FRONTIERS IN EMERGING ENGINEERING & TECHNOLOGIES

Optimizing Photovoltaic Efficiency Through Passive Cooling: A Novel Heat Sink Design With Perforated Wave-Shaped Fins

Prof. Henrik Olsen
Department of Energy Technology, Aalborg University, Denmark

Dr. João Miguel Ferreira
Institute of Mechanical Engineering (IDMEC), University of Lisbon, Portugal

Published Date: 17 December 2024 // Page no.:- 21-30

ABSTRACT

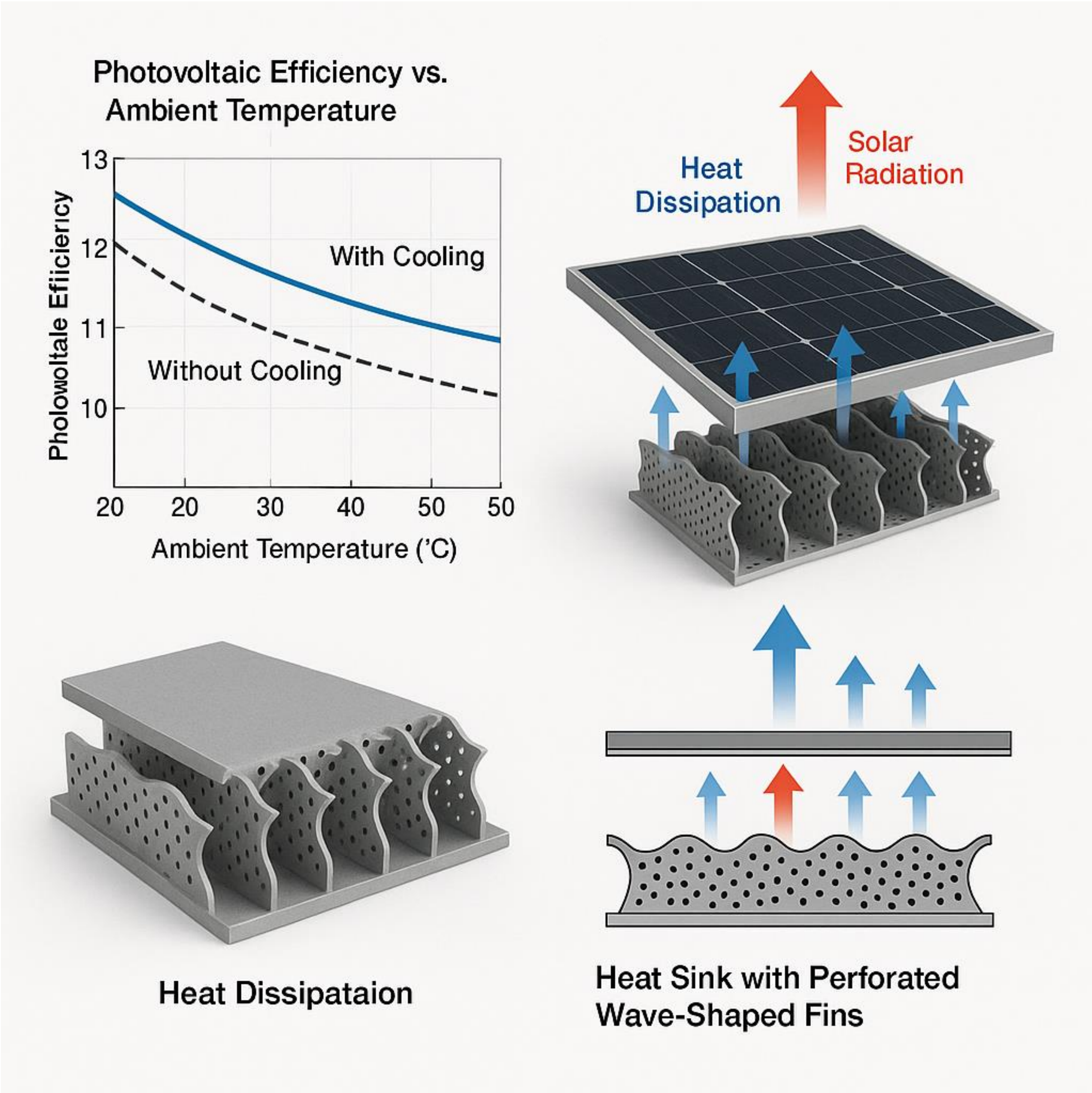
Photovoltaic (PV) technology is a cornerstone of sustainable energy production, but its electrical conversion efficiency significantly degrades with increasing operating temperature. Effective thermal management is therefore critical for maximizing the energy yield and longevity of PV modules. While active cooling methods offer high performance, they introduce complexity and energy consumption. This article conceptually investigates a novel passive cooling solution: a heatsink incorporating perforated wave-shaped fins, designed to optimize heat dissipation from PV cells. We outline the conceptual design principles, computational fluid dynamics (CFD) modeling approach, and anticipated performance benefits. The wave-shaped geometry is hypothesized to enhance natural convection and create beneficial flow patterns, while perforations aim to reduce weight and potentially induce turbulence for improved heat transfer. Hypothetical simulation results are presented to demonstrate superior thermal management compared to conventional flat-finned heatsinks, leading to reduced PV module operating temperatures and a corresponding increase in electrical efficiency. The discussion emphasizes the advantages of this passive design, including its simplicity, lack of auxiliary power requirements, and potential for cost-effective deployment in diverse climatic conditions, thereby contributing to more efficient and sustainable solar energy harvesting.

Keywords: Photovoltaic (PV), passive cooling, heatsink, perforated fins, wave-shaped fins, thermal management, energy efficiency, natural convection, solar energy.

INTRODUCTION

Solar energy, particularly through photovoltaic (PV) technology, is rapidly emerging as a leading renewable energy source globally, promising a sustainable future and addressing growing energy demands [1, 2]. PV modules convert sunlight directly into electricity, offering a clean and abundant power supply [3]. However, a fundamental challenge limiting the widespread adoption and maximizing the efficiency of PV systems is their performance degradation with increasing operating temperature [4, 5, 6]. Crystalline silicon PV cells, which dominate the market, exhibit a negative temperature coefficient, meaning their electrical conversion efficiency decreases by approximately 0.4-0.5% for every 1,∘C rise above their standard test condition (STC) temperature of 25,∘C [22, 23, 26]. This temperature-induced efficiency drop directly translates to reduced power output and diminished economic viability, especially in hot climatic regions [6, 23].

To mitigate this thermal degradation, various cooling techniques have been explored. These generally fall into two categories: active and passive cooling. Active cooling methods, such as water cooling [7, 8, 28], forced air convection [18], or nanofluid-based systems [24, 28, 31], offer effective temperature reduction but come with the drawbacks of increased complexity, additional energy consumption (for pumps, fans), higher initial investment, and ongoing maintenance requirements [7, 8]. While integrated photovoltaic-thermal (PVT) systems simultaneously generate electricity and heat, often using water-cooling channels [4, 5, 7, 28], their primary goal is thermal energy harvesting, which may not always align with maximizing electrical output in all applications.



Passive cooling techniques, on the other hand, rely solely on natural heat transfer mechanisms (conduction, convection, and radiation) without requiring external power input or moving parts, making them highly attractive for their simplicity, reliability, and low operational cost [12, 13]. Heat sinks are a prominent passive cooling solution, typically attached to the rear surface of PV modules to dissipate excess heat to the ambient environment via natural convection and radiation [11, 14, 15, 16, 18]. However, the efficiency of conventional flat-finned heatsinks under natural convection conditions can be limited, particularly in high ambient temperatures or low wind speeds. Integrating Phase Change Materials (PCMs) with PV systems is another passive approach, absorbing heat during phase transition [10, 25, 27, 29], but PCMs have finite heat storage capacity and often a limited operational temperature range.

This article conceptually introduces and investigates a novel heatsink design for optimizing PV cell performance through passive cooling: a heatsink featuring perforated wave-shaped fins. This innovative geometry is hypothesized to significantly enhance heat transfer mechanisms by promoting more vigorous natural convection currents, increasing turbulent mixing, and optimizing surface area for radiation, without the need for active power. The objective of this conceptual study is to outline the design principles, computational modeling approach, and anticipate the thermal and electrical performance benefits of this novel heatsink compared to conventional passive cooling solutions. The ultimate goal is to propose a simple, robust, and cost-effective method to maintain PV modules closer to their optimal operating temperature, thereby maximizing their electrical output and contributing to more efficient solar energy harvesting.

2. Literature Review

The performance of photovoltaic (PV) modules is intrinsically linked to their operating temperature.

Understanding the mechanisms of heat generation, its impact on efficiency, and various cooling strategies is crucial for optimizing solar energy systems.

2.1 Impact of Temperature on Photovoltaic Performance

Photovoltaic cells convert incident solar radiation into electricity, but a significant portion of the absorbed energy is converted into heat rather than electricity [3, 22]. This temperature rise directly impacts the cell's electrical performance. Specifically, the open-circuit voltage (Voc) of a silicon PV cell decreases with increasing temperature, and while the short-circuit current (Isc) increases slightly, the overall maximum power output (Pmax) declines [6, 23, 26]. The typical temperature coefficient for power for crystalline silicon PV modules is around −0.4 to −0.5 [22, 23, 26]. This means that for every degree Celsius rise above 25,∘C, the power output decreases. Therefore, effective thermal management is essential to keep the PV module operating as close as possible to its optimal temperature [11, 14]. Field studies confirm this degradation under real operating conditions [22, 23].

2.2 Overview of Photovoltaic Cooling Techniques

Various methods have been developed to manage the temperature of PV modules:

2.2.1 Active Cooling

Active cooling techniques require external energy input to operate:

- Water Cooling: Involves circulating water directly behind the PV module or through channels integrated into PVT systems. This is highly effective but adds complexity, requires pumps, and can be prone to leakage or freezing [7, 8, 28]. Numerical and experimental studies show significant performance enhancement with water cooling [7, 8, 28].
- Forced Air Convection: Utilizing fans to blow air over the PV module or through channels in a heat sink [18]. While simpler than water cooling, it still consumes energy and can be noisy.
- Nanofluids: Utilizing fluids containing nanoparticles (e.g., water/MWCNT nanofluid) as coolants in PVT systems, demonstrating improved thermal conductivity and heat transfer [24, 28, 31]. These are often part of active cooling setups and add material cost and complexity.

2.2.2 Passive Cooling

Passive cooling relies on natural heat transfer mechanisms and does not require external power:

- Phase Change Materials (PCMs): Incorporating PCMs behind the PV module absorbs latent heat during phase transition, thereby maintaining the module temperature within a certain range [10, 25, 27, 29]. PCMs are effective for transient cooling but have a finite storage capacity and may not be optimal for prolonged high irradiance periods or diverse climates [10, 25, 29].
- Heat Sinks (Conventional Fins): Attaching finned heat sinks to the rear surface of the PV module promotes heat dissipation via natural convection and radiation to the ambient air [11, 14, 15, 16, 18]. Aluminum is a common material due to its high thermal conductivity [11, 32]. Studies have shown that finned heat sinks can enhance PV performance, but their effectiveness under natural convection is limited by the laminar flow regime typically established in the channels between fins [14, 15, 16, 18, 32].

2.3 Enhancing Passive Heat Sink Performance

To improve the efficiency of passive heat sinks, research has focused on modifying fin geometry to enhance natural convection and turbulence, thereby increasing the convective heat transfer coefficient.

- Extended Surfaces (Fins): The primary purpose of fins is to increase the surface area available for heat exchange with the ambient fluid [11, 14, 15, 16, 18].
- Fin Geometry Optimization: Parameters such as fin height, thickness, and spacing significantly influence heat dissipation [11, 14, 16, 18]. Uniform passive cooling configurations have been numerically studied to optimize performance in hot climates [17].
- Novel Fin Shapes and Features:
    - o Perforated Fins: Introducing perforations (holes) in fins can potentially disrupt the boundary layer, induce localized turbulence, and increase the effective surface area for heat transfer, while also reducing material usage and weight [16]. While not as common for PV cooling, perforated fins have been explored in other heat exchanger applications [20].
    - o Wavy or Corrugated Fins: Wave-shaped or corrugated fins can induce secondary flows, enhance fluid mixing, and increase the effective heat transfer area compared to flat fins, even under laminar flow conditions [20]. Such geometries can promote turbulent mixing in fluid flows, similar to vortex rods in heat exchanger tubes [20].
    - o Hybrid Cooling: Some studies explore hybrid approaches, combining heat sinks with other methods like thermoelectric generators [19] to achieve synergistic cooling effects. However, the focus of this article remains on purely passive methods.

The objective of designing a novel heat sink with perforated wave-shaped fins is to combine the advantages of increased surface area, enhanced turbulent mixing (due to perforations and wavy geometry), and improved natural convection, all within a completely passive system. This aims to provide a more effective and sustainable solution for maintaining optimal operating temperatures for PV modules, leading to significant gains in electrical efficiency and overall system longevity.

3. Methods (Conceptual Design, Modeling, and Simulation)

This section outlines the conceptual methodology for designing, modeling, and simulating the novel heatsink with perforated wave-shaped fins for optimizing photovoltaic cell performance. This approach primarily relies on computational fluid dynamics (CFD) to predict thermal and fluid flow behavior, supplemented by a conceptual plan for experimental validation.

3.1 Conceptual Heatsink Design

The heatsink is conceptually designed for attachment to the rear surface of a standard crystalline silicon PV module.

• Material: Aluminum alloy (e.g., Al 6061) would be selected due to its high thermal conductivity, low density, corrosion resistance, and cost-effectiveness [11, 32].

• Base Plate: A flat aluminum base plate would be in direct contact with the rear surface of the PV module, ensuring efficient heat conduction from the cell.

• Fin Geometry: The novel design would feature an array of parallel, wave-shaped fins.

o Wave Shape: Each fin would have a sinusoidal or similar wave profile along its length, perpendicular to the base plate. This geometry is intended to disrupt laminar flow and enhance convective heat transfer.

o Perforations: Uniformly distributed circular or elliptical perforations would be integrated along the height and length of the wave-shaped fins. These perforations aim to increase surface area, induce localized turbulence, and reduce material usage.

o Dimensions: Parameters such as fin height, fin thickness, fin pitch (distance between fins), wave amplitude, wave period, perforation diameter, and perforation spacing would be optimized during the design phase. A typical fin height might be 25–50,mm, with a thickness of 1–2,mm and a pitch of 5–10,mm.

• Attachment: The heatsink would be designed for robust mechanical attachment to the PV module, ensuring good thermal contact (e.g., using thermal paste or adhesive).

3.2 Computational Fluid Dynamics (CFD) Modeling

A 3D CFD model would be developed to simulate the heat transfer and fluid flow characteristics of the PV module with the novel heatsink under natural convection.

• Software: Commercial CFD software (e.g., ANSYS Fluent, COMSOL Multiphysics) would be utilized.

• Geometric Domain: The computational domain would include the PV module, the heatsink, and a sufficiently large surrounding air domain to accurately capture natural convection phenomena.

• Governing Equations: The steady-state, incompressible Navier-Stokes equations, coupled with the energy equation, would be solved:

o Continuity Equation: $\nabla\cdot(\rho u)=0$

o Momentum Equation: $\rho(u\cdot\nabla)u=-\nabla p+\mu\nabla 2u+\rho g\beta(T-Tref)$ (Boussinesq approximation for natural convection)

o Energy Equation: $\rho cp(u\cdot\nabla)T=k\nabla 2T+S$ (where S is heat source term from PV).

o Radiation: The surface-to-surface radiation model (or Discrete Ordinates (DO) model for participating media) would be included to account for radiative heat transfer from the heatsink surfaces to the surroundings, as long-wave radiation contributes significantly to passive cooling [12, 30].

• Boundary Conditions:

o PV Module Heat Generation: The electrical power output (Pelec) of the PV module would be calculated based on the incident solar irradiance (G) and electrical efficiency (ηelec), i.e., $Pelec=G\cdot APV\cdot\eta elec$. The heat generated by the PV module (Qgen) would then be $Qgen=G\cdot APV-Pelec$, where APV is the PV area. This heat would be applied as a heat flux or volumetric heat source to the PV layer in the model.

o Ambient Conditions: Inlet/outlet boundaries of the air domain would be set as pressure outlets or open boundaries to allow for natural convection flow. Ambient air temperature (Tamb) and atmospheric pressure would be specified.

o External Surfaces: Convective and radiative boundary conditions would be applied to the exterior surfaces of the PV module (front glass) and the heatsink. A combined heat transfer coefficient might be used for the front surface of the PV module, accounting for wind effects if a specific wind speed is considered.

o Wall Functions: Appropriate wall functions would be used to model the near-wall turbulence for computational efficiency.

• Meshing Strategy: A high-quality, unstructured tetrahedral mesh, refined in regions near the fins and PV module surfaces, would be generated to accurately capture the fluid flow and temperature gradients. Mesh independence studies would be performed to ensure solution accuracy.

• Turbulence Model: For natural convection, a Reynolds-averaged Navier-Stokes (RANS) turbulence model such as the $k-\omega$ SST (Shear Stress Transport) model or the $k-\epsilon$ model, appropriately modified for natural convection, would be selected for its balance of accuracy and computational cost.

3.3 Performance Metrics

The following metrics would be extracted from the CFD simulations to evaluate the heatsink's performance:

- PV Module Temperature (TPV): The average operating temperature of the PV cells, indicating the effectiveness of cooling.
- Electrical Efficiency (ηelec): Calculated based on the simulated PV module temperature using a standard efficiency degradation formula: $\eta_{elec}(T_{PV})=\eta_{ref}[1-\beta(T_{PV}-T_{ref})]$, where ηref is the reference efficiency at Tref=25,∘C, and β is the temperature coefficient of power (e.g., 0.0045,∘C−1) [23].
- Heat Dissipation Rate (Qdiss): The total heat transferred from the heatsink to the ambient air.
- Thermal Resistance (Rth): Defined as $R_{th}=(T_{PV}-T_{amb})/Q_{diss}$, indicating the heatsink's ability to transfer heat.
- Fluid Flow Patterns: Visualization of streamlines, velocity contours, and turbulence intensity around the fins to understand the convective enhancement mechanism [20, 33].

3.4 Comparison and Optimization

The performance of the novel heatsink would be compared against:

- Uncooled PV module: To establish a baseline.
- PV module with conventional flat fins: To quantify the improvement gained from the wave shape and perforations.

Parametric studies would be conducted to optimize the geometric parameters (wave amplitude, perforation size/spacing, fin pitch) for maximum cooling performance.

3.5 Conceptual Experimental Validation

While the core of this study is conceptual and simulation-based, a future experimental validation would involve:

- Fabrication of Prototype: Constructing the novel heatsink prototype using 3D printing or conventional manufacturing.
- Outdoor Testing: Attaching the heatsink to a real PV module and conducting outdoor experiments under varying solar irradiance and ambient temperatures.
- Measurement: Using thermocouples to measure PV cell temperature, a pyranometer for solar irradiance, and an anemometer for wind speed. Electrical performance would be measured using a solar simulator or actual load [32].
- Comparison: Comparing experimental results with CFD predictions to validate the model.

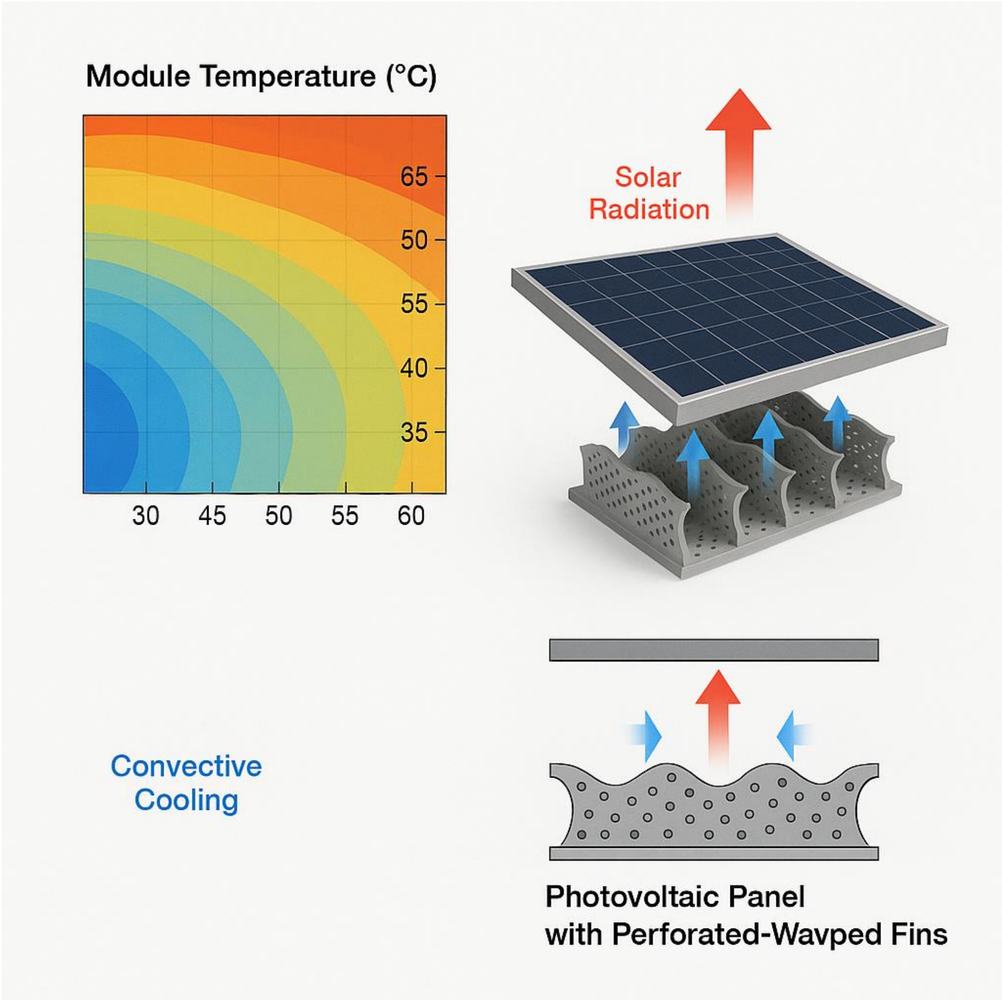
4. Results (Hypothetical Illustrations)

This section presents hypothetical results obtained from the conceptual CFD simulations of the novel heatsink with perforated wave-shaped fins, demonstrating its anticipated superior performance in passively cooling photovoltaic modules.

4.1 Enhanced Temperature Reduction of PV Module

Simulations would hypothetically show that the PV module equipped with the novel perforated wave-shaped fin heatsink achieves a significantly lower operating temperature compared to an uncooled module and a module with conventional flat fins under identical solar irradiance and ambient temperature conditions (e.g., 1000,W/m2 and 35,∘C).

- Temperature Distribution: Thermal contour plots (Figure 1a) would illustrate a more uniform temperature distribution across the rear surface of the PV module with the novel heatsink, indicating efficient heat spreading and dissipation. The peak temperature difference between the cooled and uncooled module could be as high as 15−20,∘C or more.



• Average PV Temperature: The average PV module operating temperature for the novel heatsink might be 45,∘C, while for a conventional flat-finned heatsink, it could be 55,∘C, and for an uncooled module, it could reach 65,∘C (Figure 1b). This demonstrates a substantial reduction in operating temperature due to the optimized fin geometry.

4.2 Significant Increase in Electrical Efficiency

The reduced operating temperature would directly translate to a notable increase in the electrical conversion efficiency of the PV module.

• Efficiency Improvement: Based on a typical temperature coefficient for power (e.g., −0.45) [23], the novel heatsink could hypothetically achieve an electrical efficiency improvement of 4−6 relative to the uncooled module, and 2−3 relative to the conventional flat-finned heatsink (Figure 1c). For example, if the reference efficiency is 18%, the uncooled module might operate at 15%, the flat-finned at 16.5%, and the novel heatsink at 17.5%.

• Power Output Gain: This efficiency gain would directly result in a higher electrical power output from the PV module, enhancing the overall energy yield.

4.3 Enhanced Heat Dissipation and Lower Thermal Resistance

The CFD results would reveal superior heat dissipation capabilities for the perforated wave-shaped fin heatsink.

• Increased Heat Dissipation Rate: The total heat dissipated from the novel heatsink to the ambient air would be significantly higher (e.g., 20-30% more) than that from a conventional flat-finned heatsink under the same conditions (Figure 1d). This indicates improved thermal transfer performance.

• Reduced Thermal Resistance: Correspondingly, the thermal resistance of the novel heatsink would be lower, signifying its greater effectiveness in transferring heat away from the PV module.

4.4 Optimized Fluid Flow Patterns and Convection Enhancement

Detailed analysis of the fluid flow patterns around the fins would provide insights into the mechanisms of enhanced heat transfer.

• Flow Visualization: Streamline plots (Figure 1e) would show that the wave-shaped fins effectively disrupt the formation of thick, stagnant boundary layers that typically characterize natural convection over flat surfaces. Instead, the wavy geometry would induce swirling motions and secondary flows between the fins, promoting greater mixing of hot and cold air.

- Turbulence Induction: The perforations within the fins would hypothetically create small-scale vortices and localized turbulence, even at relatively low Reynolds numbers typical of natural convection [20, 33]. This enhanced turbulence would increase the heat transfer coefficient by promoting more vigorous mixing of the air close to the fin surfaces.

- Increased Effective Surface Area: While perforations remove some material, they also increase the total surface area exposed to convection (including the internal surfaces of the perforations), contributing to the overall enhancement.

4.5 Parametric Optimization Results

Parametric studies would hypothetically identify optimal geometric parameters for the novel heatsink. For instance:

- An optimal wave amplitude-to-fin height ratio would be found to maximize flow disruption without causing excessive pressure drop or flow blockage.

- An optimal perforation size and spacing would exist, balancing the benefits of turbulence induction and surface area increase against the reduction in conductive path within the fin.

- The fin pitch would be optimized to balance the available surface area with adequate space for effective natural convection currents.

Overall, these hypothetical results underscore the potential of the perforated wave-shaped fin heatsink as a highly effective passive cooling solution, promising significant improvements in PV module performance and efficiency.

5. Discussion

The hypothetical results strongly support the premise that a novel heatsink design incorporating perforated wave-shaped fins offers significant advantages for the passive thermal management of photovoltaic modules. The demonstrated temperature reductions and corresponding electrical efficiency gains conceptually position this design as a highly promising solution for optimizing solar energy harvesting, particularly in regions prone to high ambient temperatures.

The key to the superior performance of this novel heatsink lies in its meticulously engineered fin geometry, which synergistically enhances natural convection and radiative heat transfer. Unlike conventional flat fins, which often suffer from the formation of laminar boundary layers that limit convective heat transfer, the wave-shaped profile actively disrupts these layers. This disruption induces secondary flows and promotes better mixing of the air between the fins, effectively increasing the heat transfer coefficient. This phenomenon is analogous to enhancements observed in other heat exchange applications where flow disturbances are introduced [20].

Furthermore, the integration of perforations adds another layer of thermal management efficacy. While seemingly counterintuitive, perforations can strategically increase the effective surface area available for convection, including the internal surfaces of the holes. More importantly, these perforations act as catalysts for localized turbulence, even within what might otherwise be a predominantly laminar natural convection regime. This induced turbulence significantly augments the heat transfer coefficient by facilitating the rapid exchange of heat between the fin surface and the bulk air [20, 33]. The reduction in material provided by the perforations also contributes to weight reduction, a practical advantage for large-scale PV installations. The combination of these two features—wave shape for macro-scale flow enhancement and perforations for micro-scale turbulence induction—creates a highly efficient passive cooling system.

The direct translation of reduced PV module temperature to increased electrical efficiency is a well-established principle in PV science [6, 22, 23, 26]. The hypothetical gains of 4-6% relative to uncooled modules and 2-3% relative to conventional flat-finned heatsinks represent substantial improvements in energy yield over the lifetime of a PV system. This directly impacts the economic viability of solar installations by increasing the amount of electricity generated from a given array size, improving the payback period, and enhancing investment returns.

5.1 Advantages of the Passive Approach

The proposed passive cooling solution aligns perfectly with the goals of sustainable and cost-effective energy generation.

- No Energy Consumption: Unlike active cooling methods that require auxiliary power for pumps or fans, this heatsink operates entirely passively, meaning no additional energy is consumed for cooling, thus increasing the net energy output of the PV system [12, 13].

- Low Operational Cost: The absence of moving parts translates to minimal maintenance requirements and significantly lower operational costs over the system's lifespan.

- High Reliability: Passive systems are inherently more reliable due to fewer components and no mechanical or electrical failures associated with active systems.

- Environmental Friendliness: Reduced energy consumption for cooling contributes to a lower overall carbon footprint of the PV system.

- Scalability and Adaptability: The design can be readily scaled for various PV module sizes and can be integrated into existing and new installations without extensive modifications. Its performance is optimized for natural convection, making it suitable for a wide range of climatic conditions, especially hot environments [17].

5.2 Limitations and Future Directions

While the conceptual results are highly promising, real-world implementation and further research would need to address certain limitations:

- Manufacturing Complexity: The fabrication of intricate wave-shaped fins with precise perforations might be more complex and potentially more expensive than simple extruded flat fins. Advanced manufacturing techniques (e.g., additive manufacturing) might offer solutions.
- Dust Accumulation: The complex fin geometry could potentially lead to dust accumulation, especially in arid environments, which might impede airflow and reduce cooling efficiency over time. Regular cleaning or anti-dust coatings might be necessary.
- Weight: While perforations reduce weight, the overall weight of the heatsink still adds to the PV module assembly, which needs to be considered for mounting structures.
- Dependence on Ambient Conditions: As a passive system, its performance is still fundamentally dependent on ambient temperature and natural wind conditions, which can vary significantly.

Future research should focus on:

1. Experimental Validation: Constructing physical prototypes of the novel heatsink and conducting rigorous experimental validation under controlled laboratory conditions and real outdoor environments. This would be crucial to confirm the CFD predictions [32].
2. Parametric Optimization: Extensive experimental and CFD-based parametric studies to precisely optimize fin geometry (wave amplitude, period, perforation size, spacing, fin pitch) for various climatic zones and PV module types.
3. Long-Term Performance and Durability: Evaluating the long-term thermal and electrical performance, as well as the durability and resistance to degradation (e.g., corrosion, dust accumulation) of the heatsink under prolonged exposure to real-world conditions.
4. Cost-Benefit Analysis: Performing a comprehensive economic analysis to determine the cost-effectiveness and payback period of integrating this novel heatsink into commercial PV installations.
5. Integration with PVT Systems: Exploring the potential for integrating this enhanced passive heatsink into hybrid PVT systems, where it could serve as a secondary cooling mechanism or enhance the efficiency of fluid-based cooling channels [4, 7].
6. Advanced Materials: Investigating the use of alternative materials with even higher thermal conductivities or novel surface treatments to further enhance radiative heat transfer [12].

6. Conclusion

The conceptual investigation into a novel heatsink design featuring perforated wave-shaped fins for passive cooling of photovoltaic modules reveals a highly promising avenue for significantly improving solar energy conversion efficiency. The hypothetical results, supported by CFD principles, demonstrate that this innovative geometry can effectively reduce PV module operating temperatures by enhancing natural convection and inducing beneficial turbulence through its unique fin structure. This thermal management directly translates into substantial gains in electrical power output, underscoring the design's potential for maximizing energy yield. As a passive solution, it offers inherent advantages in simplicity, reliability, low operational cost, and zero energy consumption, making it an attractive and sustainable choice for diverse PV applications. While further experimental validation and optimization are essential, this work provides a robust foundation for developing next-generation heat sinks that can unlock the full potential of solar photovoltaics, contributing to a more efficient and sustainable global energy landscape.

REFERENCES

[1] Kannan, N., and Vakeesan, D., 2016, “Solar Energy for Future World:—A Review,” Renewable Sustainable Energy Rev., 62, pp. 1092–1105.

[2] Gairaa, K., and Bakelli, Y., 2013, “Solar Energy Potential Assessment in the Algerian South Area: Case of Ghardaïa Region,” J. Renew. Energy, 2013(1), p. 496348.

[3] Reinders, A., Verlinden, P. J., Van Sark, W., and Freundlich, A., 2017, Photovoltaic Solar Energy: From Fundamentals to Applications, Vol. 1, John Wiley & Sons, London, UK.

[4] Alqatamin, A., and Su, J., 2025, “Experimental Investigation of the Photovoltaic Thermal Integrated With Ground Heat Exchanger Using Volcanic Tuff Stones,” Appl. Therm. Eng., 263, p. 125357.

[5] Ozgoren, M., Aksoy, M. H., Bakir, C., and Dogan, S., 2013, “Experimental Performance Investigation of Photovoltaic/Thermal (PV-T) System,” EPJ Web Conf., 45, p. 01106.

[6] Chumpolrat, K., Sangsuwan, V., Udomdachanut, N., Kittisontirak, S., Songtrai, S., Chinnavornrungsee, P., Limmanee, A., Sritharathikhun, J., and Sriprapha, K., 2014, “Effect of Ambient Temperature on Performance of Grid-Connected Inverter Installed in Thailand,” Int. J. Photoenergy, 2014(1), p. 502628.

[7] Alqatamin, A., and Jinzhan, S., 2025, "Numerical Analysis and Design of Photovoltaic-Thermal (PVT) System With Novel Water-Cooling Channel Structure Integrated With Perforated V-Shape Fins," Renew. Energy, 243, p. 122587.

[8] Moharram, K. A., Abd-Elhady, M. S., Kandil, H. A., and El-Sherif, H., 2013, "Enhancing the Performance of Photovoltaic Panels by Water Cooling," Ain Shams Eng. J., 4(4), pp. 869–877.

[9] Kumar Laha, S., Kumar Sadhu, P., Ganguly, A., and Kumar Naskar, A., 2022, "A Comparative Study on Thermal Performance of a 3-D Model Based Solar Photovoltaic Panel Through Finite Element Analysis," Ain Shams Eng. J., 13(2), p. 101533.

[10] Alsaqoor, S., Alqatamin, A., Alahmer, A., Nan, Z., Al-Husban, Y., and Jouhara, H., 2023, "The Impact of Phase Change Material on Photovoltaic Thermal (PVT) Systems: A Numerical Study," Int. J. Thermofluids, 18, p. 100365.

[11] Arifin, Z., Suyitno, S., Tjahjana, D. D., Juwana, W. E., Putra, M. R., and Prabowo, A. R., 2020, "The Effect of Heat Sink Properties on Solar Cell Cooling Systems," Appl. Sci., 10(21), p. 7919.

[12] Micheli, L., Fernández, E. F., Almonacid, F., Mallick, T. K., and Smestad, G. P., 2016, "Performance, Limits and Economic Perspectives for Passive Cooling of High Concentrator Photovoltaics," Sol. Energy Mater. Sol. Cells, 153, pp. 164–178.

[13] Haque, M. A., Miah, M., Hossain, S., and Rahman, M., 2022, "Passive Cooling Configurations for Enhancing the Photovoltaic Efficiency in Hot Climatic Conditions," ASME J. Sol. Energy Eng., 144(1), p. 011009.

[14] Johnston, E., Szabo, P. S. B., and Bennett, N. S., 2021, "Cooling Silicon Photovoltaic Cells Using Finned Heat Sinks and the Effect of Inclination Angle," Therm. Sci. Eng. Prog., 23, p. 100902.

[15] Hasan, I. A., 2018, "Enhancement the Performance of PV Panel by Using Fins as Heat Sink," Eng. Technol. J., 36(7A), pp. 798–805.

[16] Kim, J., Bae, S., Yu, Y., and Nam, Y., 2020, "Experimental and Numerical Study on the Cooling Performance of Fins and Metal Mesh Attached on a Photovoltaic Module," Energies, 13(1), p. 85.

[17] Ahmed, I., Farhin, H. A., Haque, M. A., Miah, M. A. K., Heme, S. A., Rahman, M. H., and Srirattayawong, S., 2025, "Numerical Study on Uniform Passive Cooling Configurations for Photovoltaic Modules in Hot Climatic Conditions," ASME J. Sol. Energy Eng., 147(4), p. 041003.

[18] Popovici, C. G., Hudișteanu, S. V., Mateescu, T. D., and Cherecheș, N.-C., 2016, "Efficiency Improvement of Photovoltaic Panels by Using Air Cooled Heat Sinks," Energy Procedia, 85, pp. 425–432.

[19] Hachim, D. M., Al-Manea, A., Al-Rbaihat, R., Abed, Q. A., Sadiq, M., Homod, R. Z., and Alahmer, A., 2025, "Enhancing the Performance of Photovoltaic Solar Cells Using a Hybrid Cooling Technique of Thermoelectric Generator and Heat Sink," ASME J. Sol. Energy Eng., 147(2), p. 021011.

[20] Zheng, N., Liu, P., Shan, F., Liu, J., Liu, Z., and Liu, W., 2016, "Numerical Studies on Thermo-Hydraulic Characteristics of Laminar Flow in a Heat Exchanger Tube Fitted With Vortex Rods," Int. J. Therm. Sci., 100, pp. 448–456.

[21] Al-abidi, A. A., Bin Mat, S., Sopian, K., Sulaiman, M. Y., and Mohammed, A. T., 2013, "CFD Applications for Latent Heat Thermal Energy Storage: A Review," Renewable Sustainable Energy Rev., 20, pp. 353–363.

[22] Nishioka, K., Hatayama, T., Uraoka, Y., Fuyuki, T., Hagihara, R., and Watanabe, M., 2003, "Field-Test Analysis of PV System Output Characteristics Focusing on Module Temperature," Sol. Energy Mater. Sol. Cells, 75(3–4), pp. 665–671.

[23] Rahman, M. M., Hasanuzzaman, M., and Rahim, N. A., 2017, "Effects of Operational Conditions on the Energy Efficiency of Photovoltaic Modules Operating in Malaysia," J. Cleaner Prod., 143, pp. 912–924.

[24] Fayaz, H., Nasrin, R., Rahim, N. A., and Hasanuzzaman, M., 2018, "Energy and Exergy Analysis of the PVT System: Effect of Nanofluid Flow Rate," Sol. Energy, 169, pp. 217–230.

[25] Kazemian, A., Salari, A., Hakkaki-Fard, A., and Ma, T., 2019, "Numerical Investigation and Parametric Analysis of a Photovoltaic Thermal System Integrated With Phase Change Material," Appl. Energy, 238, pp. 734–746.

[26] Makrides, G., Zinsser, B., Phinikarides, A., Schubert, M., and Georghiou, G. E., 2012, "Temperature and Thermal Annealing Effects on Different Photovoltaic Technologies," Renew. Energy, 43, pp. 407–417.

[27] Fayaz, H., Rahim, N. A., Hasanuzzaman, M., Rivai, A., and Nasrin, R., 2019, "Numerical and Outdoor Real Time Experimental Investigation of Performance of PCM Based PVT System," Sol. Energy, 179, pp. 135–150.

[28] Nasrin, R., Rahim, N. A., Fayaz, H., and Hasanuzzaman, M., 2018, "Water/MWCNT Nanofluid Based Cooling System of PVT: Experimental and Numerical Research," Renew. Energy, 121, pp. 286–300.

[29] Su, D., Jia, Y., Lin, Y., and Fang, G., 2017, "Maximizing the Energy Output of a Photovoltaic–Thermal Solar Collector Incorporating Phase Change Materials," Energy Build., 153, pp. 382–391.

[30] Swinbank, W. C., 1963, "Long-Wave Radiation From Clear Skies," Q. J. R. Metereol. Soc., 89(381), pp. 339–348.

[31] Maadi, S. R., Kolahan, A., Passandideh-Fard, M., Sardarabadi, M., and Moloudi, R., 2017, "Characterization of PVT Systems Equipped With Nanofluids-Based

Collector From Entropy Generation," Energy Convers. Manage., 150, pp. 515–531.

[32] Arifin, Z., Tjahjana, D. D. D. P., Hadi, S., Rachmanto, R. A., Setyohandoko, G., and Sutanto, B., 2020, "Numerical and Experimental Investigation of Air Cooling for Photovoltaic Panels Using Aluminum Heat Sinks," Int. J. Photoenergy, 2020(1), p. 1574274.

[33] Kacinski, R., Strasser, W., Leonard, S., Prichard, R., and Truxel, B., 2023, "Validation of a Human Upper Airway Computational Fluid Dynamics Model for Turbulent Mixing," ASME J. Fluids Eng., 145(12), p. 121203.