ISSN 2355-3286

Micro-Scale CPV Performance Enhancement through V-Trough Concentration and Passive Cooling

Nicholas Robert[1], Johanes Dimas Paramasatya[1], and Niki Prastomo[1,*]
[1] Physics Engineering Department,
Universitas Multimedia Nusantara, Scientia Garden, Jl. Boulevard Gading Serpong, Curug Sangereng, Kelapa Dua, Tangerang, Banten 15810, Indonesia
[1,*]niki.prastomo@umn.ac.id

Accepted June 01, 2025
Approved June 24, 2025

***Abstract*—The global reliance on fossil fuels has driven the need for clean, renewable alternatives. Concentrated Photovoltaic (CPV) systems offer a promising solution by increasing energy yield per unit area, particularly in regions with high solar irradiance. This study investigates the performance enhancement of a micro-scale CPV system through the integration of a V-trough optical concentrator and passive thermal regulation mechanisms. Five system variants were developed and tested: a baseline with no enhancement, a standard CPV, and three CPV systems incorporating heat sinks, heat pipes, and a hybrid of both. Optical simulations were performed to achieve a 2× concentration ratio using planar mirrors angled at 60°, while all cooling systems relied on passive methods to maintain simplicity and low cost. Field tests conducted in a tropical environment revealed that all CPV systems outperformed the baseline, with the hybrid-cooled system delivering the highest average power output—138.76 mW, a 32.37% improvement over the baseline. Surface temperatures were also significantly reduced, with the hybrid system lowering temperatures by up to 6.8°C. These results highlight the synergistic potential of combining optical and passive thermal enhancements in compact CPV designs, providing a scalable, cost-effective solar energy solution suitable for rural and off-grid applications in high-irradiance regions.**

***Index Terms*—CPV; heat pipe; heat sink; passive cooling; photovoltaic efficiency; V-trough concentrator**

I. INTRODUCTION

Global energy demand has risen by 4.5% between 2024 and 2025 alone and is projected to continue to increase rapidly [1]. Although fossil fuels have historically been used globally for most energy applications, they have significant drawbacks [2]. They are not renewable within human timescales [3], and contribute significantly to climate change, air pollution, and environmental destruction through their extraction and usage [2].

Solar energy is a promising and abundant renewable energy source [4]. Solar energy has immense potential to meet global energy needs and mitigate climate change [5-7]. A common method of gathering solar energy into usable electricity is via photovoltaic (PV) technology. Unfortunately, solar PV has inherent efficiency constraints. Due to its working principle, PV cells can only use a limited range of wavelengths of light efficiently; excess energy then manifests as heat. Excessive heat on solar PV cells further decreases energy collection efficiency.

A potential method of maximizing power generation from PV cells involves concentrating light rays on them, generally known as concentrated photovoltaics (CPV, also called concentrating photovoltaics). Unlike conventional PV systems, CPV aims to reduce the cost per generation capacity by using optical components called concentrators to focus sunlight onto cells. This increases the density of solar irradiance on the cells and boosts overall power production and production per unit area. Furthermore, in the case of some multi- junction cells, efficiency also rises within CPV [8].

A simple and low-cost implementation of CPV uses a V-trough design, where flat mirrors are placed next to a line of solar cells to increase the concentration of incident sunlight. Unfortunately, this also increases the amount of heat received by the cells. This issue of heat concentration would lead to a phenomenon called thermal derating and would further decrease the efficiency if left unsolved. Previous research suggests that conventional PV cells would lose efficiency at a rate of approximately 0.45–0.5% per 1 °C increase in operating temperature above the optimum [9], [10].

Cooling systems can mitigate the negative effects of this increased heat load. These systems may be passive, such as heat pipes and heat sink arrangements, which can be implemented without requiring additional power, and rely purely on natural convection and conduction. However, active cooling systems require active components such as pumps, and fans may be better suited for more intensive heat removal [11], [12].

While previous studies have separately evaluated optical concentration or passive cooling implementations in CPV systems, few have explored their combined implementation in a compact, micro-scale format tailored to tropical environments [2], [4], [12]. This study aims to address that gap by evaluating the combined effect of optical and thermal enhancements on CPV performance under real tropical conditions. We used variants of a simple V-trough CPV for this purpose, with variants that test which cooling system is the most effective and produces the greatest efficiency gains.

II. Related Works

A. History of CPV

CPV emerged in the 1970s as a method for enhancing solar efficiency in high-irradiance regions. Despite its early promise, its adoption was limited because of high system costs and poor competitiveness with conventional energy. The development slowed, but small-scale research continued. Recently, interest has grown because concentrator materials remain significantly cheaper than high-efficiency PV cells [13].

B. Low-concentration Photovoltaics

CPV systems are often classified by their concentration ratio (CR), which is expressed as multiples of the solar intensity. Low-concentration photovoltaics (LCPV), defined by concentration ratios (CR) below 10× (or 10 "suns"), offer a balance between performance gains and system simplicity. Various optical concentrators have been proposed, including Fresnel lenses, linear reflectors, and compound parabolic concentrators (CPC). However, many require active tracking systems, increasing cost and complexity [14].

C. V-Through Concentrators

V-trough concentrators are simple concentrator systems that use only two planar mirrors to focus sunlight onto PV cells without any necessary tracking [13]. Thus, they are suitable for deployment in microscale CPV systems. Prior studies reported CR values between 1.4× and 3×, with power output increases of up to 2.6× over baseline systems in the highest-CR systems [15]–[17]. Their passive geometry and low material requirements make them a practical solution for small-scale low-budget deployments in high-irradiance regions.

D. Cooling Systems

A PV system can convert solar energy into electrical energy; however, this conversion is not perfect, and some of the energy within the PV system is converted into heat [18]. The heat generated within a PV system may lead to a decrease in electrical energy production [19]. For every 1 °C increase in temperature above 25 °C, a 0.45% reduction in the PV module efficiency occurs [9]. As a result, the implementation of a cooling system for PV would mitigate the reduction or prevention of heating effects.

E. Heat Sink Cooling System

Heat-sink cooling systems have been successfully implemented in CPV systems. One study tested 36 heat sink variants to determine the most effective. It was found that a heat sink with a wide contact area and large gap between fins was the most effective variant, with an average temperature reduction of 7.5˚C [20].

Another research tested the impact of heat sink cooling on a triple junction CPV system and observed a temperature reduction of 2.8˚C to 33.3˚C based on the CPV's concentration ratio [11].

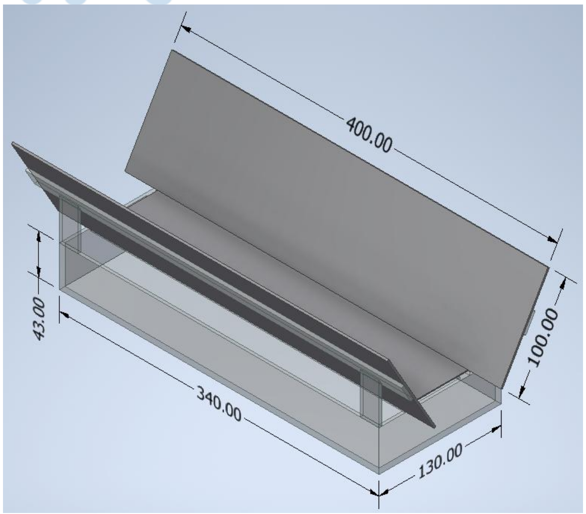
F. Heat Sink Cooling System

Considerable research has been conducted to observe the effects of heat pipe implementation on the performance of PV systems. One study utilized a curving heat pipe to increase the contact area for the cooling system on a PV system; the implementation of the heat pipe resulted in a 19.45% power production increase and a temperature reduction of 10.5 °C [19]. Another study investigated the effects of different fluid ratios on a heat pipe used for PV cooling and found that a filling ratio of 45% fluid was the most effective and resulted in a 3.2% increase in electrical energy production.

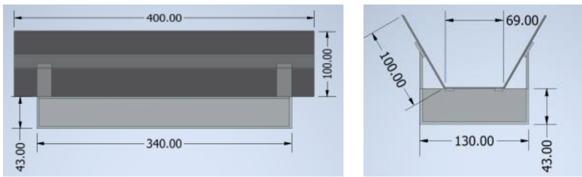
III. Methodology

A. System Architecture

This study employs a micro-scale CPV system with conventional silicon solar cells. One unit is used for each system variant. Four variants of a microscale V-trough CPV system were simulated, prototyped, and tested in real-life conditions, with another variant serving as a baseline with neither concentrators nor cooling, for a total of five systems. One variant uses no additional cooling, whereas the remaining three variants each employ a passive cooling system to manage the thermal load. Of the three variants that use cooling, one uses heat sinks, one uses heat pipes, and one uses both heat sinks and pipes simultaneously. Figure 1 shows the design renders of the CPV system with a concentrator.



(a) 3D perspective view



(b) Top view (c) Cross-sectional view

Fig. 1. Design of the V-trough CPV System (dimensions in mm)

B. System Architecture

A passive V-trough reflector was selected because of its simplicity, cost efficiency, and suitability for LCPV applications. The design consists of two planar mirrors angled to focus incoming sunlight onto a fixed PV receiver.

Simulations were performed using Phydemo Ray Optics to obtain the geometry of the appropriate CR. The target CR was 2, with a mirror angle of 60 °and receiver width of 69 mm. The 60° angle was selected as a practical compromise between concentration ratio and manufacturability. Steeper angles would increase the concentration ratio but reduce the acceptance angle and ease of assembly, which are critical factors in low-cost, rural-deployable systems [17]. Owing to material acquisition constraints, the mirrors slightly exceeded the ideal dimensions, resulting in minor optical spillovers. This configuration was chosen for its ease of assembly and repeatability under field conditions. Figure 2 shows the simulation conditions with concentrators.

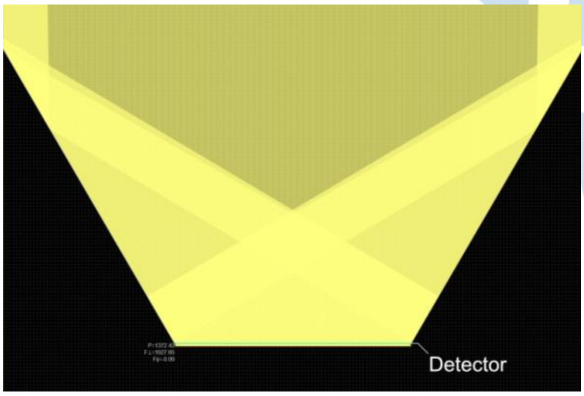


Fig. 2. Ray Simulation with Concentrator

The simulation confirms the intended focusing effect of the V-trough mirrors, with the majority of rays successfully directed toward the detector area. Although slight optical spillovers are observed due to dimensional compromises during construction, the concentration pattern remains consistent and well-aligned with the receiving surface. This validates the system's optical geometry resulting in a CR of 2.

C. Cooling System

For the purposes of this study, heat sink and heat pipe cooling systems were chosen because of their simplicity, low cost, and the relatively minor additional heat load of an LCPV system compared to non-concentrating PV systems. Both cooling systems are passive in nature, making their implementation much simpler than in an active cooling system. A third variant using a hybrid cooling system, which is a combination of a heat sink and a heat pipe cooling system used in tandem, was also designed and tested.

1) Heat sink cooling system:

Within the system, aluminium heat sinks were attached to the back of each solar cell using thermal adhesives, ensuring proper thermal conductivity. The heat sinks were placed in the geometric middle of each cell.

2) Heat pipe cooling system

A custom rounded rectangular copper pipe loop was used as the heat pipe. Half of the inner volume of the copper pipe was filled with deionized water to act as the working fluid. Each solar cell in the system was attached to a heat pipe with the ends of the heat pipe exposed to open air.

3) Hybrid cooling system

Both heat sink and heat pipe cooling systems were applied to this variant, using the same installation methods described above.

D. Experimental Setup

To evaluate the performance of the CPV variants, a series of controlled outdoor measurements were conducted. The setup involved real-time monitoring of electrical and thermal parameters under natural sunlight and subject to weather conditions. This phase uses consistent data acquisition protocols across all system configurations. Key components, instrumentation, and procedures are detailed below.

1) Location

Universitas Multimedia Nusantara (UMN) Rooftop, Tangerang Regency (6.2568˚S, 106.6185˚E)

2) Sensors and tools

- Current-voltage sensor: INA219
- Thermometer: Krisbow #10206574 IR
- Microcontroller: Arduino Uno

3) Data collection protocol

The data collection steps, as shown in Figure 3, were followed to acquire the real-world performance data of each system. Activities are done according to local solar noon at the corresponding time of year (≈ 11:40 across test days) with a total measurement time of 2 hours per day. Measurements were conducted in the timespan of one hour before solar noon and one hour after solar noon. To minimize environmental variability, all systems were tested concurrently in the same location.

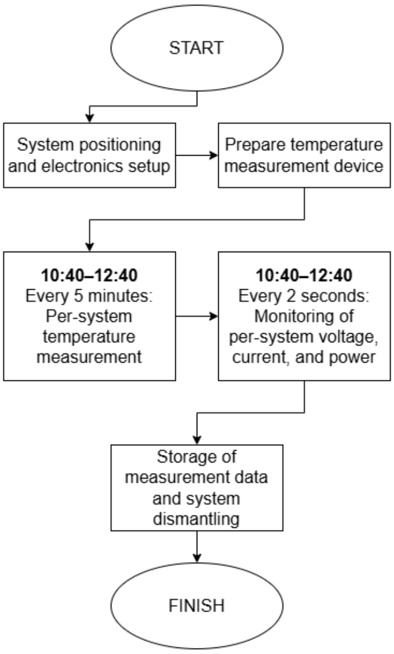


Fig. 3. Ray Simulation with Concentrator

Figure 4 shows a photograph showing all variations of the tested PV systems. The study's baseline is defined as a variant system with the same electronics and wiring as the rest, but with neither any concentrators nor cooling, measured in exactly the same manner and tested concurrently in the same location, ensuring direct comparability with the tested CPV variants.

From left to right, the order of the system variations are as follows: the baseline system without concentration, the CPV system without a cooler (CPV), the CPV system with a heat sink cooling system (CPV-HP), the CPV system with a heat pipe cooling system (CPV-HS), and the CPV system with a combination of both passive cooling systems (CPV-Hybrid).

Fig. 4. Variants of the CPV Systems

Figure 5 shows the cooling system on the back of each cell in the case of the CPV-Hybrid variant.

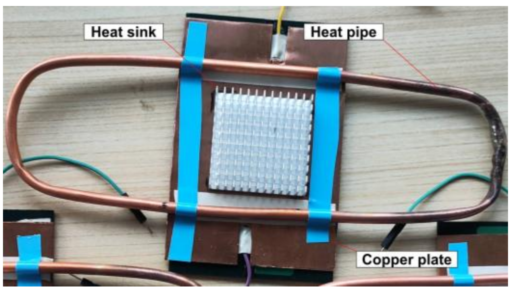


Fig. 5. Variants of the CPV Systems

The cooling configuration integrates a copper base plate as a thermal spreader in direct contact with the CPV cell, promoting efficient conduction in all three cooled variants. In the heat sink variants (CPV-HS and CPV-Hybrid), an aluminum heat sink placed in the center enhances surface area and convective heat dissipation. In the heat pipe variants (CPV-HP and CPV-Hybrid) variant, a loop of copper pipe filled halfway with deionized water to act as heat pipes is affixed along the sides of the plate to facilitate lateral heat distribution.

All components are mechanically fastened using thermally conductive adhesive and electrically insulating thermal tape, ensuring secure contact while maintaining modularity. This arrangement was designed to minimize complexity and cost while achieving significant thermal regulation gains without active cooling.

IV. Results and Discussion

A. V-Trough CPV vs Baseline

Performance analyses revealed that CPV systems show a much higher power output than non-concentrated PV systems across every test period, with maximum gains observed during peak irradiance. At irradiance levels near the peak (≈ 1000 W/m^2), the CPV system without cooling delivered up to 49.5% more power than the baseline, and the systems with cooling showed even better gains. The average performance of the CPV variant without cooling was approximately 22.2% better than that of the baseline, with the cooled systems exhibiting better performance than the non-cooled variant.

In contrast, under lower irradiance conditions, the relative performance gain decreased significantly for all the systems tested. This confirms a strong dependency relationship between CPV effectiveness and solar irradiance, where higher irradiance directly correlates with increased power output due to more effective light concentration, both in relative and absolute terms. Table I lists the relative power generation and electrical performance of each tested variant over test days.

TABLE I. AVERAGE CPV SYSTEM PERFORMANCE

Variant	Average V (V)	Average I (mA)	Average P (mW)	Improvement (vs. Baseline)
Baseline	1.03	101.84	104.95	-
CPV	0.95	136.88	129.11	22.23%
CPV-HP	0.97	136.03	132.56	25.33%
CPV-HS	1.02	133.24	136.04	29.45%
CPV-Hybrid	1.02	136.02	138.76	32.37%

These performance metrics strongly suggest that CPV systems are best suited for locations with consistently high solar irradiance. At lower irradiance, such as during cloudy periods, losses from reflection and optical inefficiencies would outweigh the concentration benefits, reducing performance gains.

B. Cooling Mechanism Impact

As mentioned, the CPV system performance further increased with the addition of cooling. Systems implementing heat sink cooling experienced an operating temperature reduction of 0.5˚C– 1.6˚C; heat pipe results in a reduction of 0.8˚C– 3.3˚C; and lastly, hybrid cooling results in a temperature reduction of 2.2˚C– 6.5˚C compared to systems without any cooling.

For energy production, the best performer, hybrid cooling, resulted in a 32.37% increase compared to the baseline and 7.47% increase compared to CPV. These observed effects show a relationship between the reduction in the system cell temperature and increase in power production. Table II lists the effects of the cooling systems on the operating temperatures.

TABLE II. CPV SYSTEM OPERATING TEMPERATURES

Variant	Operating temperature range
CPV	41.6˚C – 44.8˚C
CPV-HP	41.4˚C – 44.1˚C
CPV-HS	41.0˚C – 43.7˚C
CPV-Hybrid	38.0˚C – 42.0˚C

C. Synergistic Effect

The integration of passive cooling notably improves the thermal regulation and power output under high-irradiance conditions. As shown in Table II, the non-cooled CPV variant reached 44.8˚C, while the hybrid-cooled system maintained the lowest temperatures (38.0 °C to 42.0 °C). Figure 6 illustrates the comparative power output and operating temperatures of all the tested configurations.

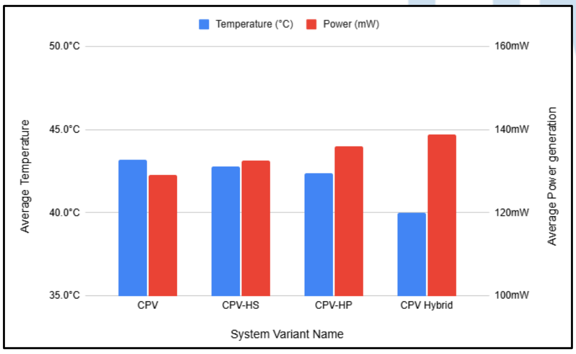


Fig. 6. Power Generation and Thermal Performance Per Variant

Table I shows that the CPV hybrid system achieved the highest average power output of 138.76 mW, a 32.37% improvement over the baseline, outperforming both CPV-HS (29.45%) and CPV-HP (25.33%), showing increased power generation aligned with reduced temperatures. This demonstrates a clear synergy between optical concentration and thermal management.

Although the hybrid system has greater assembly complexity, its superior electrical performance and thermal stability highlight the potential value of hybrid passive cooling in this implementation. The enhanced light concentration via the V-trough design effectively increased the photon flux per unit area, improving the charge carrier generation. However, it also imposes a higher thermal burden, highlighting the necessity of pairing the concentration with adequate thermal management to sustain efficiency gains.

D. Engineering Implications

The V-trough CPV system designed in this study emphasizes a low-cost and relatively scalable implementation, making it suitable as a basis for slightly larger-scale deployments in both rural and urban Indonesian contexts. And due to the exclusive use of only cheap and basic optical elements (flat mirrors) and widely available electrical components (mini conventional PV cells, Arduino, passive cooling), this implementation allows for simple replication and localized manufacturing without high upfront cost, high precision requirements, or any tracking systems.

While it can be argued that V-trough concentrators are more commonly used in testing scenarios rather than for deployment, their potential in rural settings should not be dismissed. In areas where cost, component availability, and ease of maintenance are more critical than peak efficiency, the use of inexpensive, easy-to-acquire flat mirrors and passive cooling offers a compelling trade-off for rural solar energy deployment. The absence of complex optics or solar tracking makes this system particularly attractive for localized, off-grid implementations where technical support is limited. In such contexts, the enhanced energy output enabled by basic concentration can already provide tangible benefits without significantly raising deployment cost or complexity.

In rural areas, this system offers an accessible solution for off-grid energy generation, particularly in high-irradiance regions with limited infrastructure. For urban applications, compact and passive designs enable integration on rooftops or unused land, with potentially minimal maintenance requirements. The passive cooling systems tested here also reduce the need for active thermal management, further simplifying deployment and lowering long-term costs while also increasing power generation, especially by preventing thermal derating.

Scalability is primarily limited by the need for constant irradiance and the linear arrangement required by V-trough geometry. However, the modularity of the system allows for flexible array expansion, particularly in distributed energy scenarios. This suggests the potential for broader adoption of Indonesia’s growing decentralized energy initiatives. Further, although the absolute power output is low due to the micro-scale nature of the prototype, the relative improvement between configurations is representative and scalable to higher capacity systems.

Tropical regions are characterized by high average solar irradiance and frequent fluctuations due to intermittent cloud cover, atmospheric humidity, and aerosol content. This variability presents a unique challenge for CPV systems that rely heavily on direct beam sunlight. In this study, although maximum gains were observed during peak irradiance, the relative improvement from the CPV systems was notably reduced under low-light conditions.

E. Limitations

Despite its promising results, the system remains a prototype and requires further refinement prior to large-scale deployment. The current design lacks waterproofing and must be manually disassembled and reassembled for each testing session, which limits its long-term durability and practical use.

Additionally, the absence of automated tracking may restrict the performance in non-optimal sun positions if deployed over the course of a year. Sun positions in the tropics thankfully mitigate this loss; however, further research and prototyping may reveal further increased performance with a solar tracking system.

Future studies should address these limitations through enclosure development, improved mounting systems, and passive or semi-active tracking integration. These improvements should enhance the robustness and scalability in real-world conditions over the long term.

V. Conclusion

The experimental results confirm that the V-trough CPV system significantly outperforms conventional PV setups under high irradiance. The integration of passive cooling, particularly the hybrid configuration, effectively reduced module temperatures and led to the highest power gains of 32.37% above the baseline. These findings underline the critical role of thermal management in enhancing CPV efficiency, particularly in compact, low-cost designs. The demonstrated synergy between the optical concentration and passive cooling offers a practical pathway for scalable solar solutions suitable for tropical resource-constrained environments. Future work may explore improving system durability, incorporating tracking systems, and extending deployment in real-world scenarios to validate the long-term performance.

Acknowledgment

The authors thank the Institute for Research and Community Service Universitas Multimedia Nusantara (UMN) for supporting this research through its internal funding scheme.

References

[1] [1] International Energy Agency, Electricity, Mar. 2025. [Online]. Available: https://www.iea.org/reports/global-energy-review-2025 /electricity.

[2] S. Kiyaee, Y. Saboohi, and A. Z. Moshfegh, “A new designed linear fresnel lens solar con- centrator based on spectral splitting for passive cooling of solar cells,” Energy Conversion and Management, vol. 230, p. 113 782, 2021. DOI: 10.1016/j.enconman.2020.113782.

[3] A. Ziemin´ska-Stolarska, M. Pietrzak, and I. Zbicin´ski, “Application of lca to determine environmental impact of concentrated photo- voltaic solar panels—state-of-the-art,” Energies, vol. 14, no. 11, p. 3143, 2021. DOI: 10.3390/en14113143.

[4] G. Wang, F. Wang, F. Shen, Z. Chen, and P. Hu, “Novel design and thermodynamic analysis of a solar concentration pv and thermal combined system based on compact linear fresnel reflec- tor,” Energy, vol. 180, pp. 133–148, 2019. DOI: 10.1016/j.energy.2019.05.082.

[5] H. H. Pourasl, R. V. Barenji, V. M. Khojastehnezhad, "Solar energy status in the world: A comprehensive review", Energy Reports, Vol. 10, pp. 3474-3493, 2023. DOI: 10.1016/j.egyr.2023.10.022.

[6] G. Molnár, D. Ürge-Vorsatz, S. Chatterjee, "Estimating the global technical potential of building-integrated solar energy production using a high-resolution geospatial model", Journal of Cleaner Production, Vol. 375, 2022, ISSN: 0959-6526. [Online]. DOI: 10.1016/j.jclepro.2022.134133.

[7] E. H. Adeh, S. P. Good, M. Calaf, C. W. Higgins, "Solar PV Power Potential is Greatest Over Croplands", Scientific Reports, Vol. 9, 2019, 11442. DOI:10.1038/s41598-019-47803-3.

[8] M. A. Green, E. D. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, and A. W. Ho- Baillie, “Solar cell efficiency tables (version 55),” Progress in Photovoltaics: Research and Applications, vol. 28, no. 1, pp. 3–15, Dec. 2019. DOI: 10.1002/pip.3228.

[9] E. Kozak-Jagieła, P. Cisek, and P. Ocłon´, Cool- ing techniques for pv panels: A review, Mar. 2023. DOI: 10.58332/scirad2023v2i1a03.

[10] F. Karimi, H. Xu, Z. Wang, J. Chen, and M. Yang, “Experimental study of a concentrated pv/t system using linear fresnel lens,” Energy, vol. 123, pp. 402–412, 2017. DOI: 10.1016/j.energy.2017.02.028.

[11] H. Refaey, M. Abdelrahman, M. A. Alharthi, S. Bendoukha, S. G. Khan, and M. Emam, Passive cooling of highly-concentrator triple- junction solar cell using a straight-finned heat sink: An experimental investigation, Dec. 2022. [Online]. DOI: 10.1016/j.csite.2022.102521.

[12] M. Sabry and A. Lashin, “Performance of a heat-pipe cooled concentrated photovoltaic/thermoelectric hybrid system,” Energies, vol. 16, no. 3, p. 1438, 2023. DOI: 10.3390/en16031438.

[13] A. L. Luque and A. Viacheslav, Concentrator photovoltaics. Springer-Verlag, 2007. [Online]. DOI: 10.1007/978-3-540-68798-6.

[14] A. Ejaz, H. Babar, H. M. Ali, et al., “Concen- trated photovoltaics as light harvesters: Outlook, recent progress, and challenges,” Sustainable Energy Technologies and Assessments, vol. 46, p. 101 199, 2021. DOI: 10.1016/j.seta.2021.101199.

[15] A. Ustaoglu, C. Kandilli, M. Cakmak, and H. Torlaklı, “Experimental and economical per- formance investigation of v-trough concentra- tor with different reflectance characteristic in photovoltaic applications,” Journal of Cleaner Production, vol. 272, p. 123 072, Nov. 2020. DOI: 10.1016/j.jclepro.2020.123072.

[16] R. V. Parupudi, H. Singh, and M. Kolokotroni, “Low concentrating photovoltaics (lcpv) for buildings and their performance analyses,” Applied Energy, vol. 279, 2020, ISSN: 0306-2619. [Online]. DOI: 10.1016/j.apenergy.2020.115839.

[17] M. Alnajideen and M. Gao, “A new configuration of v-trough concentrator for achieving improved concentration ratio of 3.0x,” Solar Energy Materials and Solar Cells, vol. 245, p. 111 877, Sep. 2022. DOI: 10.1016/j.solmat.2022.111877.

[18] M. G. Noxpanco, J. Wilkins, S. Riffat, "A Review of the Recent Development of Photovoltaic/Thermal (PV/T) Systems and Their Applications". Future Cities and Environment, Vol 6(1): 9, pp. 1–16, 2020. DOI: 10.5334/fce.97.

[19] U. Arachchige and S. Weliwaththage, Solar energy technology, Jul. 2020. ISSN: 2714-1837. [Online]. Available:

https://www.researchgate.net/publication/353306311_Solar_Energy_Technology.

[20] M. Krstic, L. Pantic, S. Djordjevic, et al., Pas- sive cooling of photovoltaic panel by aluminum heat sinks and numerical simulation, Jan. 2024. DOI: 10.1016/j.asej.2023.102330.

[21] E. Roslan and I. Hassim, Solar pv system with pulsating heat pipe cooling, 2019, pp. 311-318. DOI: 10 . 11591/ijeecs.v14.i1.