Numerical Performance Assessment of Uzbekistan Climatic Conditions on a Water Based Flat Plate PVT System

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Abstract. The exploitation of solar energy in the most efficient way will continue to be the staple of sustainable energy policies, particularly, in solar-rich areas, such as Tashkent, Uzbekistan. Photovoltaic/thermal (PVT) systems are appealing concept of dual-generation having the simultaneous generation of electricity and heat. An in-depth dynamic simulation was done on a calibrated model and compared a normal photovoltaic (PV) panel and a water-cooled PVT system after 100 days with synthetic hourly climate data. The analysis indicates that the cell temperatures of the PV panel were observed to be in excess of 50 ^{0}C, a fact that adversely affected its electrical efficiency. Comparatively, there was active cooling in the PVT system-so the cell temperatures were between 30 ^{0}C to 45 ^{0}C, which led to better electrical performance- as high as 6% better than that of the PV system. Also, the PVT unit discharged high heating capacity with output temperatures of water outlet in excess of 60 ^{0}C as well as maximum thermal power production of 1.2 kW. The results indicate the energy savings of the integrated thermal management in solar panels and point out the capability of PVT systems in providing heating and electric power requirements. The findings favour the increased application of the hybrid solar technologies to achieve the improved energy production and sustainability of buildings and infrastructures under various climates.

1 Introduction

Photovoltaic/thermal (PV/T) systems provide an intelligent and effective method of maximizing solar energy utilization to realize the benefits of 2 technologies in one, that is, photovoltaic modules that produce electricity and thermal collectors that produce usable thermal energy. The two functions aid in enhancing the overall energy generation levels and counter a shared problem of the traditional PV systems; loss of performance to overheating. Flat plate systems with water cooling medium are particularly viable in places such as Uzbekistan where the solar radiation is great and electricity and heating systems are both highly needed at residential and industrial levels. Researchers are becoming more and more dependent on numerical modeling to gain insights into an efficient performance of the given

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systems. It enables one to analyze a broad scope of conditions with a lot of flexibility and at a relatively low cost without necessarily having to do physical testing. The rate of mass flow of the circulating water is one of the factors that have a very strong impact on the behavior of the system. As an example, doubling it to 0.03 kg/s has been demonstrated to better cool the PV surface to more effectively retain electrical efficiency, although this reduces the outlet water temperature a little [1]. Likewise, doubling the flow (20-50 kg/h) can enhance thermal and electrical power by 22 and 1.5 respectively, but it can decrease thermal exergy by approximately 40 percent [2]. The quantity of the sun radiation is also critical. An increase in irradiance will increase the influx of thermal energy, but might impair or reduce the electrical energy in the panel in case it must overheat and does not cool sufficiently [3, 4]. The aspects of system design can also amplify energy collection especially through the use of glass covers, heat absorbing fins and good geometries of absorber plates. Thermal efficiencies as high as 54.25% [5, 6] have been achieved in some designs having 40 fins. The selection of the heat transfer fluid is another field that is getting some attention. Nanofluids, particularly those prepared with MWCNTs have been very promising when one considers their high thermal conductivity as well as light absorption capacity. MWCNT nanofluids in a concentration of 0.05 wt % had shown a 14 percent growth in the collector efficiency [7, 8]. Experimental works prove that the absorption may be incremented through the concentration of particles and layer thickness, but only up to the thickness saturation stage [8, 9]. Besides, MWCNT nanofluids compared to copper oxide-based ones have shown better and improved thermal transport, especially at varying temperatures [9]. This area of work has also developed more lately in Uzbekistan. To be more specific, a thin-film PV/T module designed and engineered on real conditions demonstrated a 6.3 ^{0}C decrease in surface temperature, and a 10.3 percent increase in the electrical power produced in comparison to a standalone PV controlled system [10]. These results were confirmed with numerical modeling and CFD simulation performed in Python where accuracy levels reached high values ($R^2 = 0.99$) [11]. Overall, the majority of the current simulations are based on commercial software products. The present paper proposes a Python numerical model specially devised to evaluate the performance of a flat PV/T water-based system at the climatic conditions of Uzbekistan (Tashkent). The aim is to make available a powerful, flexible and transparent optimization tool to fine tune important system parameters.

2 Methodology

2.1 System Description and Mathematical Modelling

The evaluated PV/T system is the flat-plate water-based hybrid collector that, on the one hand, produces electricity but, on the other hand, also captures thermal energy sources due to solar radiation. It is based on a standard crystalline silicon PV module placed on the surface of a thermo conductive absorber plate and with a serpentine channel of water flowing beneath it. Main elements of the configuration are: (i) a PV module, (ii) an absorber plate made of copper, (iii) transparent glazing layer and (iv) a water circulation loop corresponding to the inlet flow and the outlet flow connected to a storage tank. The simulation model replicates a PV/T collector operating under realistic summer climatic conditions of Tashkent, with solar irradiance ranging up to 900 W/m², ambient temperatures fluctuating between 272 K and 284 K, and variable wind speeds (0.2–6.0 m/s). Climate parameters were input hourly for 100 consecutive days to reflect transient effects in energy exchange. The Climate data for 100 days of Tashkent given in Fig.1.

The system consists of two main configurations:

Conventional PV Module: A flat-plate monocrystalline silicon PV panel rated at 255 W under Standard Test Conditions (STC), composed of 60 series-connected cells.
Flat-Plate PV/T Collector: This system incorporates both PV module and a water-cooled channel in the backside. The cooling mechanism using water has two functions, lowering the operating temperature of the PV cell and reclaiming thermal energy to be utilized in the domestic or industrial way.
A schematic layout of the flat-plate PV/T system includes the transparent cover, the photovoltaic layer, a thermal absorber (typically aluminum or copper), and a serpentine or rectangular water channel. The inlet and outlet fluid temperatures are monitored to calculate heat transfer efficiency.

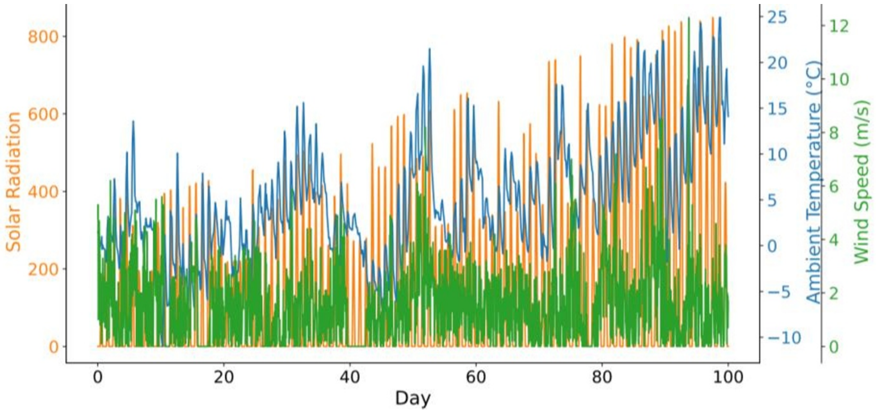

Fig.1. Climate Data for Tashkent (First 100 Days).

2.2 Specifications for PV Modules and an Electrical Modeling Method

A commercially available crystalline silicon photovoltaic module with a nominal power rating of 255 W under Standard Test Conditions (STC) is used in this work to model the photovoltaic system. Because of its dependability, advanced technology, and steady electrical behavior, this kind of module is frequently used in real-world solar energy applications. The module can achieve the necessary operating voltage for both standalone and grid-connected systems because it is made up of 60 solar cells connected in series. The numerical modeling and performance assessment used in this study are based on the electrical and thermal characteristics of the chosen PV module. Table 1 provides a thorough overview of the important datasheet parameters utilized in the simulation.

Table 1. The simulation's crystalline silicon photovoltaic module's electrical and thermal specifications under Standard Test Conditions (STC).

Parameter description	Value
Total number of series-connected cells (Ns)	60
Nominal maximum power output at STC	255 W
Temperature coefficient of current (k_i)	0.00471 $A \cdot K^{-1}$
Temperature coefficient of voltage (k_v)	$-0.122\ V \cdot K^{-1}$
Voltage at maximum power point (Vmp)	31.43 V
Current at maximum power point (Imp)	8.20 A
Open-circuit voltage (Voc)	38.09 V

Short-circuit current (Isc)	8.72 A
Nominal operating cell temperature (NOCT)	48 ± 2 °C

The aforementioned parameters, which were taken straight from the manufacturer's datasheet, are crucial for accurately depicting the PV module's electrical behavior under various operating circumstances. When modeling temperature-dependent effects and forecasting actual operating performance, these values are especially crucial.

Numerous mathematical and circuit-based models have been proposed in the literature to estimate the electrical output characteristics of photovoltaic modules. The single-diode model has been widely used among these because it strikes a balance between reasonable accuracy and ease of computation. By depicting the basic physical processes taking place within the semiconductor junction, this model successfully captures the nonlinear current–voltage (I–V) behavior of a photovoltaic cell.

A current source that represents the photo-generated current, a diode that accounts for the p–n junction behavior, a series resistance that simulates internal ohmic losses, and a shunt resistance that represents leakage currents make up the equivalent electrical circuit of the single-diode model. Fig. 2 shows the schematic diagram of this equivalent circuit.

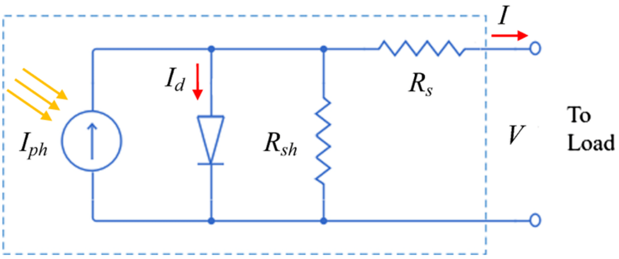

Fig.2. The single-diode PV model's equivalent electrical circuit representation.

The output current of the PV module can be calculated as the difference between the generated photocurrent and the loss components related to the diode and shunt resistance by using Kirchhoff's current law on the equivalent circuit depicted in Fig. 2.

The PV module's output current I is determined by:

$$I = I_{ph} - I_D - \frac{V+IR_S}{R_{sh}} \tag{1}$$

where I_{ph} stands for the photo-generated current, I_D for the diode current, R_s for the series resistance, and R_{sh} for the shunt resistance.

According to the Shockley diode equation, the diode current I_D can be written as follows:

$$I_D = I_s\left[exp\left(\frac{V+IR_S}{aN_sV_T}\right) - 1\right] \tag{2}$$

The number of series-connected cells in the module is represented by N_s, the diode’s reverse saturation current by I_s, the diode ideality factor by a, and the thermal voltage by V_T in this expression.

The PV cell’s operating temperature determines the thermal voltage V_T, which is described as:

$$V_T = \frac{kT}{q} \tag{3}$$

where T is the absolute cell temperature in Kelvin, q is the elementary charge of an electron (1.602×10^{-19} C), and k is the Boltzmann constant (1.38×10^{-23} J/K).

The full nonlinear current-voltage relationship of the PV module based on the single-diode model can be found by replacing Equation (1) with Equations (2) and (3).

$$I = I_{ph} - I_s\left[exp\left(\frac{V+IR_s}{aN_sV_T}\right) - 1\right] - \frac{V+IR_s}{R_{sh}} \qquad (4)$$

Equation (4) can be solved to determine the output of the module.

2.3 Model Assumptions

To simplify the model without losing fidelity, the following assumptions were made:

- Steady-state operation at each hour
- One-dimensional (1D) heat flow in the collector layers
- Constant heat transfer coefficients
- Negligible radiative losses due to glazing
- Uniform temperature distribution across each layer
- Neglecting the effects of thermal contact resistance

2.4 Energy Flow Modelling

The total solar energy incident on the PV module is calculated as:

$$Q_{solar} = G(t) \cdot A \qquad (5)$$

where *G(t)* is the time-dependent solar irradiance (W/m^2), and A is the collector surface area (m^2).

Electrical Output:

The electrical efficiency of the PV module depends on its operating temperature and is expressed as:

$$\eta_{elec}(T_c) = \eta_{ref}\left[1 - \beta(T_c - T_{ref})\right] \qquad (6)$$

$$P_{elec}(t) = \eta_{elec}(T_c) \cdot G(t) \cdot A \qquad (7)$$

Where:

η_{ref} - is the efficiency at reference temperature (typically 25°C); β - is the temperature coefficient of efficiency (≈ 0.0045/K for silicon); T_c -is the PV cell temperature in K; T_{ref} = 298.15 K.

The cell temperature Tc is estimated using the NOCT approximation:

$$T_c = T_{amb} + \left(\frac{NOCT-20}{800}\right) \cdot G(t) \qquad (8)$$

Thermal Output

The thermal energy transferred to the fluid is given by:

$$Q_{th}(t) = \dot{m} \cdot c_P \cdot (T_{out} - T_{in}) \qquad (9)$$

To solve for T_{out}, an energy balance over the water domain is applied:

$$\frac{dT_W}{dt} = \frac{hA(T_b-T_W)-\dot{m}\cdot c_P\cdot(T_W-T_{in})}{\dot{m}\cdot c_P} \qquad (10)$$

where:

T_W-mean fluid temperature; T_b-absorber bottom surface temperature; h-convective heat transfer coefficient (empirical or Nusselt-based)

2.4.1 Backplate Energy Balance

The backplate receives energy from the PV module and loses it to the flowing fluid and surroundings:

$$Q_b = Q_{solar}(1 - \eta_{elec}) - Q_{loss} \tag{11}$$

$$Q_{loss} = U_{loss} \cdot A \cdot (T_b - T_{amb}) \tag{12}$$

3 Simulation Results

This section presents the results from both the simplified analytical model and the dynamic simulation using Python. The focus is on comparing the energy performance of conventional and aerogel-based insulation systems under different climatic conditions.

3.1 Numerical Implementation

All the modeling is performed using Python. The simulation lasts 2400 hourly time steps (100 days) with synthetic climate data of controlled variability:

- Solar Radiation: Normally distributed around 500 W/m²
- Ambient Temperature: Ranging 273–318 K
- Wind Speed: Mean 2.5 m/s, capped at 12 m/s

The solver evaluates PV and PVT behavior at each time step. In thermal modeling, the calculation of heat extraction is done using the inlet and outlet fluid temperatures. The electrical model uses voltage and current performance correction with reference to temperature.

The efficiency of the system, the total energy yield and the comparative measures are computed and stored in arrays to be processed later. Final products are I-V and P-V characteristics of both systems, dynamic plots of output power, panel temperature and cumulative energy gain.

3.2 Simulation Results and Comparisons

The above equations were used in the simulation with a synthesized data that was used to represent the first 100 days of climate in Tashkent. It was observed and compared as follows:

Panel Temperature Trends: Temperature at the uncooled PV system increased by up to 60 ^{0}C during the peak radiation hours hence decreasing electrical efficiency. On the other hand, the active cooling of PVT panel resulted in lower operation temperatures ranging between 25-50 ^{0}C.

Electrical Output: The PVT panel performed 3-6 above the standalone PV panel on average about electrical output. The cooling process enhanced the voltage output and neural degradation was minimized.

Thermal Output: Thermal energy was recovered between 0.6 and 1.1 kWh/day and applicable in water heating.

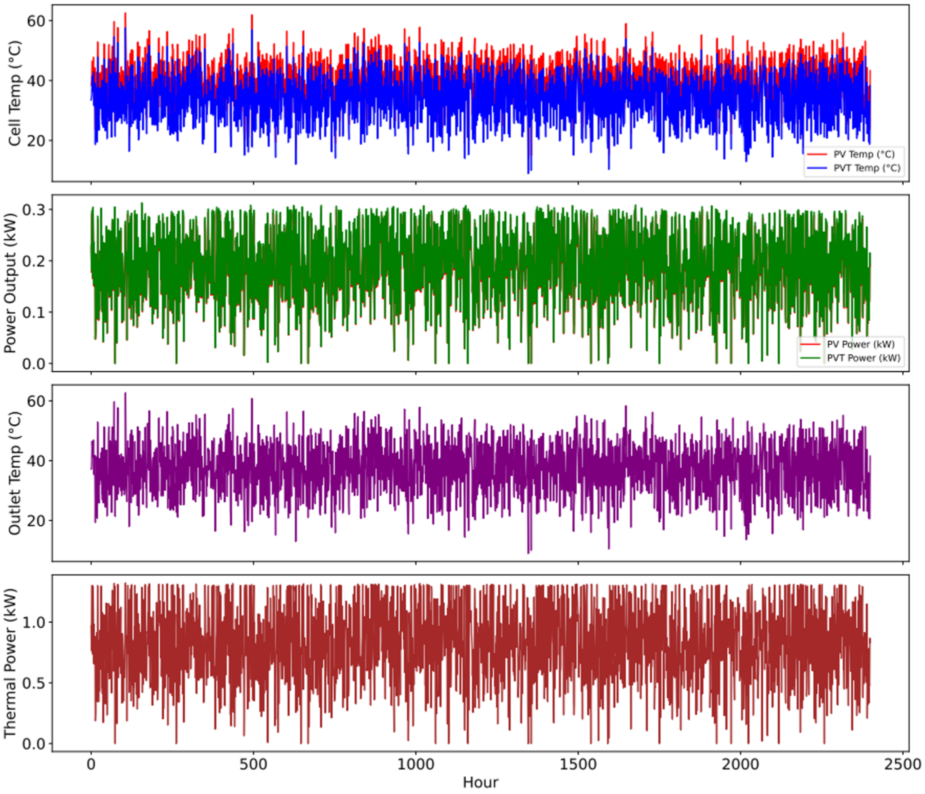

Fig.3. Output parameters comparison of PV and PV/T panel.

4 Simulation Results and Comparison

This part delivers an in-depth investigation of a dynamic simulation finding between the commonly used photovoltaic (PV) system and its counterpart, the photovoltaic/thermal (PVT) system (which is based on water-cooling). Synthetic hourly weather data (100 days, 2400 hours) characterizes the climate of Tashkent and serves as a model to carry out the analysis. The primary performance indicators of the system such as the temperature of cells, the electrical power output, water outlet temperature, and the recovery of thermal energy are examined in order to determine the advantage of active cooling of the solar systems.

4.1 Cell temperature behaviour PV and PVT

The first subplot indicates the hourly change of the temperatures of solar cells of the conventional PV configuration and the PVT water-cooled variant. As observed in the red trace, standalone PV system can exceed the temperature of more than 50 C most of the time particularly during peak sun hours. In contrast, the PVT system, shown in blue, maintains a significantly lower temperature range, typically between 30°C and 45°C. This is a direct result of the continuous removal of excess heat by the circulating coolant in the PVT system. The lower operating temperature observed in the PVT system has important implications. It is well-known that PV efficiency decreases with increasing temperature due to effects such as higher series resistance and reduced open-circuit voltage. Therefore, cooling the panel surface through an integrated thermal system not only protects the module but also ensures higher conversion efficiency during hot and sunny conditions. This makes PVT systems more reliable and efficient in regions with high solar irradiance like Uzbekistan.

4.2 Electrical Power Output Comparison

In the second subplot, the electrical power output profiles of both systems are compared over time. PVT panel is found to have better performance than the PV panel particularly at midday where temperatures are highest. Although during these times, the output will slightly decrease in comparison to the conventional PV system, the PVT panel will continue its higher, and more stable output. It is found that the PVT system mostly is beyond 0.27 kW of power generation whereas the PV panel remains slightly less than the required. This repeatable electrical upper edge can be ascribed to the reduced panel temperature that comes about because of the cooling effect in the PVT system pushing the panel temperature nearer its ideal working point. The PVT configuration helps lower the temperature effects of degradation so the solar cells can work at closer to Standard Test Conditions (STC), a reference point to define rated power output.

4.3 Water Outlet Temperature in PVT System

The third side plot displays the thermodynamic feature of the PVT system as it illustrates the fluctuation of the outlet water temperature with the flow of time. Outgoing water temperature varies between about 25 o C and over 60 o C with respect to the level of solar irradiance and ambient conditions. Such values can be considered rather encouraging in terms of real life usage, in particular, at home.

This result leads to the fact that the PVT system has not only cooled the PV panel. It is also advantageous in thermal energy that can be utilized in hot water, space heating or even in industrial processes where the heat-needs are of low- to medium-grade. Such a multi-purpose will result in a more energy efficient and cost-effective system as a whole and a viable one when it comes to sustainable and integrated building design.

4.4 Thermal Energy Output of PVT System

The fourth subplot concentrates on thermal energy that is withdrawn by the PVT system. The amount of power generated (thermal) varies considerably throughout the simulated time and its maximum value is approximately 1.2 kW. Those variations are related closely to changes in solar irradiance and surrounding temperature. The thermal energy is consistently produced more than the electricity output on average. This fact underlines the importance of such cogeneration systems as PVT. Being able to generate electricity and heat, the device makes better use of the solar energy coming in compared to standalone PV modules. The need to have electricity, and thermal energy makes such integrated solutions especially desirable in areas where such energy is seasonal. In addition, any thermal energy captured may be stored, or deployed in absorption cooling systems further enhancing year-round operation of the system.

5 Conclusion

This paper would analyze and compare the output of a typical photovoltaic (PV) system and hybrid photovoltaic/thermal (PVT) system on the climate conditions of Tashkent on a 100-day basis with one-hour synthetic weather reports. Creating and simulating a thermoelectric model using Python helped us to see the nature of these systems when it came to cell temperature, electrical output and thermogenic energy generation. One of the most important findings is that the PVT system kept the panel temperatures much lower than the conventional PV panel. While the temperature of the PV panel often climbed above 55–60°C during sunny hours, the PVT panel—thanks to its cooling system—operated in a safer and more efficient range, around 30–45°C. This reduced temperature prevents the system to operate more effectively because the high temperatures are known to decrease the electrical performance of solar cells. The PVT system was also a clear winner in terms of electrical power generation. The difference between PV and PVT might be insignificant on an hour-by-hour basis (approximately 36 percent more power than PV in the PVT), but in the long term, this will come to represent a considerable gain. The cooling system facilitated the PVT panel to offer a more stable voltage and overall functioning in large hot environments. One more significant advantage of the PVT system is that it does not only generate electricity, but it also gathers thermostatic energy. The water that is used to cool the panel is heated and can attain temperatures of more than 60°C which could be utilized in heating household water or even heating structures. The PVT system generated higher amounts of thermal energy on average than electrical and reached peaked amounts of 1.2 kW. The PVT system is far more efficient in a combination of both sources of energy electrical and thermal. This comes in particularly handy in areas such as Uzbekistan which has a lot of sunshine and also seasonally where heating is required. PVT is a great option to consider in energy-efficient buildings and sustainable urban planning since the technology allows obtaining both electricity and hot water simultaneously.

In conclusion, Tashkent is a sunny area where the PVT system can greatly increase the level of solar energy. Not only does it enhance the power output, but also it harnesses the precious heat energy. The work in the future may be based on testing these systems under the real conditions and investigating the ways of their implementation into smart buildings in order to fully utilize solar energy.

References

1. A. S. Kurhade, E. Amruth, P. S. Joshi, et al., Enhancing Flat-Plate Solar Collector Efficiency: A Numerical Study, J. Mines, Metals Fuels, **73**, 4, (2025).
2. S. T. A. Al-Aridhee and M. Moghiman, Yearly Energy, Exergy, and Environmental (3E) Analyses of a Photovoltaic Thermal Module and Solar Thermal Collector in Series, Al-Khwarizmi Eng. J., **19**, 1, (2023).
3. A. K. Azad and S. Parvin, Photovoltaic Thermal (PV/T) Performance Analysis for Different Flow Regimes: A Comparative Numerical Study, Int. J. Thermofluids, **18**, 100319, (2023).
4. E. Vengadesan and R. Senthil, Experimental Thermal Performance and Enviroeconomic Analysis of Serpentine Flow Channeled Flat Plate Solar Water Collector, Environ. Sci. Pollut. Res., **29**, no. 10, pp. 14321–14330, (2022).
5. A. Khelifa, M. E. H. Attia, Z. Driss, and A. M. Manokar, Performance Enhancement of Photovoltaic Solar Collector Using Fins and Bi-Fluid: Thermal Efficiency Study, Solar Energy, **252**, pp. 178–188, (2023).
6. S. Chandan, V. Suresh, S. M. Iqbal, et al., 3-D Numerical Modelling and Experimental Investigation of Coupled Photovoltaic Thermal and Flat Plate Collector, Solar Energy, **214**, pp. 55–66, (2021).
7. Bin Sun, Xinjie Xu, Di Yang, Hongwei Li, Experimental investigation on photothermal conversion performance of MWCNT-DW/EG nanofluids for low-temperature direct

absorption solar thermal energy systems, Applied Thermal Engineering **230**, 20786 (2023). https://doi.org/10.1016/j.applthermaleng.2023.120786.

8. E. Elshazly et al., 4E study of experimental thermal performance enhancement of flat plate solar collectors using MWCNT, Al_2O_3, and hybrid MWCNT/Al_2O_3 nanofluids, Results in Engineering **16**, 00723, (2022). https://doi.org/10.1016/j.rineng.2022.100723.
9. T. I. Juraev and J. S. Akhatov, Thermal and Viscosity Behavior of MWCNT and CuO Nanofluids for Flat Plate Solar Collectors, UNEC J. Eng. Appl. Sci., **5**, no. 3, pp. 61–67, (2022).
10. I.R. Jurayev, I. Yuldoshev, and Z. Jurayeva, Experimental Study of a Thin-Film Photovoltaic Thermal Battery in Natural Conditions, Appl. Solar Energy, **59**, no. 2, pp. 104–110, (2023). doi: 10.3103/S0003701X23601278.
11. I.R. Jurayev, I. Yuldoshev, Z. Jurayeva, et al., Results of Study of Photovoltaic Thermal Battery Based on Thin-Film Module by Modeling and Computational Methods, in Proc. Int. Conf. Appl. Innov. IT, (2024).