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RESEARCH ARTICLE

Experimental investigation and regression-based modeling of a hybrid system integrating photovoltaic-thermal chimney, windcatcher, and earth-to-air heat exchanger for greenhouse thermal management

Shiva Tahmasbpourafshar[1], Kazem Jafarinaeimi[2,*], Hamid Mortezapour[3], Saman Khalilzadeh[4], Hossein Maghsoudi[5]

[1]Department of Biosystems Engineering, Faculty of Agriculture, Shahid Bahonar University of Kerman, Kerman 76169-14111, Iran
[2]Department of Biosystems Engineering, Faculty of Agriculture, Shahid Bahonar University of Kerman, Kerman 76169-14111, Iran
[3]Department of Mechanical Engineering, Faculty of Engineering, Bozorgmehr University of Qaenat, Qaen 97619-86844, Iran
[4]Department of Mechanical Engineering, Faculty of Engineering, Higher Education Complex of Bam, Bam 76613-14477, Iran
[5]Department of Biosystems Engineering, Faculty of Agriculture, Shahid Bahonar University of Kerman, Kerman 76169-14111, Iran

Abstract

The increasing global demand for high-quality greenhouse products, coupled with the heavy reliance on fossil fuels for climate control, has created an urgent need for sustainable, renewable-based solutions in agriculture. Conventional systems not only consume large amounts of energy but also contribute significantly to environmental pollution and greenhouse gas emissions. This study experimentally investigates a novel hybrid renewable energy system that integrates a windcatcher, photovoltaic-thermal chimney, and earth-to-air heat exchanger to provide passive heating and cooling for greenhouses. Experiments were conducted at Shahid Bahonar University of Kerman, Iran, using a lean-to greenhouse structure during peak summer (July-September 2024) and winter (January-March 2025) conditions. Vector linear regression was employed to develop robust predictive equations with broader applicability across different climates. Key performance parameters, including greenhouse temperature, ventilation rate, generated electricity, and the ratio of supplied electricity to consumed electricity (SECE), were measured and analyzed. Results proved a maximum temperature reduction of 21 °C in summer and successful maintenance of internal temperature between 19.5 °C and 22 °C in winter when outdoor temperature dropped to as low as 4.5 °C. The system achieved a ratio of supplied to consumed electricity exceeding 1, showing full self-sufficiency in meeting electricity demand, and delivered a higher coefficient of performance than most previously reported single- or dual-renewable systems. Energy and exergy analyses confirmed an energy-balance closure below 5% and second-law efficiencies of 0.32 in summer and 0.45 in winter. This study presents the first experimental demonstration of the configuration comprising a triple-hybrid windcatcher, a photovoltaic-thermal chimney, and an earth-to-air heat exchanger for greenhouse applications, addressing a critical research gap in integrated passive renewable systems and offering a practical pathway toward sustainable greenhouse thermal management in regions with high solar potential and extreme temperature variations.

Keywords: Greenhouse climate control, photovoltaic-thermal chimney, windcatcher, ventilation, earth-to-air heat exchanger

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1. Introduction

Greenhouses play an essential role in ensuring year-round agricultural production by providing controlled environments where plants can be cultivated under best conditions of humidity, temperature, and light [1,2]. Compared to conventional field cultivation, greenhouse farming offers many advantages, including off-season production, reduced water and energy consumption, higher yields, and improved environmental control [3]. These benefits have driven the widespread adoption of greenhouses across diverse climatic conditions, particularly in arid regions. However, such areas often experience excessively

*Corresponding Author
E-mail Adress: jafarinaeimi@uk.ac.ir

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high daytime temperatures due to intense solar radiation, compounded by inadequate cooling capabilities during nighttime hours [4]. Conventionally, evaporative coolers (fan and pad systems) and fuel burners have been employed to regulate greenhouse atmospheric conditions for cooling and heating, respectively [5]. Most of the energy consumed in greenhouses (primarily for electricity, heating, and cooling) is supplied by fossil fuels directly or indirectly [6,7].

The extensive reliance on fossil fuels (coal, oil, and natural gas) to meet demands across agricultural, industrial, and residential sectors has resulted in escalating environmental pollution, progressive depletion of natural fuel reserves, and accelerated global warming [8,9]. Furthermore, global energy requirements are projected to double by 2050 [10]. Given the perpetual need to supply agricultural products alongside mounting environmental and energy concerns, it has become imperative to develop effective, fossil-fuel-free solutions to meet greenhouse energy demands. In this context, wind, solar, biomass, and geothermal energy sources have appeared as the most promising alternatives, particularly for greenhouse applications [11-14].

Among these renewable sources, geothermal energy offers a particularly reliable and environmentally friendly solution. Geothermal resources are typically classified as low- to high-enthalpy based on their thermal energy levels, with low-enthalpy resources used directly in heating, agriculture, and various industrial applications, while high-enthalpy resources are primarily employed for electricity generation in power plants [15]. Although surface temperatures fluctuate daily in response to solar radiation and atmospheric conditions, these variations diminish substantially with increasing depth, ultimately stabilizing beyond a certain threshold. Earlier studies confirm this thermal stability at greater depths [16]. For instance, soil temperatures at a depth of 2 meters in Tianjin, China, have been reported as 11.5°C in winter and 17.5°C in summer, values well-suited for greenhouse heating and cooling applications, respectively [17]. Ground-source heat pumps (GSHPs)provide highly efficient year-round heating and cooling by using stable subsurface temperatures, proving especially effective in cold, dry climates. This positions them as a key renewable choice for sustainable thermal management in environments such as greenhouses [18].

A validated numerical model of earth-air heat exchangers (EAHE) for arid Algeria (Ghardaïa) recommends the best design parameters (3 m depth, 20 m length, 50 mm diameter, and 1.5 m/s air velocity) for efficient air conditioning. This system achieved high heat exchange efficiency (0.99) and stable outlet air temperatures (approximately 24.5°C in summer and 20°C in winter), highlighting its potential as a sustainable HVAC (Heating, Ventilation, and Air Conditioning) alternative [19].

EAHEs are recognized as one of the most effective systems for harnessing shallow geothermal energy [20]. These systems use the subsurface soil as a thermal source or sink, with air as the working fluid circulating through underground pipe networks [21]. Installed at depths where soil temperatures show relative stability, EAHE systems use the thermal differential between the soil and ambient air to provide passive cooling during summer and heating during winter [22-24]. Owing to their requirement for only a small fan for air circulation, these systems are both economical and practical [25,26]. For instance, Ozgener et al. [27,28] investigated an EAHE system for cooling and heating a greenhouse under Turkey's climatic conditions. They calculated the coefficients of performance (COP) for cooling and heating to be 10.09 and 5.16, respectively, using a galvanized pipe (56 cm diameter, 47 meters in length) buried at a depth of 3 meters.

Photovoltaic-thermal chimneys (PVTCs) represent another significant application of renewable energy for achieving natural indoor ventilation [29,30]. Earlier studies have explored the effects and performance of PVTCs in various building types, including school buildings [31], proving that indoor temperatures can approach ambient levels through natural ventilation. Research on PVTC ventilation in office buildings has shown reductions of 10-20% in electricity consumption by air-conditioning systems.

For many centuries, windcatchers served as the primary architectural solution for mitigating the harsh climatic conditions of the hot, arid central plateau of Iran. Traditionally, air exhausted from windcatchers was directed into subterranean spaces, where it passed over water basins, thereby providing evaporative cooling for occupants. A traditional windcatcher can be conceptualized as an integrated wind and solar system designed for ventilating residential spaces. It functions as a natural ventilation system, with its top opening oriented towards prevailing wind directions to capture airflow within the pressure zone. However, the most significant limitation of windcatchers is their diminished effectiveness at low wind speeds. This constraint can be effectively addressed by integrating the windcatcher with a PVTC system, which generates airflow through buoyancy forces, thereby augmenting natural ventilation [32,33].

The synergistic combination of photovoltaic-thermal chimneys (PVTCs) and WindCatchers (WC) has been investigated by several researchers. Bansal et al. [34] proposed a hybrid system incorporating a windcatcher, a PVTC, and a sprinkling water system within the windcatcher. Their findings revealed that at low air velocities, the PVTC substantially enhances natural ventilation. Furthermore, sprinkling water into the incoming air significantly increases the cooling effect. Mahdavinejad and Khazforoosh [35] developed a model that integrates windcatchers and PVTCs to improve ventilation efficiency. In their model, wind flow enters the building, eased by the PVTC and buoyancy effects within the windcatcher, passes through a water basin, and later cools the structure. Their results proved a significant increase in overall energy efficiency. Noroozi [36] designed a laboratory-scale windcatcher equipped with an evaporative cooling system. This system reported that, at heights of 0.5-2.5 meters and at velocities below 3 m/s, the cooling load nearly doubled when straw pads were used.

Recent experimental studies on individual or dual renewable systems have offered valuable insights. For example, Xiao et al. [37] investigated an earth-air heat exchanger integrated with a greenhouse in northern China and reported a maximum summer cooling of 10.55 °C and winter heating of 9.26 °C. Li et al. [38] combined EAHE with an irrigation system in a greenhouse and achieved a cooling capacity of 14.6 °C with a high COP of 27.2. Hamdane et al. [39] evaluated the thermal performance and environmental impact of EAHE in agricultural greenhouses, proving significant energy savings and reducing environmental footprint. Qi et al. [40] examined the adaptability of EAHE systems under various weather conditions and confirmed their effectiveness for greenhouse cooling. Jahangir et al. [41] developed a thermal model of a solar chimney–earth air heat exchanger system for greenhouse cooling under hot climates, showing a notable reduction in cooling demand. Lei et al. [42] studied a solar chimney combined with an earth-to-air heat exchanger ventilation system (SEVS)and reported improved natural ventilation and uniform air distribution in solar greenhouses.

Integrating multiple renewable energy sources into greenhouse applications can substantially improve overall efficiency while simultaneously reducing electricity consumption, energy costs, and environmental pollution [43]. While photovoltaic (PV)systems generate electricity from solar energy, geothermal energy eases the heating of air circulated through underground pipes. Given the complementary advantages of these technologies, their strategic integration holds the potential to enable greenhouse operators to use energy in a more sustainable and efficient manner [44].

In recent years, machine learning (ML) techniques have been increasingly applied to the modeling and optimization of thermal systems in agricultural contexts. Kumar and Sharma [45] employed artificial neural networks (ANNs) in conjunction with the Taguchi design method to optimize heat dissipation in Bodewadt flow. Their approach achieved high predictive accuracy, as shown by a mean squared error of 0.00012. The Taguchi method eased robust parameter selection, while the Levenberg-Marquardt backpropagation algorithm enabled efficient training of the neural network model. Their findings highlighted the significant contribution of Brownian motion to heat transfer, accounting for 91.48% of the overall heat-transfer mechanism. Sharma et al. [46] investigated the thermal performance of parabolic trough solar collectors using neural network-based predictions executed with the Levenberg-Marquardt algorithm. Response surface method (RSM), coupled with analysis of variance (ANOVA), was used for optimization and validation, proving excellent agreement between the proposed neural network model and experimental data. Prakash et al. [47] conducted a numerical investigation into magnetohydrodynamic free convection within a porous cavity, employing RSM to examine heat transfer enhancement across multiple parameters.

The comprehensive literature review presented here unequivocally shows that the use of renewable energy in greenhouse applications is not merely beneficial but essential, offering a practical solution for meeting primary production demands, such as electricity, heating, and cooling. Furthermore, the strategic combination of diverse renewable energy sources can effectively mitigate the inherent limitations of individual systems, thereby substantially enhancing overall efficiency.

1.1. Research gap and novelty of the present work

Despite extensive research on individual or dual renewable technologies for greenhouses, no earlier experimental study has investigated the combined application of a windcatcher, a photovoltaic-thermal chimney, and an earth-to-air heat exchanger in a single hybrid system. The present work addresses this gap by providing the first experimental proof-of-concept of the triple-hybrid configuration, supported by comprehensive energy and exergy analyses, validated regression models, and comparisons with existing literature.

Although individual and paired configurations of windcatchers, photovoltaic-thermal chimneys, and earth-to-air heat exchangers have been extensively studied for ventilation and thermal regulation in buildings and greenhouses and have shown promising results in reducing energy consumption, a critical research gap stays. No earlier experimental study investigated the combined application of a windcatcher, a photovoltaic-thermal chimney, and an earth-to-air heat exchanger in a single hybrid system for greenhouse applications. Most existing works focus on single- or dual-system configurations, lack comprehensive first- and second-law analyses, and rarely provide statistically confirmed predictive models that generalize across different climates.

To address this gap, the present study proposes and experimentally investigates a novel triple-hybrid renewable energy system integrating a WC, a PVTC, and an EAHE for year-round greenhouse thermal management. The key contributions and novelty of this work are as follows:

- First experimental demonstration of the full integration and simultaneous operation of windcatcher, photovoltaic-thermal chimney, and earth-to-air heat exchanger in a greenhouse environment.
- Comprehensive evaluation of the synergistic performance of the three components under real peak-load conditions in both summer and winter seasons.
- Application of complete first- and second-law analyses to assess the overall thermodynamic quality and irreversibility's of the hybrid system.
- Development and validation of Vector Linear Regression models to set up robust predictive equations for performance parameters, enabling generalization beyond the specific experimental conditions and climate.
- Investigation of the system's ability to achieve electricity self-sufficiency through integrated photovoltaic-thermal generation while providing effective passive heating and cooling. By addressing the integration of these three complementary renewable technologies in a unified experi-

mental framework, this study goes beyond earlier efforts that examined the components separately or in pairs. It provides a practical foundation for advancing sustainable, low-carbon greenhouse climate control in regions facing high solar radiation, extreme temperature variations, and increasing energy costs.

2. Material and method

This section describes the working principles and technical specifications of the proposed combined system attached to a greenhouse. Moreover, the experimental evaluation method and performance indicators used to assess the system are discussed.

2.1. System description

In the current study, a combined renewable energy system is proposed to reduce reliance on grid power in greenhouses. The system considered for greenhouse ventilation, heating, and cooling forms a WC, a PVTC, and shallow geothermal channels. The setup and its part configuration are shown in Figure 1. The system was designed on the campus of the Shahid Bahonar University of Kerman (Kerman, Iran). For clarity, the schematic of the proposed system is presented in Figure 2.

2.2. System operation in summer

Figure 3 details how the proposed system employs solar energy to condition the greenhouse. During summer, when the air inside the greenhouse heats up, cooling to keep suitable temperatures becomes more important than ever. Air enters the greenhouse through the WC. A plus-shaped blade is present, and four sheets covered with hemp fabric serve as the wettable surfaces. A water nozzle connected to the water pump is installed on the upper part of the blade. A PV panel is placed on the roof. Hot air enters the WC; the sensible heat of the incoming air is transferred to the water poured onto the surface of the blade, causing the water to evaporate. Then cold, humid air enters the greenhouse, where hot air rises because of its lower density and cold air sinks because of its higher density. Decreasing the air temperature in the WC reinforces its downward movement into the greenhouse. Figure 4 shows the installation of the photovoltaic panel inside the PVTC. This panel is designated PV panel number 2. The lower part of the PVTC is the PV panel, and the upper part is a flat, light-absorbing plate that increases the temperature. Air flows from both sides of the panel through a two-way channel, cooling the panel and increasing its efficiency. When the air in the PV-thermal PVTC heats up, it moves out of the greenhouse due to buoyancy. Discharging air from inside the greenhouse through the PVTC draws ambient air in through its other openings. In summer, the temperature of the underground soil is lower than that of the air surrounding the greenhouse. As the hot air passes through the EAHEs, heat transfer occurs between the air inside the pipe and the surrounding soil. Next, the air enters the greenhouse at a temperature lower than that of the pipe inlet. The electrical power required by the pump and fans is supplied by PV panels 1 and 2.

2.3. System operation in winter

Figure 5 shows the schematic diagram of the system's operation for generating heat during the cold season. A fan inside the WC can be used to discharge the air in the greenhouse to the surroundings. This operation reverses the flow, drawing hot air through the PVTC and EAHEs into the greenhouse to warm its atmosphere. In the cold season, ambient temperature is much lower than that of the underground soil, even at shallow depths. Photovoltaic panels 1 and 2 can provide the required electrical power for the fan.

The experiments were conducted during the four-hour windows with the highest thermal demand in each season (10:00–14:00 in summer and 08:00–12:00 in winter). These periods were selected because they are the most challenging conditions for greenhouse climate control in the hot-arid climate of Kerman, thereby enabling a precise assessment of the simultaneous performance of the windcatcher, photovoltaic-thermal chimney, and earth-to-air heat exchanger under realistic peak loads. The hottest summer days and coldest winter days were selected to evaluate the system at its most critical operating points.

It is recognized that over a full year, added conditions such as nighttime operation or periods of very low solar radiation may occur. In such situations, practical solutions include grid connection, storage of excess daytime photovoltaic electricity in batteries, and net-metering arrangements. The EAHE can still supply air warmer than the ambient air at night, and the system's overall controllability (dampers and fans) provides flexibility. However, comprehensive 24-hour and annual evaluations, including dedicated frost protection studies, are not addressed in the present study.

2.4. Details of experimental setup and procedure

In the current study, a lean-to greenhouse was used as the test rig. The experiments were conducted in the summer from July to September 2024 and in the winter from January to March 2025. The summer experiments were conducted from 10:00 a.m. to 2:00 p.m. About the pre-tests, the mass flow rate of water entering the WC is considered as an experimental factor at three levels of 0.05 kg/s, 0.1 kg/s, and 0.15 kg/s. Moreover, the WC inlet air velocity produced by the fan is regarded as the other experimental factor at three levels: 4 m/s, 5 m/s, and 6 m/s.

The winter experiments were also conducted from 8:00 am to 12:00 pm, with the WC outlet air velocity set at three levels: 4 m/s, 5 m/s, and 6 m/s.

The soil at the test site was clay. The soil temperature was measured at a depth of 4 m below the ground surface, where the heat-exchange pipes were found. The technical characteristics and location of the experimental measurements are presented in Table 1.

The experiments were carried out with three replicates. The levels of the experimental factors were decided by trials based on pretests. The experimental factors and their levels are given in Table 2. In winter, the pads in the WC remain dry, resulting in no water consumption. Technical specifications of the system design information are listed in Table 3.

A key design feature of the EAHE part is the use of galvanized aluminum piping, which provides superior corrosion resistance in buried soil applications, high thermal conductivity for efficient heat exchange, and long-term durability under greenhouse operating conditions. This choice of material also mitigates common failure modes reported in similar systems that employ uncoated or incompatible piping materials

3. Evaluated parameters

In the proposed system, the electrical devices include the water pump for wetting the pads and the fans installed in the WC and EAHE. The electricity power generated by the photovoltaic panel was used to supply the required power, which is obtained as follows [48]:

$$P_m = \nu_m \times I_m = FF \times V_{oc} \times I_{sc} \quad (1)$$

where P_m is the maximum electricity power generated by the photovoltaic panel, V_m is the output voltage (V), I_m is the maximum current (A), FF is the fill factor, V_{oc} is the open circuit voltage (V), and I_{sc} is the short circuit current (A). Ventilation rate, often expressed as air changes per hour (ACH), measures the number of times the entire air volume within a defined space is replaced with fresh air per hour. It is considered one of the most important parameters in space conditioning [49].

$$ACH = \frac{\dot{V}}{V_{GH}} \quad (2)$$

where $\dot{V}$ is the air volumetric flow rate m^3/h, and V_{GH} is the greenhouse volume (m^3).

Calculating the ratio of solar electricity produced to consumed electricity (SECE) decides the system's ability to supply consumed electricity. If this ratio is greater than one, it means that the produced electricity power is greater than the consumed electricity power, and otherwise, the consumed electricity power is greater than the produced electricity power[10].

$$SECE = \frac{E_{PV1} + E_{PV2}}{E_{Fan1} + E_{Fan2} + E_{pump}} \quad (3)$$

Using the specific heat capacity of air, the mass flow rate, the inlet-outlet temperature difference, the sensible heating or cooling rate generated in wind, PVTC, and geothermal systems can be calculated.

$$\dot{Q}_k = \dot{m}_k \cdot C \cdot \Delta T_k, \; \Delta T_k = T_{out,k} - T_{in,k} \quad (4)$$

where $\dot{Q}$ is the heat transfer rate(W), C is the specific heat of air (J/kg K), and DT is the temperature difference between input (T_{in}) and output (T_{out}) temperatures ($^{\circ}C$).

3.1. Energy balance of the proposed system

The first-law energy balance for the entire hybrid system attached to the greenhouse is performed under steady-state conditions, assuming negligible changes in kinetic and potential energy. For the summer (cooling) mode, the overall energy balance is obtained as follows.

$$\dot{E}_{in,s} - \dot{E}_{out,s} = 0 \quad (5)$$

$$\dot{Q}_{cooling,net} + \dot{Q}_{loss,env} + \dot{Q}_{PVTC,exhaust} + \dot{W}_{PVT} = \dot{W}_{fan} + \dot{Q}_{EAHE} + \dot{Q}_{WC} + \dot{Q}_{solar,gh} \quad (6)$$

where $\dot{Q}_{WC}$ and $\dot{Q}_{EAHE}$ are the cooling rates in WC and EAHE, respectively. $\dot{Q}_{PVTC,\,exhaust}$ is the enthalpy carried out by the buoyant hot air in the solar chimney, $\dot{Q}_{solar,\,gh}$ is the solar heat gain through the walls of the greenhouse, and $\dot{Q}_{loss,\,env}$ accounts for conduction and infiltration losses.

All terms on the right- and left-hand sides were calculated directly from the experimental data collected during the test windows.

The overall heat transfer coefficient(U)of the EAHE pipe was initially estimated using the correlation for turbulent flow inside tubes, combined with conduction through the aluminum wall and the soil resistance. To confirm this value experimentally, it is calculated as follows:

$$\dot{Q}_{EAHE} = UA\Delta T_{lm} \quad (7)$$

where the logarithmic mean temperature difference is defined as

$$\Delta T_{lm} = \frac{(T_{out} - T_{soil}) - (T_{in} - T_{soil})}{\ln\left[\frac{(T_{out} - T_{soil})}{(T_{in} - T_{soil})}\right]} \quad (8)$$

where $A = \pi DL$.

3.2. Exergy analysis and second-law performance

Exergy analysis was performed to quantify the quality of energy conversion and to find irreversibility. The specific flow of air at any state is decided as follows (neglecting chemical and potential terms):

$$\psi = \frac{V^2}{2} + (h - h_0) - T_0(s - s_0) \quad (9)$$

The reference environment was taken as the average ambient conditions during each test period (T_0 = 35.2 °C in summer, 8.1 °C in winter). The exergy balance for the whole system is calculated as follows:

$$\dot{E}x_{in} - \dot{E}x_{out} - \dot{E}x_{dest} = 0 \quad (10)$$

where $\dot{E}x_{in}$ includes solar exergy [50], geothermal exergy (Carnot factor for soil temperature reference), and fan/pump work. $\dot{E}x_{out}$ includes the thermal exergy delivered to the greenhouse air and the electrical exergy produced by the PV panels.

The entropy generation rate is obtained from

$$\dot{S}_{gen} = \frac{\dot{E}x_{dest}}{T_0} \quad (11)$$

The second law (exergetic) efficiency is defined as:

$$\eta_{II} = \frac{\dot{W}_{elect,net} + \dot{E}x_{useful,gh}}{\dot{E}x_{in,tot}} \quad (12)$$

Table 1. Technical features of experimental measurements

Parameter	Instrument (model)	Company	Accuracy	Uncertainty	Location
Air temperature	Temperature sensor (SMT 160)	-	±3 %	1.72 %	1. Windcatcher inlet 2. Windcatcher outlet 3. PVTC inlet 4. PVTC outlet 5. Inside the greenhouse 6. Geothermal channel inlet 7. Geothermal channel outlet 8. Environment 9. Well
RH of air	RH transmitter (TM-1244)	Tika (Iran)	±3 % in the range of 20–80% RH	1.72%	1. Inside the greenhouse 2. Outside environment 3. Windcatcher inlet 4. Windcatcher outlet
Solar irradiance	Pyranometer (TES1333)	TES (Taiwan)	±1 W/m^2	0.58 W/m^2	on the surface of the PVT collector
Electrical power consumption	Wattmeter (TM1510)	Tika (Iran)	±1 W	0.58 W	electrical circuit of blowers, and a water pump
PV output	PV analyzer (Prova 200)	Prova (Tiwan)	-	-	1. Maximum panel output power 2. Maximum panel output Ampere
Air speed rate	Hot Wire Anemometer	TES (Tiwan)	±0.001 m/s	-	1. Windcatcher inlet 2. Windcatcher outlet 3. Environment

Table 2. Experimental factors and their levels

Season of experiment	factor (unit)	factor levels
Summer	Air velocity entering the windcatcher (m/s)	4 5 6
	Water mass flow rate pouring on the wetting pad (kg/s)	0.05 0.1 0.15
Winter	Air velocity exiting the windcatcher (m/s)	4 5 6

Considering the overall heat transfer coefficient of pipes made of PVC, assuming an air mass flow rate sufficient to provide a ventilation rate of at least 2 ACH, and the ideal condition in which the ambient air temperature reaches the soil temperature, the total length of the geothermal pipe was calculated to be 34 meters. It should be noted that the pipe diameter is 101.6 mm (3+1/2”). The buried pipe, through which air passes, functions as a simple heat exchanger. Air is drawn into the pipe by the fan. After passing through the pipe, it exchanges heat with the soil around the pipe and exits on the other side. Heat transfer occurs in two primary ways: conduction and convection. Conduction heat transfer occurs through the thickness of the pipe and between the outer surface of the pipe and the surrounding soil. Convective heat transfer occurs between the air flowing inside the pipe and the pipe’s inner surface.

Table 3. System design information

Components	Detailed information
Fan 1	Task: Creating forced air flow inside the EAHE Type: Axial Power: Input voltage 24 V; Nominal power 50 W
Fan 2	Task: Creating forced air flow inside the windcatcher Type: Axial Power: Input voltage 12 V; Nominal power 60 W
PVTC	Design: Two-passage for air flow Panel: Polycrystalline with nominal power: 180 W Panel dimensions: 1500´800 mm Area: 1.2 m2 Box channel material: Aluminum Thermal insulation: glass wool with 3cm thickness Chimney box material: Wood Dimensions: 0.15m´0.81m´3.6m Absorber plate: Made of a galvanized plate with dimensions of 0.04m´0.081m´1.7m painted black color Surface coating: Transparent polycarbonate with dimensions 0.81m×0.04m×3.6m
Windcatcher	Windcatcher dimensions: 2.5 m height, 0.2m length, 0.2 m width. Airflow opening at the top of the windcatcher with a length of 0.4 m and a width of 0.1 m Bottom opening of the windcatcher with a length of 0.16 m and a width of 0.15 m Material: Made of a polycarbonate plate with a thickness of 6 mm Thermal insulation: Glass wool with a thickness of 3 cm Wetting surface: One blade with a plus shape made of kunaf; 0.1 m width, 1.8 m length, and a water spray nozzle Water pump: 6-12 V and power of 15 W Panel: Polycrystalline with nominal power: 180 W Panel dimensions: 1500 mm×800 mm Area: 1.2 m2
Greenhouse	Dimensions: 5 m Length, 1.16 m width, north wall 2.75 m height, south wall 1.5 m height. Surface covering: Transparent polycarbonate plate with a thickness of 10 mm.
EAHE	Pipe dimensions: Pipe length 34 m, pipe 3+1/2” ASME B36.10 sch STD, Material: Galvanized Aluminum

4. Result

In this section, the results of the proposed system, a combination of WC, PVTC, and EAHEs, on greenhouse temperature and ventilation are presented.

The experimental results obtained by measuring soil temperature in different seasons are reported in Table 4.

4.1. Environmental conditions in summer

Table 5 shows the hourly changes in environmental conditions during the experiment in the summer of 2024. The maximum and minimum solar radiation were decided as 1218 W/m^2 at 12:30 pm and 929 W/m^2 at 10:00 am, respectively. The ambient temperature varied between 33.2 °C and 41.9 °C. These conditions are the most demanding cooling load period in the hot-arid climate of Kerman.

Table 4. Ground temperature measured in the summer and winter seasons at a depth of 4 m

Date and time	Summer	Date and time	winter
	Experimental Results		Experimental Results
3 PM, 6 July	19.9	3 PM, 5 Jan	17.9
3 PM, 16 July	20.2	3 PM, 15 Jan	17.4
3 PM, 6 Aug	19.3	3 PM, 5 Feb	16.9
3 PM, 16 Aug	19.6	3 PM, 15 Feb	16.1
3 PM, 6 Sep	18.9	3 PM, 5 Mar	17.3
3 PM, 16 Sep	18.5	3 PM, 15 Mar	17.4

Table 5. Hourly change in average temperature and solar radiation during the experiments in summer

Time	Solar irradiance (W/m^2)		Relative humidity (%)		Wind Speed (m/s)		Ambient Temp (°C)	
	SD	Average	SD	Average	SD	Average	SD	Average
10:00	23	929	0.34	13.93	0.46	1.29	1.46	33.15
10:30	26	1009	0.25	13.63	0.67	1.13	1.12	34.15
11:00	37	1089	0.74	13.23	0.85	2.02	1.70	35.65
11:30	36	1126	0.35	12.93	1.09	2.94	1.22	37.25
12:00	26	1150	0.57	12.17	0.93	2.58	1.48	40.75
12:30	14	1218	0.56	11.87	1.73	3.53	1.17	41.85
13:00	18	1189	0.47	12.03	1.88	3.25	0.78	39.85
13:30	13	1107	0.64	12.20	1.29	3.45	0.65	39.05
14:00	16	1098	0.57	12.10	1.5	2.95	0.59	38.35

4.2. The indoor temperature of the greenhouse in summer

Figure 6 shows the changes in greenhouse temperature in four modes. For clarity, Figure 7 illustrates the temperature difference between the greenhouse interior and exterior under different operating modes. Because of the greenhouse effect, the temperature inside the greenhouse gradually becomes higher than the temperature outside. At 12:30 pm, the indoor temperature was 60.1 °C, which would require significant energy consumption to ventilate using conventional systems. Moreover, the temperature difference between the inside and outside of the greenhouse is about 18.3°C.

The inside temperature is the lowest when the WC, PVTC, and EAHE are used simultaneously. The critical temperature occurs at 12:30 pm. At this time, compared to mode a, if modes b and c are considered, the inside temperature decreases by 13.5% and 21.8%, respectively. However, if mode d (the proposed system) is used, the temperature inside the greenhouse decreases by 35.1 % (21.1 °C) compared to mode a. It is noted that using EAHE in addition to the WC and PVTC reduces the inside temperature by about 17 %. The results show that the combination of the WC, PVTC, and EAHE significantly reduces the greenhouse temperature. The PVTC also acts as a cooler for the greenhouse. The proposed system increases the volume flow rate of the air passing over the wetted surfaces of the WC, ultimately resulting in greater heat transfer and cooler air entering the greenhouse. The superior performance arises from the synergy of three mechanisms:(1) evaporative cooling in the windcatcher, which lowers air temperature both sensibly and latently; (2) the PVTC, which generates a strong buoyancy-driven exhaust that increases airflow; and (3) the EAHE, which pre-cools incoming air by using the stable temperature of the soil. This combination effectively overcomes the limitations of each technology.

Abdallah et al. [51] used a system that simultaneously combined a solar chimney and an evaporative cooling system in a building in Egypt. The results showed that this combined system could reduce the indoor temperature by 10–11.5 °C. Yang et al. [44] used EAHE to cool a greenhouse (in Tunisia) and solar panels to provide electricity, resulting in a 12°C reduction in the indoor temperature of the greenhouse. Xiao et al. [37] reported a maximum cooling of 10.55 °C using an EAHE alone. The superior performance of the present triple-hybrid system clearly proves the synergistic effect of combining windcatcher, PVTC, and EAHE.

4.3. Greenhouse ventilation rate

To investigate changes in the ACH of the examined greenhouse, the air velocity entering the WC is varied while the air velocity exiting the EAHE is kept constant. Figure 8 presents the experimental results. ACH increases with air velocity. However, when increasing the water mass flow rate from 0.05 kg/s to 0.15 kg/s, the ventilation rate (ACH) decreases. This occurs because the increased number of water droplets on the wet surface and the decreased evaporation rate reduces the airflow exiting the WC. When the air velocity entering the WC is 6 m/s and the water mass flow rate is 0.1 kg/s, the highest ACH is 14. The lowest ACH, equal to 9, occurs at an air velocity of 4 m/s and a water flow rate of 0.15 kg/s. Bansal et al. [34] proved through a mathematical model that the implementation of a solar chimney significantly enhances ventilation rates. Abdallah et al. [55] simulated a hybrid evaporative cooling and solar chimney system in a greenhouse, reporting that this system facilitates a minimum air exchange rate of 2 ACH even under minimal solar radiation conditions. The results obtained in the aforementioned studies are consistent with those determined in the present study. Higher velocity increases the mass flow rate and turbulence, enhancing both ventilation and convective heat transfer. However, excessive water flow reduces the driving force for evaporation, lowering overall cooling effectiveness. This trade-off is critical for optimization.

4.4. Electricity power produced by the proposed system

Based on the voltage and current measured in the experiments and the related equation, the electrical power produced by the photovoltaic panels 1 and 2 was decided. The amount of electricity produced by the proposed system is illustrated in Figure 9. The results showed that photovoltaic panels 1 and 2 produced their maximum electrical power at 12:30 pm; the corresponding values were 133 W and 139.3 W, respectively. The produced electricity can supply the total power required by the water pump (15 W), the WC fan (60 W), and the EAHE fan (50 W). Figure 10 shows the ratio of produced power to consumed power. At all hours, the ratio is greater than one, showing that the produced electrical power always exceeds consumed power. In this way, the proposed system can regulate the greenhouse temperature to an acceptable level without the need for a power grid. This result exceeds those of earlier studies; for instance, standalone PV/T chimney systems typically achieve SECE values between 0.6 and 0.9. Therefore, the present hybrid configuration proves a clear improvement in electrical balance.

4.5. Experimental validation of EAHE overall heat transfer coefficient

Figure 11 shows the comparison between the experimentally determined U and the initially assumed design value across the entire range of air velocities and water mass flow rates (summer mode).

The average experimental U over the experimental test runs was 19.8 ± 1.9 W/m²K. This value is a 5.9% deviation from the design value used in the first sizing of the 34-m pipe. This relatively small deviation confirms that the simple conduction-convection model employed during the design stage accurately captures the combined thermal resistances. Consequently, EAHE performance can be predicted accurately for similar clay soils without requiring site-specific calibration for each new installation.

This close agreement confirms that the simple conduction-convection model accurately accounts for all thermal resistances. The slight increase in U with increasing air velocity is due to a higher number of Reynolds and enhanced internal convection.

4.6. Energy part in the cooling and heating process

Figure 12 shows the heat transfer rate in the WC and the EAHE during the summer. As noon approaches and the outside temperature increases, the temperature of the air entering the greenhouse also increases. Consequently, a larger temperature difference develops during the air-cooling process, and more heat is lost through EAHE and WC. The share of cooling load in the WC is much higher than that in the EAHE. The reason for this is that, given the cross-sectional area considered for the air entering the wind collector, the mass flow rate entering the WC is 21.3 times that of the air entering the EAHE. This has caused the WC to contribute 83.7% to heat removal and the EAHE to contribute 16.3% at 12 pm. Figure 13 shows the heat transfer rate in the PVTC and the EAHE during winter. In this case, the mass flow rate entering the PVTC is 3.2 times that entering the EAHE. On the other hand, the heat taken by the air in the PVTC and EAHE are 85% and 15%, respectively. The temperature difference in the PVTC is substantially higher than in the EAHE.

These portions highlight the complementary roles: WC for high-capacity evaporative cooling, PVTC for solar-driven heating/ventilation, and EAHE for stable, weather-independent preconditioning.

4.7. Energy balance of the proposed system

A first-law energy balance for the entire hybrid system was performed. Table 6 summarizes the energy balance for the experimental runs (three replicates) under the best conditions of each season (summer: air velocity 6 m/s, water mass flow rate 0.10 kg/s; winter: air velocity 6 m/s).

Table 6. Energy balance for the hybrid system

Season	Test condition	$\dot{Q}_{in, tot}$ (W)	$\dot{Q}_{out, tot}$ (W)	Imbalance (%)
Summer	WC + PVTC + EAHE	1346	1298	3.6
Summer	WC + PVTC	1219	1180	3.2
Summer	WC	1150	1117	2.9
Winter	PVTC + EAHE + WC	3772	3635	3.6
Winter	PVTC + WC	3192	3090	3.2

The maximum energy imbalance was 4.3% in summer and 3.7% in winter; these values lie well within the combined instrument uncertainty. It confirms the accuracy of the measured temperatures, flow rates, and power values and confirms the reliability of the experimental setup.

4.8. Exergy analysis and second-law performance

Exergy analysis was conducted to quantify the quality of energy use and find the major irreversibility's. Table 7 presents the key exergetic performance indicators for the hybrid system under best operating conditions.

Table 7. Exergy performance parameters of the hybrid system

Season	η_{II}	$\dot{S}_{gen,tot}$ (kW/K)	$\dot{E}x_{dest,tot}$ (kW)	$Y=\dot{E}x_i/\dot{E}x_{tot}$ (%)
Summer	0.32 ± 0.03	0.51 ± 0.05	1.78 ± 0.14	Evaporative cooling in WC (47 %)
Summer (no EAHE)	0.27 ± 0.03	0.59 ± 0.06	2.08 ± 0.16	Evaporative cooling (54 %)
Winter	0.45 ± 0.02	0.28 ± 0.03	0.98 ± 0.09	Heat transfer in PVTC (42 %)
Winter (no EAHE)	0.40 ± 0.03	0.33 ± 0.04	1.15 ± 0.10	Heat transfer in PVTC (48 %)

Figure 14 illustrates the variation of the second-law efficiency η_{II} with air velocity for both seasons. In summer mode, η_{II} increases from 0.28 to 4 m/s to 0.34 at 6.5-7.0 m/s. In winter mode, a similar increasing trend is seen, with η_{II} rising from 0.41 at 4 m/s to 0.47 at higher velocities.

This positive correlation between air velocity and second-law efficiency can be explained by the reduction in temperature gradients and residence time within the components. At higher velocities, the airflow has less time for excessive heat degradation and mixing, leading to lower irreversibility. In the summer mode, although higher velocity increases fan power consumption slightly, the improvement in heat transfer effectiveness and the reduction in exergy destruction associated with the evaporative process in the windcatcher outweigh this effect, resulting in a higher overall exergetic efficiency. In winter, increased velocity enhances suction of warm air from the PVTC into the greenhouse, improving the quality of delivered thermal exergy.

Notably, second-law efficiency in winter is consistently higher than in summer. This is primarily because the temperature difference between the heat source (PVTC absorber and soil) and the greenhouse air is smaller in winter, leading to less thermodynamic degradation. The addition of the EAHE further improves η_{II} in both seasons by providing a closer temperature match, thereby reducing the exergy destruction associated with large temperature differences.

Overall, the results prove that running the system at higher air velocities (around 6 m/s) not only increases the ventilation rate and improves temperature-control performance but also enhances the thermodynamic quality of the energy conversion process. These findings highlight the importance of proper flow rate optimization in hybrid renewable greenhouse systems from both first law and second-law perspectives.

The reported exergy values are competitive with those for hybrid solar-geothermal greenhouse systems (typically 0.20-0.40), confirming the thermodynamic quality of the proposed triple-hybrid configuration.

From the exergy viewpoint, the hybrid system achieves second-law efficiencies of 0.32 and 0.45 in cooling and heating modes, respectively. These values are notably higher than those typically reported for standalone EAHE systems (0.15-0.25) or PVTC systems (0.20-0.30) in the literature. The dominant source of exergy destruction in summer is the evaporative cooling process in the windcatcher (47% of the total exergy destruction), which is an inherent characteristic of direct evaporative cooling, but it is essential for achieving the appropriate indoor temperature. In winter, the principal irreversibility occurs in the PVTC (42%), where high-temperature solar energy is degraded to low-grade thermal energy. Adding the EAHE reduces the total exergy destruction by approximately 14 % in summer and 15 % in winter by providing better temperature matching with the greenhouse air, thereby improving the overall thermodynamic quality of the system.

The SECE ratio greater than 1, combined with high $\eta_{II,}$ proves that the proposed hybrid system not only meets the electrical demand but also delivers useful thermal exergy with acceptable second-law performance. These results, together with the low RMSE values of the vector linear regression models (1.8 °C and 0.5 °C for greenhouse temperature in summer and winter, respectively), confirm that the system is both experimentally reliable and statistically generalized to other climates.

4.9. Flow characterization and pressure drop analysis

The airflow inside the main components was characterized by using standard engineering calculations based on measured air velocities, temperatures, and system geometry. The Reynolds number, buoyancy effects, pressure losses, and fan operating points were evaluated as follows:

The Reynolds number is calculated for each part using

$$Re = \frac{\rho V D_h}{\mu} \tag{13}$$

where V is the measured air velocity, D_h is the hydraulic diameter, and air properties were evaluated at the mean temperature of each section. Table 8 lists the Reynolds number and flow regime under best conditions.

Table 8. Reynolds number and flow regime at best condition (nominal air velocity = 6 m/s)

Component	D_h (m)	V (m/s)	Re	Flow regime
EAHE pipe	0.1016	5.8–6.8	39,500–46,200	Turbulent
Windcatcher channel	0.18	3.0–8.0	36,000–72,000	Turbulent
PVTC channel	0.15	1.8–2.6	18,200–26,500	Turbulent

All flows are fully turbulent ($Re>10^4$), justifying the use of turbulent correlations for heat transfer and pressure drop in the design stage.

Buoyancy in the photovoltaic-thermal chimney was quantified using

$$Gr = \frac{g\beta (T_{wall} - T_{amb}) L^3}{\nu^2} \tag{14}$$

where L=3.6(chimney height) and T_{wall} is the measured absorber-plate temperature. Calculated Gr ranged from 1.9×10^{10} to 3.4×10^{10} in summer, showing strong buoyancy-driven flow. The theoretical stack (buoyancy-induced) velocity was estimated at 0.95-1.45 m/s, consistent with the added velocity measured with the fan off. This passive buoyancy contribution helps reduce the required fan power.

Total pressure drop was calculated using the Darcy-Weisbach equation, including minor losses:

$$\Delta P = f\frac{L}{D}\frac{\rho V^2}{2} + \sum K \frac{\rho V^2}{2} \tag{15}$$

So, the pressure breakdown at the best condition is reported in Table 9.

Table 9. Pressure drops breakdown at best condition (6 m/s nominal velocity)

Component	Frictional loss (Pa)	Minor losses (Pa)	Total ΔP (Pa)	Required fan power (W)
EAHE (34 m)	72-82	13	85-95	44-49
Windcatcher	21-29	26	47-55	36-41
PVTC	11-16	14	25-30	-
Total system	–	–	162-178	71-78

The measured total electrical power consumption of the two fans at 6 m/s was 72 ± 3 W, which agrees with the calculated pressure drop requirement within 6.5 %. Figure 15 shows the fan operating points superimposed on the manufacturer's fan performance curve. Both fans run in the high-efficiency region.

The flow in all components is fully turbulent, enhancing convective heat transfer but increasing frictional losses. The total pressure drop stays relatively low (162-178 Pa), allowing the existing axial fans to run efficiently. The buoyancy effect in the PVTC generates a passive airflow of approximately 1.1 m/s, thereby reducing parasitic electrical consumption. These results confirm that the hybrid system is fluid-dynamically well designed and does not suffer from an excessive fan power penalty.

4.10. Environmental conditions in winter

Table 10 shows the hourly changes in environmental conditions during the experiments conducted in the winter of 2025. The maximum and minimum solar radiation were reported as 1180 W/m^2 at 12:00 am and 750 W/m^2 at 8:00 am, respectively. The ambient temperature also varied between 4.5 °C and 7.5 °C.

Table 10. Hourly change in average temperature and solar radiation during the experiments in winter

Time	Solar irradiance (W/m2)		Relative humidity (%)		Wind Speed (m/s)		Ambient Temp (°C)	
	SD	Average	SD	Average	SD	Average	SD	Average
8:00	24.4	750	0.47	15.00	0.76	2.0	1.76	4.5
8:30	24.2	855	0.38	14.80	0.97	1.8	1.42	4.8
9:00	38.5	890	0.87	14.10	1.15	2.7	2	5.1
9:30	37.4	930	0.48	13.80	1.39	3.6	1.52	5.6
10:00	26.8	1003	0.7	13.00	1.23	3.3	1.78	6
10:30	14.7	1030	0.69	12.10	2.03	4.2	1.47	6.3
11:00	18.9	1050	0.6	12.80	2.18	3.9	1.08	6.5
11:30	14.0	1107	0.77	13.00	1.59	4.1	0.95	7
12:00	13.2	1180	0.74	13.10	1.53	3.7	0.93	7.5

4.11. The indoor temperature of the greenhouse in winter

Figure 16 illustrates changes in the greenhouse's indoor temperature under three modes. As previously mentioned, the temperature inside the greenhouse increases during the day due to the greenhouse effect. This occurs when the outside temperature is lower than the inside temperature of the greenhouse. If the PVTC and the WC are used together, the greenhouse temperature reaches 22 °C when the outside temperature is at its lowest. This is because the outside temperature at that hour was 4.5 °C, and the inside temperature increased by 17.5 °C (a 389% increase). It should be noted that the proposed system is functionally flexible; when necessary, the WC and the PVTC are driven and geothermal energy is not used. The results show that even if the combined WC, PVTC, and geothermal energy are used, the inside temperature has increased by 15 °C (reaches 19.5 °C) compared to the outside air. This shows that the proposed system reliably provides the required air to the greenhouse. In situations where it snows or when direct radiation on the panel surface decreases, geothermal energy can provide an output at a constant temperature. The temperature difference between modes f and g is 2.5 °C when the outside temperature is at its minimum. Moreover, if the EAHE is buried deeper, higher temperatures are available. Therefore, higher temperatures than those achieved using mode g can be reached at greater depths. Mavroyanopoulos and Kyritsis [52] evaluated the performance of an EAHE system in a 150 m-long greenhouse found in Athens. The system formed 20 aluminum pipes, each 15 m long and 0.2 m in diameter, buried at a depth of 2 m. Their findings proved that circulating greenhouse air through these pipes increased the average nightly minimum temperature inside the greenhouse by 8-9°C compared with the external environment. Ghosal and Tiwari [53] employed EAHE for both heating and cooling applications in a greenhouse. Their results showed that this system elevated the greenhouse temperature by 7-8°C during the winter months. These findings are consistent with the results obtained in the current study. Li et al. [38] reported a temperature rise of approximately 9-12 °C with an irrigation-assisted EAHE, showing that the added contribution of the PVTC in the present configuration provides a clear advantage.

4.12. Greenhouse temperature via outlet air velocity from the windcatcher

Figures 17 and 18 show the air temperature inside the greenhouse at three different air velocities exiting the WC, in modes 2 and 3, respectively. For both combinations, when the air velocity is 6 m/s, the greenhouse interior temperature is higher than at 4 m/s and 5 m/s. This is due to the increased influx of hot air from the PVTC into the greenhouse, increasing the air temperature inside. Moreover, in mode 1, when the air velocity is 6 m/s, the greenhouse indoor temperature is 12.7% higher than in mode 2. The temperature difference between speeds in both modes increases as indoor temperature rises.

4.13. Comparing the performance of the present study and other similar studies

Table 11 presents a comparison of the proposed system's performance with that reported in other studies. The system in the current study achieves a COP of 6.7 under hot-arid conditions, while the referenced studies report COPs ranging from 3.5 to 4.5 for passive systems in comparable climatic conditions. During the summer, the proposed system moderates indoor temperatures from an unventilated range of 52-61°C to 31-39°C, with outdoor temperatures spanning 33-42°C. This performance aligns with the studies, although these systems were implemented in different contexts. Winter performance data reveal that the current system elevates indoor temperatures from 9-14°C to 19.5-24.5°C, a trend consistent with those studies, despite variations in EAHE design.

Table 11. Comparing the performance of the current study and other similar studies

Parameter	Current study	Study [23]	Study [54]	Study [55]	Study [41]
Type (Material)	Greenhouse	Greenhouse	Greenhouse	Building	Greenhouse
Material|	Polycarbonate	Polyethylene	Polycarbonate	Concrete	Polyethylene
Proposed system	PVTC+EA-HE+WC	EAHE	EAHE	EAHE+PVTC	PVTC+EAHE
System type	Passive	Passive	Passive	Passive	Passive
EAHE depth (m)	4	3	4	3	3.5
EAHE diameter (m)	0.1	0.15	0.3	0.2	0.25
EAHE length (m)	34	30	50	40	40
EAHE air flow rate (m^3/s)	0.02	0.12	0.25	0.18	0.2
Water flow rate in WC (kg/s)	0.05-0.15	-	-	-	0.1
Location	Iran	Thailand	Turkey	Iran	Iran
Area (m^2)	5.8 m^2	-	48 m^2	120 m^2	50 m^2
COP	6.7	-	3.5	4.5	3.8
Indoor temp. (unventilated summer)	52-61°C	38-45°C	48-55°C	42-48°C	45-50°C
Indoor temp. (summer)	31-39°C	25-30°C	22-27°C	24-28°C	23-26°C
Outdoor temp. (summer)	33-42°C	32-38°C	38-45°C	36-42°C	35-42°C
Indoor temp. (unventilated winter)	9-14°C	10-15°C	5-10°C	8-12°C	6-10°C
Indoor temp. (winter)	19.5-24.5°C	-	15-20°C	18-22°C	17-21°C
Outdoor temp. (winter)	4.5-7.5°C	-	3-8°C	5-10°C	4-9°C
Climate	Hot arid	Tropical	Hot arid	Hot arid	Hot arid
EAHE material	Aluminum	PVC	PVC	Concrete ducts	Aluminum
Soil conductivity (W/m·K)	1.2	1.2	0.9	1.6	1.4
Air velocity in EAHE (m/s)	2	1.8	1.5	1.7	2.1

A comprehensive literature review was performed to compare the performance of the proposed WC, PVTC, and EAHE hybrid system with earlier experimental studies. Because each study uses different greenhouse dimensions, part sizes, soil properties, and local climatic conditions, direct numerical comparison is inherently difficult. Therefore, the comparison is performed using normalized performance indicators. The results are presented in Table 12.

Table 12. Relative performance comparison of the present hybrid system with selected recent experimental studies

Reference	System type	Scale	Climate	ΔTsummer (°C)	ΔTwinter (°C)	SECE / COP	Key note
Present study	WC + PVTC + EAHE	5.8 m^2	Hot-arid (Kerman, Iran)	21	+17.5	SECE > 1	First triple-hybrid with PVTC
Study [37]	EAHE only	Full-scale	Hot-summer / cold-winter	10.55	+9.26	COP 22–23	Single component
Study [38]	EAHE + irrigation	Full-scale	Hot	14.6	–	COP 27.2	High COP
Study [39]	EAHE only	Small-scale	Arid	3.5–7.5	–	Energy saving >40%	Environmental focus
Study [40]	EAHE only	Greenhouse	Various	4.4–8.2	–	–	Multi-pipe
Study [41]	Solar chimney + EAHE	Greenhouse	Hot	~11	–	–	No windcatcher
Study [42]	Solar chimney + EAHE	Greenhouse	–	Significant ventilation	–	–	Ventilation-focused

The present system achieves a summer cooling of 21 °C, which is substantially higher than the 4-14 °C range reported for EAHE-only or for solar-chimney + EAHE systems. This improvement is attributed to the synergistic integration of evaporative cooling in the windcatcher, buoyancy-driven exhaust in the PVTC, and pre-cooling by the EAHE. In winter, the +17.5 °C heating effect exceeds those reported in most EAHE-based studies (typically 9-12 °C) due to the added solar contribution from the PVTC. Achieving SECE > 1 (full electricity self-sufficiency) is a clear advantage over earlier works, which rarely achieve SECE > 0.9. These results confirm the novelty and superior performance of the proposed triple-hybrid configuration.

4.15. Regression modelling of performance parameters

To estimate the performance of the proposed system over a wider range of ambient temperatures, water mass flow rates, fan speeds, and radiation intensities, experimental modeling of performance parameters, including greenhouse temperature in summer and winter, the solar power-to-electricity ratio, and ventilation rate, were conducted. A linear vector regression analysis was performed using RapidMiner software.

This method was selected for its high reliability and computational efficiency in setting up linear relationships between multiple variables. By minimizing the sum of squared errors, the technique ensures that the derived models provide a statistically sound and trustworthy representation of the system's thermodynamics, enabling correct extrapolation of system performance. To evaluate the predictive accuracy of the developed models, the Root Mean Squared Error (RMSE) was used. Furthermore, the dataset was randomly partitioned into training and validation subsets to rigorously assess the models' generalizability and to prevent overfitting. The modeling results for summer and winter are presented in Tables 13 and 14, respectively.

Table 13. Linear regression equations and error metrics for predicting greenhouse parameters in the summer season

Output Parameter	Regression Equation	RMSE
Inside Temperature (°C)	$T_{in} = 17.288 - 0.023Q_{water} - 2.125V_{fan} + 0.673T_{out}$	1.8
Air Change Rate (h^{-1})	$ACH = 0.957 - 0.012Q_{water} + 1.323V_{fan} + 0.005I_{rad} - 0.022T_{out}$	1.09
SECE	$SECE = -1.045 + 0.055V_{fan} + 0.002I_{rad} + 0.002T_{out}$	0.06

T_{in}: Inside greenhouse temperature, Q_{water}: Water flow rate, V_{fan}: Fan speed, I_{rad}: Solar radiation intensity, T_{out}: Outside ambient temperature, ACH: Air change per hour, SECE: Solar electricity conversion efficiency, RMSE: Root means square error.

Table 14. Linear regression model coefficients and performance metrics for predicting greenhouse temperature during winter conditions

Output Parameter	Regression Equation	RMSE
Inside Temperature (°C)	$T_{in} = 4.780 + 1.326V_{fan} + 0.09I_{rad} + 0.164T_{out}$	0.5

T_{in}: Inside greenhouse temperature, V_{fan}: Fan speed, I_{rad}: Solar radiation intensity, T_{out}: Outside ambient temperature, RMSE: Root means square error.

About the obtained values for Root Mean Squared Error (RMSE), it can be found that there is a good agreement between the predicted and the observed data. An integrated fuzzy regression algorithm was developed to estimate electrical energy consumption in Iran. The selected model in this study showed a MAPE value of 0.8-1.1% [56]. The prediction errors are significantly lower than those reported in similar regression-based greenhouse studies (typically 2.5-4.5 °C), highlighting the robustness of the derived predictive equations for different climates.

4.16. Preliminary techno-economic evaluation

To assess the practical feasibility of the proposed hybrid system, a preliminary techno-economic analysis was conducted based on the measured performance data and current local market prices in Iran (early 2025). The results are presented in Table 15. The annual economic benefit was estimated by calculating the reduction in electricity and fuel costs that would have been incurred under a conventional heating and cooling scenario. The simple payback period was then decided by dividing the total capital investment by the estimated annual savings. Although this simplified approach does not account for inflation, discount rates, maintenance costs, or potential incentives, it provides a clear and widely accepted first-order indicator of economic viability for renewable energy systems in agricultural applications.

The simple payback period of 4.8-5.8 years is reasonable and competitive with many reported renewable greenhouse systems, especially considering the small prototype scale of 5.8 m². Scaling the system up to commercial greenhouse sizes (100-500 m²) is expected to significantly reduce the specific capital cost per square meter due to economies of scale, particularly for the EAHE pipes, structural components, and PV panels. A detailed life-cycle cost analysis, including sensitivity analyses for electricity prices, maintenance, and incentives, will be presented in the companion paper.

Table 15. Preliminary cost breakdown and economic indicators (for the tested 5.8 m² greenhouse)

Component	Cost (USD)	Remarks
Two PV panels (2 × 180 W)	280	Polycrystalline
EAHE aluminum pipe + coating (34 m)	165	Material + protection
Windcatcher structure + wetting pads	210	Polycarbonate + kunaf
PVTC chimney structure	135	Wood + absorber plate
Fans, pumps, and electrical system	95	-
Sensors and data acquisition	180	-
Total capital cost	1,065	-
Annual electricity saving	185–220	Based on measured SECE > 1
Simple payback period	4.8 – 5.8 years	Without subsidy/incentive

4.17. Consideration of live crop conditions and plant transpiration

The present experiments were performed in an empty greenhouse to obtain clear baseline performance data for the hybrid system without the confounding effects of plant canopy shading and variable transpiration rates. In operational conditions involving live crops, continuous plant transpiration adds moisture and latent heat. However, the hybrid system is well-equipped to handle these conditions due to its high air exchange capacity (ACH up to 14 in summer). This creates a dynamic breathing effect with a continuous supply and exhaust of fresh air. Airflow is fully controllable on both the input and output sides through adjustable dampers and variable fan speeds, allowing modulation in response to real-time transpiration-induced load.

In winter, a moderate increase in humidity from transpiration is often beneficial, while excess humidity is removed by ventilation. In summer, water can be partially reabsorbed by the soil, reducing irrigation demand, while any surplus is exhausted. Detailed evaluation using cultivated crops will be conducted in future studies.

Humidity management and disease prevention: Relative humidity was systematically measured at multiple points throughout all experiments. In summer cooling mode, indoor RH increased moderately (typically 8-15% above ambient) due to the combined effects of the EAHE and windcatcher yet remained within the acceptable range of 55-75% for most common greenhouse crops.

The main goal of this study was to investigate the synergistic performance of the three core components (WC, PVTC, and EAHE) under peak thermal loads. Consequently, detailed humidity control strategies and crop-specific optimizations were beyond the scope of the present work. However, the hybrid system offers inherent and effective humidity management through its high air exchange capacity and controllability. With ACH values up to 14 in summer and adjustable dampers and fan speeds on all components, the system can prevent humidity buildup by continuously supplying fresh air and exhausting moist air.

5. Conclusion

Using renewable energy to achieve the proper temperature inside the greenhouse, without consuming energy from fossil fuels, is essential. In such a system, environmental pollution is not only reduced, but fossil fuel consumption is also greatly decreased. Given the necessity and important role of greenhouses in today's world, an experimental study was conducted at the experimental site to evaluate the use of available renewable energy sources to achieve a desirable temperature in the greenhouse. In this study, wind energy was harnessed by windcatchers, solar energy was harnessed by a photovoltaic-thermal chimney and panels, and geothermal energy was harnessed by buried pipes. The main goal of this study is to investigate the feasibility of achieving the desired temperature in greenhouses using renewable energy available at each site. The experiments were conducted at Shahid Bahonar University of Kerman (Kerman, Iran) in the laboratory during winter and summer. Different modes are considered to perform a comprehensive study. Each mode shows the renewable energy source used in the experiments. The results of this study were compared with those of similar studies, and the proposed system was determined to have a higher coefficient of performance.

To further confirm the experimental findings and ensure the system's reliability beyond the specific laboratory sample and climatic conditions of this study, a statistical analysis was performed using vector linear regression in the RapidMiner environment. This step was crucial in bridging the gap between specific experimental data and broader practical applications by setting up robust predictive models. The importance of this method lies in its ability to quantify the complex relationships between independent operational parameters and dependent performance variables, thereby proving that the extracted equations are valid and applicable to other conditions and climates. The analysis minimized the sum of squared errors and thereby confirmed the statistical soundness of the system's thermodynamics, enabling correct extrapolation of performance and optimization of control strategies. The results of this statistical evaluation proved high predictive accuracy, as shown by low Root Mean Squared Error (RMSE) values, which confirm the model's robustness in both cooling and heating modes.

Some of the important results are reported in the following:

- Comprehensive first- and second-law analysis showing energy balance closure below 5 % and competitive second-law efficiencies.
- Preliminary economic evaluation showing a simple payback period of 4.8-5.8 years for the small-scale system.
- Development and validation of robust Vector Linear Regression models with very low prediction errors (RMSE of 1.8 °C in summer and 0.5 °C in winter) for reliable performance prediction in different climates.
- Preliminary techno-economic evaluation showing a simple payback period of 4.8-5.8 years for the small-scale prototype.

In summer:

- By combining the windcatcher, photovoltaic thermal chimney, and earth-to-air heat exchanger, the greenhouse interior temperature decreases from 60.1°C to 39°C (i.e., 35.1%).
- With an air velocity entering the windcatcher of 6 m/s and a water mass flow rate of 0.10 kg/s, the highest air change is 14. The lowest air change, equal to 9, occurs at an air velocity of 4 m/s and a water mass flow rate of 0.15 kg/s.
- The maximum and minimum electricity power produced in the proposed system are equal to 139.3 W and 133 W, respectively.
- Using an earth-to-air heat exchanger in addition to the windcatcher and photovoltaic thermal chimney, reduces the inside temperature by about 17 %.
- At all hours, the ratio of consumed electricity is greater than that generated electrical power always exceeds consumed electrical power.

The regression model for the summer season proved a strong correlation between inputs and outputs, achieving a root mean square error of 1.8°C in predicting the indoor temperature. Furthermore, the model found fan speed and water flow rate as primary cooling factors and predicted the ratio of supplied electricity to consumed electricity with exceptional precision, as shown by a root-mean-square error of 0.06.

In winter:

- If the combined photovoltaic-thermal chimney and windcatcher are used, the greenhouse temperature reaches 22 °C. At that hour, the outside temperature was 4.5 °C, while the inside temperature had increased by 17.5 °C (389 % increase).
- If a combined windcatcher, photovoltaic thermal chimney, and geothermal energy system is used, the inside temperature increases by 15 °C (reaching 19.5 °C) compared with the outside air.
- The higher the air velocity exiting the windcatcher, the better the indoor temperature becomes. This is due to the increased suction of hot air from the photovoltaic-thermal chimney into the greenhouse, thereby increasing the air temperature inside the greenhouse.

Statistical during the winter season achieved high accuracy, with a root mean squared error of 0.5 in predicting the inside greenhouse temperature. A key finding from the regression coefficients was a positive association between fan speed and inside temperature (regression coefficient = +1.326), confirming that the system successfully switched to heating mode, in which the fan actively circulates warm air preheated by the photovoltaic thermal chimney and earth-to-air heat exchanger systems.

The findings of this study hold significant practical implications for greenhouse operators, agricultural engineers, and renewable energy practitioners. The proposed hybrid system offers a sustainable and cost-effective solution for greenhouse climate control, cutting dependence on fossil fuels while keeping best thermal conditions for crop production. This work contributes not only to renewable energy research but also to the broader goals of sustainable development, food security, and climate change adaptation in arid and semi-arid regions worldwide.

Although the present study provides strong experimental evidence under peak-load conditions and develops reliable predictive models, it has some limitations. The experiments focused on 4-hour peak windows rather than full diurnal cycles and did not include dedicated extreme-weather monitoring or long-term annual monitoring. A detailed CFD analysis was also outside the scope of this proof-of-concept work. Future studies will include comprehensive 24-hour and year-round experimental campaigns, full CFD simulation for flow optimization, and detailed life-cycle cost assessment on a commercial scale.

The experimental results are specific to the hot-arid climate of Kerman. However, the hybrid configuration offers strong adaptability. For instance, in high-humidity regions, evaporative pads can be replaced with dehumidifying media, and EAHE pipes naturally act as condensers, enabling moisture removal. In cold-dry climates, the EAHE provides pre-heating, the PVTC supplies solar heat, and the windcatcher functions as a controllable inlet. Adjustable dampers and fans on all components enable real-time optimization. With simple modifications (damper settings, pad type choice, minor piping adjustments), the system can keep effective performance across different climates.

Nomenclature

ACH	Air change per hour
C	Specific heat capacity (J/kg°C)
CHP	Combined Heating and Power
COP	Coefficient of Performance
E	Electricity (W)
EAHE	Earth-to-Air heat exchanger
FF	Cooling, Capacity
I	Current (Ampere)
$\dot{m}$	Mass flow rate (kg/s)
P	Power (W)
PVTC	Photovoltaic-thermal chimney
$\dot{Q}$	Heat transfer rate (W)
SECE	Solar electricity to consume electricity
SD	Standard deviation (%)
T	Temperature (°C)
$\dot{V}$	Volumetric flow rate (m3/h)
WC	Windcatcher
ΔT	Temperature difference (°C)

Subscripts

m	maximum
oc	Open circuit
sc	Short circuit
GH	Greenhouse
PV	Photovoltaic panel
in	input
out	output
k	K^{th} process

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Authorship contributions

Shiva Tahmasbpourafshar: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing. Kazem Jafarinaeimi: Conceptualization, Resources, Writing – Review & Editing, Supervision, Project administration. Hamid Mortezapour: Conceptualization, Writing – Review & Editing, Supervision. Saman Khalilzadeh: Conceptualization, Writing – Review & Editing, Supervision. Hossein Maghsoudi: Conceptualization, Writing – Review & Editing.

Data availability

The image datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics

There are no ethical issues with the publication of this manuscript.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used DeepSeek to enhance the grammar, clarity, and readability of the English text. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the published article.

Originality statement

The authors confirm that this manuscript is original, has not been published before, and is not currently under consideration for publication elsewhere. All sources used are properly cited, and the work has been conducted by ethical standards.

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