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Performance Analysis and Energy Conversion of Control's Solar-Geothermal Combined Cooling, Heating and Power (CCHP) Systems with Hydrogen Production

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ABSTRACT

This study employs the Response Surface Method (RSM) and transient analysis to optimize the design of a solar-assisted-geothermal combined cooling, heating, and power (SG-CCHP) system, integrated with hydrogen storage, for residential applications. The optimization focuses on both energy efficiency and economic performance. The SG-CCHP system comprises two steam turbines (STs), photovoltaic/thermal (PV/T) collectors, a fuel cell circuit, an absorption chiller, a heat pump (HP), and energy storage systems, including battery cells and a hydrogen storage unit. System performance is evaluated through transient analysis using the TRNSYS modeling tool. Key design parameters are identified, and the Design of Experiments (DOE) method is utilized to determine their optimal configuration. Multiple simulation scenarios are generated using DOE, and RSM is applied to analyze the results. Once the optimal SG-CCHP configuration is identified, the transient interactions between control design factors and techno-economic metrics are examined. The findings reveal that the optimized system achieves significant reductions in annual life cycle costs, thermal comfort levels, total energy consumption, and natural gas usage by the auxiliary boiler. Furthermore, the integration of battery and hydrogen storage components enhances system efficiency, with the electrolyzer, fuel cell, PV/T thermal, and electrical systems reaching annual efficiencies of 90%, 60%, 23%, and 18%, respectively. These results demonstrate the potential of the optimized SG-CCHP system to improve both energy performance and economic viability in residential settings.

1. INTRODUCTION

The global attention towards renewable energy has increased due to the depletion of fossil fuels, climate change, air pollution, and other environmental problems linked to their use. The dependence on fossil fuels, particularly oil and coal, has become more unsustainable than ever, leading to significant environmental degradation and climate

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change. As a result, energy from renewable sources has become crucial, as these sources are clean, environmentally friendly, and renewable [1,2].

At present, global concerns focus on issues like climate change and the rising demand for energy. Energy demand has surged due to population growth, while the accumulation of greenhouse gases poses a serious threat to the environment. Additionally, with the increasing demands for heating and cooling in some regions, global energy consumption has risen by about 3 percent, marking the highest increase of the decade. To reduce reliance on fossil fuels, alternative renewable energy sources have become the focus of recent research. To address growing energy needs and provide affordable energy, integrating renewable energy into existing energy systems is a viable alternative. Renewable energy-driven combined cooling, heating, and power (CCHP) systems are attracting significant attention for their potential to meet energy demands efficiently [3-6].

The successful integration of CCHP systems relies on three key steps: unit analysis, component design, and overall system management. These stages involve precise mathematical analyses to determine the optimal design and functionality of each system component. During the design phase, the potential of each component and its energy conversion method are selected, while the management phase involves setting up control strategies for the system.

Investors continuously seek to enhance energy efficiency, reduce costs, and minimize environmental impacts. As such, optimization is crucial for the implementation of CCHP systems [7-9]. For instance, Ozden and Tari used computational fluid dynamics to study the performance of fresh and degraded polymer electrolyte membrane (PEM) components in a hydrogen cycle and assessed the impact of fuel cell degradation on overall energy system efficiency. Their results showed that PEM degradation significantly impacted system efficiency, leading to a system outage for about a month [10].

In another example, Kavian et al. proposed a hybrid system combining solar panels and a geothermal heat pump, optimized for maximum efficiency using TRNSYS and MATLAB. Their solution showed a solar participation coefficient of 31% and a return on investment of about 3 years [11]. Wang et al. developed a dynamic technique to address the energy production-consumption imbalance in CCHP units, which improved operational efficiency and plant productivity [12].

With the growth of distributed power generation infrastructure, there is an increasing trend of combining multiple renewable energy sources, particularly solar and geothermal, to meet electricity and thermal energy demands. Takleh et al. proposed an efficient solar-geothermal system to generate electricity, heating, and cooling, achieving a reduction in costs of heating, cooling, and electricity by up to 91% and 73% compared to conventional methods [13]. Ren et al. studied flexible CCHP systems with components such as steam turbines, absorption systems, and ground-source heat pumps, using a decision-making technique to optimize the system's economic, energy, and environmental performance [14].

Musharavati et al. described a multi-generation system combining an absorption chiller, organic flash cycle, photovoltaic panel, and reverse osmosis module, resulting in improved energy efficiency and output compared to conventional systems [15]. Similarly, Li et al. integrated renewable energy systems like CCHP, wind energy, and hydrogen production to reduce transportation emissions, achieving a hydrogen production rate of 500 kg and an energy efficiency of 72% [16].

The installed system can meet the energy needs of the building with an energy efficiency of 72%, and based on the results, it can achieve a maximum hydrogen production of 500 kg. The combined heat and power (CHP) process with PV/T collectors and fuel cell modules, as presented by Bernoosi et al. [17], utilizes the fuel cell's capacity to capture both electrical and thermal energy, enabling the proposed hybrid installation to reduce overall operating costs in line with optimized design considerations.

The performance of distributed energy generators is commonly estimated using Response Surface Methodology (RSM) as a computational approach [18]. RSM allows for the simultaneous analysis of the effects of control parameters on various system variables at a low computational cost, unlike traditional optimization methods where one parameter is optimized while others remain constant [19].

For example, Kazemian et al. [20] applied the RSM evaluation technique to investigate the CCHP process in combination with a Ground Source Heat Pump (GSHP) for a residential complex. Their study demonstrated that the return on assets of the proposed system is significantly influenced by the rate at which electricity is sold. To determine the optimal area for solar collectors in a CCHP process, Ref. [21] employed the RSM procedure. Their findings revealed that the RSM-recommended design performed the best, achieving a total electricity generation of approximately 62 MW. Additionally, Ref. [22] provided an optimized solution for covering the heating, cooling, and water needs of a typical house, combining a desiccant cooling/heating system with solar energy and humidity harvesting technology.

2. DESCRIPTION AND MODELING OF THE SYSTEM

The solar-geothermal renewable CCHP system integrated with battery banks and hydrogen energy storage systems is described in this section. Then, a discussion of the essential components of the proposed system's modeling approach is introduced.

2.1 Detailed description of SG-CCHP

Figure 1 illustrates the proposed hybrid Combined Cooling, Heating, and Power (CCHP) system, which incorporates a hydrogen energy storage system and renewable solar and thermal energy sources. The schematic shows that the SG-CCHP system consists of a geothermal loop, a PV/T (photovoltaic/thermal) collector loop, a fuel cell system, an electrolyzer for hydrogen generation, an absorption chiller for cooling, a heat pump (HP), and two steam turbines (STs) for power generation.

The fuel cell system, backup boiler, PV/T collectors, and hot water storage tank are all interconnected within the domestic hot water loop. The loop is served by a four-port hot water storage tank. The first port is dedicated to the PV/T collector loop, where fresh water flows through solar collector tubes, absorbing heat from solar radiation, which increases the water's temperature. As the fresh water temperature rises and the panel surface temperature drops, the efficiency of power generation increases. The heated fluid is then transferred to the first port of the storage unit. After heat transfer occurs, the circuit resets as the cooled fresh water exits the first port of the storage unit.

The second port of the storage tank is connected to the fuel cell subsystem, which uses oxygen from the air and hydrogen from the integrated hydrogen storage tank as fuel. The energy produced by the fuel cell is directed to the second port to further heat the fresh water in the internal hot water tank. The backup boiler receives fresh water from the fourth port of the storage unit and, via the heat pump, raises its temperature to meet domestic hot water demands.

The steam turbine ST-1 (at the top of Figure 1) provides two different flow paths. One path feeds the absorption chiller, which addresses the cooling needs of the building, while the other path provides the heating loads through the heat pump. Air is cycled through each of the chambers, returning to the associated heat pump, where fresh air is mixed with the returning air, and the process continues. The thermal energy for the absorption chiller is supplied by the high-temperature exhaust gas from steam turbine ST-2 (at the bottom of the figure).

In terms of power generation, the SG-CCHP system combines power from the fuel cells, PV/T collectors, steam turbines, and storage batteries. The primary power source is the PV/T collectors. However, due to the variability of solar energy and its reliance on environmental conditions, predicting the power output from the PV/T subsystem is highly challenging. If the PV/T output is insufficient to meet the DC demand, hydrogen storage and storage batteries are utilized to bridge the gap. The power output from the steam turbines can also fluctuate due to varying exhaust gas temperatures. Any excess energy from the steam turbines is directed to the electrolyzer, where it is used to produce and store hydrogen in the hydrogen storage tanks.

Additionally, any extra electricity generated by the solar panels or steam turbines, whether or not needed for immediate demand, is directed to the storage systems. This ensures that the storage batteries are charged, and the electrolyzer continues to operate, maintaining the required hydrogen storage capacity. If the storage batteries alone cannot meet the demand, the fuel cell system will provide backup power. Excess energy is then sold to the grid. If the SG-CCHP system cannot fully meet the energy demand of the residents, the grid will supply the remaining energy required.

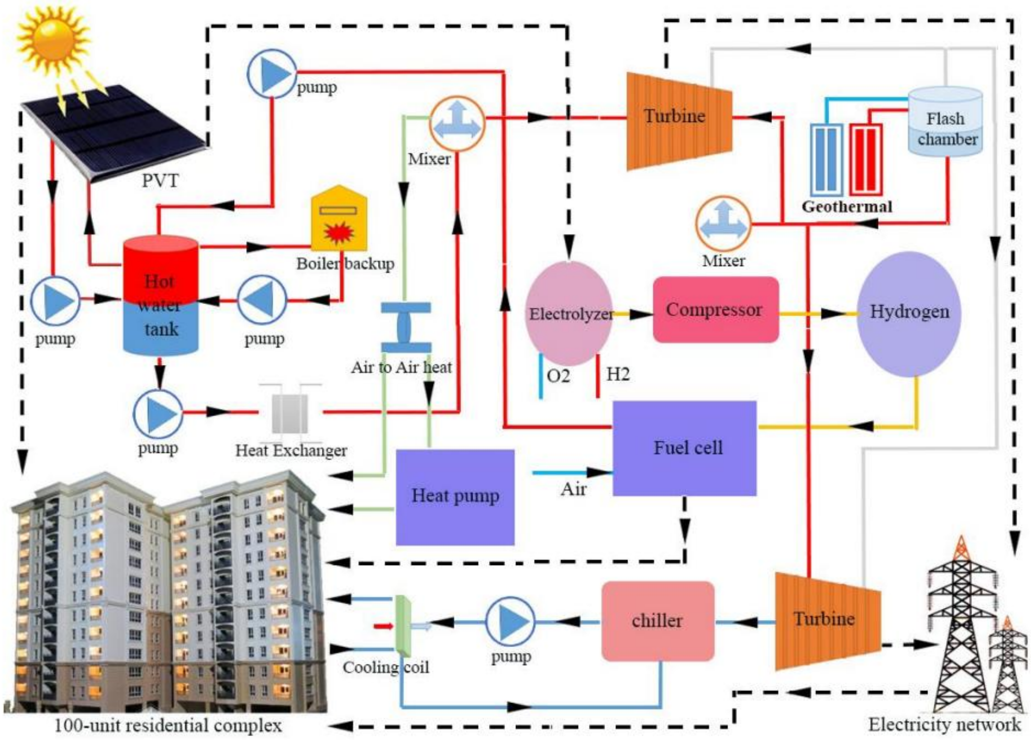


Fig. 1. Schematics of the proposed SG-CCHP system.

2.2 Modeling method for SG-CCHP

The performance of the SG-CCHP process is dynamically simulated using the open-source TRNSYS tool, which is built in Fortran. Each module in TRNSYS is represented by a type that contains a Fortran-coded differential algorithm, which governs its behavior. For simulating the SG-CCHP process, the TRNSYS library was used in conjunction with the TESS (Thermal Energy System Specialists) library. This combination was chosen due to the reliability of the TRNSYS-TESS library in previous research and its extensive experimental validation across multiple studies [23, 24–30].

Below are the key subsystem control equations used for the SG-CCHP system, which describe how each component of the system operates under varying conditions to ensure efficient energy production, heating, cooling, and power generation.

2.3 Governing Steam Turbine (ST) Equations

To evaluate the efficiency of Steam Turbine (ST) in terms of steam penetration, the TESS library type 592 is employed. This library utilizes the isentropic efficiency method and accounts for the turbine's back-pressure. The actual enthalpy after expansion is determined using Equation (1) [31]. The work performed during this expansion phase is calculated using Equation (2). To compute the complete set of steam properties—temperature, enthalpy, pressure, and entropy—the steam function is initialized by injecting a combination of steam enthalpy and pressure. This systematic approach ensures accurate simulation of steam behavior within the turbine and supports efficiency assessment.

$$h_{out,actual} = h_{in} - \eta_{isentropic}\left(h_{in} - h_{out,actual}\right) \quad (1)$$

$$\dot{W}_{GT} = \dot{m}_{in}\left(h_{in} - h_{out,actual}\right) \quad (2)$$

2.4 Governing equations of PV/T collectors

The Type 560 of TRNSYS models the behavior patterns of PV/T solar collectors by having PV cells produce power and have multiple pipes at the backside surface of the Photovoltaic modules that pump a heat transfer fluid to receive heat energy. Eqs. (3) and (4) [32] are used to calculate the total power produced by the PV/T solar collector and the fluid's outflow temperature:

$$E_{PV/T} = \left(\tau\alpha\right)_n \cdot IAM \cdot G_T \cdot A \cdot \eta_{PV/T} \quad (3)$$

$$T_{f,out} = \left(T_{f,in} + \frac{\varepsilon_m}{\kappa}\right)\exp\left(\frac{N_{tubes}}{\dot{m}_f c_f}\frac{\kappa}{\theta}L\right) - \frac{\varepsilon_m}{\kappa} \quad (4)$$

The governing equations for absorption chiller, heat pump, fuel cell, and electrolyzer sections were also analyzed and solved.

3. OPTIMIZATION STRATEGY

Developing a method to track the impact of key control factors on the performance metrics of SG-CCHP systems is essential, as many critical control factors influence the behavior of such ultra-hybrid systems. To achieve optimal resource utilization from both an energy and economic perspective, the optimization approach designed in this study seeks to identify the most critical control factors in the design of the SG-CCHP unit. In contrast, standard optimization methods are computationally intensive and often fail to predict the influence of control factors on operational parameters [33]. Statistical approaches, however, can address the simultaneous impacts of multiple control factors [22], and this approach is applied in the optimization strategy of this study.

The process utilizes Response Surface Methodology (RSM), a statistical technique, alongside TRNSYS software, which serves as the transient modeling platform. The Design of Experiments (DOE), a powerful technique for determining the values of key control factors to be used in simulations, is the initial step in the optimization strategy. Therefore, RSM is employed as one of the most reliable DOE strategies. The TRNSYS transient simulation software is used to model the complete sequence of hybrid system simulation scenarios specified by the DOE. Using data from these simulated scenarios, response surfaces are constructed for each of the energy and economic performance indicators, or responses, of the proposed SG-CCHP system. Once all DOE-recommended simulation scenarios are completed, the optimization procedure reaches its termination threshold.

The final result of this procedure presents the optimal strategy, highlighting the most critical economic and energy responses of the SG-CCHP unit.

4. Response surface methodology

The Response Surface Methodology (RSM) is a statistical predictive approach used to model the relationship between various design factors and performance metrics, referred to as responses. The objective of RSM is to identify an optimal set of variables by assessing the impact of different factors on the responses [34]. Compared to traditional methods, which analyze each factor independently, RSM offers the advantage of reducing the number of required simulation scenarios, providing a more organized and efficient evaluation of variables and their integrated effects [35].

The central composite design (CCD) is the most widely used and practical setup in RSM, employing a reduced sequence of factors and a coherent curved projection. This design is ideal for analyzing factor interactions through multiple assessments [36].

In this study, the regenerative SG-CCHP system was designed and optimized using five primary parameters, as shown in Table 1. Factor 1 corresponds to the number of PV/T solar collectors, with the total surface area of the PV/T panels directly influencing the total energy output and natural gas consumption of the auxiliary boiler. Factor 2 is the thermal capacity (HT), which significantly impacts both system construction costs and overall energy production. The third factor, the fuel cell capacity, determines the amount of electricity generated, heat stored, and hydrogen produced, used, and stored. Factors 4 and 5 correspond to the cooling and heating capacities, respectively, which are provided by the absorption chiller and heat pump (HP) to ensure the thermal comfort of the building.

The variable intervals for the selected factors are provided in Table 1. All factors have lower bounds set to 0, representing scenarios in which the factor is not utilized. The upper bounds for factors 1, 2, and 3 are determined by the maximum heating and cooling requirements of the residential unit, with a 10% safety margin. The upper limits for factors 4 and 5 are constrained by mounting space limitations. RSM and CCD generate 32 simulation scenarios based on the selected factors and their variation limits. The statistical analysis of the simulation results was conducted using the Design-Expert program.

The performance indicators used to assess the optimization strategy include total electricity usage (TEU), auxiliary fuel use (ABFU) as energy consumption, the predicted mean vote (PMV) as a thermal comfort metric, and life cycle cost (LCC) as an economic indicator of system performance.

Table 1. The controlling design factors and their margin of changes.

Design variables (factors)	Lower limit	Upper limit	Unit
A: Number of PV/T collectors	0	300	-
B: Steam turbine (ST) capacity	0	100	kW
C: Fuel cell power	0	100	kW
D: Absorption chiller cooling capacity	0	80	kW
E: HP heating capacity	0	80	kW

Table 2 summarizes the aim of the established optimization strategy after taking into consideration selected energy and economic indicators.

Table 2. The aim of the established optimization strategy.

Indicator/response	Objective	Unit
Total electricity usage (TEU)	minimize	kWh/year
Auxiliary boiler fuel consumption (ABFU)	minimize	m^3/year
Predicted mean vote (PMV)	target = 0	-
Life cycle cost (LCC)	minimize	$

5. RESULTS

5.1. Optimization results

The results for each simulation scenario outlined by the DOE are presented in the table, along with the corresponding corrective actions. The RSM (Response Surface Method) optimization technique determines the optimal configuration of the selected control design factors based on the short-term calculation results shown in Table 3. As indicated, the SG-CCHP system is configured with 187 PV/T panels, a solar thermal (ST) capacity of

37.05 kW, fuel cells with a capacity of 45.47 kW, absorption coolers rated at 51.04 kW, and 20 kW heat pump (HP) heaters to ensure the best techno-economic performance.

Table 4 summarizes the performance results of the SG-CCHP system integrated with solar and geothermal energy sources, under the optimal conditions determined by the RSM in Table 3. The system is then tested under these optimized conditions, and the results are verified for accuracy. The optimization process yields a maximum error of 6.82%, as shown in Table 4. Additionally, the system's optimal values for TEU (Total Energy Utilization), ABFU (Annual Base Fuel Utilization), PMV (Predicted Mean Vote), and LCC (Levelized Cost of Care) are -48,613.18 kWh/year, 44,324.39 m^3/year, 0.262, and $479,120, respectively.

Table 3. Optimum integration of the chosen controlling factors.

Factor	Description	Optimal design
A	Number of PV/T collectors	187
B	Steam turbine (ST) capacity (kW)	37.05
C	Fuel cell power (kW)	45.47
D	Absorption chiller cooling capacity (kW)	51.04
E	HP heating capacity (kW)	20.00

Table 4. Findings of the responses obtained utilizing the controlling design factors (The best optimal system or BOS).

Performance metric	TEU (kWh/year)	ABFU (m^3/year)	PMV	LCC ($)
RSM estimation	-50082.37	46271.40	0.257	514188.21
Confirmation run	-48613.18	44324.39	0.262	479120.57
Estimation error	2.93 %	4.21 %	1.91 %	6.82 %

5.2. Influence of controlling design factors

Figure 2a illustrates the relationship between the number of PV/T panels and solar thermal (ST) collectors and the Levelized Cost of Care (LCC) of the SG-CCHP system, which is the economic metric used in this study. As shown, increasing the number of PV/T panels results in a 43.3% reduction in LCC, dropping from 900,000 to 480,000. This indicates that although increasing the number of PV/T panels raises the initial capital costs, the electrical and thermal output generated by the PV/T collectors more than compensates for these expenses. Furthermore, the system generates substantial savings over its lifetime, demonstrating its potential to lower the LCC. A similar effect is observed when increasing the capacity of the STs, which also significantly reduces LCC. Figures 2b and 2c reveal that while increasing the capacities of the absorption chiller and heat pump (HP) for cooling and heating leads to an increase in LCC, enhancing the fuel cell capacity has a more pronounced effect on minimizing LCC.

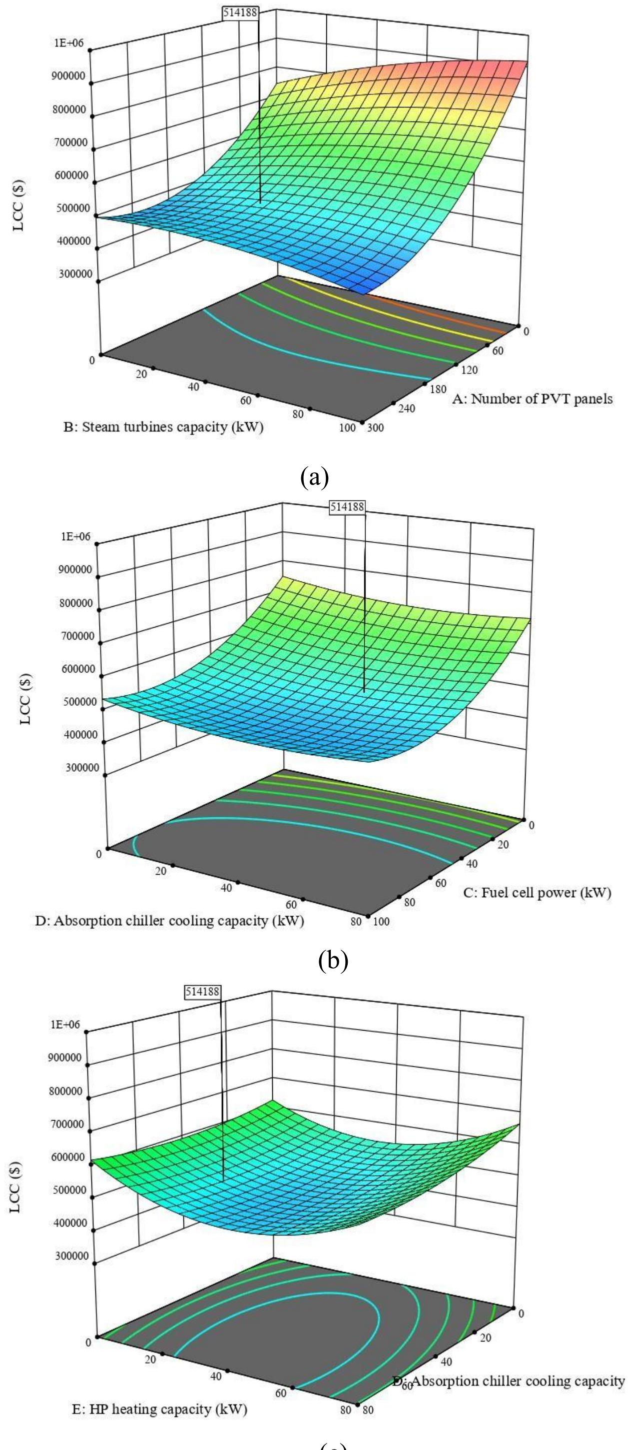
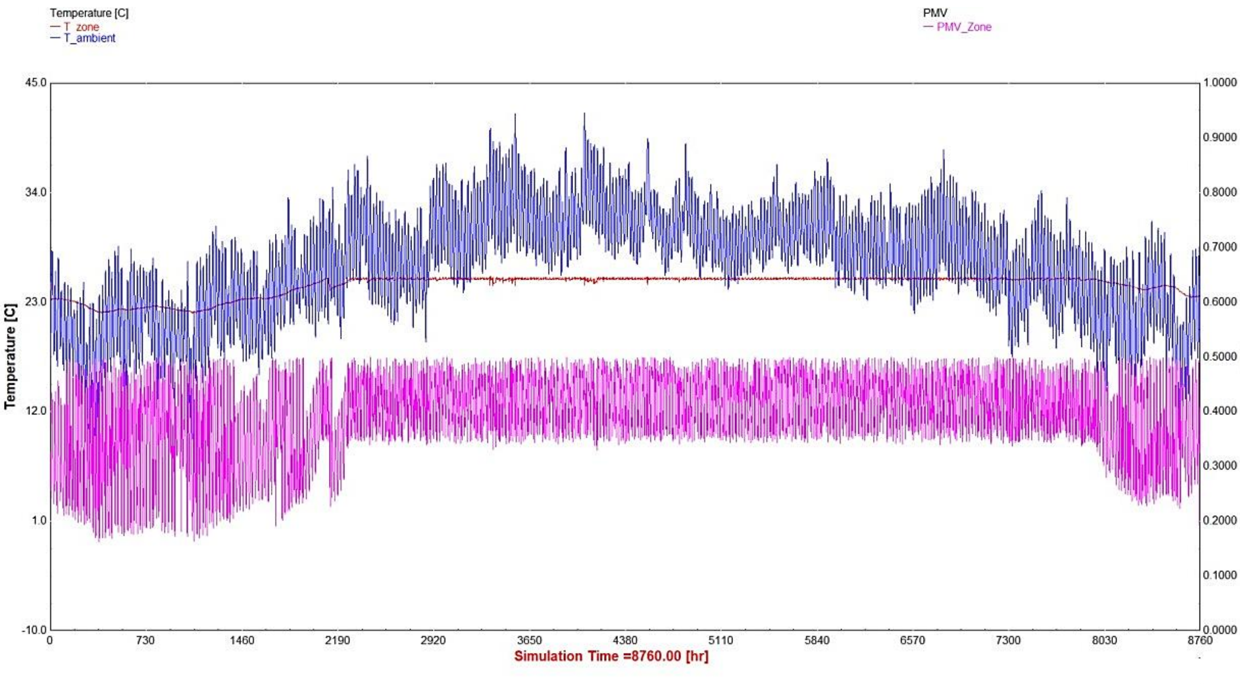


Fig. 2. The influences of controlling design factors on the life cycle cost (LCC) of the system: (a) influence of factor A and B (b) influence of factor C and D (c) influence of factor D and E.

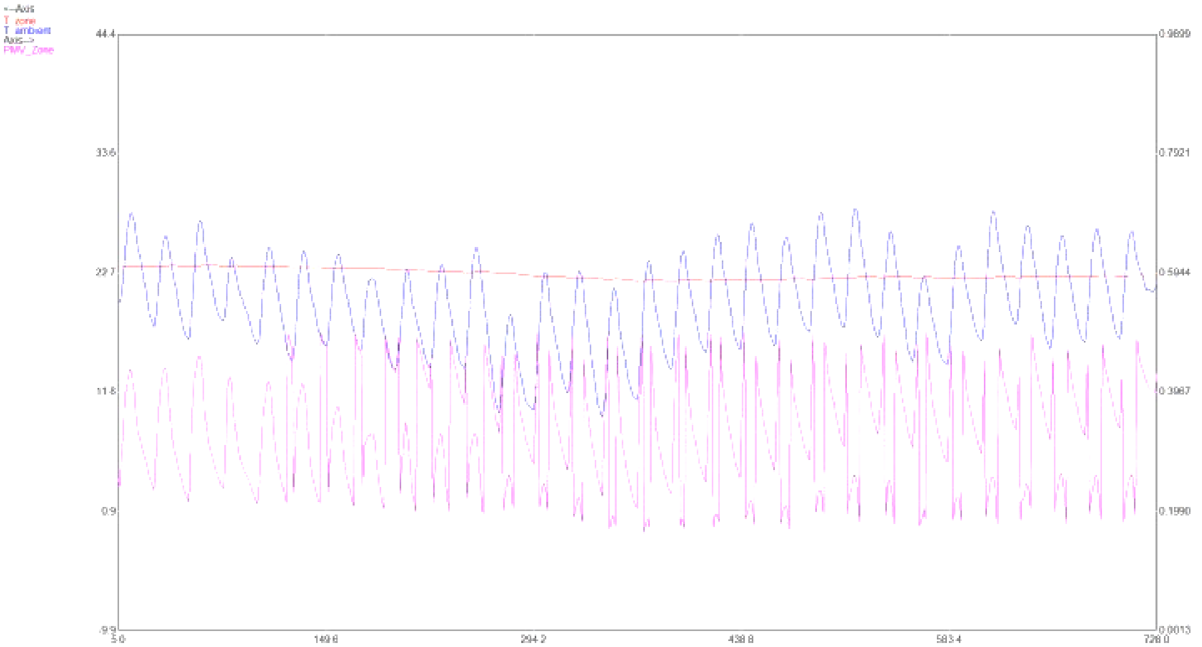
5.3. Transient analysis of SG-CCHP

This subsection presents the temporary performance of the SG-CCHP system, along with its solar energy sources and energy storage mechanisms. Figure 3a illustrates the total power consumption of the selected residences (shown in red), the total power produced by the SG-CCHP system (in blue), and the total power received from the grid (in cyan) over the course of a year. As seen, the system's average power output slightly exceeds the energy demand between January 1st (hour 0) and January 30th (hour 730), with the deficit covered by purchasing grid power. This suggests that the SG-CCHP system could be viable for use in remote areas disconnected from the energy infrastructure, as the total power drawn from the grid is significantly lower than the total energy provided by the system.

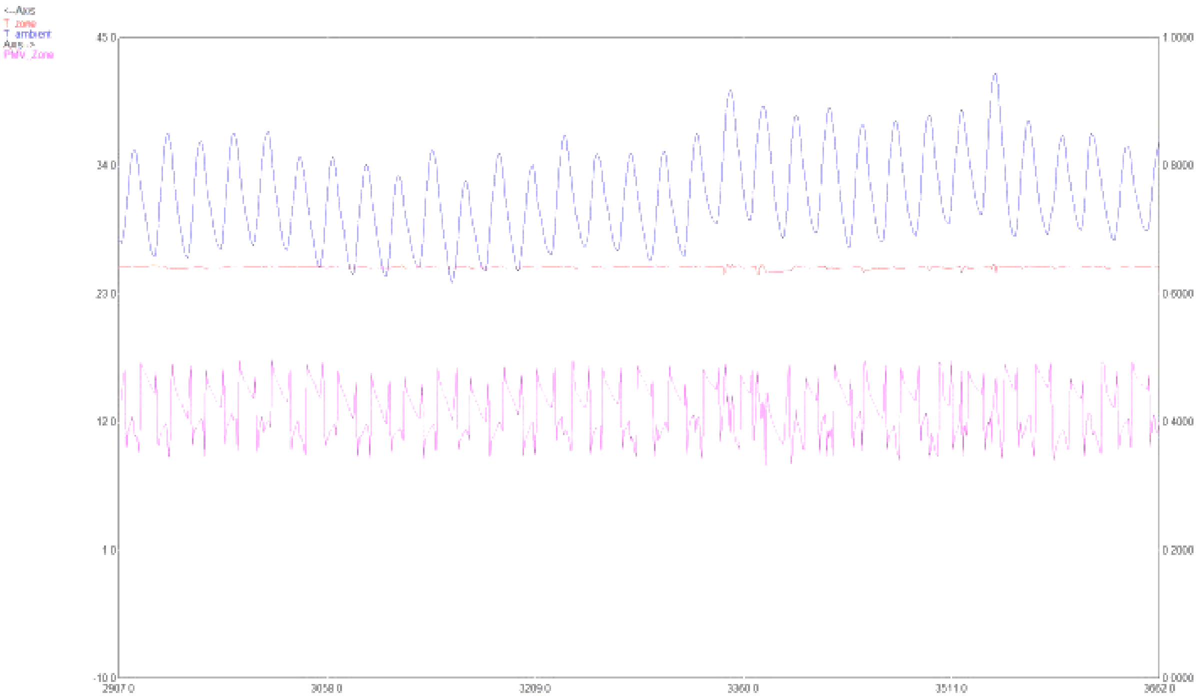
The residential area in question consists of two buildings with a total of 100 units, supplied by an absorption chiller for cooling and a heat pump (HP) for heating, as previously mentioned. Among the 100 building units considered, Figure 12a shows the air temperature variation in the unit with the highest cooling or heating demand, representing the worst-case scenario in this study. The air temperature fluctuates between 23 °C and 25 °C, indicating that the SG-CCHP system operates efficiently year-round, even in the zone with the highest demand compared to the other areas in the selected residences. Figures 3b and 3c display the variations in ambient temperature, sector temperature, and PMV for the coldest and hottest months. As shown, during the coldest month, the sector temperature fluctuates around 22.7 °C, and the PMV ranges from 0.198 to 0.442. In the hottest month, the sector temperature remains around 24.5 °C, and the PMV ranges from 0.381 to 0.523. This demonstrates that the SG-CCHP system can maintain the ASHRAE recommended PMV range for both cooling and heating under the most demanding conditions.



(a)



(b)



(c)

Fig. 3. The fluctuations of the air temperature and PMV in the apartment flat with the critical cooling/heating load compared to the other zones of the chosen apartments over the course of the year. (a) the variation of ambient temperature, zone temperature and PMV during the year; (b) the variation of ambient temperature, zone temperature and PMV for the coldest month (c) the variation of ambient temperature, zone temperature and PMV for the hottest month

6. CONCLUSIONS

This study focuses on the techno-economic analysis of a solar-assisted geothermal combined cooling, heating, and power (SG-CCHP) system, integrated with rechargeable batteries and a hydrogen generation subsystem for a residential location. The primary components of the SG-CCHP system include steam turbines (STs), photovoltaic/thermal (PV/T) collectors, fuel cell circuits, an absorption chiller, a heat pump (HP), rechargeable batteries, and a hydrogen storage unit. The study employs Response Surface Methodology (RSM) and transient modeling with the TRNSYS software to optimize key control parameters of the SG-CCHP system, specifically the number of PV/T collectors, the capacity of the STs, fuel cell output, absorption chiller cooling capacity, and HP heating capacity.

The key performance metrics used to assess the system include auxiliary boiler fuel usage (ABFU), total energy usage (TEU), the thermal comfort level measured by the predicted mean vote (PMV), and the life cycle cost (LCC) as the economic criterion.

The optimization results revealed that the most efficient configuration for the SG-CCHP system over its lifetime consisted of 187 PV/T panels, 37.05 kW capacity STs, 45.47 kW fuel cell output, 51.04 kW absorption chiller cooling capacity, and 20 kW HP heating capacity. Additionally, the performance analysis showed that fuel cell output had a significant impact on TEU and ABFU compared to other design parameters. Specifically, ABFU decreased by 13.04% as fuel cell capacity increased from 0 to 100 kW. The SG-CCHP system with a 100 kW fuel cell not only met the energy demands of the entire system and residential area but also generated approximately 350,000 kWh of excess energy annually, which could be sold to the electrical grid.

The findings also indicated that the optimized SG-CCHP setup significantly improved key techno-economic metrics. The system achieved high efficiencies in several components, with the electrolyzer, fuel cell, PV/T thermal, and electrical systems achieving efficiencies of 90%, 60%, 23%, and 18%, respectively, throughout the year.

Transparency Statement

The data supporting this study are available upon reasonable request to the corresponding author, subject to ethical and confidentiality considerations.

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Declaration of Interest

The authors declare that they have no competing interests.

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