New Trends in Energy Harvesting Through Magnetic Nanofluids

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Abstract: The global shift towards sustainable energy solutions has intensified research into advanced energy harvesting systems, with nanofluids – especially their magnetic variants – becoming key materials. This comprehensive study synthesizes bibliometric and scientometric analyses to map the development of nanofluid applications in energy technologies between 2020 and 2025 using tools such as VOSviewer and the Web of Science database. The findings reveal a consistent increase in publications, underscoring growing global interest and collaboration, particularly between countries such as China, India, Saudi Arabia, Pakistan, and Iran. Key thematic groups include: Efficiency and thermal performance: improving the thermal conductivity and heat transfer properties of nanofluids is key to advancing energy harvesting technologies; Energy conversion and photothermal effects: integrating nanofluids into solar collectors and photovoltaic-thermal systems increases their efficiency; Fluid dynamics and optimization: research focuses on viscosity, stability, and system-level optimization for efficient energy transfer; Magnetohydrodynamic, thermoelectric, and thermomagnetic applications: Magnetic nanofluids are increasingly used in systems utilizing magnetohydrodynamics, thermoelectric and thermomagnetic effects (Seebeck and Nernst effects), and the conversion of vibrational energy to transform thermal and mechanical gradients into electricity. Current studies point to the emergence of hybrid and smart magnetic nanofluids with improved stability and long-term performance, offering promising possibilities for thermoelectric devices, waste heat utilization, and motion-based energy harvesting. Despite significant progress, challenges remain in optimizing the properties of nanofluids for industrial applicability and economic viability. This study highlights the transformative potential of nanofluids, particularly magnetic ones, in the development of sustainable technologies through the combination of magnetism, thermodynamics, and nanotechnology.

Keywords: Energy harvesting; Nanofluids; Fe_3O_4; Multi – walled carbon nanotubes (MWCNT); SiO_2

1 Introduction

Energy is a critical quantitative property that must be transferred—via work or heat—before any system can perform work. In the context of energy harvesting, heat transfer occurs whenever a temperature difference exists, moving energy from high to low temperatures. This phenomenon is fundamental to numerous applications, ranging from the conversion of solar energy into power in thermal collectors, to the regulation of temperature in electronic devices and so on [1], [2], [3], [4].

While Maxwell first discussed suspending micro-scaled particles over a century ago, those suspensions suffered from rapid settling and channel clogging. The solution emerged with the introduction of "nanofluids" by Choi and Eastman—engineered colloidal suspensions of nanoscaled particles (10–100 nm). These particles, often composed of metals, metallic oxides, or carbon-based elements, offer significantly enhanced thermophysical properties compared to pure fluids. Specifically, mechanisms such as the Brownian motion of particles and particle/fluid nanolayers allow for intensified heat transfer with reduced pump power requirements [4], [5], [6], [7].

Despite challenges related to sedimentation, agglomeration, and production costs, the application of nanofluids has received increasing attention for its potential to change the field of energy harvesting. Research indicates that 512 papers were published on this subject in the period of 2020–2025 alone, highlighting a shift toward optimizing these fluids for next–generation heat transfer devices. This review explores the progression of these technologies, serving as a foundation for understanding new trends in manipulating these fluids—such as through magnetic fields—to maximize energy harvesting efficiency [4], [8], [9].

2 Scientometric Analysis

Scientometrics, first conceptualized by Nalimov et al. in 1971 [10], represents a quantitative methodological approach to analyzing the evolution of science as an informational process. Fundamentally, it involves the study of the quantitative dimensions of science and technology viewed through the paradigm of communication. The primary objectives of this discipline include the evaluation of scientific performance, the mapping of research impact within specific domains of interest, and the development of productivity metrics to provide strategic guidance for scientific endeavors. Its core areas of focus encompass methodologies for assessing research quality and influence, elucidating citation dynamics, delineating scientific fields, and applying these indicators to research policy and management [11], [12].

Although the scope of scientometrics encompasses the investigation of numerous facets of science and technology, in practice, it is predominantly anchored in citation analysis. The citation of external research within scientific literature establishes a relational network among authors, creating a field of connections that is subject to quantitative assessment.

These visual representations of interconnectivity are termed **bibliometric maps.** Such mapping tools facilitate the analysis of core themes and their interrelationships within a specific domain, allow for the longitudinal tracking of developmental trends, and enable the identification of key actors, including researchers, institutions, and journals. The previously discussed citation databases serve as the primary data repositories for generating these visualizations.

2.1 Scietometric Analysis of the Energy Harvesting

To systematically illustrate the characteristics and prevailing trends of publications within the area of interest, a bibliometric analysis was conducted utilizing the VOSviewer software. The underlying dataset was retrieved from the Web of Science (WoS) database through an advanced search strategy employing logical operators to ensure the precision and relevance of the gathered literature. This analysis focuses on the timeframe from January 1, 2020, to October 9, 2025, facilitating the mapping of scientific influence, key thematic clusters, and the structural evolution of research during this period.

Significance of this area of research is higlighted in growing number of publications throughout the given timeframe, reflecting the growing significance of this research area, particularly given the global imperative for enhanced energy efficiency and sustainable technology. The quantitative progression of this research output, highlighting the continuous year-on-year growth within the examined timeframe, is visually summarized in the Figure 1.

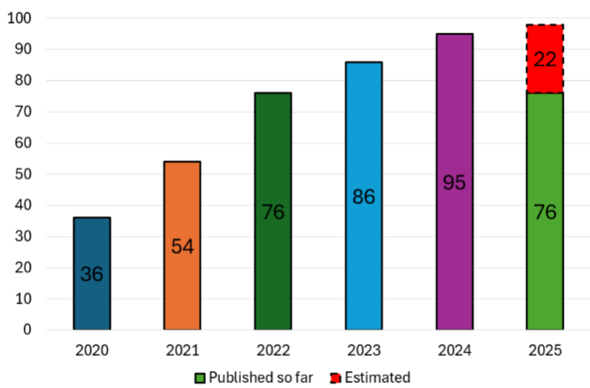

Figure 1
Number of publications in the area of interest throughout the years

2.1.1 Co – Autorship Bibliometric Map of the area of interest

The Figure 2 presents a network visualization of international collaboration (co-authorship) among countries active in this research domain. In this map, the size of each circular node is proportional to the number of published documents associated with that country, indicating its total research output. The lines connecting the nodes represent co-authorship links, where the thickness and distance reflect the strength and frequency of collaboration between nations. Colors signify distinct clusters of countries that frequently collaborate with one another.

Key Observations:

1. Dominant Research Hubs: The map reveals a multipolar research landscape heavily dominated by Asian and Middle Eastern nations. The People's Republic of China (Yellow cluster) appears as the largest node, signifying its leading position in terms of publication volume in this field. India (Blue cluster) and Saudi Arabia (Red cluster) follow as major contributors, highlighting the significant scientific investment and output from these regions regarding magnetic nanofluids and energy harvesting. The top 5 list of major contributors is completed by Pakistan and Iran.
2. Clustering and Collaboration Patterns: The VOSviewer algorithm has grouped the countries into several distinct clusters, revealing geographical and strategic research alliances:
    - **The Yellow Cluster:** Centered around China, this group shows strong collaborative ties with Pakistan, Turkey, Japan, Poland, and Thailand;
    - **The Blue Cluster:** Anchored by India, this cluster includes the USA, Canada, the United Arab Emirates, and Malaysia. This grouping indicates that India serves as a crucial hub connecting Western research institutions (North America) with Asian and Middle Eastern partners;
    - **The Red Cluster:** Dominated by Saudi Arabia, this group demonstrates a strong regional network involving Egypt, Jordan, and Lebanon, extending to Taiwan and Nigeria;
    - **The Green Cluster:** This cluster largely represents European and South American collaboration, featuring England, France, Spain, Russia, Brazil, and Turkiye;
    - **The Purple Cluster:** Iran forms the core of a smaller cluster, showing distinct collaborative links with Australia.

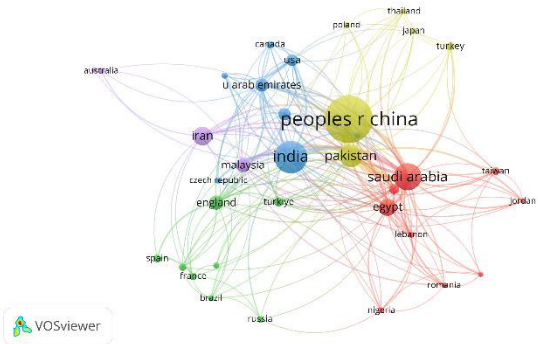

Figure 2
Co – authorhip Bibliometric map of Countries Active in the Research Area

2.1.2 Co – Occurrence Keyword Analysis

The Figure 3 presents a network visualization of keyword co-occurrence, illustrating the conceptual structure and most frequently discussed topics within the examined literature. In this map, the size of each node represents the frequency of the keyword's appearance in the dataset, while the lines indicate the strength of the relationship (co-occurrence) between terms. The distance between nodes reflects their thematic relatedness, and distinct colors represent clusters of closely related research topics.

Key Observations:

1. Central Themes and Dominant Concepts: The map is anchored by the term "nanofluids", which appears as the largest node in the Green Cluster, serving as the central hub connecting all other thematic areas. This confirms that nanofluids are the foundational subject of the dataset. Closely linked to this are high-frequency terms such as "heat-transfer" (Red Cluster) and "performance" (Green Cluster), indicating that the primary research objective is the enhancement of thermal transfer capabilities and overall system efficiency.
2. Thematic Clustering: The VOSviewer algorithm has segregated the research interests into four primary clusters, each representing a specific sub-field or approach:
   - **The Green Cluster (Applications and Performance):** This cluster focuses on the practical application of nanofluids in energy systems. Key terms include "performance", "collector", "energy", "nanoparticles", and "photothermal conversion". This suggests a heavy emphasis on solar collectors and the efficiency gains realized through nanoparticle integration;

- **The Red Cluster (Fluid Dynamics and Transport Phenomena):** This group represents the fundamental physics and theoretical analysis of the field. Dominant terms include "heat-transfer", "flow", "convection", "entropy generation", "porous medium", and "thermal radiation". Notably, terms like "MHD" (Magnetohydrodynamics) and "stretching sheet" appear here, pointing to theoretical modeling of fluid behavior under various physical forces, including magnetic fields;
- **The Yellow Cluster (Thermophysical Properties and Characterization):** Located at the top, this cluster deals with the fluid properties themselves. Keywords such as "stability", "thermal conductivity", "viscosity", and "graphene" highlight the focus on synthesizing stable fluids and characterizing their material properties to ensure they are suitable for heat transfer;
- **The Blue Cluster (System Design and Optimization):** This cluster, situated at the bottom, links the fluid science to engineering systems. Keywords like "solar energy", "design", "optimization", "exergy", and "storage" (including phase change materials) indicate research into the thermodynamic optimization of complete energy systems and storage units;

3. Interconnectivity: There is a high density of links between the **Yellow Cluster** (properties) and the **Red Cluster** (heat transfer), as well as between the **Green Cluster** (performance) and the **Blue Cluster** (systems). This demonstrates that the field is highly interdisciplinary, where material synthesis (Yellow) directly informs theoretical modeling (Red), which is then applied to system performance (Green) and engineering design (Blue).

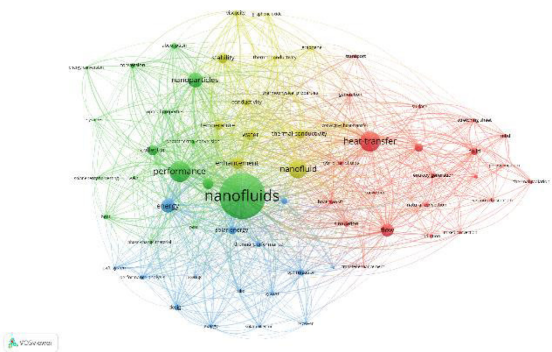

Figure 3

Co – Occurence Bibliometric map of Countries Active in the Research Area

3 Trends in the Research of Energy Harvesting Nanofluids

This chapter reviews current trends in this rapidly evolving field, highlighting key developments and methodologies. In particular, two original researches—one conducted in China and another in Iran—are analyzed to illustrate regional research approaches, experimental techniques, and performance outcomes. These researches provide insight into the global progress and future directions of energy harvesting nanofluid technology.

3.1 Publication no. 1

This publication [13] by researchers from China and South Korea named *Improvement of Photo-thermal Energy Conversion Performance of MWNCT/*Fe_3O_4 *Hybrid Nanofluid* was published in the journal *Energy* in the beginning of 2020.

The primary objective of this research was to enhance the photo-thermal energy conversion properties of magnetite (Fe_3O_4) nanofluids by creating a hybrid nanofluid through the addition of multi-walled carbon nanotubes (MWCNTs).

While Fe_3O_4 nanofluids have unique magnetic properties useful for separation and heat transport, they lack the high optical absorption capabilities of carbon-based nanomaterials. Consequently, the study aimed to investigate the thermal conductivity, optical transmittance, and photo-thermal energy conversion efficiency of this hybrid mixture ratio suspended in a base fluid of water and ethylene glycol with 80:20 ratio.

3.1.1 Key Findings

The study provided significant insights into the superior performance of hybrid nanofluids over single-component nanofluids:

- **Enhanced Optical Absorption:** addition of MWCNTs drastically improved light absorption. The base fluid was transparent, and pure Fe_3O_4 showed a maximum light transmittance of 89% (meaning it let most light pass through). In contrast, the hybrid nanofluid exhibited significantly lower transmittance (higher absorption), with the best sample allowing only 29% of light to pass. The solar weighted absorption fraction for the hybrid fluid was 1,0 (100% absorption) at almost all mixing ratios;
- **Superior Thermal Properties:** thermal conductivity of the fluids increased with both temperature and nanoparticle concentration. The hybrid nanofluids demonstrated higher thermal conductivity than pure

Fe_3O_4 fluids, attributed to the high intrinsic conductivity of MWCNTs and the increased specific surface area for heat transfer;

- **Photo-thermal Conversion Improvement:** hybrid nanofluid demonstrated a much faster temperature response and higher overall efficiency than the pure Fe_3O_4 fluid. Specifically, the hybrid fluid containing the highest amount of MWCNT had nearly two times the photo-thermal energy conversion efficiency of the Fe_3O_4 nanofluid at the same weight concentration.

3.1.2 Best Sample

The study concluded that the MWCNT/Fe_3O_4 hybrid nanofluid with a mixing ratio of 4/1 (MWCNT to Fe_3O_4) at a total concentration of 0,01 wt% was the most effective. It achieved:

- **Highest maximum thermal conductivity:** 0,562 W/m·°C at 50 °C (**Hiba! A hivatkozási forrás nem található.**);
- **Lowest light transmittance** of 29%;
- **Highest maximum total stored energy:** 2400 kJ/kg ().

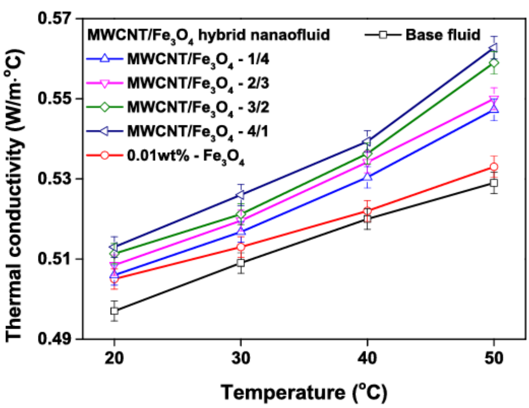

Figure 4
Thermal Conductivity dependant on the Temperature of examined MWCNT/Fe_3O_4 hybrid nanofluid samples [13]

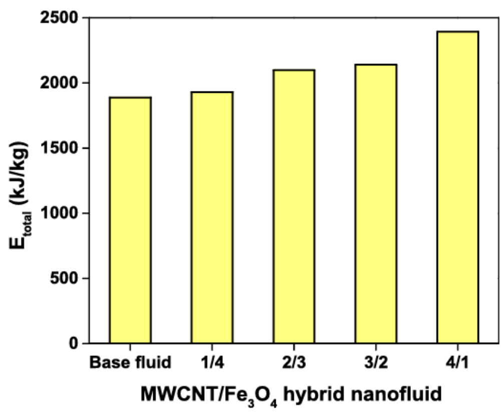

Figure 5
Total Stored Energy dependant on the Concentration of examined MWCNT/Fe_3O_4 hybrid nanofluid samples [13]

3.2 Publication no. 2

This publication [14] by researchers from Iran and China named *Exergetic and environmental assessment of a photovoltaic thermal – thermoelectric system using nanofluids: Indoor experimental tests* was published in the journal *Energy Conversion and Management* in mid 2020.

The primary objective of this study was to experimentally evaluate the performance of a hybrid photovoltaic thermal-thermoelectric (PVT/TE) system. The researchers aimed to solve the issue of overheating in Photovoltaic (PV) cells—which reduces electrical efficiency—by integrating a Thermoelectric Generator (TEG) to recover waste heat and convert it into additional electricity. To optimize this system, the study investigated five different cooling approaches to manage the temperature of the TEG's cold side:

- Natural air cooling;
- Forced air cooling;
- Pure water cooling;
- SiO_2 - water nanofluid;
- Fe_3O_4 - water nanofluid.

The performance was assessed based on energy efficiency, exergy efficiency, and environmental impact (carbon mitigation).

3.2.1 Key Findings

The experimental results highlighted the superiority of nanofluids over conventional cooling methods (water and air) in all tested categories:

- **Superior Thermal Properties:** the use of nanofluids resulted in better cooling of the PV cell and a higher temperature gradient across the TE module compared to water and air. This enhancement was attributed to physical phenomena such as the Brownian motion of nanoparticles, which increases the effective thermal conductivity of the fluid, and the reduction of the thermal boundary layer thickness;
- **Enhanced Optical and Heat Absorption:** the study noted that adding nanoparticles improves the working fluid's capability to absorb radiation (heat). The SiO_2-water nanofluid, in particular, yielded the highest outlet temperature 47,5 °C, indicating effective heat absorption from the system;
- **Photo-thermal Conversion Improvement:** the system achieved its maximum energy efficiency when using the SiO_2-water nanofluid at a fixed irradiation of 900 W/m^2. Furthermore, the total exergy efficiency

and exergy gain were significantly increased by using nanofluids compared to pure water;

3.2.2 Best Sample

The study concluded that the **SiO_2-water nanofluid** was the best performing coolant. It achieved:

- **Highest electrical efficiency of PV cell** (Figure **6**);
- **Highest temperature gradient across the thermoelectric module** (28,9 °C);
- **Maximum electrical efficiency for the thermoelectric module** (Figure 7).

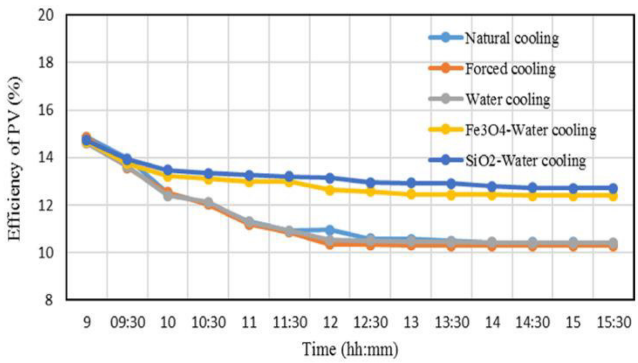

Figure 6

Electrical Efficiency of PV cell dependant on time for different cooling techniques [14]

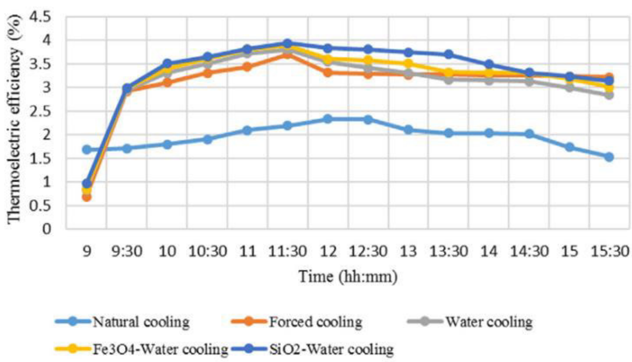

Figure 7

Electrical Efficiency thermoelectric module dependant on time for different cooling techniques [14]

4 Conclusion

The core finding across both studies is that dispersing nanoparticles into a base fluid significantly enhances thermal conductivity and optical properties, leading to higher overall system efficiency. The best performance is application-dependent:

1. For Direct Absorption Solar Collectors, the MWCNT/Fe_3O_4 hybrid nanofluid was found to be the best, achieving superior solar absorption and a 26,6% increase in stored thermal energy due to its carbon-based light absorbance.
2. For PVT/TE systems, the SiO_2-water nanofluid was the most effective coolant, maintaining a higher temperature gradient across the thermoelectric module and maximizing electrical output by efficiently removing waste heat from the PV cell.

In summary, the utilization of advanced nanofluids is critical for maximizing both the energy and exergy efficiency, and for improving the environmental profile, of next-generation energy harvesting technologies.

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References

[1] V. Murali Krishna and M. Sandeep Kumar, 'Numerical analysis of forced convective heat transfer of nanofluids in microchannel for cooling electronic equipment', *Materials Today: Proceedings*, vol. 17, pp. 295–302, 2019, doi: 10.1016/j.matpr.2019.06.433.

[2] T. L. Bergman and A. S. Lavine, *Fundamentals of heat and mass transfer*, Eighth edition. Hoboken, NJ: John Wiley & Sons, 2017.

[3] N. Zhao, S. Li, and J. Yang, 'A review on nanofluids: Data-driven modeling of thermalphysical properties and the application in automotive radiator', *Renewable and Sustainable Energy Reviews*, vol. 66, pp. 596–616, Dec. 2016, doi: 10.1016/j.rser.2016.08.029.

[4] E. C. Okonkwo, I. Wole-Osho, I. W. Almanassra, Y. M. Abdullatif, and T. Al-Ansari, 'An updated review of nanofluids in various heat transfer devices', *J Therm Anal Calorim*, vol. 145, no. 6, pp. 2817–2872, Sept. 2021, doi: 10.1007/s10973-020-09760-2.

[5] J. C. Maxwell, *A treatise on electricity and magnetism*. in Third, no. 3. New York, NY, U.S.A.: Dover Publications Inc, 1954.

[6] S. U. S. Choi and J. A. Eastman, ‘Enhancing thermal conductivity of fluids with nanoparticles’, Argonne National Lab. (ANL), Argonne, IL (United States), ANL/MSD/CP-84938; CONF-951135-29, Oct. 1995. Accessed: Dec. 20, 2022. [Online]. Available: https://www.osti.gov/biblio/196525

[7] P. Sivashanmugam, ‘Application of Nanofluids in Heat Transfer’, 2012. doi: 10.5772/52496.

[8] N. Ali, J. A. Teixeira, and A. Addali, ‘A Review on Nanofluids: Fabrication, Stability, and Thermophysical Properties’, *Journal of Nanomaterials*, vol. 2018, no. 1, p. 6978130, 2018, doi: 10.1155/2018/6978130.

[9] S. K. Das, S. U. S. Choi, and H. E. Patel, ‘Heat Transfer in Nanofluids—A Review’, *Heat Transfer Engineering*, vol. 27, no. 10, pp. 3–19, Dec. 2006, doi: 10.1080/01457630600904593.

[10] V. V. Nalimov and Z. M. Mulchenko, ‘Measurement of Science. Study of the Development of Science as an Information Process.’, Foreign Technology Div Wright-Patterson AFB Ohio, AD735634, 1971. Accessed: Mar. 04, 2025. [Online]. Available: https://ntrl.ntis.gov/NTRL/dashboard/searchResults/titleDetail/AD735634.xhtml

[11] J. Mingers and L. Leydesdorff, ‘A Review of Theory and Practice in Scientometrics’, *European Journal of Operational Research*, vol. 246, no. 1, pp. 1–19, Oct. 2015, doi: 10.1016/j.ejor.2015.04.002.

[12] S. López-Pernas, M. Saqr, and M. Apiola, ‘Scientometrics: A Concise Introduction and a Detailed Methodology for Mapping the Scientific Field of Computing Education Research’, in *Past, Present and Future of Computing Education Research : A Global Perspective*, M. Apiola, S. López-Pernas, and M. Saqr, Eds, Cham: Springer International Publishing, 2023, pp. 79–99. doi: 10.1007/978-3-031-25336-2_5.

[13] Y. Tong, T. Boldoo, J. Ham, and H. Cho, ‘Improvement of photo-thermal energy conversion performance of MWCNT/Fe3O4 hybrid nanofluid compared to Fe3O4 nanofluid’, *Energy*, vol. 196, p. 117086, Apr. 2020, doi: 10.1016/j.energy.2020.117086.

[14] S. Soltani, A. Kasaeian, A. Lavajoo, R. Loni, G. Najafi, and O. Mahian, ‘Exergetic and enviromental assessment of a photovoltaic thermal-thermoelectric system using nanofluids: Indoor experimental tests’, *Energy Conversion and Management*, vol. 218, p. 112907, Aug. 2020, doi: 10.1016/j.enconman.2020.112907.