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REVIEW ARTICLE **RENEWABLE ENERGY**

Review of Synergistic Thermal Management in Photovoltaic/Thermal (PV/T) Systems: Nanofluids, Phase-Change Materials, and Finned Structures

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ABSTRACT

Operating temperature surges pose a major operational barrier to photovoltaic (PV) performance, causing significant declines in electrical output. Advanced thermal management approaches including Phase Change Materials (PCM), nanofluids, and structural modifications (fins/heat sinks) have emerged as viable mitigation pathways. However, existing literature frequently examines these technologies in isolation. In this paper, a critical evaluation of two review articles published in 2026 collectively citing 24 recent scientific studies—was conducted. The comparative analysis was carried out using the 16 papers most pertinent to the synergistic ternary hybrid ('Tri-Hybrid') system This paper provides a comparative synthesis of recent studies on active and passive cooling enhancements, merging comparative datasets across diverse configurations. By integrating structural enhancements (lapping fins and metal foams), high-conductivity nanofluids (Al_2O_3, MWCNT, Carbon Black), and latent heat storage (Paraffin wax, Coconut oil), this study evaluates the synergistic performance gains of multi-layered cooling systems, providing design insights for high-efficiency solar energy systems. To the best of the authors' knowledge based on literature up to 2026, no previous study has simultaneously integrated internal lapping fins, nanofluids, and PCMs within a single hybrid PV/T system—a novel synergistic approach expected to significantly boost both electrical and thermal. Ultimately, these advanced materials and hybrid frameworks present a durable pathway toward optimizing solar-to-thermal energy harvesting and storage.

مراجعة للإدارة الحرارية التآزرية في الأنظمة الكهروضوئية/الحرارية (PV/T): الموائع النانوية، ومواد تغيير الطور، والهياكل ذات الزعانف

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الكلمات المفتاحية
فوتوضوئية/حرارية
الموائع النانوية
مواد تغيير الطور
الزعانف الداخلية
الإدارة الحرارية
ليبيا

الملخص

تُمثّل الارتفاعات المفاجئة في درجات حرارة التشغيل عائقاً تشغيلياً رئيسياً أمام أداء الخلايا الكهروضوئية (PV)، مما يتسبب في انخفاض ملحوظ في الإنتاجية الكهربائية. وفي هذا السياق، ظهرت نهج الإدارة الحرارية المتقدمة بما في ذلك مواد تغير الطور ، والموائع النانوية ، والتعديلات الهيكلية (كالزعانف) كمسارات تخفيف مجدية. ومع ذلك، غالباً ما تتناول الأدبيات الحالية هذه التقنيات بشكل معزول. وفي هذه الورقة، أُجري تقييم نقدي لورقتي مراجعة نُشِرتا في عام 2026، وتستشهدان مجتمعتين بـ24 دراسة علمية حديثة. وقد نُفّذ التحليل المقارن باستخدام الأوراق ال16 الأكثر صلة بنظام الهجين الثلاثي المتآزر "Tri-Hybrid". وتُقدّم هذه الورقة توليفة مقارنة للدراسات الحديثة حول تحسينات التبريد النشطة والسلبيّة، دمجاً لمجموعات البيانات المقارنة عبر تكوينات متنوعة. ومن خلال دمج التحسينات الهيكلية (كالزعانف المتداخلة [lapping fins] والرغوة المعدنية)، والموائع النانوية عالية التوصيل مثل (Al_2O_3، وأنابيب الكربون النانوية متعددة الجدران [MWCNT]، والكربون الأسود)، وتخزين الحرارة الكامنة في مواد مثل (شمع البارافين، وزيت جوز الهند)، تُقيّم هذه الدراسة مكاسب الأداء التآزري لأنظمة التبريد متعددة الطبقات، مُقدّمةً رؤى تصميمية لأنظمة الطاقة الشمسية عالية الكفاءة. وعلى حد علم الباحثين، وبناءً على الأدبيات المنشورة حتى عام 2026، لم تُجرِ أي دراسة سابقة دمجاً متزامناً للزعانف المتداخلة الداخلية، والموائع النانوية، ومواد تغير الطور (PCMs) ضمن نظام هجين أحادي (PV/T) وهو نهج تآزري مبتكر يُتوقع أن يعزز بشكل كبير الكفاءتين الكهربائية والحرارية. وفي النهاية، تُمثّل هذه المواد المتقدمة والأطر الهجينة مساراً مستداماً نحو تحسين عمليات حصاد الطاقة الشمسية وتخزينها.

Introduction

The global energy transition

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Although Solar PV and PV/T collectors play a pivotal role in the global energy transition, achieving this transformation also relies on a diverse mix of renewable energy sources, energy storage systems, and grid modernization. Increasing the operating temperature compared to the Standard Test Conditions (STC at 25 °C) is responsible for an average power loss of about 0.4% - 0.5% per °C of the silicon cells. One of the objectives of thermal management systems is to keep the solar cells in a safe operating zone and recover some useful thermal energy. Meanwhile, the thermal dissipating performance of each individual improvement, including the nanofluid circulation, PCMs, or finned absorber heat exchangers, is relatively small in the limiting conditions. Besides the active cooling of nanofluids, the latent heat storage of PCMs could stabilize the working temperature during the change of solar radiation. Adding the finned geometry could disturb the boundary layer, induce more turbulence for flow, and enlarge the contact surface. Building these mechanisms into one "Tri-Hybrid" structure, the hope for triple-boost of efficiency would be brought forward.

Solar Energy Potential and Energy Demand in Libya

Overview Libya lies in the sun belt of North Africa with some 88% of its landmass constituted of desert land. As per the reports from the Institute of Thermodynamics Engineering at the German Space Center, the direct solar radiation in Libya ranges from 1900 kWh/m² in the extreme North up to more than 2800 kWh/m² in the South-East [1, 15]. Since, solar power plants are generally considered to be economical if the solar radiation is more than 1,800 kWh/m², almost 100% of Libya's landmass has an untapped potential of solar energy [2, 16].

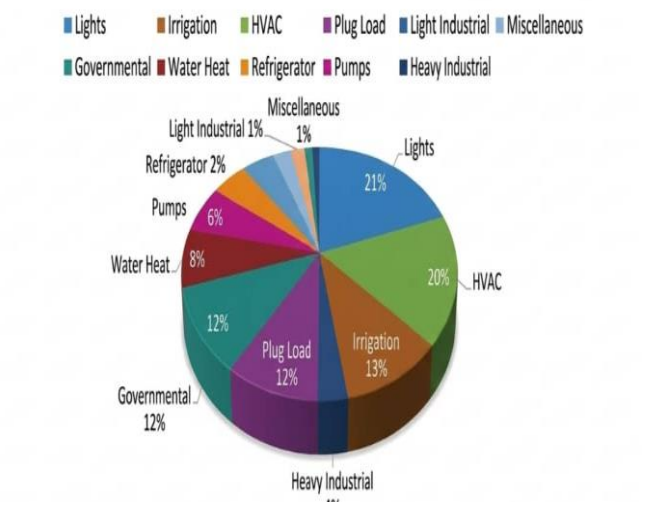


Figure 1: Percentage of energy consumption, by end use, for the institutional and commercial building sectors in LIBYA 2024. [5,6]

Simultaneously, the building sector is one of the largest energy end-users of the global energy demand. This is the case in Libya, where nearly 60% of the total electricity is used in the building sector and approximately 30% of the primary energy is consumed [3, 4]. Due to the common use of traditional vapor-compression air-conditioning systems for thermal comfort maintenance in indoor spaces, the increased demand for electricity is also clear during the hot summer days. Statistics at the national level show that the residential sector, as well as the public lighting system, are the leading end-users of the peak demand, since street lighting accounts for almost a quarter of the total demand Figure.1. [5, 6]. These consumption rates highlight the importance for the need of developing sustainable and energy-efficient technologies that satisfy thermal comfort requirements and consume less electricity. [9, 10].

Integrated Cooling Mechanisms and Comparative Synthesis

Phase Change Materials (PCM & Nano-PCM):

PCMs take up energy by phase transition at near isothermal conditions. With traditional PCMs, their rate of heat uptake is limited because they have low intrinsic thermal conductivity. This shortcoming is overcome by doping the PCMs matrix with nanoparticles (Nano-PCM). It is observed in literature [36, 38] that nano-PCM compounds increase heat storage rates under forced and natural convection by 21.2% and 20.7%, respectively, then the undoped PCMs. [36, 38].

Nanofluids:

Distributing nanoparticles (Al_2O_3, MWCNT, Carbon Black) in conventional base liquids creates nanofluids with higher thermal conductivity. Active nanofluid circulation in PV/T collectors lowers cell operating temperatures (up to 20.0 °C reductions), improving electrical output by over 15%. [8, 11, 12].

Finned Extensions & Structural Enhancements

Incorporating internal micro-fins, lapping fins Figure.2 or gradient-porosity aluminum metal foam heat sinks expands surface contact areas, disrupts thermal boundary layers, and induces turbulence. For example, lapping fins with planar reflectors yield cell temperature drops of up to 24.57 °C, translating to direct electrical gains. [7, 8].



Figure 2: Tubes with Internal Lapping Fins to enhance convection heat transfer [13].

The internally finned copper tubes shown in the previous figures will be purchased ready-made from NEOTISS, with the detailed specifications and dimensions of the tubes. Figure.3.

Metallic elements (e.g., (Cu) and silver (Ag)), metal oxides (e.g., aluminum oxide (Al2O3), zinc oxide (ZnO) and titanium dioxide (TiO2)), and carbonaceous nanostructures such as carbon nanotubes (CNTs) and graphene, represent the most widely adopted nanoparticle materials. [40]. By being dispersed in the working fluid of the solar collector, the optical absorption and thermal transportation behavior of the nanofluids can be increased, which leads to an increased

overall energy efficiency of the system. The typical preparation steps for preparing the two-step methods of preparing the nanofluid are shown in Figure.5 and Figure.7, [39, 45 and 53]. However, colloid stability and dispersion are still technical bottlenecks due to the increasing aggregation and sedimentation of nanoparticles causing performance degradation of the system. [36, 37].

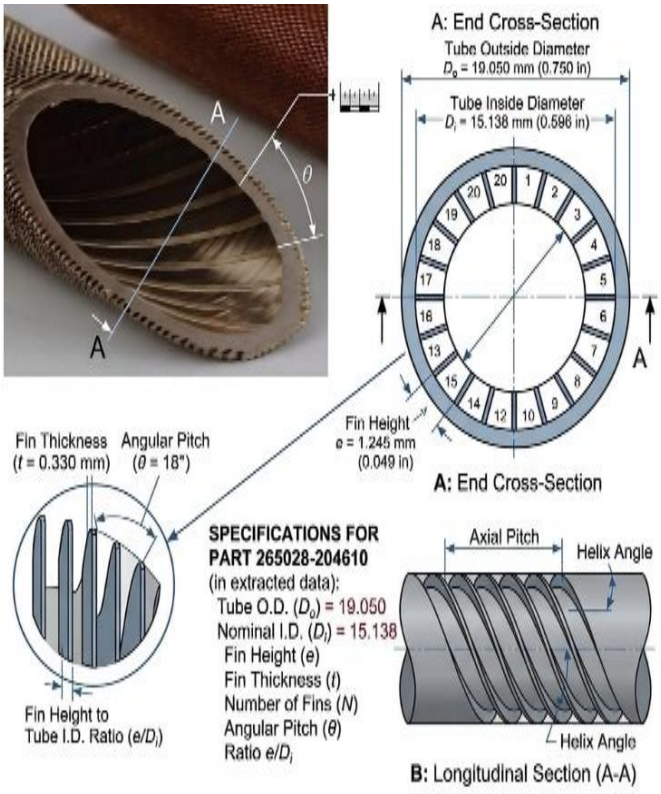


Figure 3: A detailed 2D drawing showing the geometry of the internal lapping fins (e.g., thickness, pitch, number, and fins height to tube diameter ratio) [13].

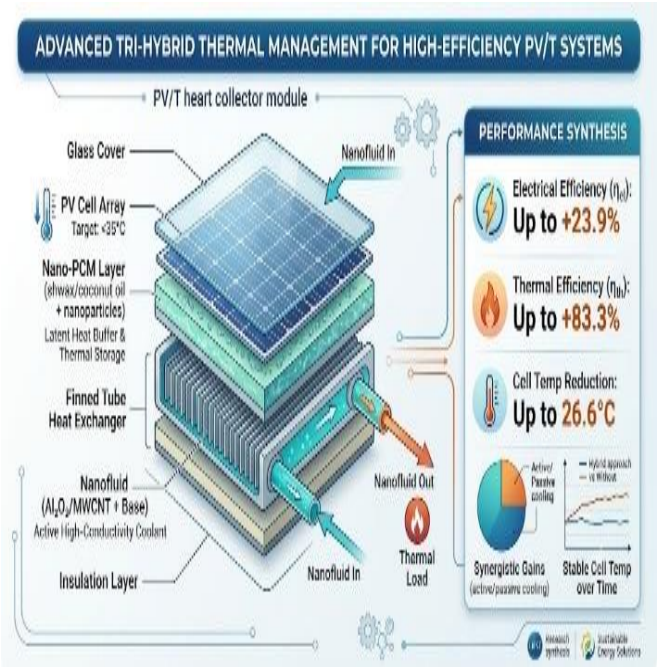


Figure 4: Advanced Tri-Hybrid Photovoltaic (PV) and Photovoltaic/Thermal (PV/T) systems.[16].

Methodology and Selection Criteria

This critical review analysis relied on a systematic multi-stage selection criteria process to collate, compare and analyze the most recent high-impact literature relevant to tri-hybrid advanced thermal management schemes for solar photovoltaic (PV) and photovoltaic/thermal (PV/T) solar cells are shown in Figure.4. The primary review theme was to consider the combined synergistic thermal performance tri-hybrid benefits gained through active nanofluid thermal management, passive latent heat storage with Phase Change Materials (PCMs) and extended cell surface area using a subsequent internally finned geometry step.

Inclusion Criteria and Scope of Selection

To establish a high-impact focused review, literature selection proceeded against the following inclusion criteria:

Tri-hybrid synergy minimum threshold: relevant literature was segregated to focus on: Active removal of heat using nanofluid-based cooling schemes (e.g., Al2O3, MWNCT, Carbon Black, etc.). Latent heat-based thermal energy storage using phase change materials (solid-liquid, nano-phase change materials). Cell and panel thermal management using extended internal geometries (internally finned heat exchangers, micro-grooves, metal-foam matrixes). Relevance / recency: in order to capture the high-impact latest advances in the space, the review database was constrained to recent high-impact publications (from 2020 to 2026).

Literature comparison framework

From an initial database of twenty-four recent scientific studies, and based on particular focus on synergistic tri-hybrid cooling system efficiency augmentation, sixteen core papers were ultimately identified as relatively aligned to the synergistic tri-hybrid system configuration, and this subset of literature was comparative benchmarked against measured operating cell temperature, electrical efficiency and thermal system efficiency.

Comprehensive Comparative Data Analysis

Quantitative results from the two baseline reviews are consolidated here to compare energy conversion efficiencies for different experimental and numerical configurations. [8, 34].Together, the two studies reference a total of 24 recent scientific papers. A comparison was conducted using the 16 papers most relevant to the synergistic ternary system "Tri-Hybrid", as presented in the table1.Comprehensive Multi-Study System Comparison The integrated cooling methods, tested configurations, and performance evaluations are listed in the below table across different experiments and numerical studies.

Research Gap

Despite this, by using nanofluids, PCM and an advanced heat exchanger geometry, several studies have proven that there is promise for the application of these techniques to increase the heat transfer performance of PV/T systems. However, most of these studies have focused on these techniques individually, or in a partially integrated system. In particular, the literature shows that little work has been conducted on the integration of an internal finned absorber tube, PCM and nanofluid as a thermal energy storage system all within the same PV/T system. As such, there is room for development of a hybrid heat transfer enhancement strategy that would incorporate these three mechanisms into the same PV/T system to increase the overall heat transfer performance, energy efficiency and PV temperature control capability, as shown in Figure.6.

Table 1: Comparative Analysis of the Sixteen Selected Research Papers on PV and PVT System.

Reference	System Type	Integrated Cooling Strategy	Key Performance Enhancement
[17]	PVT	Inner Plate-Finned Cooling + Nanofluids	Enhanced Electrical and Thermal Performance (Experimental/Mathematical Analysis).
[18]	PV	Aluminum Nanofluid + Heatsink	Electrical Efficiency: +13.5%; PV Temp. Reduction: 13.08–16.34 °C
[19]	PVT	Al_2O_3 Nanofluid + Serpentine Coil	Electrical Efficiency: +15.5%; PV Temp. Reduction: 20.0 °C
[20]	PV	Lapping Fins + Planar Reflector	Electrical Efficiency: +1.39% (from 9.81% to 11.2%); PV Temp. Reduction: 24.57 °C
[21]	CPV-T	Nanofluid + Finned PCM Heatsink	Electrical Efficiency: up to 17.02%; Thermal Efficiency: up to 61.25%; PV Temp. Reduction: 26.6 °C
[22]	FPSC	PCM Bags + Hybrid Nanofluid	Energy Gain: max 26%
[23]	PV/T-PCM	PCM + Nanofluid	Enhanced solar energy absorption
[24]	PV	PCM Infused Graphite + Aluminium Fins	Regulated PV panel temperature
[25]	PVT	Nano-PCM + Finned Collector	Thermal Energy Storage: +21.2% (Forced Convection)
[26]	PVT	Nano-PCM + Micro-fins Tube + Nanofluid	Electrical Efficiency: up to 23.9%; Thermal Efficiency: up to 17.5%; Max Thermal Efficacy: 83.3%
[27]	PV/T	PCM + Finned Tube Heat Exchanger	Improved overall PV/T system performance
[29]	CS- PCM	Nanofluids + Phase Change Materials (PCM).	Synergistic effect; high conductivity and latent heat storage.
[30]	PVT	Energy evaluation and optimization framework.	Maximized energy harvest in high-temperature applications.
[31]	PV/T -PCM	Coconut oil -based PCM.	Stable heat discharge during low radiation periods.
[32]	PVT	Carbon Black Nanofluid (PumpFree)	Enhanced heat transfer via natural convection (Applicable to passive PV/T)

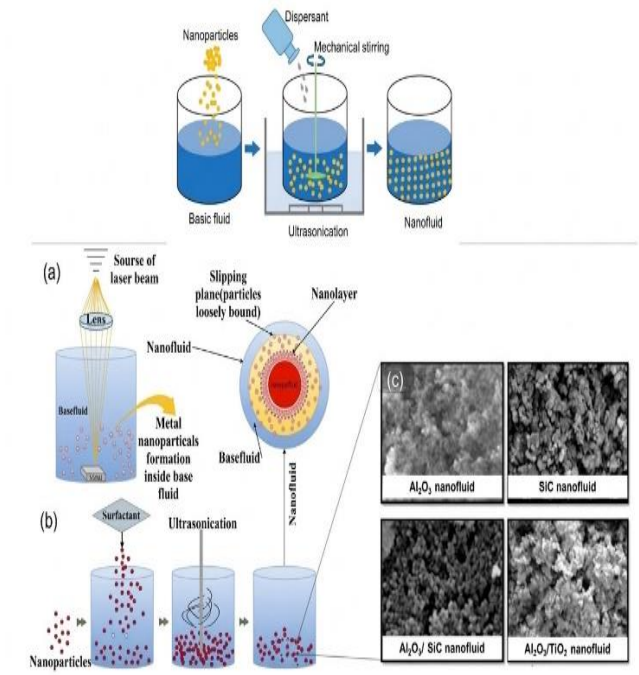


Figure 5: Preparation and stability analysis of nanofluid: (a) with source of laser beam (b) By ultra sonification [45,53].

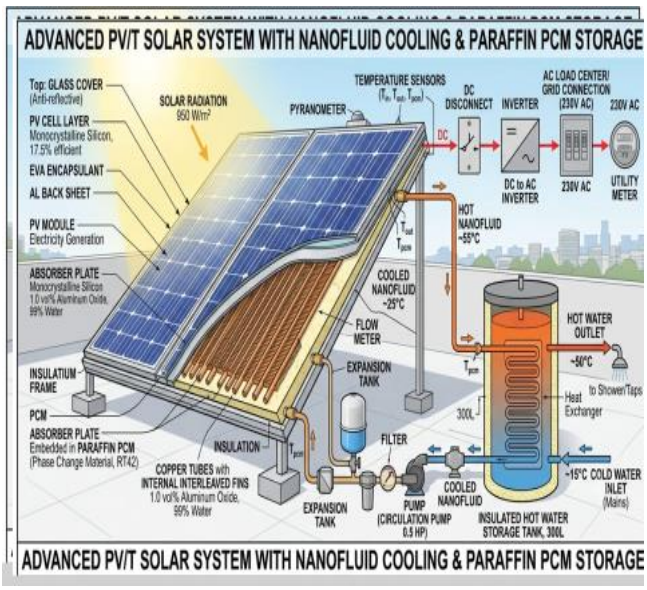


Figure 6: Schematic diagram of the advanced PV/T solar system with nanofluid cooling and paraffin PCM storage [34].

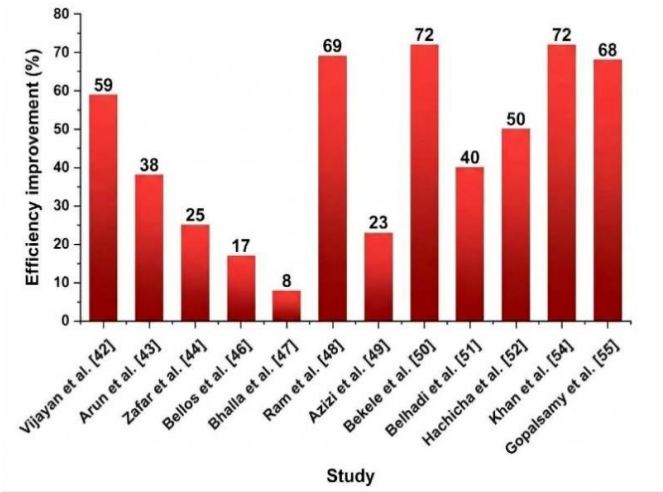


Figure 7: Thermal efficiency improvement comparisons [29].

Review Summary

Nanofluids significantly enhance the instantaneous heat transfer within the solar collector [41], and yet are limited by the inherent intermittency of solar radiation [42]. The challenge of intermittency can be tackled with nanosuspensions that expand the theoretical and practical envelope of latent heat storage with PCMs [43, 57], providing a synthesized overview of nanofluids, PCMs and nano-enhanced phase change materials (NEPCMs) in CSP systems. The presence of dispersed nanostructures (e.g., Al2O3, CuO, TiO2, MWCNT, graphene) in a conventional fluid phase enhances the thermal conductivity and heat transport efficiency of the fluid, leading to collector efficiencies of 10-70% with effective viscosity penalty and long-term stability control. Incorporation of PCMs (e.g., fatty acids, salt hydrates and paraffins) leads to latent heat storage, which smooths the thermal transient response, extends the operational timeframe and drives the exergy efficiency of the system up to 6-85%. NEPCMs increase the rate of phase change by 6-92%, driving the power conversion efficiency to 93%, while the use of metallic foams, multi-stage PCMs or fins minimizes entropy generation and facilitates 100% power supply after sunset [29, 56]. as shown in Figure.7.

Conclusion

This review rigorously studied, simulated and synthesized state-of-the-art advances in the realm of solar thermal and hybrid PV/T coalescing active and passive means of cooling - notably nanofluids, phase change materials (PCMs/Nano-PCMs) and geometric intervention (internal fins and porous foams). It considered not just thermo-hydraulic improvements but also feasibility and practicality of implementation, unlocking operational conditions or regimes where hybrid and tri-hybrid systems are significantly superior to traditional heat transfer fluids. Here, the major takeaways and conclusions are enumerated and described. as shown in Figure.8.

- The removal of high-conductivity particles occurs in the nanoparticle-permeated fluid. This disperses the nanoparticles and, because of increased surface-to-volume interaction, enhances heat transfer and results in thermal efficiency increase of 30-40%. In three-hybrid PV/T systems, where cool nanofluids, non-coated Nano-PCMs and an extended heat-sink geometry are employed, the operating temperature of the solar cells can be reduced to 30-35 °C providing an electrical efficiency enhancement of up to 23.9% and a thermal efficiency enhancement of > 83%.
- Synergistic & transient effects: Hybrid nanofluid combinations clearly outperform single-particle fluids of lower conductivity, when nanoparticle loading is accurately optimized. At the same time PCM adds inertia, smears transient variations in solar flux and increases days of operation after sunset.
- Scale-Up Bottlenecks: Limited commercial scale-up due to nanoparticle agglomeration and sedimentation, higher viscosity induced parasitic pumping losses, and structural/mechanical challenges with large scale integration.

In order to translate these high-performance designs to viable market-ready solutions, further work would include long-term chemical and colloidal stability testing, comprehensive LCA/life cycle costing and cost economics evaluation, and topological optimization of low-parasitic (or pump-less) thermal management architectures.

In order to systematically downscale the synthesized review conclusions into an improved system configuration, a sufficient technical basis is required for the selected working media and energy-storing media. The type of working media strongly defines the thermo-hydraulic performance, global energy utilization ratio, and sustainability over the lifetime of the hybrid system. The subsequent part illustrates the scientific-technical justification for selecting the particular nanofluid and PCM engaged in this work.

Scientific Rationale for Material Selection

Selection of Alumina/Water Nanofluid (Al_2O_3 / Water)

- The use of Al_2O_3 nanoparticles enhances the thermal conductivity rate of PV/Al_2O_3 nanofluid significantly over pure water. This brings improved heat transfer efficiency and increased thermal power extraction from the PVs.
- Chemical stability and outstanding dispersion properties: Outstanding chemical stability and dispersion stability of Al_2O_3 nanoparticles in aqueous base liquids, with little aggregated sediments are observed with moderately high shear and good flow conditions.
- Cost Effectiveness and availability: Alumina nanoparticles are a very cost effective and commercially viable proposition for practical implementation than other carbon based or noble metal nanoparticles such as Ag or Au.
- Tribological Compatibility: They exhibit a less erosive and abrasive effect on the internal surfaces of internally finned copper tubes, safeguard the micro-grooved structures under continuous flow.

Selection of Phase Change Material (Paraffin Wax PCM - RT42HC)

- When phase changes (melting) the metal enjoys high latent heat storage capacity and when phase changes take place large quantity of thermal energy is absorbed with less change of temperature.
- We have chosen the optimal phase-change temperature for RT42HC grade, with a melting temperature close to 42 °C. This temperature is adapted to the control of the PV cells' working temperature, to keep the electrical efficiency and to limit the thermal degradation of the PV cells in hot hyper-arid climates.
- Stability: non-corrosive, thermally stable, no phase segregation or supercooling effect as occurs in inorganic salt hydrates, and moisture free during repeated freezing and melting cycles in Paraffin PCM.
- Off-Peak thermal Management: It acts as a thermal buffer, absorbing peak solar radiation at the time of maximum irradiance and discharging stored thermal

energy as hot water for domestic use during low radiation or off-peak hours.

Note: To resolve the natural low thermal conductivity of paraffin wax, it is pressed into an aluminum foam/matrix structure with the intention of improving total effective thermal conductivity and heat charge / discharge rate.

Integration of Finned Extensions & Structural Enhancements

Advanced Additive Manufacturing: Utilization of 3D-printed copper tubes featuring internal interlocking fin structures allows for precise fabrication of complex geometries that maximize heat dissipation.

Expanded Surface Contact Area: Incorporating internal micro-fins, lapping fins, significantly expands surface contact areas.

Boundary Layer Disruption & Turbulence: The structural enhancements and internal fin configurations disrupt thermal boundary layers and induce beneficial turbulence to maximize convective heat transfer.

Direct Electrical Performance Gains: Practical applications, such as lapping fins paired with planar reflectors, yield substantial cell temperature drops of up to 24.57 °C, translating directly into enhanced electrical efficiency.

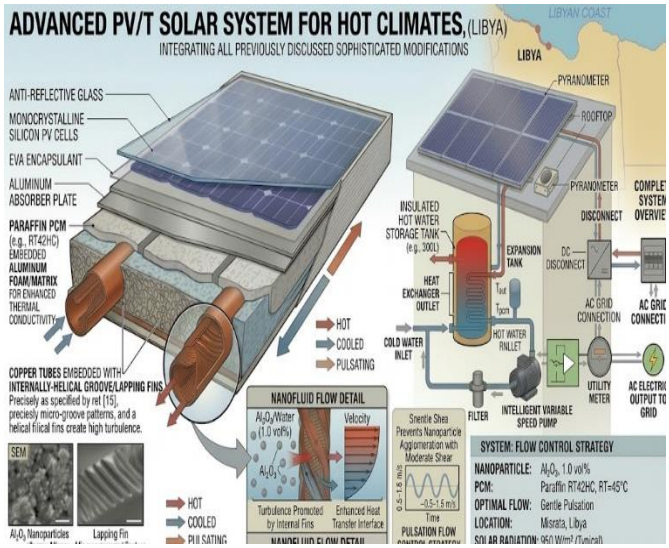


Figure 8: Detailed schematic of the advanced PV/T solar system showing cross-sectional layers, internal finned tubes, and nanofluid flow dynamics for hot climates (Misrata, Libya). [34].

A Review of Synergistic Thermal Management in Photovoltaic/Thermal (PV/T) Systems: Nanofluids, Phase-Change Materials, and Finned Structures.

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