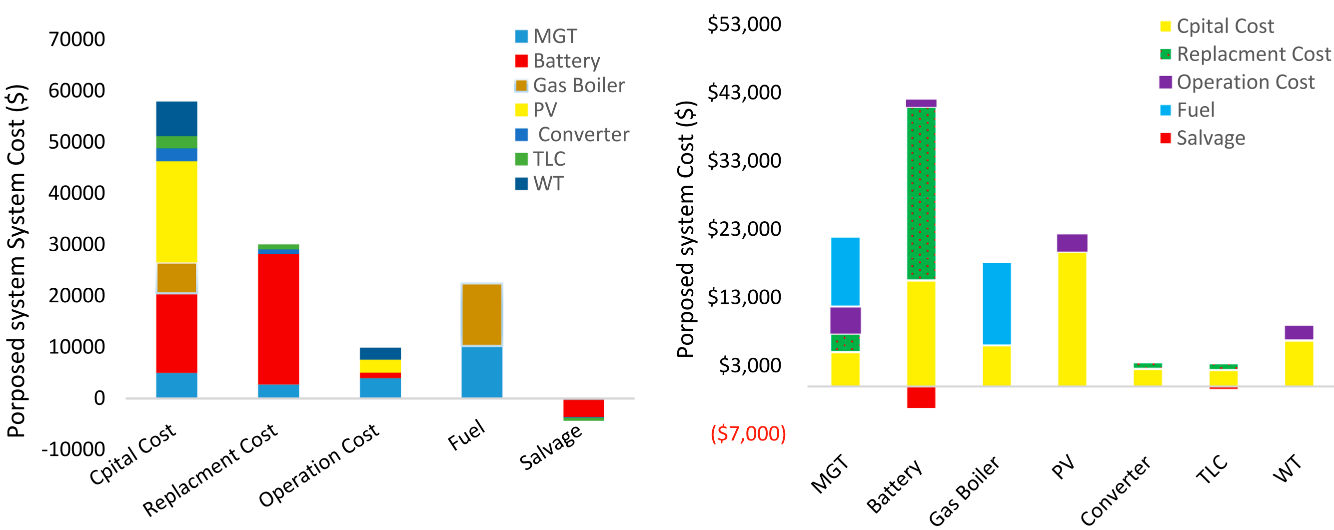

Fig. 14. Cost summery of proposed system based on components (b) and economic variables (a).

- The optimal scenario for meeting an electrical load of 97 kWh/day and 92 kWh/day thermal load involves a CHP system with 19 kW of PV panels, 6 kW of WT, 10 kW of MGT, and boiler and 92 batteries. Based on this proposed system, the NPC is calculated to be $113,950, and the COE is determined to be $0.215 per kWh.
- The integration of waste energy recovery reduces the system cost by 15 %, which is achieved through the implementation of a TLC system and the recovery of heat from the electrical system.
- Adjusting the capital cost of components has a direct impact on both COE and NPC. The solar system and batteries are key cost contributors to the overall system, followed by the fuel cost.

This study demonstrated that it was possible to assess each CHP system from a comprehensive techno-economic perspective by integrating HOMER pro energy evaluation software with MATLAB software. In future studies, it is recommended to expand the proposed strategy to other renewable energy applications, considering the weaknesses identified. One area of focus could be the incorporation of exergy economic analysis, which takes into account the cost associated with exergy destruction and losses in the system. By minimizing these losses, the overall efficiency and performance of the system can be improved. Furthermore, exploring alternative techniques such as deep learning and machine learning for system sizing would be valuable. These advanced approaches have the potential to optimize system design and operation by leveraging large datasets and complex algorithms. The proposed strategy can also be extended to energy systems utilizing fuel cells, electrolyzers, and biogas generators. Investigating the integration of these technologies into the load following and cycle charging strategies would provide valuable insights into their performance and potential synergies. Additionally, it is important to integrate exergy assessment with other techno-economic optimization tools. By combining exergy analysis with economic considerations, such as cost-benefit analysis and financial modeling, a more comprehensive evaluation of the system's performance and economic feasibility can be achieved.

CRediT authorship contribution statement

Mohammad Reza Maghami: Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Conceptualization. **Arthur Guseni Oliver Mutambara:** . **Chandima Gomes:** Validation, Supervision, Methodology. **Jagadeesh Pasupuleti:** Validation, Supervision, Methodology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mohammad Reza Maghami reports administrative support was provided by University of Johannesburg.

Data availability

No data was used for the research described in the article.

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Appendix 1

Component	Technical Specifications	Capital Cost $	RC$	O & M Cost $
PV	Capacity; 1 kW Lifetime; 25 yr Temperature coefficient; −0.41 %/°C Operating temperature; 45 °C Efficiency at STC; 17.3 % Tracking system: no tacking Panel type; flat plate	1100	1000	20 yr
WT	Rated capacity; 1 kW Lifetime; 25 yr Electrical bus; AC Hub height; 25 m Rotor diameter; 6.3	1400	1200	40 yr
Generic boiler	Efficiency; 85 % Fuel type; natural gas LHV; 45 MJ/kg Density; 0.79 kg/m^3 Carbon content: 67 % Natural gas price; 0.3 $/$m^3$	6000	5000	200 yr
MGT	Capacity; 10 kW Lifetime; 20 yr Electrical bus; AC	5000	4000	200
Battery	Lifetime; 10 yr Rectifier efficiency; 95 % Rectifier relative capacity; 85 % Inverter efficiency; 95 %	200$/kw	200$	5$

CCS: capital cost of the system; **RC:** Replacement cost; **O&M**: Operation and Maintained cost.

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