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Enhancing Efficiency and Power Output of a Typical Hybrid Photovoltaic Thermal System

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Abstract

The economy's expansion relies heavily on energy consumption, leading to an environmental imbalance marked by global warming, glacier melting, degradation of fertile land, and food shortages. To ensure the survival of humanity, a transition towards renewable resources becomes imperative. Despite having lower solar radiation conversion efficiency, photovoltaic panels offer significant utility. The present work addresses the current trend of enhancing the power output of photovoltaic systems through innovative approaches. In this study, we propose a hybrid photovoltaic system that combines the power generated by a photovoltaic panel with a turbine in a solar chimney. Our objective is to improve the overall efficiency and power generation capability of the system. To evaluate the hybrid system's performance, we conducted a comprehensive experiment with a reference photovoltaic panel under identical conditions. The experimental investigation involved monitoring power generation and efficiency over three days while considering various environmental factors, such as geometric parameters, dynamic parameters, solar radiation, temperature, and location. The overall power is developed via a Photovoltaic panel and the solar chimney system. Also, to create a more extensive system with a higher power rating, an Empirical model is established using the Theory of Experimentation. The empirical model is developed using the theory of experimentation. The mean percentage error between the measured and predicted value for the training dataset is 2.9957%, whereas the coefficient of determination is 0.9089. Also, the mean percentage error between the experiment and the predicted value is 1.174%, and the coefficient of determination is 0.9868, respectively. The empirical model generated can help different researchers create a more extensive system with a higher power rating. The results demonstrate that the proposed hybrid photovoltaic system consistently outperforms the reference panel across all three days of the study i.e., 12.5% daily average efficiency gain. The integration of passive cooling techniques, airflow dynamics, and the buoyancy effect facilitated by the chimney significantly contribute to the system's improved performance. The hybrid system exhibits higher efficiency during morning and evening periods, with peak power generation occurring in the afternoon.

Keywords: Photovoltaic panel, Solar Radiation, Passive cooling, Airflow, Buoyancy effects

1. Introduction

The energy consumption of a country significantly influences its economic growth. However, India's heavy reliance on conventional power plants for electricity generation has resulted in the country becoming the third-largest emitter of CO_2 [1], causing an environmental imbalance. This imbalance has led to various consequences such as a global rise in temperature, melting glaciers, desertification of fertile land, and food shortages. To ensure sustainable development, a transition to renewable energy sources is imperative. Many countries have already taken steps to promote renewable energy, and India, being the seventh-largest country [2], situated in the northern hemisphere between the equatorial and tropical of cancer, enjoys an abundance of sunshine throughout the year. Most parts of India receive approximately 2300 to 3200 sunny hours annually, with an average solar radiation of 5-5.5 kWh/m2/day [3].

In India, significant progress has been made in promoting the use of solar energy for both commercial and household purposes through policy modifications and subsidies [1]. These changes have encouraged research and development organizations, private companies, and startups to contribute to the development of solar energy in the country. The introduction of the National Solar Mission on January 11, 2010, has been instrumental in boosting solar energy generation in India. The mission aimed to produce 20 GW of clean energy by 2022, a target that was surpassed in 2018 [4]. As of November 20, 2020, the installed capacity stands at 36.9 GW, with 42 solar parks across India. Additionally, rooftop PV panels contribute 2.1 GW of energy. Presently, India generates 34.627 GW of solar power, including both rooftop and ground-mounted grid-connected systems, with the photovoltaic panel being the most commonly used technology for converting solar energy into electricity [5].

However, the conversion efficiency of solar radiation to electric energy using photovoltaic panels ranges from a mere 8% to 20%. [6] Research has shown that as the cell temperature increases by 1o C above the operating temperature, the efficiency decreases by 0.4% to 0.65%. Consequently, enhancing the efficiency of PV panels has been a focal point of research, including material studies and cooling techniques such as active cooling and passive cooling. Another approach to convert solar energy into electricity is through thermal systems. In 1982, Schlaich introduced the concept of a solar chimney, with a prototype installed in Manzanares, Spain [7] with a capacity of 50 kW. However, it was found that the efficiency of an updraft tower with a

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chimney height of 1000 m is only 1% [8] The efficiency of such systems can be improved by combining different techniques, such as integrating photovoltaic panels and thermal systems. [9], developed a hybrid system by integrating a solar updraft tower collector with photovoltaic and polycarbonate panels, resulting in an efficiency of 16 to 18% higher than conventional solar towers. [10] increased convective heat transfer using a transpired solar collector combined with waste heat, achieving a 2.5 times higher power output compared to conventional solar updraft power plants. [11] proposed a novel hybrid system that converts each mountain into a power plant, replacing the solar chimney with a hole in the mountain. The integration of the downhill side of the mountain with a solar collector exponentially increased power production. Abdullah et al. [12] developed a hybrid system combining solar cell technology and a solar storage collector for low-cost and efficient solar energy storage in households. The system demonstrated an overall efficiency of 63.02% under load conditions in the summer and 40.88% without load conditions.

Various studies have shown that integrating solar cells with thermal systems or adopting hybrid photovoltaic systems can significantly increase power generation efficiency compared to conventional systems. Ahmed et al. [13] conducted experiments to predict the performance of a hybrid PV system and observed a 44% increase in thermal efficiency and a 20% increase in electrical efficiency . Hasan et al. [14] demonstrated how using solar cells in a solar chimney system can raise the efficiency by 70%, with an electrical efficiency of 23.2%. Ahmed et al. [15] explored two different designs of hybrid solar chimneys and found that system (A) had higher thermal gain, while system (B) had a slightly higher daily average of electrical power.. Ahmed et al. [16] integrated solar chimneys and solar cells in a hybrid system and achieved an electrical efficiency of 10.5% while increasing power generation compared to conventional systems. Mohammad et al. [17] worked on heat response data collected from a PVT system, under normal conditions, with steady water acting as a coolant. Experimental and simulation values were compared and analyzed in the work.

Based on the literature review, it is evident that the efficiency of photovoltaic panels is relatively low. Researchers are exploring various techniques such as material analysis, passive cooling, and active cooling to increase the power output of PV panels. Chakrabarti et al. [18] worked on passive evaporative cooling technique to control the temperature rise of the PV module and enhancement in efficiency.

In this study, our primary objective is to propose a hybrid photovoltaic system that can enhance the overall efficiency compared to using standalone photovoltaic panels. The proposed hybrid PV system combines thermal and photovoltaic technologies, harnessing electricity from PV panels and utilizing the buoyancy effect of heated air passing through a turbine. Furthermore, the hybrid system provides passive cooling to the PV panels to enhance the efficiency. The experimentation is also validated by the development of an empirical model by using the Theory of Experimentation, taking into account geometric parameters, dynamic parameters, solar radiation, temperature, and location. This model aims to create a more extensive system with a higher power rating, thus improving the overall performance efficiency.

2. Methodology

A) Experimentation

Several methods exist for harvesting solar energy, but the most effective approach is through the use of photovoltaic panels. It is known that the efficiency of these panels decreases as temperature increases, prompting researchers to explore active and passive cooling techniques for improving their efficiency. In Figure 1, the upper surface of the system comprises the photovoltaic panel, which absorbs solar radiation and converts it into electricity. This surface also acts as the absorber plate, heating the air through energy radiated from the panel's back surface. The hot air then flows from the backside of the photovoltaic panel, serving as a passive cooling medium. The buoyancy of the hot air causes it to rise up the chimney, creating a hot wind that acts as a driving force due to the lower density of the hot air compared to the cold air in the surrounding environment. Consequently, the airflow energy is converted into mechanical energy at the base of the chimney and ultimately into electrical energy. Figure 1 illustrates the side view and front view of the proposed hybrid system, which consists of the following components:

1. **Wooden Box:** The upper surface of the wooden box is covered with a photovoltaic panel, while the other three sides are closed. The front portion of the wooden box is open (inlet) to the atmosphere, and the opposite end is connected to a chimney to enable air movement.
2. **Photovoltaic Panel:** The photovoltaic panel is mounted on the upper surface of the wooden box and absorbs solar radiation to convert it into electric energy.
3. **Chimney:** The inlet of the chimney is connected to the wooden box, and the other end is open to the atmosphere (outlet).
4. **Turbine:** A turbine is connected at the base of the chimney's inlet, allowing the kinetic energy of the airflow to be converted into electrical energy.

Figure 1 also provides the dimensions of the proposed hybrid system. The wooden box has a length of 1320 mm, a width of 750 mm, and a height of 300 mm. The inlet section, through which air enters, has dimensions of 750 mm in width and 220 mm in height. The chimney's height is 1800 mm, and its diameter is 127 mm, serving as the exit for the airflow. On the upper surface of the wooden box, a photovoltaic panel with dimensions of 1280 mm in length and 710 mm in width is mounted. The hybrid photovoltaic panel is completely sealed using heat-resistant tape to prevent any escape of hot air from the sides. Multiple temperature probes are placed on the upper and lower surfaces of both the hybrid and reference photovoltaic panels. These probes are connected to a multi-input data logger. Additionally, a digital anemometer measures the flow velocity through the chimney, and a Voltage Current multimeter is used to determine the power output of the solar panel. A pyrometer is employed to observe the intensity of solar radiation. Readings from all the mentioned devices are recorded at 15-minute intervals.

Figure 2 showcases the actual image of the proposed hybrid system. The main objective of this hybrid system is to increase the efficiency of electricity generation in relation to the photovoltaic panel. Alongside the proposed hybrid system, a reference photovoltaic panel is installed for comparison purposes. By comparing the electricity generated by the proposed hybrid system with the reference panel, the percentage increase in efficiency can be calculated. Both the reference photovoltaic panel and the one mounted on the proposed hybrid system are of the same make and specifications. Specifically, the BP Solarex Millennia Photovoltaic panel with model type MST-50 MV is utilized in this study. Figure 3 depicts the instruments employed during the testing process.

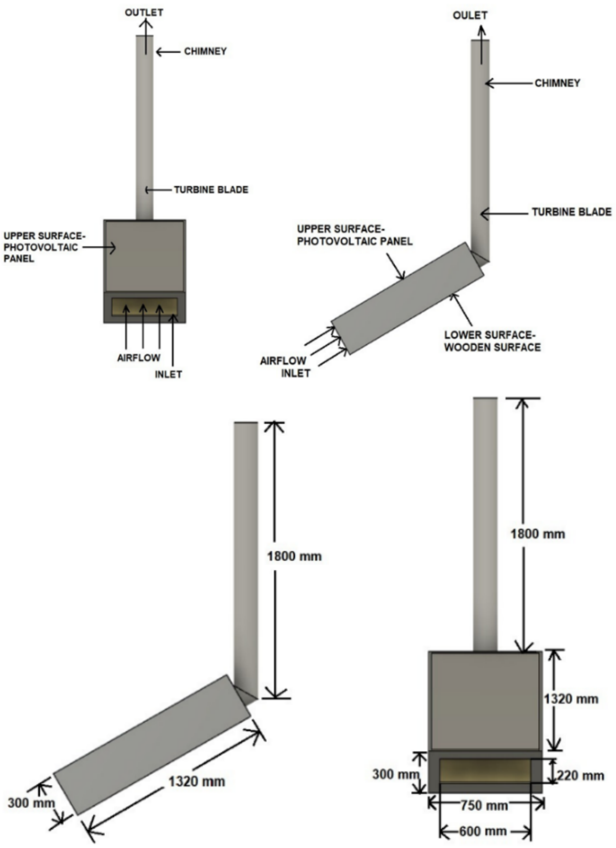

Fig. 1. Indicate the side & front view of the proposed system with Essential parts and dimensions considered in the present work.

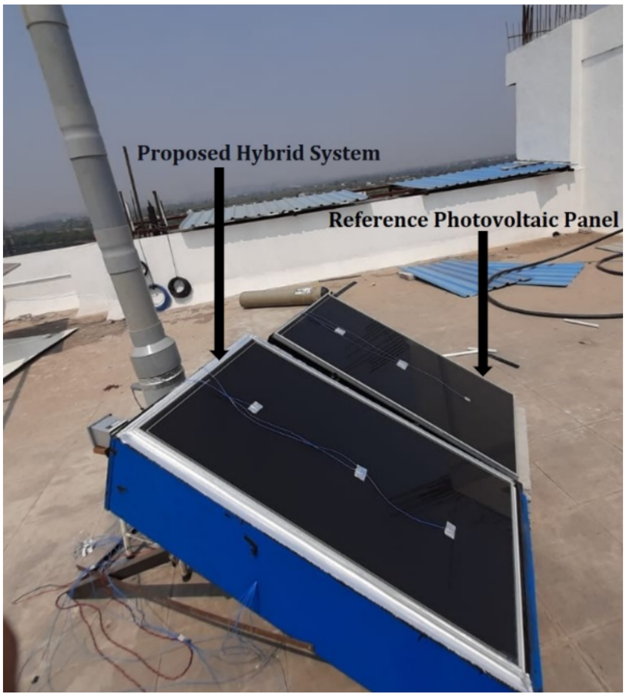

Fig. 2. The actual Image of the Hybrid System & Reference Photovoltaic Panel.

Fig. 3. indicate the instruments used during the testing.

B) Uncertainty Analysis

The accuracy of the measured values during the experimental study is important. Several factors affect the accuracy of the data. The related errors associated with the measuring instruments and the set-up is presented in this section.

Table 1. Reparents uncertainties detected in the measurement devices.

Measurement devices	Uncertainty Values
Temperature measurement	± 0.03 ºC (0 ~ 60 ºC)
Solar radiation flux meter	± 10 W/m^2 (0 ~ 1999 W/m^2)

PV measurements are subject to a number of errors. In the uncertainty analysis, the total error calculation of the errors that may occur while measuring a value can be done with Eq. 1 [19].

$$w_R = \pm[(\frac{\partial R}{\partial x1} w_{x1})^2 + (\frac{\partial R}{\partial x2} w_{x2})^2 + \cdots . + \left(\frac{\partial R}{\partial xn} w_{xn}\right)^2]^2 \quad (1)$$

Here, R is the size to be calculated, n independent variables affecting this size $x1$, $x2$, $x3$,…., xn , constant error amount of the independent variable $\pm wx1$, $\pm wx2$,$\pm wx$ 3,…., $\pm wxn$, the uncertainty of the magnitude R is expressed by $\pm wR$. With this uncertainty analysis, the independent variable causing the biggest error is determined.

C) Formulation of the model using Buckingham's pi theorem

In the present work, the power output (P) is considered as the dependent variable, also called the response variable, whereas the Area of the chimney (A_c), the velocity at the chimney inlet (V_c), density at chimney inlet (ρ_c), Area of PV panel (A_P), Area of duct (A_D), the height of duct (h), Time of testing (T), Solar radiation (I), ambient temperature (T_∞), Temperature on the upper surface of the panel (T_{PUS}), Temperature on the lower surface of the panel (T_{PBS}), Temperature on the surface of the duct (T_{DS}), Temperature at the Inlet of the chimney (T_C), Latitude (ϕ) and Longitude (ψ) are considered the independent variable. Table 8.1 indicate the Independent & Dependent variable with SI units for the Hybrid PV System.

Table 1. Indicate the dependent and independent variables with SI. Units.

S. N.	Variables	Symbol	Unit	Dependent/ Independent	Variable/ Constant
01	Power output	P	W	Dependent	Response Variable
02	Area of Chimney	(A_c)	M^2	Independent	Variable
03	Density at the inlet of the Chimney	(ρ_c)	Kg/m^3	Independent	Variable
04	Velocity at inlet of Chimney	(V_c)	m/s	Independent	Variable
05	Area of PV panel	(A_P)	M^2	Independent	Variable
06	Area of duct	(A_D)	M^2	Independent	Variable
07	Height of the duct	(h)	m	Independent	Variable
08	Time of testing	(T)	s	Independent	Variable
09	Solar radiation	(I)	W/m^2	Independent	Variable
110	Ambient temperature	(T_∞)	ºC	Independent	Variable
111	Temperature on the upper surface of the panel	(T_{PUS})	ºC	Independent	Variable
112	Temperature on the lower surface of the panel	(T_{PBS})	ºC	Independent	Variable
113	Temperature on the surface of the duct	(T_{DS})	ºC	Independent	Variable
114	Temperature at the Inlet of the chimney	(T_C)	ºC	Independent	Variable
115	Latitude	(ϕ)	rad	Independent	Variable
116	Longitude	(ψ)	rad	Independent	Variable

In the present investigation, 15 independent variables have been considered with one response variable. According to dimensional analysis, the system's total power output can be written as.

$$P = f\left(A_c, V_c, \rho_c, A_P, A_D, h, T, I, T_\infty, T_{PUS}, T_{PBS}, T_{DS}, T_C, \phi, \psi\right) \quad (2)$$

From the parametric study, it is observed that the number of Pi terms will be 12. Thus, the dependent pi-term can be assumed as a function of 12 independent pi-terms.

$$\pi_d = f\left(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8, \pi_9, \pi_{10}, \pi_{11}, \pi_{12}\right) \quad (3)$$

Therefore, using Buckingham's pi theorem of dimensionality, we will get as follows;

$$f\left[\left(\frac{P}{A_c\rho_c V_c{}^3}\right)_{\pi_1}\left(\frac{A_P}{A_c}\right)_{\pi_2}\left(\frac{A_D}{A_c}\right)_{\pi_3}(\phi)_{\pi_4}(\psi)_{\pi_5}\left(\frac{h}{\sqrt{A_c}}\right)_{\pi_6}\left(\frac{V_c T}{\sqrt{A_c}}\right)_{\pi_7}\left(\frac{T_\infty}{T_C}\right)_{\pi_8}\left(\frac{T_{PUS}}{T_C}\right)_{\pi_9}\left(\frac{T_{PBS}}{T_C}\right)_{\pi_{10}}\left(\frac{T_{DS}}{T_C}\right)_{\pi_{11}}\left(\frac{I}{\rho_c V_c{}^3}\right)_{\pi_{12}}\right] = 0 \quad (4)$$

The product of the π terms will also be a dimensionless number. This property is used to achieve further reduction of the number of variables. Thus, few π terms are formed by logically taking the product of a few other π terms as given below.

Geometric term related to Solar radiation;

$$\pi_1 = \frac{I}{\rho_c V_c{}^3} \quad (5)$$

Geometric term related to temperature;

$$\pi_2 = \frac{T_\infty T_{PUS} T_{PBS} T_{DS}}{T_c^4} \quad (6)$$

Geometric Term related to Shape of the system;

$$\pi_3 = \frac{A_P A_D h}{A_c^{5/2}} \quad (7)$$

Geometric term related to Volume of heating;

$$\pi_4 = \frac{V_c T}{\sqrt{A_c}} \quad (8)$$

Geometric term related to the orientation of system;

$$\pi_5 = \phi\psi \quad (9)$$

Thus, in substitution equation (5 to 9) in equation (4), we get

$$f\left[\left(\frac{P}{A_c\rho_c V_c^3}\right)\left(\frac{I}{\rho_c V_c^3}\right)\left(\frac{T_\infty T_{PUS}T_{PBS}T_{DS}}{T_c^4}\right)\left(\frac{A_P A_D h}{A_c^{5/2}}\right)\left(\frac{V_c T}{\sqrt{A_c}}\right)(\phi\psi)\right]=0 \quad (10)$$

$$P = K\left(A_c\rho_c V_c^3\right)\left[\left(\frac{I}{\rho_c V_c^3}\right)^{\theta_1}\left(\frac{T_\infty T_{PUS}T_{PBS}T_{DS}}{T_c^4}\right)^{\theta_2}\left(\frac{A_P A_D h}{A_c^{5/2}}\right)^{\theta_3}\left(\frac{V_c T}{\sqrt{A_c}}\right)^{\theta_4}(\phi\psi)^{\theta_5}\right] \quad (11)$$

Equation 11 indicates the generalized model to estimate the power output of the Hybrid PV System, where K, θ_1, θ_2, θ_3, θ_4 and θ_5 are unknown coefficients that can be calculated using the theory of Experimentation.

3. Result and Discussion

In this study, a hybrid photovoltaic system has been proposed that surpasses the performance of a photovoltaic panel by incorporating passive cooling techniques, airflow dynamics, and buoyancy effects. The hybrid system combines power generation from the photovoltaic panel with the turbine in the solar chimney, resulting in enhanced power output. To evaluate its effectiveness, we conducted a comparison with a reference photovoltaic panel under identical conditions. The results consistently demonstrate that the proposed hybrid photovoltaic system outperforms the reference photovoltaic panel throughout the three-day study. Notably, the percentage increase in efficiency is highest during the morning and evening periods but decreases during the afternoon. Conversely, both the proposed hybrid system and the reference panel exhibit peak power generation in the afternoon, with lower power output during the mornings and evenings.

Figures 4-6 provide a clear comparison of power generation between the Proposed Hybrid System and the Reference Photovoltaic Panel, as well as the percentage increase in efficiency of the hybrid system. The scientific investigation was conducted on the terrace of MIT School of Engineering, with readings taken at 15-minute intervals between 10:00 AM and 5:00 PM. On day 1 (Figure 4), the peak power generated occurred at 12:45 PM, reaching 66.56 W. Day 2 (Figure 5) and day 3 (Figure 6) recorded peak power values of 66.71 W and 59.609 W, respectively.

Throughout day 1, the system's efficiency exhibited a declining trend from approximately 13% at 10 AM to around 9% between 12 PM to 2:30 PM. However, it started to rise again and reached its peak of 21% at 5 PM. Concurrently, power generation gradually increased from approximately 60 W and 56 W at 10 AM to 66 W and 61 W at 12:30 PM for the solar hybrid system and reference panel, respectively. Overall, the hybrid system generated 3.71 W to 7.37 W more power than the reference system on day 1.

Day 2 displayed a similar pattern of power generation and increased efficiency. At 10 AM, the power generation for the hybrid system and reference panel was 18 W and 13 W, respectively, with an increase of 35%. The power generation peaked at noon, reaching 67 W and 62 W for the hybrid system and reference panel, respectively, representing the highest values observed across the three days. Subsequently, power generation gradually declined, with a drop at 4 PM to 26 W and 21 W for the hybrid system and reference panel, respectively. The percentage increase in efficiency experienced a sharp rise from 4 PM to 5 PM, peaking at approximately 25%. Simultaneously, power generation reached its lowest point during the investigation, at 15.5 W and 12.5 W for the hybrid system and reference panel, respectively. On day 2, the hybrid system generated 6.52% to 35.15% more power than the reference system.

Day 3 exhibited frequent fluctuations in power generation and the percentage increase in efficiency due to dynamic weather conditions. Power generation at 10 AM was 44 W and 40 W for the hybrid system and the reference panel, respectively, peaking at approximately 59 W and 53 W between 12:45 PM and 2:15 PM. Afterward, there was a steep decline until the end of the duration. The percentage increase in efficiency also had two distinct peaks during the same period, one at noon and the other at 2:30 PM, with values of 35.5% and 32%, respectively. Similarly, the increase in power generation in the proposed hybrid system ranged from 3.04 W to 7.28 W.

The daily average percentage increase in efficiency for the proposed hybrid system was as follows: Day 1 (10.88%), Day 2 (13.16%), and Day 3 (13.52%). The average percentage increase over the three days of investigation was 12.52%. Consequently, we conclude that the proposed hybrid system exhibits greater efficiency in converting solar radiation into electrical energy compared to the photovoltaic panel, thanks to the passive cooling provided by the airflow beneath the PV panel and the buoyancy effect enabled by the chimney.

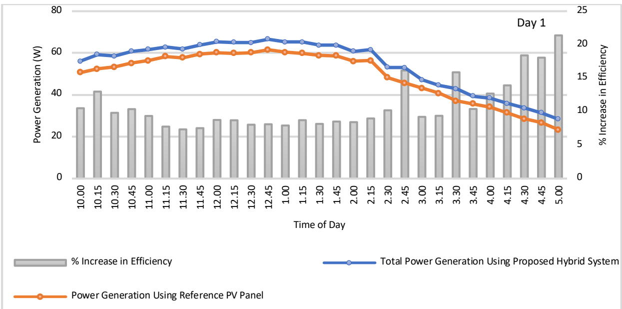

Fig. 4. Comparison of Power generation using the Proposed Hybrid System and Reference Photovoltaic Panel and percentage increase in efficiency.

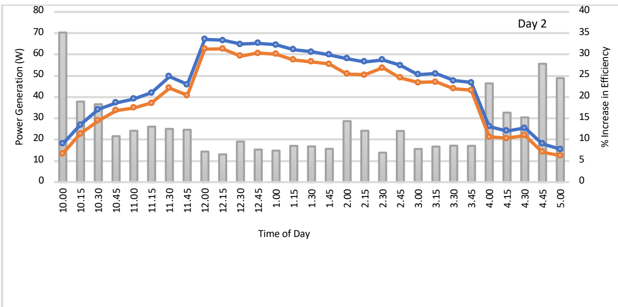

Fig. 5. Indicates the comparison of Power generation using the Proposed Hybrid System and Reference Photovoltaic Panel and the percentage increase in efficiency.

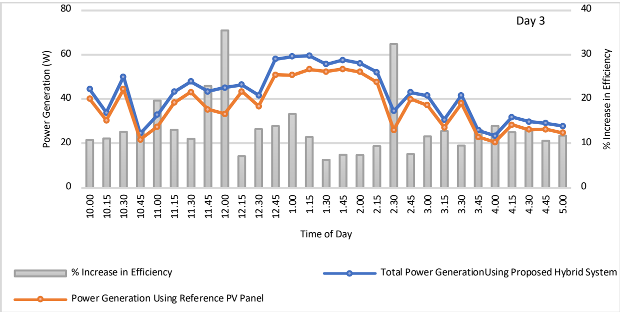

Fig. 6. Indicates the comparison of Power generation using the Proposed Hybrid System and Reference Photovoltaic Panel and a percentage increase in efficiency.

Further, the experimental dataset is divided into training and testing datasets. Additionally, Equation 10 indicates the generalized model to estimate the power output of the Hybrid PV System, where the value of the coefficients are as follows K=1.0049, θ_1 =0.01, θ_2 =-0.0009, θ_3 =0.9832, θ_4 =0.045, and θ_5 =0.1875, respectively, the empirical model generated can help different researchers to create a more extensive system with a higher power rating. The mean percentage error between the measured and predicted value for the training dataset is 2.9957%, whereas the coefficient of determination is 0.9089. Figure 7 indicates the comparison of Power generation using the proposed hybrid system and the predicted power utilizing the Theory of Experimentation, which suggests a smooth fit between the measured and predicted value. The mean percentage error between the experiment and the predicted value is 1.174%. The coefficient of determination is 0.9868, respectively, indicating a perfect fit between the experiment and the predicted value, which can also be observed using Figure 8. Thus, it is evident from Figures 7 &8 that the empirical model developed using the theory of experiment can be used to design and develop a hybrid system for higher power ratings.

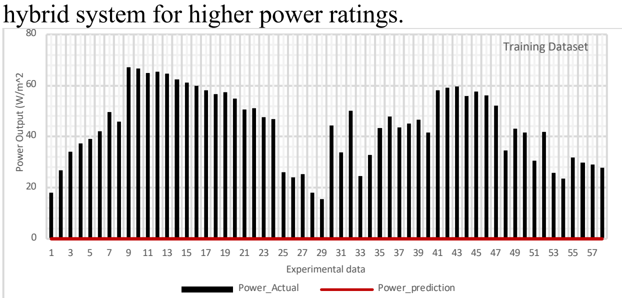

Fig. 7. Comparison of Power generation using the Proposed Hybrid System and the predicated power utilizing the Theory of Experimentation.

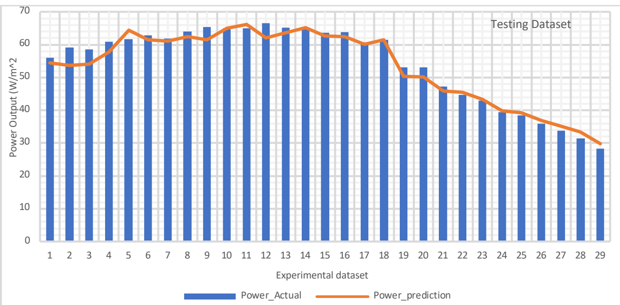

Fig. 8. Comparison of Power generation using the Proposed Hybrid System and the predicated power utilizing the Theory of Experimentation.

Furthermore, the empirical model, considering various environmental factors, confirms the accuracy and reliability of the experimental results.

5. Conclusion

In this study, we proposed a hybrid photovoltaic system that combines the power generated by a photovoltaic panel with a turbine in a solar chimney. The goal was to enhance the system's power output compared to a standalone photovoltaic panel. To evaluate the system's performance, we conducted comprehensive experiments. Our findings consistently demonstrate that the hybrid system outperforms the reference panel.

a. The superior performance of the hybrid system can be attributed to several key factors. Firstly, the incorporation of passive cooling techniques effectively regulates the temperature of the photovoltaic panel, optimizing its efficiency and increasing power output. Secondly, the airflow dynamics within the chimney efficiently harness the rising hot air, converting it into mechanical and electrical energy that would otherwise be wasted in a conventional panel. Lastly, the buoyancy effect facilitates the circulation of air, dissipating heat and improving the overall efficiency of the system.
b. The experimental data collected over three days consistently demonstrate the higher efficiency of the hybrid system compared to the reference panel. The percentage increase in efficiency is particularly significant during the morning and evening periods, while power generation peaks in the afternoon for both systems. Based on the average percentage increase in efficiency over the three-day investigation, we can confidently conclude that the proposed hybrid system effectively converts solar radiation into electrical energy. The integration of passive cooling techniques and the utilization of the chimney's buoyancy effect contribute to its enhanced performance.
c. The empirical model is developed using the theory of experimentation. The mean percentage error between the measured and predicted value for the training dataset is 2.9957%, whereas the coefficient of determination is 0.9089. Also, the mean percentage error between the experiment and the predicted value is 1.174%, and the coefficient of determination is 0.9868, respectively.
d. It is important to note that the specific design and configuration of the hybrid system, including chimney dimensions, airflow control, and cooling mechanisms, play a critical role in optimizing its performance. Further research and development in these areas hold great potential for advancing hybrid photovoltaic systems, leading to improved efficiency and increased power output. This research contributes to the advancement of hybrid photovoltaic systems and highlights the importance of system design and configuration for optimizing performance.
e. The future work may include the testing of the hybrid system on all year changing sky conditions. To investigate the impact of the more inherent design parameters, Computational Fluid Dynamics (CFD) programs may be created. The results indicate that installation of the hybrid energy system is more economical than the conventional electricity network.

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