Journal of Ovonic Research Vol. 22, No. 2, March– April 2026, p. 161-177

Original Research

Structure-Dependent Ovonic-Inspired Thermal Behavior of Graphite-Modified Natural Zeolite Back Layers in Photovoltaic–Thermal Systems

CANAN KANDİLLİ [1]

[1] Electric&Energy Department, Usak University, Usak, 64200, Türkiye.
* Correspondence: canan.kandilli@usak.edu.tr

Received: February 3, 2026; Accepted: April 7, 2026

Abstract: In this study, the structure-dependent thermal behavior of natural zeolite–based back layers is experimentally investigated as a stable alternative to conventional phase change materials. Graphite-modified and unmodified natural zeolite materials were implemented in consolidated plate and loose powder configurations and tested under identical real meteorological conditions using two geometrically and hydraulically equivalent PVT systems. Thermal performance was evaluated based on the inlet–outlet temperature difference of the working fluid and the corresponding thermal efficiency. The results demonstrate that material architecture plays a decisive role in governing thermal behavior. Plate-form configurations exhibit higher and more stable temperature differences together with smoother efficiency profiles than powder-form systems, indicating enhanced thermal inertia and reduced internal thermal resistance. Graphite modification significantly improves heat spreading and effective thermal conductivity, with the most stable and pronounced performance observed for graphite-modified zeolite plates. Thermal efficiency values exceeding unity occur during low-irradiance periods due to sensible heat storage and delayed heat release, confirming the functional role of zeolite back layers as active thermal buffers rather than passive elements. From an ovonic-inspired perspective, this behavior represents a structure-driven, history-dependent thermal response governed by material architecture rather than phase change phenomena, establishing graphite-modified natural zeolite plates as robust functional back layers for next-generation PVT systems.

Keywords: natural zeolite; graphite modification; ovonic materials; functional back layer; photovoltaic–thermal systems; material architecture

---

1. Introduction

Photovoltaic–thermal (PVT) systems integrate photovoltaic electricity generation with thermal energy capture to improve overall solar energy utilization. However, current PVT designs generally feature functionally passive back surfaces on PV modules, which are unable to adaptively regulate excessive thermal loads. This absence of an active, functional back-layer material capable of moderating transient thermal peaks limits both electrical efficiency and system reliability under real operating conditions. To fill this functional gap, phase change materials (PCMs) have been widely explored as back-layer thermal regulators due to their ability to absorb and release significant amounts of heat at nearly constant temperature via latent heat effects. A comprehensive review of PCM applications highlights their high storage capacity and broad thermal energy storage utility across solar energy systems, including PVT integration, but also notes persistent challenges in implementation and performance enhancement strategies [1]. Specifically, PCMs have been shown through numerical and experimental studies to reduce PV cell temperature and enhance electrical performance in PVT systems, yet these benefits are often constrained by practical drawbacks [2]

The integration of phase change materials (PCMs) into PV and PV/T systems has received renewed attention in recent years as a passive strategy to suppress cell temperature rise and mitigate thermally induced electrical losses, while simultaneously enabling short-term thermal buffering. Recent reviews synthesize the rapidly expanding PV–PCM landscape and emphasize that the net benefit strongly depends on PCM melting range, packaging/containment, and the ability to fully "reset" (solidify) under night-time conditions, particularly in transient outdoor environments and varying climates. A persistent limitation identified across PV–PCM implementations is the inherently low thermal conductivity of most organic PCMs, which motivates the widespread adoption of high-conductivity fillers and porous conductive scaffolds. In this context, expanded graphite and graphene-derived additives are increasingly used to create percolating heat-spreading networks and shape-stabilized composites, leading to more uniform temperature fields and improved thermal response of PV modules. Representative experimental studies have demonstrated PV thermal management using graphite-foam/paraffin composites, exfoliated graphite/graphene nanofiller-supported shape-stabilized PCMs, and ZnO/expanded-graphite-enhanced bio/organic PCMs, reporting notable temperature reductions and associated electrical gains. In parallel, graphene/graphite-engineered porous aerogel frameworks have been proposed to simultaneously suppress leakage and accelerate heat transfer, enabling more robust temperature regulation and improved solar-to-thermal conversion characteristics of PCM back layers. Collectively, these studies highlight both the promise and the practical constraints of PV/PVT thermal buffering via PCMs, and they underscore the continuing need for alternative "phase-transition-free" thermal buffer concepts whose performance is governed by stable material architecture and heat-spreading capability rather than melt/solidification dynamics [3-12].

Recent contributions in the field of ovonic materials highlight that ovonic behavior is fundamentally governed by structure-property relationships and history-dependent response mechanisms rather than phase transition phenomena. In particular, it has been shown that even in the absence of conventional phase change processes, non-classical ovonic behavior can emerge in functional materials through architecture-oriented organization and interconnection. This perspective provides a relevant conceptual framework for interpreting the structure-dependent thermal response observed in this study, where natural zeolite backlayers exhibit system-level ovonic-inspired functionality through stable material architecture rather than latent heat effects [13,14].

Despite the theoretical advantages of PCM-based thermal regulation, real-world applications reveal significant limitations. Key challenges include inhomogeneous melting, low intrinsic thermal conductivity, phase segregation and supercooling, leakage and containment issues, and limited long-term cycle stability, all of which degrade thermal performance and complicate integration into outdoor PVT systems. These issues represent fundamental constraints on PCM adoption as "functional back layers" that must adapt efficiently and reliably to dynamic thermal inputs.

As an alternative to latent heat storage approaches, sensible heat storage (SHS) materials offer inherently stable thermal performance without phase change-related risks. In particular, natural zeolites, crystalline porous aluminosilicate minerals, have emerged as promising sensible heat storage media with high thermal stability and substantial heat capacity. Kandilli and colleagues first introduced natural zeolite plates as novel thermal management layers in PVT systems and characterized their thermophysical properties, demonstrating their potential to moderate excessive heat accumulation on PV modules. Subsequent work on enhanced zeolite composites—such as those modified with conductive additives like aluminum—has further shown improved heat transfer and storage capability in PVT applications [15-17]

In analogy with classical electronic ovonic devices, where system response is governed by structure-dependent and history-dependent behavior rather than simple linear conduction mechanisms, the zeolite back layer investigated in this study acts as a thermally functional architecture whose response emerges from internal structural organization and heat-transfer pathways rather than from conventional phase-change processes.

Although natural zeolites do not undergo latent phase transitions and therefore are not PCMs in the classical sense, their structure-dependent thermal response mechanisms, especially when combined with conductive additives like graphite or aluminum, suggest that they may exhibit ovonic-inspired functional behavior at the thermal system level. Unlike traditional PCMs, this behavior relies on enhanced thermal inertia, conductive pathways, and heat diffusion dynamics rather than on phase transitions, enabling a more stable and repeatable response to fluctuating thermal loads without concerns of leakage or degradation.

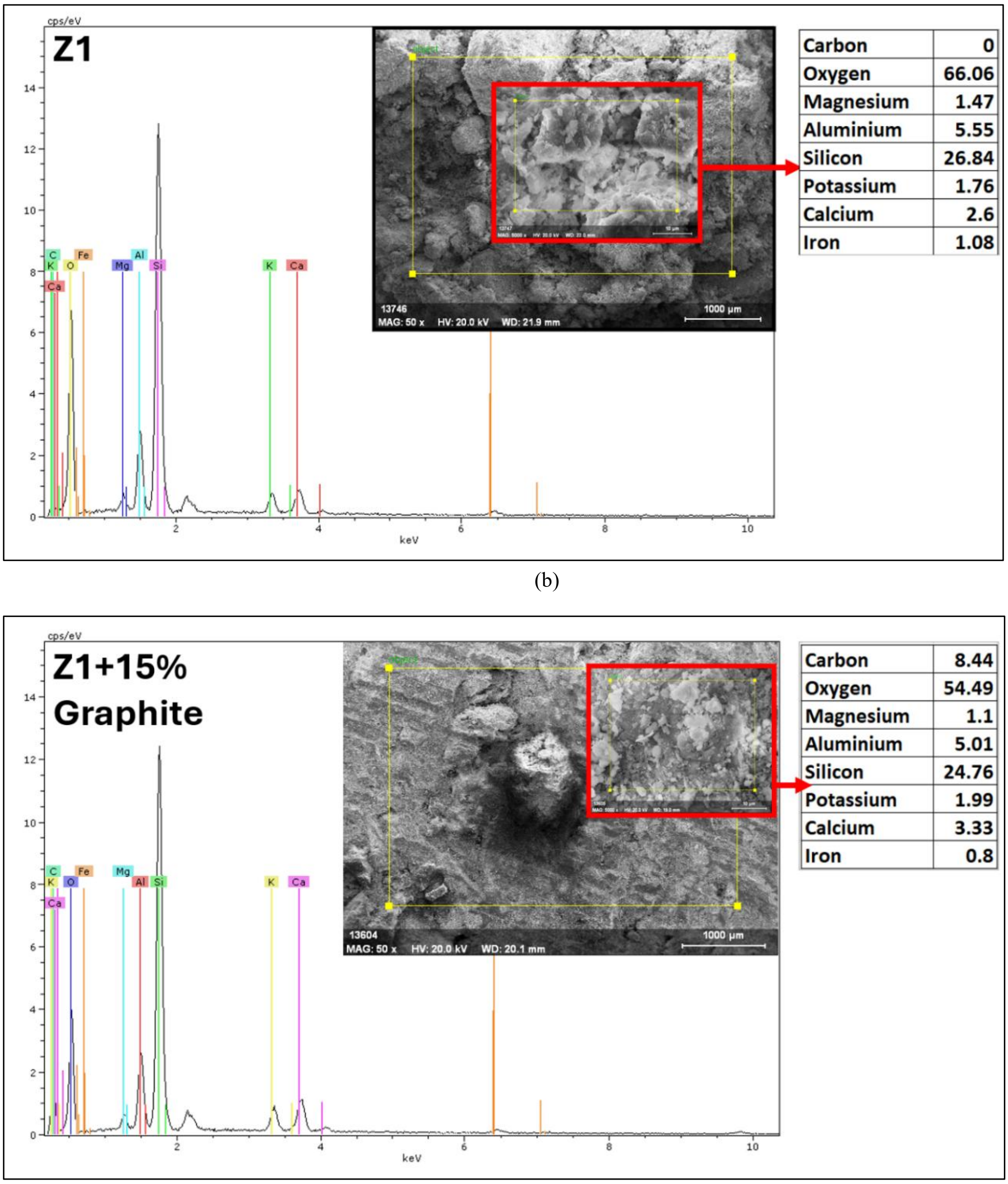
Nevertheless, critical gaps remain in the current literature. The thermal behavior of PVT systems equipped with graphite-modified and unmodified natural zeolite back layers under identical real meteorological conditions has not been systematically evaluated. Furthermore, the potential impact of material configuration—specifically the comparison between consolidated plate forms and loose powder forms of natural zeolite, with and without graphite modification—on thermal performance remains unexplored. Because material configuration can significantly influence heat conduction pathways and thermal inertia, a comparative analysis is essential for understanding structure-driven functional behavior in PVT systems.

Therefore, the present study experimentally investigates the thermal response of PVT systems incorporating natural zeolite back layers in both plate and powder configurations, with and without graphite modification, under identical outdoor operating conditions. By elucidating how material form and composition affect heat accumulation and dissipation, this work aims to advance the development of functional, ovonic-inspired back-layer strategies for next-generation PVT systems that avoid the inherent limitations of conventional PCM solutions. The novelty of this study arises from a structure–function-oriented investigation of natural zeolite back layers in PVT systems, explicitly accounting for the intrinsic porosity, high thermal stability, and compatibility with carbon-based modifications of zeolite materials. While natural zeolites have previously been proposed as sensible thermal storage media for PVT applications, their functional thermal behavior as a back-layer material has not been systematically evaluated as a function of material form and conductive modification. In this work, graphite-modified and unmodified natural zeolite layers, implemented in both consolidated plate and loose powder configurations, are experimentally compared under identical real meteorological conditions. The analysis focuses on the temperature difference between the inlet and outlet of the PVT working fluid (water) and the resulting thermal efficiency, thereby directly linking back-layer material characteristics to system-level thermal performance. From a theoretical standpoint, graphite addition is expected to enhance effective thermal conductivity, improve heat spreading within the porous zeolite matrix, and reduce thermal contact resistance at the PV–back-layer interface. These effects are examined in conjunction with scanning electron microscopy (SEM) analyses, which reveal microstructural differences between graphite-modified and unmodified zeolite structures and provide insight into heat transfer pathways at the microscale. By jointly evaluating material composition (graphite-modified vs. unmodified) and structural configuration (plate vs. powder) through experimentally measurable PVT performance indicators, this study establishes a previously unexplored structure-dependent thermal response framework. The findings demonstrate how natural zeolite-based back layers can function as stable, ovonic-inspired thermal regulation components in PVT systems, offering a practical and durable alternative to conventional phase change materials.

2. Experimental methodology and material

The experimental methodology was designed to systematically evaluate the structure-dependent thermal behavior of natural zeolite back layers in photovoltaic–thermal (PVT) systems. To this end, PVT configurations incorporating graphite-modified and unmodified natural zeolite, implemented in both plate and powder forms, were tested under identical real outdoor meteorological conditions. The experimental framework focuses on quantifying the influence of back-layer material composition and configuration on heat transfer to the working fluid (water), using the inlet–outlet temperature difference and thermal efficiency as primary performance indicators. In parallel, microstructural characterization via scanning electron microscopy (SEM) was conducted to support the interpretation of macroscopic thermal behavior in terms of material morphology and heat transfer pathways. This combined system-level and material-level approach enables a consistent and reproducible assessment of the thermal regulation capability of natural zeolite-based functional back layers in PVT applications.

(a)



Carbon	0
Oxygen	66.06
Magnesium	1.47
Aluminium	5.55
Silicon	26.84
Potassium	1.76
Calcium	2.6
Iron	1.08

(b)

Carbon	8.44
Oxygen	54.49
Magnesium	1.1
Aluminium	5.01
Silicon	24.76
Potassium	1.99
Calcium	3.33
Iron	0.8

Figure 1. SEM micrographs and corresponding EDS spectra of (a) unmodified natural zeolite in plate form and (b) 15 wt.% graphite-modified natural zeolite in plate form. The SEM images reveal the porous aluminosilicate framework of natural zeolite and the microstructural changes induced by graphite addition, while the EDS analyses confirm the elemental composition and successful incorporation of carbon into the zeolite matrix.

The natural zeolite used in this study was obtained from the Aegean region of Türkiye and is characterized by a clinoptilolite-rich composition, which is widely recognized for its thermal stability and porous aluminosilicate structure. The material was prepared with a granular particle size of 1–3 mm, providing a representative and application-oriented morphology for both powder and plate configurations in PVT systems. From Figure 1, The microstructural and elemental characteristics of the unmodified and graphite-modified natural zeolite samples were investigated using scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS). SEM observations of the unmodified natural zeolite reveal a highly porous and heterogeneous aluminosilicate framework, characterized by irregular particle morphology and interconnected voids. This porous structure is consistent with the intrinsic crystalline nature of natural zeolites and is favorable for sensible heat storage, as it provides a large internal surface area while maintaining thermal stability. The corresponding EDS spectrum of the unmodified zeolite confirms its typical chemical composition, dominated by oxygen (66 wt.%), silicon (27 wt.%), and aluminum (5–6 wt.%), with minor contributions from magnesium, potassium, calcium, and iron. The absence of detectable carbon peaks indicates that the pristine zeolite matrix does not contain carbon-based phases, in agreement with its natural aluminosilicate origin. In contrast, the SEM micrographs of the 15 wt.% graphite-modified natural zeolite exhibit a noticeably denser and more interconnected microstructure, where graphite particles are distributed within the zeolite matrix and partially bridge adjacent zeolite grains. This microstructural modification reduces large voids and enhances solid–solid contact between particles, which is expected to improve effective thermal conductivity and facilitate heat spreading within the back-layer material. The EDS analysis corroborates this observation by revealing a clear carbon signal (8.4 wt.%), confirming the successful incorporation of graphite into the zeolite structure. Simultaneously, the relative contents of silicon and aluminum remain largely unchanged, indicating that graphite addition does not disrupt the fundamental aluminosilicate framework of the zeolite. These microstructural and compositional changes are directly relevant to the observed thermal behavior of the PVT systems. The preservation of zeolite porosity ensures thermal stability and heat storage capacity, while the graphite-induced conductive pathways enhance heat transfer from the PV rear surface to the working fluid. Such a synergistic combination of porous heat storage and conductive enhancement supports the interpretation of the graphite-modified zeolite as a functional, ovonic-inspired thermal regulation layer, where structure-dependent heat transfer behavior plays a key role in system-level performance.

Table1. Properties of natural zeolite plates with and without graphite modification.

Plate Material	Thermal Conductivity (W/mK)	Total surface area	Pore Volume	Pore size	Porosity	Bulk Density
Z	0.1503	7.0405 ± 0.0185 m²/g	0.046804 cm³/g	265.916 Å	31.82%	1.349 g/mL
Z+Graphite 15%wt	0.3393	3.8919 ± 0.0116 m²/g	0.032030 cm³/g	329.202 Å	21.41%	1.5368 g/mL

Table 1 presents the textural and thermophysical characteristics of the unmodified natural zeolite plate (Z) and the 15 wt.% graphite-modified natural zeolite plate (Z + 15% Graphite), including thermal conductivity (for plate form), total surface area, pore volume, average pore size, porosity, and bulk density. The thermal conductivity increased markedly from 0.1503 to 0.3393 $W \cdot m^{-1} \cdot K^{-1}$, indicating that graphite incorporation significantly enhances heat transfer by establishing effective conductive pathways within the porous matrix. The unmodified zeolite exhibits a high specific surface area (7.0405 ± 0.0185 $m^2\ g^{-1}$) and larger pore volume (0.0468 $cm^3\ g^{-1}$), reflecting its intrinsically porous aluminosilicate framework, which is beneficial for sensible heat storage and thermal inertia. Upon graphite incorporation, a pronounced reduction in both total surface area and pore volume is observed, decreasing to 3.8919 ± 0.0116 $m^2\ g^{-1}$ and 0.0320 $cm^3\ g^{-1}$, respectively. This behavior indicates that graphite particles partially occupy or bridge the zeolite pore network, leading to a more consolidated internal structure. Consistent with this interpretation, the average pore size increases from approximately 266 Å to 329 Å, suggesting a transition from a highly heterogeneous pore distribution toward fewer but wider effective heat-transfer channels. The porosity correspondingly decreases from 31.82% to 21.41%, while the bulk density increases from 1.349 to 1.5368 g mL^{-1}, confirming structural densification induced by graphite addition. These textural modifications explain the superior thermal performance of the graphite-modified zeolite plate in PVT applications. The coexistence of reduced porosity, enlarged pore channels, and increased bulk density supports faster heat spreading and more efficient heat transfer from the PV rear surface to the working fluid, reinforcing the role of the 15 wt.% graphite-modified natural zeolite plate as a functional, ovonic-inspired thermal regulation layer. In the frame of the material structure, Table 1 demonstrate a clear structure–property relationship between porosity-related parameters and thermal conductivity. The graphite-modified zeolite plate exhibits a pronounced increase in thermal conductivity despite a substantial reduction in total surface area and pore volume, accompanied by a decrease in overall porosity. This behavior indicates that heat transfer is no longer governed primarily by pore-mediated mechanisms but instead by enhanced solid-phase conduction. The reduction in surface area and pore volume suggests partial pore filling and improved interparticle contact induced by graphite incorporation, which facilitates the formation of continuous conductive pathways across the zeolite matrix. Furthermore, the increase in average pore size, together with the higher bulk density of the graphite-containing sample, implies a transition toward a more compact and thermally connected microstructure. Consequently, the thermal transport performance becomes increasingly dominated by microstructural connectivity rather than by the extent of porosity, confirming that graphite modification effectively transforms the zeolite plate into a functionally conductive material suitable for thermally active applications.

The form in which the back-layer material is implemented plays a decisive role in both PVT layer architecture and dominant heat transfer mechanisms. When used in powder form, natural zeolite establishes a discontinuous thermal network characterized by increased interparticle contact resistance and localized heat accumulation, whereas consolidation into plate form promotes continuous solid–solid contact, reduced thermal resistance, and more uniform heat spreading along the PV rear surface. These structural differences directly influence conductive heat transfer pathways, thermal inertia, and the effectiveness of heat extraction by the working fluid. Accordingly, a comparative evaluation of plate and powder configurations is essential to elucidate how back-layer morphology governs thermal regulation behavior in PVT systems and to identify configuration-dependent performance advantages under real operating conditions.

The textural trends summarized in Table 1 are in close agreement with the SEM observations presented in Figure 1. While the unmodified natural zeolite exhibits a highly porous and loosely connected microstructure, the graphite-modified sample shows a more compact and interconnected morphology, where graphite particles partially occupy pore spaces and bridge adjacent zeolite grains. This structural densification explains the observed reduction in total surface area and porosity, alongside the increase in average pore size and bulk density. At the same time, the SEM images reveal the formation of continuous solid–solid contact pathways, which are consistent with the enhanced effective thermal conductivity reported for the graphite-modified zeolite plate. Together, the SEM and textural analyses confirm that graphite addition induces a structure-driven transition from pore-dominated heat storage toward conduction-enhanced thermal regulation, providing a microstructural basis for the improved PVT thermal performance.

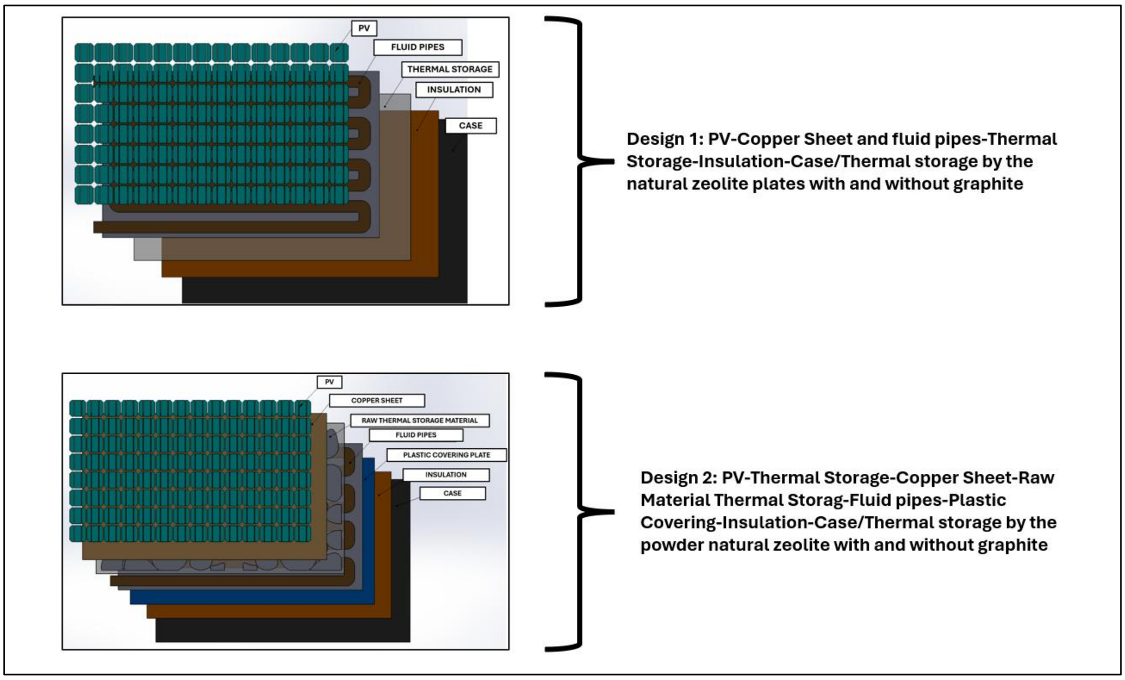


Figure 2. Conceptual designs of PVT systems with natural zeolite-based back layers.

Schematic representations of the two PVT back-layer configurations investigated in this study are given in Figure 2. (a) Design 1, consisting of a PV module, copper sheet with integrated fluid pipes, natural zeolite plate-based thermal storage layer (with and without graphite modification), insulation, and external casing; (b) Design 2, consisting of a PV module, copper sheet, raw powder-form natural zeolite thermal storage layer (with and without graphite modification), fluid pipes, plastic covering plate, insulation, and casing. The two designs highlight the structural differences between consolidated plate and loose powder configurations and their potential influence on heat transfer pathways and thermal regulation behavior in PVT systems.

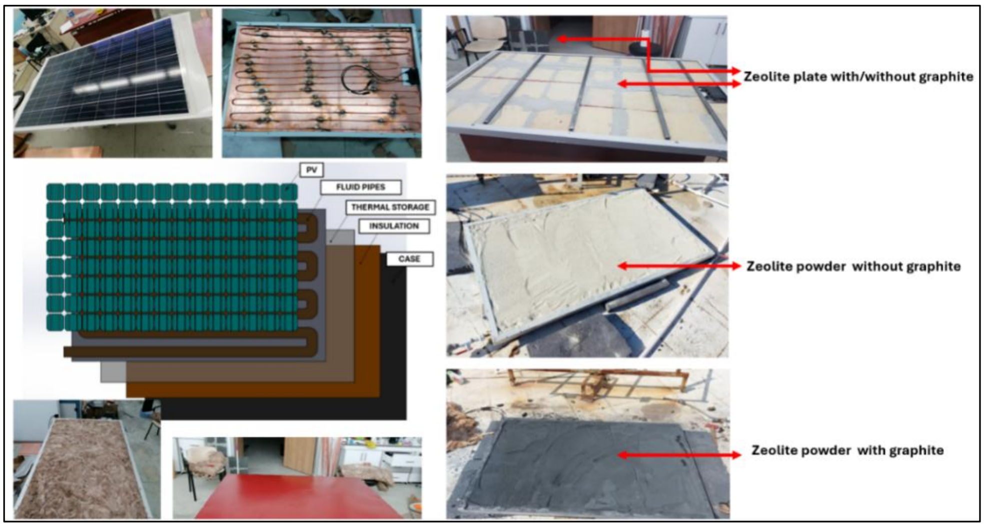


Figure 3. Experimental realization of plate- and powder-form natural zeolite back layers in PVT systems.

Photographs of the experimental PVT configurations employing natural zeolite back layers in plate and powder forms are presented by Figure 3. The images show (i) the PV module and copper heat exchanger with fluid pipes, (ii) natural zeolite plates with and without graphite modification, (iii) powder-form natural zeolite layers without graphite, and (iv) powder-form natural zeolite layers with graphite addition. These visualizations demonstrate the practical implementation of different back-layer morphologies and compositions used to investigate their effects on thermal performance and working fluid temperature response under real outdoor conditions. In Figure 4, the photographs of the outdoor experimental setup used for the thermal performance evaluation of the photovoltaic–thermal (PVT) system are given. The figure illustrates the general rooftop installation layout as well as the key measurement components, including the PVT module, working fluid circulation unit (boiler), thermocouples positioned at the inlet and outlet of the fluid channels, data logger, flowmeter, radiation probe, infrared thermometer, and the on-site weather station. This instrumentation framework enabled synchronized acquisition of thermal, hydraulic, and meteorological data, ensuring consistent and reproducible comparison of the plate- and powder-form natural zeolite back-layer configurations under identical real meteorological conditions.

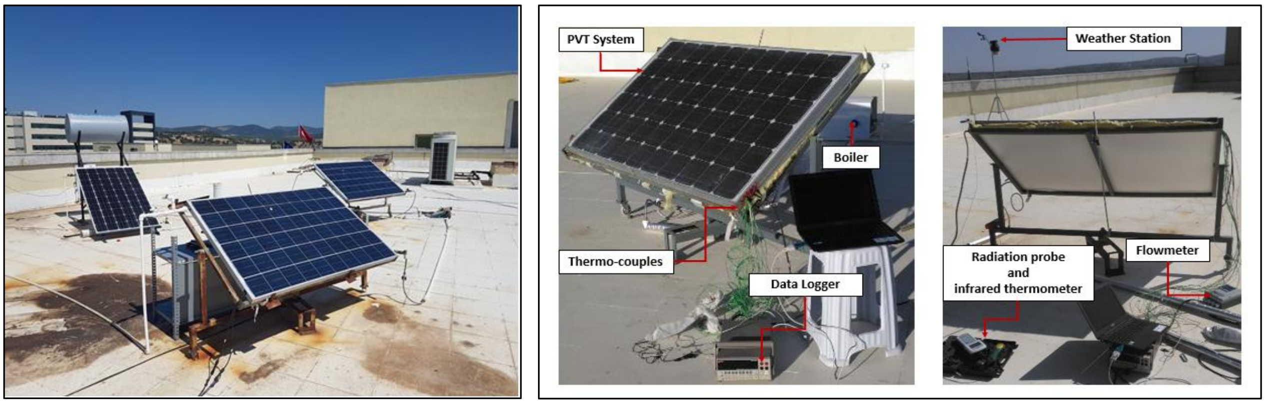


Figure 4. Outdoor experimental setup of the PVT systems

Table 2. Measurement instruments and accuracy specifications used in the experimental setup.

Measurement parameter	Instrument	Measurement range	Accuracy / Resolution
Solar irradiance	Radiation probe	0–2000 W m^{-2}	±5 W m^{-2}
Fluid inlet–outlet temperature	K-type thermocouples	−50 to 250 °C	±0.5 °C
Ambient temperature	Weather station sensor	−40 to 80 °C	±0.3 °C
Volumetric flow rate	Digital flowmeter	0–10 L min^{-1}	±2% of reading
Data acquisition	Multi-channel data logger	—	16-bit resolution

In Table 2, measurement instruments and accuracy specifications used in the experimental setup listed. For real scale application, all measurement instruments were selected to ensure sufficient accuracy for thermal performance assessment, and the combined measurement uncertainty was considered acceptable for comparative analysis of the different PVT back-layer configurations. The experimental database employed in this study was obtained from long-term outdoor tests conducted under real meteorological conditions on the rooftop of the Faculty of Engineering at Uşak University. For the plate-type configuration, a total of 457 validated data points were collected between 19 August and 4 September 2020, whereas the powder-type configuration was evaluated using 334 validated data points acquired during the period 6–16 October 2020. In both experimental periods, two geometrically and hydraulically equivalent systems—incorporating graphite-modified and non-modified natural zeolite materials—were operated simultaneously, ensuring identical boundary conditions and enabling a direct and unbiased comparison of material form and graphite incorporation effects. All measurements were performed under naturally varying solar irradiance, ambient temperature, and wind conditions, without artificial control or data filtering beyond standard validation procedures. The experimental datasets utilized in this work have not been analyzed in any previous study, providing an original and robust empirical basis for assessing the thermal performance characteristics of zeolite-based absorber configurations.

3. Results and discussion

This section presents and discusses the experimental results obtained from the PVT systems equipped with natural zeolite back layers in plate and powder configurations, with and without graphite modification. The analysis focuses on elucidating how material composition and structural form govern thermal regulation behavior under real outdoor operating conditions. System-level thermal performance is evaluated primarily through the inlet–outlet temperature difference of the working fluid and the resulting thermal efficiency, while the observed trends are interpreted in light of the thermophysical, textural, and microstructural characteristics of the zeolite materials. By integrating macroscopic performance metrics with SEM–EDS and textural analyses, this section establishes a structure–property–function relationship that explains the ovonic-inspired thermal response of natural zeolite-based functional back layers in PVT applications. Although the plate- and powder-form experiments were conducted during different seasonal periods, each configuration was evaluated through the simultaneous operation of geometrically and hydraulically identical PVT systems under the same instantaneous meteorological conditions. Therefore, the observed performance differences primarily reflect material architecture effects rather than seasonal variability.

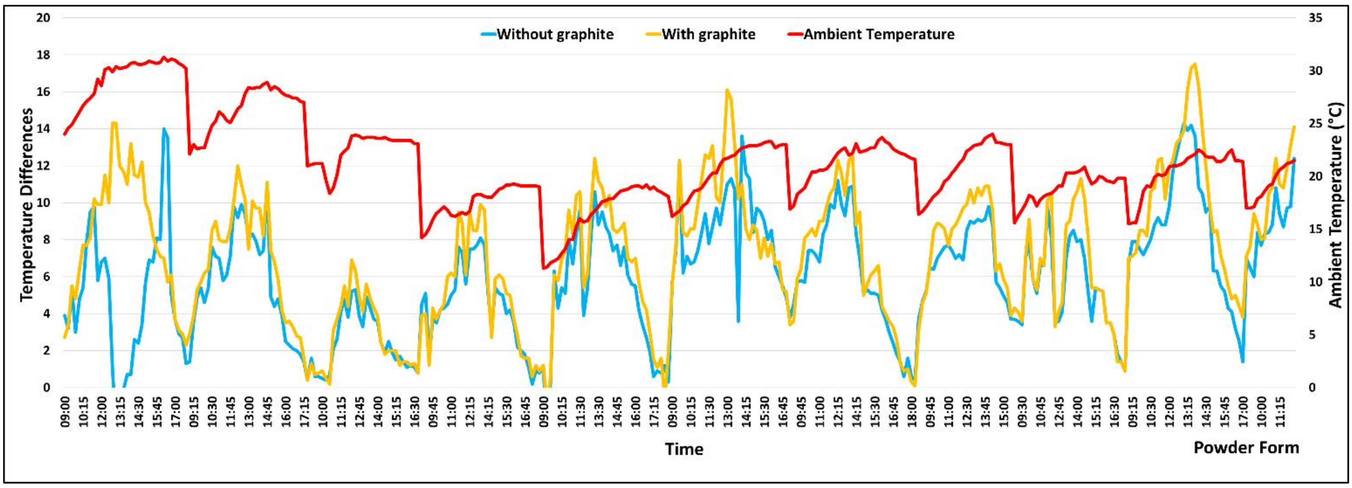


Figure 5. Variation of the temperature differences of the PVT in powder form.

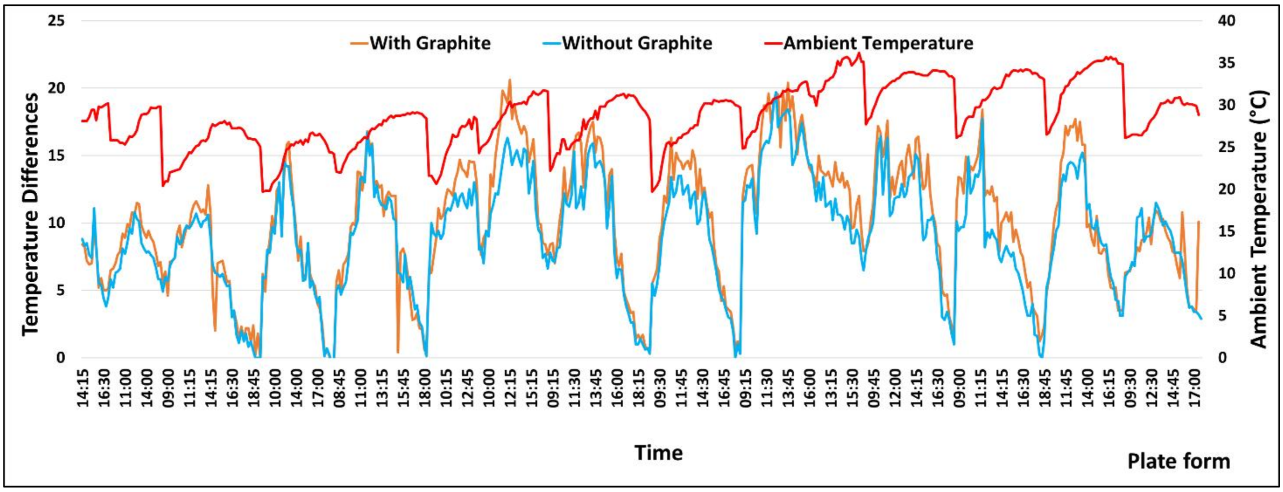


Figure 6. Variation of the temperature differences of the PVT in plate form

Figure 5 illustrates the temporal evolution of temperature differences for the powder-form samples under ambient temperature variations. In the graphite-free configuration, the temperature difference generally fluctuates within the range of approximately 2–10 °C, exhibiting pronounced drops that closely follow changes in ambient temperature. With graphite addition, the peak temperature differences increase to about 12–18 °C, indicating an enhanced heat transfer capability. However, the graphite-containing powder sample also shows relatively sharp fluctuations and higher sensitivity to ambient temperature oscillations. This behavior suggests that, although graphite improves conductive heat transfer, the loose packing and limited interparticle contact in powder form restrict the stabilization of thermal response, leading to intermittent heat dissipation and non-uniform temperature profiles. In contrast, Fig. 6 shows that the plate-form samples exhibit higher and more stable temperature differences over the same operational period. For the graphite-free plate, temperature differences predominantly vary between 5–15 °C, while the graphite-modified plate reaches values up to approximately 18–22 °C. Compared to the powder form, the plate configuration demonstrates smoother temporal profiles with reduced abrupt drops, even under fluctuating ambient conditions. The graphite-containing plate consistently maintains higher temperature differences, reflecting improved heat spreading and reduced thermal resistance due to enhanced solid-phase continuity and compact microstructural arrangement. When Figures 5 and 6 are evaluated together, it becomes evident that the material form plays a critical role in governing thermal behavior. Although graphite addition enhances temperature differences in both configurations, the improvement is significantly more pronounced and stable in the plate form. The powder samples exhibit higher short-term variability and stronger coupling with ambient temperature changes, whereas the plate samples provide a more controlled and sustained thermal response. This comparison indicates that the combination of graphite modification and plate geometry promotes effective conductive pathways and thermal inertia, resulting in superior and more predictable heat transfer performance compared to the powder form.

Figure 7 shows the temporal variation of thermal efficiency for the powder-form configuration under changing solar irradiance. In the graphite-free case, thermal efficiency generally remains below 1.0, with limited and short-lived peaks during periods of relatively high irradiance. In contrast, the graphite-modified powder sample exhibits pronounced efficiency peaks that can significantly exceed 1.0, reaching values of approximately 10–12. These values are particularly evident during late afternoon periods, when solar irradiance rapidly decreases. This behavior can be attributed to the heat previously stored within the zeolite layer, which continues to be released to the working fluid even as the incident solar flux diminishes. However, the efficiency response in the powder form is highly transient, characterized by sharp spikes and rapid fluctuations, indicating that the stored thermal energy is released in a relatively uncontrolled manner due to limited particle-to-particle thermal continuity. In Figure 8, the plate-form configuration demonstrates a markedly different efficiency behavior. Thermal efficiency values for both samples generally remain within the range of 0.2–1.2, while the graphite-modified plate occasionally reaches peak values of approximately 2.5–3.0. Similar to the powder form, efficiency values exceeding 1.0 are observed primarily during periods of declining solar irradiance, confirming the contribution of thermal energy stored in the zeolite layer. However, unlike the powder form, the plate configuration exhibits smoother temporal profiles and significantly reduced fluctuation amplitudes. This indicates that heat storage and subsequent release occur in a more gradual and controlled fashion, facilitated by the compact geometry and enhanced solid-phase heat conduction pathways within the plate structure. A comparative evaluation of Figures 7 and 8 reveals that while both configurations exhibit thermal efficiency values exceeding the theoretical limit of 1.0 due to heat storage effects, the magnitude and stability of this behavior strongly depend on material form. The powder form with graphite produces exceptionally high instantaneous efficiency values, driven by rapid discharge of stored thermal energy during low-irradiance periods, but suffers from pronounced instability and strong sensitivity to irradiance fluctuations. Conversely, the plate form shows lower maximum efficiency values but offers a more stable and predictable thermal response, indicating a more effective integration of heat storage and heat transfer mechanisms. These findings highlight that the plate configuration enables a more controlled utilization of stored thermal energy, which is advantageous for practical PVT operation where sustained and reliable thermal output is preferred over short-lived efficiency peaks.

Recent studies on PV/PVT thermal regulation have largely focused on phase change materials (PCMs) due to their latent-heat buffering capability, often coupled with carbon-based fillers to mitigate the intrinsically low thermal conductivity of PCMs. For example, exfoliated graphite/graphene-supported shape-stabilized PCMs have been shown to substantially reduce PV temperature and improve electrical performance, highlighting the effectiveness of creating conductive pathways inside the storage medium [18,19]. Similarly, multi-layer bio-based PCM architectures reinforced with carbon fibers have been proposed to broaden the effective operating window and enhance heat spreading under realistic conditions. Nevertheless, comprehensive syntheses emphasize that PCM-based designs remain sensitive to practical issues such as incomplete melting/solidification, long-term cycling stability, leakage/containment constraints, and performance degradation under highly transient boundary conditions. In this context, the present results provide a complementary, phase-transition-free route: the natural zeolite back layer behaves as a durable sensible-heat buffer, and the performance is governed primarily by material architecture (continuous plate vs. discontinuous powder) and conductive modification (graphite), rather than by melting dynamics [20]. Consistent with this interpretation, the plate-form zeolite—particularly with graphite—exhibits smoother temperature difference and efficiency trajectories and a more predictable release of stored heat during low-irradiance periods, whereas the powder form tends to show sharper transients, evidencing the central role of contact resistance and thermal-network continuity.

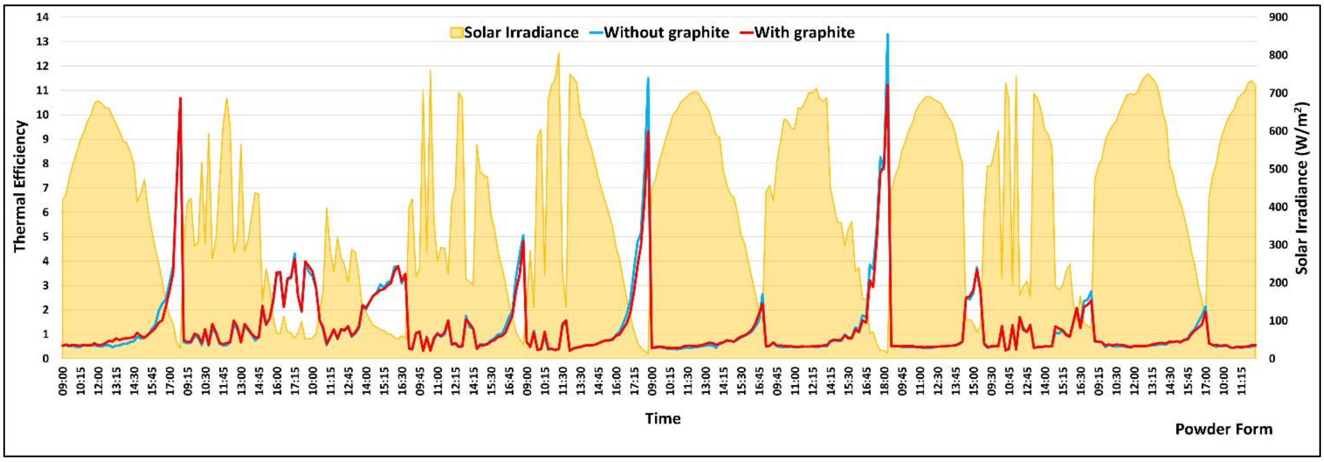


Figure 7. Variation of the thermal efficiency of the PVT in powder form.

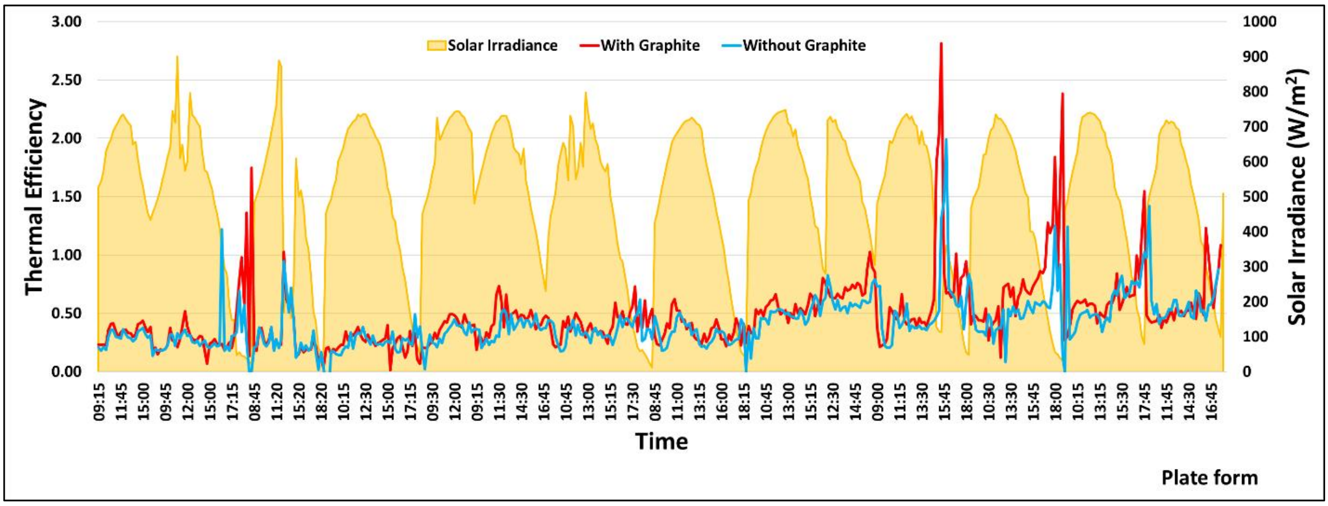


Figure 8. Variation of the thermal efficiency of the PVT in plate form.

The improved thermal conductivity of the graphite-modified zeolite enhances heat spreading within the back layer and reduces internal thermal resistance, thereby promoting more effective heat transfer to the working fluid. This behavior results in higher and more stable temperature differences, which in turn contributes to the smoother and more predictable thermal efficiency profiles observed in the plate-form configuration.

3.1. Effect of material form

The experimental results clearly demonstrate that the form in which the natural zeolite back layer is implemented—powder or plate—fundamentally governs the thermal behavior of the PVT system. As observed in the temperature difference time series for the powder configuration (Fig. 5), the inlet–outlet temperature difference of the working fluid exhibits pronounced fluctuations and abrupt drops, particularly under rapidly changing ambient conditions. This behavior reflects the discontinuous thermal contact network inherent to loose powder layers, where interparticle contact resistance varies spatially and temporally. In contrast, the plate-form configuration (Fig. 6) shows a markedly different response. The temperature difference profiles are smoother and more continuous, indicating a well-organized thermal contact structure between the PV rear surface, the zeolite plate, and the heat exchanger. The consolidation of the zeolite into plate form promotes continuous solid–solid contact and well-defined heat conduction pathways, enabling more effective and uniform heat transfer to the working fluid. These differences are further reflected in the thermal stability of the system. While the powder form responds rapidly to short-term ambient temperature variations, it lacks the ability to buffer thermal loads consistently. The plate form, on the other hand, exhibits enhanced thermal inertia, resulting in more stable and predictable temperature difference behavior over extended operating periods.

3.2. Influence of graphite modification

The effect of graphite modification on the thermal behavior of the PVT system is evident in both material forms but manifests differently depending on the underlying structure. In the powder configuration (Fig. 5), graphite addition generally increases peak temperature difference values compared to the unmodified case, confirming that graphite enhances effective thermal conductivity within the zeolite matrix. However, this improvement is accompanied by increased sensitivity to irradiance and ambient temperature fluctuations, leading to sharp temperature difference spikes followed by rapid decay.

A similar but more controlled trend is observed in the plate configuration (Fig. 6). Here, graphite-modified plates consistently deliver higher temperature difference values than unmodified plates, while maintaining relatively smooth temporal profiles. This behavior indicates that, in the presence of a continuous structural framework, graphite acts as an effective conductive enhancer, facilitating heat spreading and reducing internal thermal resistance without compromising overall thermal stability.

The thermal efficiency results reinforce this interpretation. In the plate-form efficiency graph (Fig. 7), the graphite-modified configuration achieves higher instantaneous and average thermal efficiencies across a wide range of solar irradiance levels. In contrast, the powder-form efficiency data (Fig. 8) show pronounced efficiency peaks under high irradiance but also extended low-efficiency periods, highlighting the dual effect of graphite: while it improves heat transfer, excessive reduction in porosity and thermal inertia can limit sustained performance in loosely packed structures.

3.3. Comparative thermal behavior

A direct comparison of all configurations reveals clear performance hierarchies. In terms of temperature difference trends, the graphite-modified plate configuration consistently exhibits the highest and most stable Temperature difference, followed by the unmodified plate, graphite-modified powder, and unmodified powder configurations. This ordering emphasizes the dominant role of material architecture over composition alone. Thermal efficiency comparisons further support this conclusion. The plate-form systems maintain higher efficiency levels over broader irradiance ranges and show better alignment with daily solar profiles (Fig.7). Powder-form systems, although capable of achieving high efficiency peaks under favorable conditions (Fig. 8), suffer from strong intermittency and reduced predictability. From an engineering perspective, the most notable distinction lies in predictability and reproducibility. Plate-form configurations demonstrate narrower efficiency and temperature difference bands under similar meteorological conditions, which is essential for reliable system design and performance forecasting. Powder-form configurations, by contrast, are inherently more stochastic due to variable internal heat transfer paths.

3.4. Ovonic-inspired interpretation

When interpreted from an ovonic-inspired perspective, the observed behaviors suggest that the natural zeolite back layer functions as more than a passive thermal storage medium, particularly in plate form. The material architecture induces a structure-dependent thermal response, where heat accumulation, dissipation, and temporal smoothing depend on the internal organization of the material rather than solely on its chemical composition.

Although no phase transition occurs, the plate-form zeolite exhibits a history-sensitive and non-linear thermal response analogous to ovonic systems at the functional level. The back layer adapts its thermal behavior to changing external stimuli (irradiance and ambient temperature) through its architecture-driven conduction and storage mechanisms. Importantly, this response is largely independent of the specific PVT system layout, indicating that the extracted material-level insights can be generalized to other thermal management applications.

3.5. Design implications for ovonic-inspired PVT systems

The findings of this study have direct implications for the design of next-generation, ovonic-inspired PVT systems. First, plate-form back layers offer clear advantages in terms of thermal stability, predictability, and sustained efficiency, making them preferable to powder-based solutions for practical implementations. Second, while graphite modification enhances thermal performance, its influence is inherently coupled to material architecture, underscoring the need for careful optimization of graphite content rather than indiscriminate conductivity enhancement.

Most importantly, the results demonstrate that material architecture can be more decisive than material composition in governing PVT thermal behavior. By engineering the internal structure of sensible heat storage materials, it is possible to achieve functional, ovonic-inspired thermal regulation without relying on conventional phase change materials, thereby avoiding their associated limitations.

4. Conclusions

This study experimentally investigated the structure-dependent thermal behavior of natural zeolite-based back layers in photovoltaic–thermal (PVT) systems, focusing on the combined effects of material form (powder versus plate) and graphite modification under identical real outdoor operating conditions. The results clearly demonstrate that material architecture plays a decisive role in governing thermal regulation performance, often outweighing the influence of composition alone.

The comparison between powder and plate configurations reveals that consolidated plate-form zeolite back layers provide significantly higher and more stable inlet–outlet Temperature difference and thermal efficiency profiles than their powder-form counterparts. While powder-based layers exhibit rapid thermal responses and high instantaneous efficiency peaks—particularly during periods of declining solar irradiance—these responses are highly transient and strongly coupled to external fluctuations. In contrast, plate-form configurations promote continuous solid–solid contact, reduced thermal resistance, and enhanced thermal inertia, resulting in smoother and more predictable thermal behavior over extended operating periods.

Graphite modification further enhances thermal performance by increasing effective thermal conductivity and improving heat spreading within the zeolite matrix. However, its impact is strongly architecture-dependent. In powder form, graphite addition leads to pronounced but unstable efficiency peaks due to rapid and uncontrolled release of stored thermal energy. When combined with plate geometry, graphite modification produces a controlled and sustained enhancement in both temperature difference and thermal efficiency, confirming that conductive additives are most effective when integrated into a continuous structural framework.

An important outcome of this work is the observation of thermal efficiency values exceeding the theoretical limit of unity during low-irradiance periods. This behavior is physically explained by sensible heat storage in the zeolite back layer, which enables delayed heat release to the working fluid even as incident solar flux decreases. Rather than indicating a violation of thermodynamic principles, this response highlights the functional role of zeolite layers as thermal buffers that decouple instantaneous solar input from thermal output.

From an ovonic-inspired perspective, the plate-form natural zeolite back layer exhibits a history-dependent and non-linear thermal response governed by its internal structure and heat transfer pathways, despite the absence of phase change phenomena. This structure-driven behavior enables adaptive thermal regulation at the system level while avoiding the intrinsic limitations of conventional phase change materials, such as leakage, phase instability, and long-term degradation.

These findings clearly indicate that material architecture, particularly the transition from powder to plate form, plays a more decisive role than material composition alone in governing the thermal response and stability of PVT systems.

Finally, the findings establish that engineering the architecture of sensible heat storage materials is more effective than increasing intrinsic thermal conductivity alone for achieving stable and functional thermal regulation in PVT systems. Natural zeolite plates, particularly when moderately modified with graphite, emerge as robust, ovonic-inspired functional back layers capable of delivering reliable and predictable thermal performance. These insights provide a clear experimental foundation for the design of next-generation PVT systems that rely on structure-driven thermal functionality rather than phase change-based solutions.

Declarations

Availability of data and material: The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Author contributions: The author was solely responsible for conceptualization, methodology, experimental and computational work, data analysis, interpretation of results, and manuscript preparation. The author has read and approved the final manuscript and agrees to be accountable for all aspects of the work.

Acknowledgments: The author gratefully acknowledges the support of the Uşak University Scientific Research Projects Coordination Unit (BAP) through project LP0003, which provided the material analysis data used in this study. The experimental system data were obtained from the system established within the scope of TÜBİTAK 1505 project no. 5180034.

Funding: This study was funded by TÜBİTAK (grant no. 5180034) and Usak University BAP Project ID:LP0003.

Conflicts of interest: The author declares no conflict of interest.

References

[1] Mao, S.; Liu, Y.; Wu, X.; Zhang, L.; Chen, J.; Zhou, T. Thermal energy storage performance, application and challenge of phase change materials: A review. *Energy Storage and Saving* 2025, 4(3), 300-322. https://doi.org/10.1016/j.enss.2025.03.001

[2] Ying, S.; Zhang, X.; Wu, Y.; Pan, Z. Solar photovoltaic/thermal (PV/T) systems with/without phase change materials (PCMs): A review. *Journal of Energy Storage* 2024, 89, 111582. https://doi.org/10.1016/j.est.2024.111582

[3] Mazzeo, D., Colombo, L.P.M., Leva, S. A review of photovoltaic cooling with phase change materials: Technical advances, modeling approaches, efficiency gains and economic/environmental

impact. *Applied Thermal Engineering* 2025, 280, 128222. https://doi.org/10.1016/j.applthermaleng.2025.128222

[4] Tang, L., Luo, Y., Yin, L., Li, J., Cao, X. Thermal-management performance of phase-change material on PV modules in different climate zones. *Energies* 2024, 17(23), 6200. https://doi.org/10.3390/en17236200

[5] Guo, X., Zheng, K., Shi, H., Chen, L., Shen, Y., Chen, J., Tao, X., Yu, M. Thermal regulation of photovoltaic panels using shape-stabilized phase change materials supported by exfoliated graphite/graphene nanofillers. *Journal of Cleaner Production* 2024, 446, 141435. https://doi.org/10.1016/j.jclepro.2024.141435

[6] Nishad, S., Ahmad, Z., Krupa, I. Enhancement of photovoltaic module performance by thermal management using shape-stabilized PCM composites. *Solar Energy Materials and Solar Cells* 2024, 273, 112948. https://doi.org/10.1016/j.solmat.2024.112948

[7] Sharifzadeh, E., Rahimi, M., Azimi, N., Abolhasani, M. Thermal management of photovoltaic panels using PCMs and hierarchical ZnO/expanded graphite nanofillers. *Energy* 2024, 306, 132324. https://doi.org/10.1016/j.energy.2024.132324

[8] He, F.; Hong, W.; Liu, Z.; Zhu, Y.; Li, Y.; Jiang, Z.; Chen, Z.; Yang, W. Phase change materials encapsulated in graphene hybrid aerogels for thermal management of solar photovoltaic panels. *Thermochimica Acta* 2024, 740, 179853. https://doi.org/10.1016/j.tca.2024.179853

[9] Wang, J.-X.; Mao, Y.; Miljkovic, N. Nano-enhanced graphite/phase change material/graphene composite for sustainable and efficient passive thermal management. *Advanced Science* 2024, 11(38), 2402190. https://doi.org/10.1002/advs.202402190

[10] Murugesan, M.; Chandrika V S; Sitharaj, A.; Chinnaiyan V, K. Performance enhancement of solar photovoltaic modules using graphene-enhanced Glauber's salt eutectic phase change material for advanced thermal management. *Proceedings of the IMechE, Part A: Journal of Power and Energy* 2025, 1−20. https://doi.org/10.1177/09576509251410980

[11] Liu, Y.; Zhang, X.; Hua, W.; Fang, M.; Zhang, J. Research progress of photovoltaic cooling systems based on phase change materials: An overview. *Energy Technology* 2024, 12(6), 2301614. https://doi.org/10.1002/ente.202301614

[12] Sontay, K.K., Öğüt, E., Ustaoğlu, A., Özkan, D., Kurşuncu, B. Experimental and optimization study of nanofluid-utilized PVT systems with hydrocarbon-based PCM: An energetic–exergetic approach. *Applied Thermal Engineering* 2025, 273, 126468. https://doi.org/10.1016/j.applthermaleng.2025.126468

[13] Popescu, M. Structural modeling of Ovonic materials. *Journal of Ovonic Research* 2006, 2(4), 45−52. https://chalcogen.ro/Popescu-ovonic.pdf

[14] Popescu, M. Medium range order in non-crystalline materials. *Journal of Ovonic Research* 2005, 1(1), 7−19. https://chalcogen.ro/Popescu5.pdf

[15] Kandilli, C. Exploring the potential of natural zeolites to enhance solar energy systems: A concise review. *Research & Design* 2024, 1 (1), 13–21. https://doi.org/10.17515/rede2024-001en1101rv

[16] Kandilli, C., Acikbas, Y., Uzel, M. Thermophysical properties of natural zeolite plates enhanced with aluminum granule for thermal management of photovoltaic thermal systems. *Journal of Energy Storage* 2022, 50, 104331. https://doi.org/10.1016/j.est.2022.104331

[17] Kandilli, C., Acikbas, Y., Uzel, M. Investigation of thermophysical properties of natural zeolite plates enhanced with graphite powder for thermal management of PV thermal systems. *Journal of Cleaner Production* 2021, 318, 128558. https://doi.org/10.1016/j.jclepro.2021.128558

[18] Ma, W., Yu, L., Zong, Y., Wan, D. Enhanced thermal regulation in photovoltaic panels using milled carbon fiber-reinforced multi-layer bio-based phase change materials. *Thermal Science and Engineering Progress* 2026, 70, 104500. https://doi.org/10.1016/j.tsep.2026.104500

[19] Benseddik, Z., Mortadi, M., Derraz, A., Ahachad, M., Radoine, H., Mahdaoui, M. Beyond traditional PV systems: An annual study on incorporating thermal, phase change material, and thermoelectric generator technologies for performance optimization under various climatic conditions. *Applied Thermal Engineering* 2025, 268, 125967. https://doi.org/10.1016/j.applthermaleng.2025.125967

[20] Tang, L., Luo, Y., Yin, L., Li, J., Cao, X. (cross-climate validation emphasis) Thermal-management performance of phase-change material on PV modules in different climate zones. *Energies* 2024, 17(23), 6200. https://doi.org/10.3390/en17236200