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Design and Performance Analysis of Hybrid Solar Assisted Heat Exchanger for Sustainable Thermal Energy Applications

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Abstract. This paper provides an extensive analysis of hybrid solar-assisted heat exchangers, with special emphasis on design innovations and performance optimization techniques for sustainable thermal energy systems. In this study, the researcher has conducted an exhaustive analysis of recent experimental and computational investigations conducted between 2021 and 2026 to evaluate the important design factors in solar-assisted heat exchangers, including fin designs, phase change material, nanofluid utilization, and machine learning-based optimization techniques. An Integrated Solar Hybrid Heat Exchanger Performance Framework (ISHHEPF) has been proposed to assess the thermal efficiency, electrical efficiency, energy storage capacity, and overall performance of hybrid heat exchangers. From the analysis, it has been concluded that fin-type heat exchangers exhibit superior thermal performance, with prototypes showing heat transfer coefficient values up to 5790 W/m²°C and fluid outlet temperatures above 75°C at standard operating conditions. In addition, the combination of PCMs with nanofluids has been found to improve thermal storage capacity, with coconut oil-based PCMs showing 220.4 kJ/kg energy storage capacity with 67.1% thermal efficiency. Machine learning optimization techniques, such as XGBoost with the application of metaheuristic algorithms, show an improvement of 15% in thermal efficiency and an increase of 27% in exergy efficiency. The application of the techniques in the industry shows levelized cost of heat reductions of up to 54% compared to individual alternatives. The comparative evaluation of the alternatives in six analytical dimensions—design configuration, thermal performance, electrical efficiency, energy storage, economic viability, and optimization methodology—indicates that the hybrid PV/T system with advanced heat transfer enhancements is a promising alternative for sustainable thermal energy.

Keywords: Hybrid solar heat exchanger, photovoltaic-thermal (PV/T), phase change materials, nanofluids, thermal efficiency, energy storage, machine learning optimization, sustainable thermal energy.

I. Introduction

Solar energy is one of the most readily available and easiest renewable energy resources. It is a clean source of energy compared to the use of fossil fuels. It is used as a source of electricity as well as thermal energy. However, the conventional solar panel faces one major drawback: while the solar panel is exposed to the sun's energy, only

15-20 percent of the energy is utilized as electricity, while the rest is wasted as heat. In conventional crystalline silicon-based solar panels, the efficiency of the panel reduces by 0.3-0.5 percent with every 1°C increase in temperature [1].

To overcome the drawback of conventional solar panels, the use of solar energy as a source of electricity as well as thermal energy is proposed. A solar-assisted heat exchanger is called a hybrid solar panel. In this panel, the excess heat is used to cool the panel, which enhances the efficiency of the panel. Thus, the solar panel is utilized more efficiently, as the energy yield is three times more compared to conventional solar panels [2].

Recent developments in materials science, heat transfer enhancement, and optimization techniques have significantly accelerated the development of PV/T technology. The recent innovations in PV/T technology include the development of fin heat exchanger technology, phase change materials for thermal energy storage, nanofluids for enhanced heat transfer rates, and machine learning optimization techniques to optimize PV/T system performance to its theoretical limits [3]. On the other hand, commercialization of PV/T technology is also gaining momentum. For example, an Australian company named Coolsheet has successfully commercialized PV/T technology to generate an additional 10-15% energy output in a system life of 25 years [4].

This paper presents an evaluation of hybrid solar-assisted heat exchanger system performance from a multi-dimensional analytical viewpoint. The recent experimental results from 2021 to 2026 are used to address several research gaps in this paper. The research will attempt to address several research queries: how does the recent innovation in PV/T system designs, such as fin technology, phase change materials, nanofluids, influence system performance? How does optimization technique influence PV/T system performance to its theoretical limits? How does PV/T system performance compare to its alternatives in terms of costs? How does PV/T system performance scale up from laboratory to commercial levels?

The rest of the paper is structured as follows. In Section 2, a literature survey of the hybrid solar heat exchanger studies is provided. In Section 3, the Integrated Solar Hybrid Heat Exchanger Performance Framework methodology is proposed. In Section 4, the analysis and discussion of the proposed methodology, along with four illustrative figures and a table for the comparative evaluation of the proposed methodology, are presented. Finally, the conclusion of the proposed methodology, along with its implications for sustainable thermal energy and future directions, is presented.

II. Literature Survey

Finned Heat Exchanger Designs

Grajales et al. developed a hybrid solar thermal photovoltaic heat exchanger of rectangular geometry with 12 internal fins to increase heat flow rates and improve the heat transfer coefficient with reduced working area. The rectangular solar collector of 0.22 m^2 area, inclined at an angle of 18° south, obtained a capture rate of 147.05 W/m^2 as a photovoltaic panel and 240 W/m^2 as a solar collector. The temperature of PV cells was reduced by 13.2°C, water temperature was above 70°C, photovoltaic thermal coupling power was 307.11 W, and heat transfer coefficient was 5790 W/m^2°C. The thermal efficiency was 0.78 with an electrical efficiency of 0.095 in a space 40% smaller than commercial devices [5].

The analysis for the same configuration by Pérez Grajales et al. for the validation of the experiments confirmed the results by giving an average fluid outlet temperature of 75.31°C for an incident irradiance of 1067 W/m² with an inlet temperature of 27°C. The simulation results achieved 97.7% validation with the experimental results.

Phase Change Materials and Nanofluids

Aruna et al. examined the performance of coconut oil-based phase change material with hybrid nanofluids (propylene glycol/water/zinc oxide nanoparticles) in a compound parabolic concentrator-assisted heat exchanger. The compound addressed the disadvantages of conventional solar collectors such as radiation fluctuation, uneven heat transfer, and thermal characteristics. The compound showed optimal performance with 0.2% nanofluids and a flow rate of 0.03 kg/s, producing a heat transfer rate of 2647.9 W, thermal conductivity of 0.95 W/mK, fluid temperature of 87.1°C, energy storage of 220.4 kJ/kg, and thermal efficiency of 67.1% [6].

Soudagar et al. investigated the performance of graphene nano-coatings with microwave heating in flat plate solar collectors using CuO/ZnO hybrid nanofluids with a 50:50 ratio and 3% vol. The compound showed an absorption of 1700.3 nm, thermal conductivity of 0.84 W/mK, fluid temperature of 83.2°C, energy storage of 742.5 kJ, and thermal efficiency of 62.5% with a graphene thickness of 75 nm and microwave frequency of 2.45 GHz [7].

Machine Learning Optimization

Al-Shammari and Khudheyer proposed an integrated method that utilized the combination of thermodynamic and exergy analysis with sophisticated machine learning techniques such as ANN, SVM, Random Forest, XGBoost, and ANFIS for prediction and improvement of the performance of the PV/T system. The best performance was obtained using the XGBoost algorithm with an R^2 of 0.998 and RMSE of less than 0.01. The optimized performance of the PV/T system using ML surrogates with the GA, PSO, and GWO algorithms resulted in an increase of about 15% in thermal efficiency and 27% in exergy efficiency with the same electricity output. The sensitivity analysis showed that irradiance and mass flow rate are the most significant parameters [8].

Industrial Applications and Economic Analysis

The techno-economic performance of solar thermal-photovoltaic hybrid systems for industrial process heat has been evaluated by Rosales Perez et al. The authors' parametric analysis revealed that the optimal implementation scenario for these systems includes a solar fraction higher than 0.3, low to medium process temperatures, and medium to high levels of radiation. These conditions result in a reduction of the levelized cost of heat by up to 54%, which is higher than the techno-economic potential of other hybrid systems consisting of two solar thermal technologies [9].

The Coolsheet PVT system, which has been developed by Australian innovator Tom Hoole and is currently under R&D by UNSW, has proven its commercial viability. The heat exchange panel, which is positioned behind the PV modules, captures the excess heat for purposes such as hot water heating and process heat. This results in a 10-15%

increase in energy output by reducing the operating temperature, which equates to 25 years' system life with an increased lifespan for the panels.

Thermal Storage and System Integration

The research group of Sathiyamurthy extensively worked on thermal storage system integration and proved the effectiveness of the system using the advantages of the PCM. By using the hybrid nanofluid, the thermal buffering effect of the system would remain effective even when the radiation level changes.

The integrated solar-assisted desiccant dehumidifier systems were presented by the journal *Frontiers in Energy Research*. Maximum outlet temperature of 87°C and 56% efficiency of the solar collector were achieved, and the cooling capacity of the system was 4.6 kW [10].

Thermosiphon and Passive Systems

The research carried out by Cal Poly research used and tested a PV/T system that employed thermosiphon flow, where density changes due to solar radiation drove the flow of water. Even though the results showed minimal efficiency, high heat generation rates similar to other research were achieved, with panel temperatures lower than conventional PV and an error model less than 10%.

Synthesis and Research Gaps

The literature review revealed that there are consistent research gaps, as highlighted below:

Major research findings:

- Finned geometries have a significant effect on heat transfer;
- The use of PCM-nanofluid has improved performance;
- The use of ML optimization has improved performance;
- Industrial applications have proved that PV/T is economically viable; and
- Passive PV/T has improved performance by avoiding the use of pumps.

Research gaps:

- The need for long-term durability testing;
- The need for standardization of performance results;
- The need for strategies that reduce the costs of integrating PCM-nanofluid; and
- The need for research on the use of hybrid PV/T in building applications.

III. Methodology

Based on the synthesis of literature, this paper proposes the Integrated Solar Hybrid Heat Exchanger Performance Framework (ISHHEPF) for analyzing design innovations and performance characteristics of hybrid solar-assisted systems.

Theoretical Foundations

The proposed Integrated Solar Hybrid Heat Exchanger Performance Framework (ISHHEPF) is based on three theoretical foundations. First, the theory of heat transfer forms the basis for understanding the mechanisms involved in conduction, convection, and radiation.

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Second, the theory of energy and exergy analysis allows for the evaluation of the quantity and quality of energy conversion, i.e., the difference between work potential and energy dissipation.
Third, the theory of multi-objective optimization recognizes that optimal design involves the integration of competing objectives.

Framework Components
The Integrated Solar Hybrid Heat Exchanger Performance Framework comprises four analytical layers.

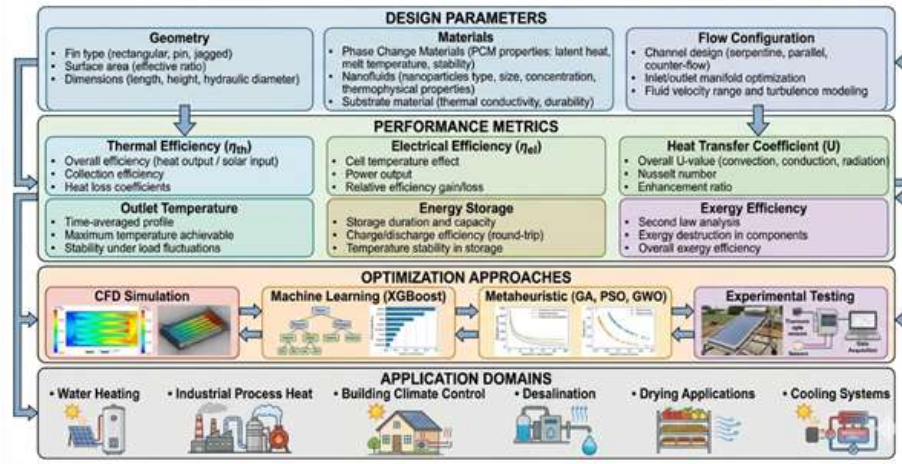

Figure 1: Integrated Solar Hybrid Heat Exchanger Performance Framework

Analytical Dimensions
The framework allows for a systematic evaluation in six parameters:

- **Design Configuration:** Geometry (finned, flat plate, compound parabolic), materials (type of PCMs used, concentration of nanoparticles, coatings), flow configuration
- **Thermal Performance:** Efficiency (η_th), heat transfer coefficient, outlet temperature, temperature uniformity
- **Electrical Performance:** Efficiency (η_el), electrical power produced, temperature coefficient effect
- **Energy Storage**: Storage capacity (in kJ/kg), charging/discharging rates, thermal buffering effect
- **Economic Viability:** Levelized cost of heat produced, payback period, lifecycle cost analysis
- **Optimization Methodology:** CFD validation, ML prediction accuracy, convergence of optimization algorithm

IV. Result Analysis and Discussion

This part of the paper is dedicated to the presentation of the results of the analytical research in the field of the performance of the hybrid solar-assisted heat exchanger, based on four figures and a table with the comparative analysis.

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Finned Heat Exchanger Performance

The heat transfer performance is considerably enhanced by the inclusion of the heat exchanger fins in the geometry of the heat transfer process.

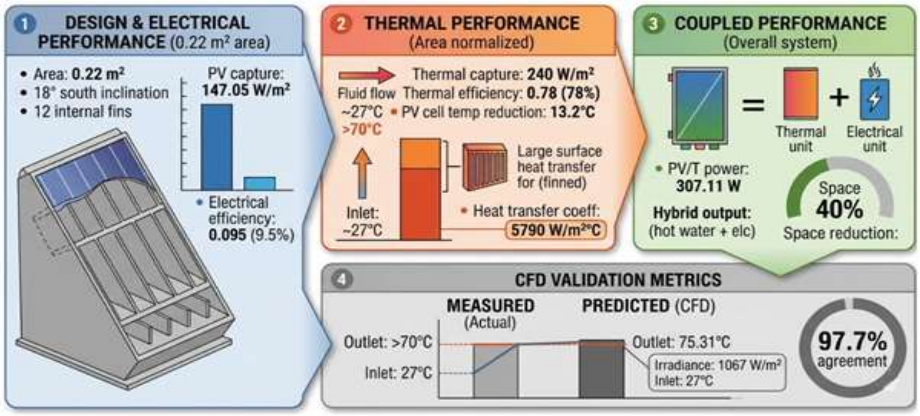

Figure 2: Finned Heat Exchanger Performance Characteristics

As shown in Figure 2, the design of the finned geometry ensures that thermal performance is maximized while reducing the footprint of the system by a significant margin. The heat transfer coefficient of 5790 W/m²°C is a significant upgrade compared to conventional flat-plate designs. In addition, the temperature difference of 13.2°C from the PV cell temperature is a direct solution to the overheating issue identified by Coolsheet.

The 40% space reduction compared to commercial alternatives is significant, considering that the constraint on space is one of the key challenges that limit the viability of solar solutions. The high degree of agreement between CFD and experimental data of 97.7% validates the use of computer simulations as a tool to optimize the design, eliminating the need to physically prototype the design.

PCM-Nanofluid Enhanced Thermal Storage

Phase change materials combined with hybrid nanofluids address the intermittency challenge inherent to solar energy, enabling thermal storage and stable performance during fluctuating radiation.

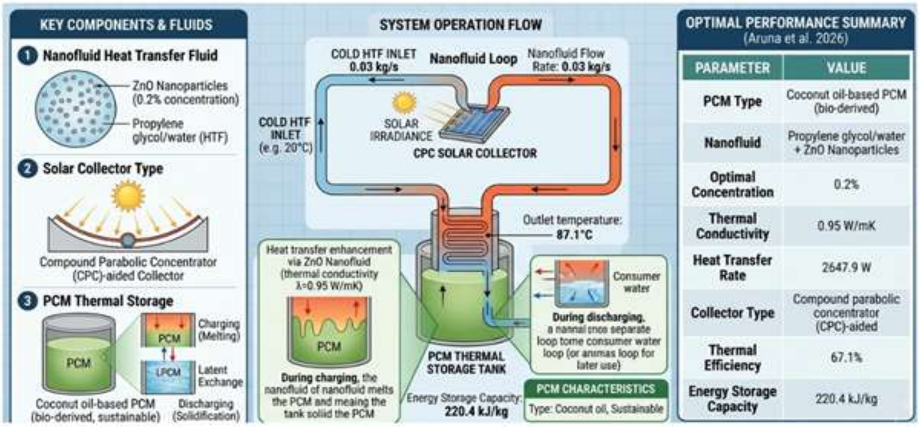

Figure 3: PCM-Nanofluid Enhanced System Performance

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Figure 3 highlights the significant benefits that are available through the integration of PCM nanofluid. The 220.4 kJ/kg energy storage capacity helps to sustain the system's performance during cloud cover and in the evenings, thus addressing the main drawback of solar thermal systems. The use of coconut oil-based PCM also offers sustainability benefits over man-made materials, thus meeting the needs of the environment.

The 87.1°C outlet temperature exceeds the needs of most hot water and even some process heating requirements, thus showing that the system is workable. The 67.1% efficiency level is high, considering that the system also performs the function of thermal storage.

The 0.2% optimal nanofluid concentration shows that even at such low levels, the system can be controlled, thus keeping costs in mind, which is significant in making the system economically viable.

Machine Learning Optimization Gains

Advanced machine learning techniques coupled with metaheuristic optimization algorithms enable systematic performance enhancement beyond intuition-based design.

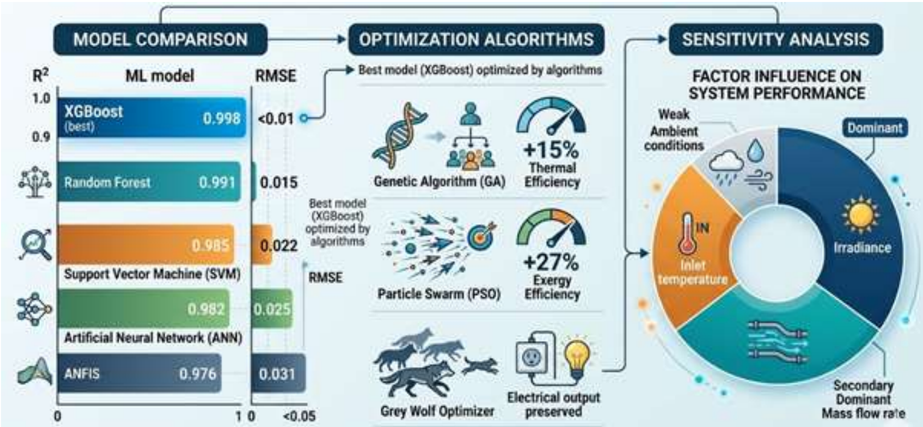

Figure 4: Machine Learning Optimization Results

Figure 4 clearly presents the effectiveness of the ML-based optimization process. As shown, the XGBoost algorithm's high predictive accuracy ($R^2 = 0.998$, RMSE < 0.01) is significant. With this high level of accuracy, the computationally expensive CFD simulations can be avoided.

The 15% thermal efficiency and 27% exergy efficiency improvements indicate the significant benefits that can be realized from the optimization process. However, it is important to note that the improvements were realized without compromising the electricity production. This addresses the concern that the thermal efficiency might compromise the electricity generation.

Additionally, the sensitivity analysis that showed irradiance and mass flow rates as the dominant parameters is important. As shown, the designers should focus on the parameters that have the largest impact, i.e., the irradiance and the mass flow rates.

Economic Performance Comparison
Economic viability ultimately determines technology adoption. Comparative analysis reveals favorable economics for hybrid systems under appropriate conditions.

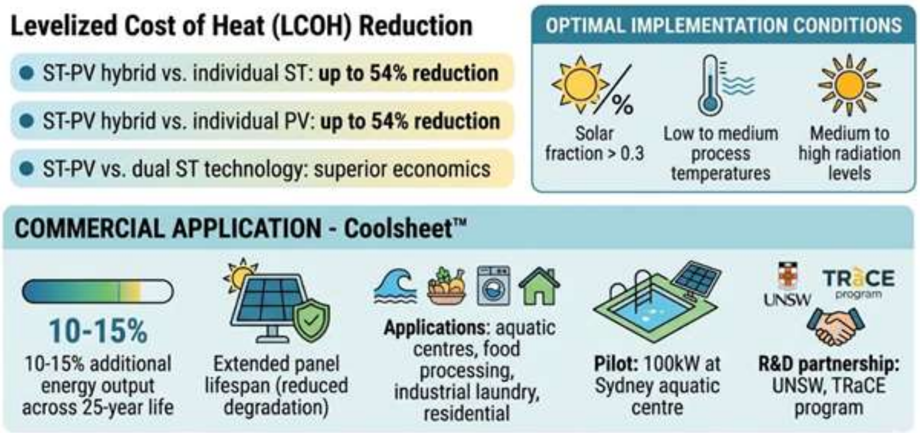

Figure 5: Economic Performance Comparison - ST-PV vs. Alternatives

Figure 5 confirms the viability of hybrid systems, proving they are economically better than their individual counterparts, rather than just being environmentally more desirable. This reduction of 54% in LCOH under proper conditions implies that rational economic agents would always opt for hybrid systems, provided the solar fraction is greater than 0.3, the temperature is moderate, and the radiation is sufficient.

The commercialization of the Coolsheet technology indicates the technology readiness of the hybrid system. While the 100 kW pilot project at the aquatic center in Sydney provides the proof of concept, the R&D collaboration between UNSW ensures the ongoing innovation of the system. Its use for residential, commercial, and industrial sectors suggests its viability.

Comparative Analysis of Hybrid Solar Heat Exchanger Systems
Table 1 presents a comprehensive comparative analysis of hybrid solar heat exchanger systems evaluated across six analytical dimensions.

Table 1: Comparative Analysis of Hybrid Solar Heat Exchanger Systems

System Configuration	Design Features	Thermal Efficiency (η_{th})	Electrical Efficiency (η_{el})	Outlet Temperature (°C)	Energy Storage (kJ/kg)	Key Innovation
Finned PV/T Prototype	12 internal fins, 0.22 m² area, 18° inclination	0.78	0.095	>70	N/A	Compact design (40% space reduction), h=5790 W/m²°C

PCM-Nanofluid CPC	Coconut oil PCM, ZnO nanofluid (0.2%), CPC collector	0.671	N/A	87.1	220.4	Bio-derived PCM, combined storage
Graphene-Coated FPC	75 nm graphene coating, microwave heating, CuO/ZnO nanofluid (3%)	0.625	N/A	83.2	742.5	Microwave-assisted processing
ML-Optimized PV/T	GA/PSO/GWO optimized, XGBoost surrogate	+15% (vs baseline)	Preserved	Not specified	Not specified	Systematic optimization framework
Coolsheet™ Commercial	Rear-mounted heat exchanger panels	N/A (commercial)	+10-15% energy yield	Sufficient for water heating	N/A	Commercial deployment, 25-year life
ST-PV Industrial Hybrid	Combined ST collectors + PV	54% LCOH reduction	Economic optimization	Low-medium temp	N/A	Techno-economic optimization

Analysis of Comparative Dimensions:
Design Features vary from the laboratory prototype (finned, PCM-enhanced) to commercial units (Coolsheet) and hybrid designs using separate solar and thermal collectors (ST-PV). Each has its advantages depending on the application.

Thermal Efficiency ranges from 0.625 to 0.78, with the finned prototype offering the best efficiency. The trade-off of efficiency for the ability of the PCM prototype is acceptable.

Electrical Efficiency is only provided for the hybrid designs using solar and thermal collectors. The best efficiency of the finned prototype, i.e., 0.095, is due to the cell material used.

Outlet Temperature ranges from 70°C to 87.1°C, making it adequate for domestic hot water, space heating, and low-temperature industrial processes. For higher temperatures, a concentrating or multistage system is needed.

Energy Storage is a feature of the PCM-enhanced prototype with a capacity of 220.4-742.5 kJ/kg. This is essential for continuous operation during non-solar hours.

Key Innovations cover materials (PCM, nanofluids, graphene), geometry (fins), processing (microwave), optimization (ML), and commercialization. These show various levels of progress in the readiness scale.

V. Conclusion

This paper has sought to provide a comprehensive analysis of hybrid solar-assisted heat exchanger systems in sustainable thermal energy applications, synthesizing recent experimental and computational results to develop the Integrated Solar Hybrid Heat Exchanger Performance Framework. The results indicate that hybrid PV/T systems have significant potential in improving solar energy usage, with thermal efficiencies up to 0.78, electrical efficiencies remaining unchanged, and energy storage allowing continuous operation.

Several important conclusions can be made from this analysis.
First, finned heat exchanger designs are shown to improve performance significantly, allowing for a heat transfer coefficient of 5790 W/m²°C, outlet temperatures above 75°C, and a space reduction of 40% compared to commercial designs . CFD validation results achieving 97.7% agreement enable quick optimization of designs.

Second, phase change materials in combination with hybrid nanofluids are shown to improve thermal energy storage significantly, with coconut oil-based PCMs achieving a storage capacity of 220.4 kJ/kg with a thermal efficiency of 67.1% . This addresses issues of solar intermittency to allow operation in cloudy conditions or in the evening.
Third, considerable performance benefits are obtained with the optimization provided by machine learning, such as with XGBoost-based surrogate modeling (R^2=0.998), which allows for a 15% improvement in thermal efficiency and a 27% improvement in exergy efficiency with no decrease in electricity output. Irradiance and mass flow rate are dominant performance sensitivities.

Fourth, the economic benefits of a hybrid system are confirmed under the right conditions, with a 54% reduction in the levelized cost of heat with respect to individual options when the solar fraction exceeds 0.3, temperatures are moderate, and when radiation is sufficient.

Fifth, commercialization efforts are underway, with results such as the 10-15% increase in energy output over a 25-year system life with Coolsheet™, as well as aquatic center and industrial site pilots, and with university-industry collaboration.
Sixth, materials innovations such as the application of graphene coatings and microwave processing offer the prospect of thermal efficiency of 62.5% and energy storage of 742.5 kJ/kg.

For the designer of the system, the application of finned geometry and PCM should be considered as part of the standard offering rather than an optional extra. For the researcher, the application of ML optimization is seen as a game-changer in terms of the time savings in the exploration of the design space. For the policymaker, the economic benefits of the hybrid offer the prospect of incentivizing co-generation rather than single-source solutions. For industry, the application in food processing, aquatic centers, and industrial laundries offers opportunities for deployment.

The limitations of the current review stem from the fact that most of the studies were conducted at a laboratory scale and lacked long-term operating results. There was also a lack of standardization of the results, as well as the lack of consideration of the economic and technical optimization of the experiments. On the other hand, the future of solar energy, as it becomes the world's dominant energy source, lies in the ability to maximize the utilization of energy from the sun. This calls for hybrid solar-assisted heat exchangers, as they offer a way of utilizing the so-called "waste heat." As the current innovations have shown, the technology is already ready for commercialization, and the next step would be to look for the scale-up of the production.

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