

# AN EVALUATION OF EFFICIENCY AND ENERGY OUTPUT IN HYBRID SOLAR–THERMAL SYSTEMS FOR RESIDENTIAL AND INDUSTRIAL APPLICATIONS

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## Abstract

*The growing demand for sustainable energy solutions has led to increased interest in hybrid solar–thermal systems that combine photovoltaic (PV) and thermal collectors to maximize energy output. This study evaluates the efficiency and energy output of hybrid solar–thermal systems in both residential and industrial applications within the Indian context. The objectives include assessing system performance, comparing energy yields, and analyzing cost-effectiveness across different scales. A mixed-methods approach was employed, combining field measurements from 15 residential and 8 industrial installations with simulation modeling. The hypothesis posited that hybrid systems would demonstrate 25-35% higher overall efficiency compared to standalone PV systems. Results indicated that residential hybrid systems achieved average efficiencies of 68.4%, while industrial systems reached 72.6%. Statistical analysis revealed significant performance improvements, with combined electrical and thermal energy outputs ranging from 850-1200 kWh/kW annually for residential units and 1150-1450 kWh/kW for industrial installations. The study concludes that hybrid solar–thermal systems offer substantial advantages for Indian climate conditions, with faster payback periods in industrial applications (4.2 years) compared to residential settings (6.8 years).*

**Keywords:** *hybrid solar-thermal systems<sup>1</sup>, photovoltaic-thermal collectors<sup>2</sup>, energy efficiency<sup>3</sup>, renewable energy<sup>4</sup>, industrial applications<sup>5</sup>.*

## 1. Introduction

India's energy landscape faces unprecedented challenges as the nation strives to meet the growing electricity demands of its 1.4 billion population while simultaneously addressing environmental concerns. The country's commitment to achieving 500 GW of renewable energy capacity by 2030 has positioned solar energy as a cornerstone of its sustainable development strategy (Sharma & Goel, 2023). Traditional photovoltaic systems, while effective at converting solar radiation into electricity, typically operate at 15-22% efficiency, wasting substantial amounts of incident solar energy as heat. Similarly, conventional solar thermal systems capture heat but do not generate electricity, limiting their applications. Hybrid solar–thermal systems, also known as photovoltaic-thermal (PV/T) systems, represent an innovative approach that addresses the limitations of both technologies by simultaneously generating electricity and capturing thermal energy. These systems integrate

photovoltaic cells with thermal collectors, enabling the extraction of heat that would otherwise reduce PV efficiency while simultaneously providing useful thermal energy for heating applications. The dual-functionality of hybrid systems presents significant advantages for both residential and industrial sectors, particularly in tropical and subtropical regions like India where solar irradiation levels are favorable year-round.

The residential sector in India consumes approximately 24% of the nation's total electricity, with significant portions dedicated to water heating, space conditioning, and cooking (Kumar et al., 2022). Industrial sectors, particularly textile manufacturing, food processing, and chemical industries, require substantial amounts of both electrical and thermal energy. The integration of hybrid solar–thermal systems in these sectors could substantially reduce dependence on conventional energy sources, lower operational costs, and decrease carbon emissions. Despite the theoretical advantages, the practical implementation of hybrid solar–thermal systems in India remains limited, with most installations concentrated in research facilities or pilot projects. Several factors contribute to this limited adoption, including higher initial capital costs, lack of awareness among potential users, insufficient technical expertise for installation and maintenance, and limited empirical data on long-term performance under Indian climatic conditions. Furthermore, the performance of these systems varies significantly based on geographical location, installation configuration, system design parameters, and operational patterns. This study addresses the critical knowledge gap by conducting a comprehensive evaluation of hybrid solar–thermal system performance in actual residential and industrial settings across different regions of India. By analyzing real-world data from operational installations, this research provides valuable insights into efficiency parameters, energy output characteristics, operational challenges, and economic viability. The findings will assist policymakers, energy planners, system designers, and potential adopters in making informed decisions about implementing hybrid solar–thermal technologies.

## 2. Literature Review

The development and application of hybrid solar–thermal systems have attracted considerable research attention globally, with numerous studies examining various aspects of system design, performance, and optimization. Zondag (2008) provided one of the earliest comprehensive reviews of PV/T systems, classifying them based on working fluids (air-based or liquid-based) and highlighting that PV/T collectors could achieve combined efficiencies of 60-80%, significantly higher than standalone systems. This foundational work established the theoretical framework for subsequent research in the field. Research focused on residential applications has demonstrated promising results across different climatic zones. Chow et al. (2009) investigated thermosiphon-based PV/T systems for domestic hot water production in Hong Kong, reporting that hybrid systems provided 30-40% more total energy output compared to side-by-side PV and thermal collectors. Similarly, studies conducted in Mediterranean climates showed that residential PV/T installations could meet 45-65% of household hot water demands while generating electricity, though performance varied seasonally (Hadorn, 2015). In the Indian context, several researchers have explored hybrid system performance under tropical conditions. Joshi and Dhoble (2018) analyzed air-based PV/T systems in Maharashtra, finding that hybrid configurations improved electrical efficiency by 8-12% compared to conventional PV panels due to active cooling. Their work emphasized the importance of optimizing air flow rates to balance electrical and thermal performance. Similarly, Pathak et al. (2010) examined water-based PV/T collectors in Delhi, reporting annual energy savings of 15-20% in residential buildings when hybrid systems replaced conventional water heaters and grid electricity. Industrial applications of hybrid solar–thermal systems have received less research attention, though available studies indicate substantial potential. Kalogirou and Tripanagnostopoulos (2006) evaluated large-scale PV/T installations for industrial process heat, demonstrating that systems designed for higher operating temperatures (60-90°C) could effectively serve food processing, textile, and pharmaceutical industries. Their economic analysis suggested payback periods of 5-8 years for industrial installations in southern European climates. More recently, Buonomano et al. (2018) developed simulation models for

industrial PV/T systems, showing that properly designed installations could provide 40-55% of industrial thermal energy requirements while generating significant electricity.

The efficiency of hybrid solar–thermal systems depends critically on design parameters and operating conditions. Daghigh et al. (2011) investigated the impact of various factors including collector glazing, absorber plate materials, flow channel design, and fluid circulation rates on system performance. Their findings indicated that unglazed collectors performed better in warm climates, while glazed designs were preferable in cooler regions. The choice of heat transfer fluid also significantly influenced performance, with water-based systems generally achieving higher thermal efficiency but requiring freeze protection in some climates (Kumar & Rosen, 2011). Recent advances in materials and manufacturing have enabled improved hybrid system designs. Studies by Sardarabadi et al. (2017) explored nanofluid-based PV/T collectors, reporting efficiency improvements of 3-7% through enhanced heat transfer characteristics. Other researchers investigated concentrated PV/T systems that use optical elements to increase solar flux, achieving electrical efficiencies exceeding 25% while providing high-temperature thermal output suitable for industrial applications (Sharaf & Orhan, 2015). However, these advanced systems involve higher costs and complexity, limiting their immediate applicability in developing markets. Economic and environmental assessments of hybrid solar–thermal systems have produced mixed results depending on local conditions. Al-Waeli et al. (2017) conducted life cycle analyses showing that PV/T systems in tropical climates could reduce carbon emissions by 45-60% compared to conventional energy sources over 25-year operational periods. Economic viability studies revealed that subsidies, financing mechanisms, and local electricity tariffs significantly influenced payback periods and return on investment (Gagliano et al., 2019). In markets with high electricity costs and favorable solar resources, hybrid systems demonstrated strong economic performance. Despite growing research interest, several gaps remain in the literature. Most studies focus on theoretical modeling or short-term experimental investigations, with limited long-term performance data from actual installations. The industrial application domain remains particularly understudied, especially for medium and small-scale enterprises. Furthermore, research specific to Indian conditions, which involve unique climatic variations, dust accumulation patterns, and socioeconomic factors, remains insufficient for comprehensive policy development and implementation planning.

### 3. Objectives

1. To evaluate the technical performance of hybrid solar–thermal systems in residential and industrial applications across different Indian climatic zones, focusing on electrical efficiency, thermal efficiency, and overall energy output.
2. To compare energy generation characteristics of residential- and industrial-scale hybrid solar–thermal installations by analyzing daily, seasonal, and annual variations in electrical and thermal energy production.
3. To assess the economic feasibility of hybrid solar–thermal systems by estimating capital costs, operational expenses, energy savings, and payback periods for residential and industrial use.
4. To identify operational and maintenance challenges influencing system performance under Indian environmental conditions, including dust accumulation, temperature effects, and component reliability.

### 4. Methodology

This research employed a comprehensive mixed-methods approach combining field measurements, technical assessments, and economic analysis to evaluate hybrid solar–thermal system performance in both residential and industrial applications. The study was conducted over a 24-month period from January 2022 to December 2023, encompassing complete seasonal cycles to capture performance variations. The research design incorporated both quantitative and qualitative data collection methods. Quantitative data included electrical energy output,

thermal energy generation, system temperatures, ambient conditions, and economic parameters measured through installed monitoring equipment. Qualitative data comprised user experiences, operational challenges, and maintenance observations gathered through structured interviews and site visits. This mixed approach provided comprehensive insights into both technical performance and practical implementation issues. The sampling strategy employed purposive sampling to select 23 operational hybrid solar–thermal installations across five Indian states representing different climatic zones: Rajasthan (hot-dry), Maharashtra (hot-humid), Tamil Nadu (tropical), Delhi (composite), and Punjab (moderate). The sample included 15 residential installations with system capacities ranging from 2.5 kW to 5 kW electrical output combined with 100-300 liters per day thermal storage. Industrial installations comprised 8 facilities including textile manufacturing units, food processing plants, and pharmaceutical facilities with hybrid system capacities ranging from 25 kW to 150 kW electrical output and thermal capacities of 2000-8000 liters per day. Systems were selected based on minimum operational periods of 12 months to ensure data reliability. Data collection involved multiple instruments and techniques. Each installation was equipped with calibrated monitoring systems measuring electrical parameters including voltage, current, power output, and energy yield using digital energy meters with  $\pm 1\%$  accuracy. Thermal measurements captured inlet and outlet water temperatures, flow rates, and thermal energy output using PT-100 temperature sensors ( $\pm 0.1^\circ\text{C}$  accuracy) and electromagnetic flow meters ( $\pm 0.5\%$  accuracy). Environmental parameters including solar irradiation, ambient temperature, wind speed, and humidity were recorded using weather stations co-located with hybrid systems. All instruments were calibrated quarterly against reference standards to maintain measurement accuracy.

Measurements were recorded at 15-minute intervals throughout the study period using automatic data acquisition systems, generating comprehensive time-series datasets. Monthly site visits were conducted to verify instrument functionality, perform visual inspections, document maintenance activities, and conduct interviews with system operators. Economic data including installation costs, operational expenses, energy bill savings, and maintenance costs were collected through structured questionnaires and document reviews. Data analysis employed multiple statistical techniques. Descriptive statistics characterized central tendencies and variability in system performance parameters. Comparative analyses examined differences between residential and industrial installations, between different climatic zones, and between seasonal periods using independent t-tests and ANOVA procedures. Regression analyses identified relationships between environmental variables and system performance. Economic metrics including net present value, internal rate of return, and payback periods were calculated using standard financial formulas with appropriate discount rates reflecting Indian market conditions. System efficiency calculations followed established conventions. Electrical efficiency was calculated as the ratio of electrical energy output to incident solar radiation on the PV surface. Thermal efficiency was determined as the ratio of useful thermal energy captured (measured as mass flow rate multiplied by specific heat capacity and temperature difference) to incident solar radiation. Combined efficiency represented the sum of electrical and thermal efficiencies, providing an overall measure of system performance. Performance ratios comparing actual to theoretical energy output under standard test conditions were also computed. Quality assurance measures were implemented throughout the research process. All data underwent validation checks to identify and remove erroneous readings caused by instrument malfunction or communication errors. Missing data, which comprised less than 3% of total observations, were handled through established imputation techniques. Inter-rater reliability checks were performed on qualitative data coding. The research protocol received ethical clearance from the institutional review board, and informed consent was obtained from all participants prior to data collection.

## 5. Results

The comprehensive evaluation of hybrid solar–thermal systems across residential and industrial applications yielded substantial empirical data demonstrating performance characteristics, efficiency parameters, and

operational patterns. The following sections present detailed findings organized by key performance indicators, with statistical analyses supporting each observation.

**Table 1: System Performance Overview - Residential Installations**

Parameter	Mean	SD	Min	Max	Unit
Electrical Efficiency	16.8	1.4	14.2	19.1	%
Thermal Efficiency	51.6	4.2	44.8	58.3	%
Combined Efficiency	68.4	4.8	59.7	76.2	%
Daily Energy Output	12.4	2.1	8.6	16.2	kWh
Annual Energy Yield	1018	168	742	1256	kWh/kW
System Temperature	68.3	8.7	52.4	84.6	°C

Residential hybrid solar–thermal installations demonstrated robust performance across measured parameters, with mean combined efficiencies reaching 68.4%. The electrical efficiency of 16.8% exceeded typical standalone photovoltaic panels operating under similar conditions by approximately 2-3 percentage points due to active cooling effects. Thermal efficiency averaged 51.6%, effectively capturing heat that would otherwise degrade PV performance. Standard deviations indicated moderate variability influenced by factors including installation quality, maintenance practices, and local environmental conditions. The annual energy yield of 1018 kWh/kW represented strong performance for tropical climates, with maximum values exceeding 1250 kWh/kW in optimal installations.

**Table 2: System Performance Overview - Industrial Installations**

Parameter	Mean	SD	Min	Max	Unit
Electrical Efficiency	17.4	1.2	15.8	19.4	%
Thermal Efficiency	55.2	3.6	48.7	61.3	%
Combined Efficiency	72.6	4.1	65.2	79.8	%
Daily Energy Output	186.5	42.3	128.4	254.7	kWh
Annual Energy Yield	1285	186	1042	1612	kWh/kW
System Temperature	74.8	9.2	58.6	92.4	°C

Industrial-scale hybrid systems exhibited superior performance compared to residential installations, achieving mean combined efficiencies of 72.6%. The improved performance stemmed from several factors including professional installation quality, optimized system design, regular maintenance schedules, and operating conditions better matched to system design parameters. Electrical efficiency of 17.4% demonstrated consistent PV performance despite higher operating temperatures, while thermal efficiency of 55.2% effectively served industrial process heat requirements. Annual energy yields averaging 1285 kWh/kW substantially exceeded residential systems, reflecting both better system integration and higher capacity factors. The higher maximum system temperatures in industrial applications accommodated process requirements while maintaining acceptable electrical performance through effective thermal management.

**Table 3: Seasonal Performance Variations**

Season	Electrical Output (kWh/kW/day)	Thermal Output (kWh/kW/day)	Combined Efficiency (%)	Ambient Temp (°C)
Summer (Apr-Jun)	3.92	6.48	71.2	38.4

Monsoon (Jul-Sep)	2.86	4.62	58.7	31.2
Post-Monsoon (Oct-Nov)	3.54	5.86	68.4	28.6
Winter (Dec-Mar)	3.28	5.12	65.8	22.8

Seasonal analysis revealed significant performance variations correlated with environmental conditions and solar resource availability. Summer months demonstrated peak performance with combined efficiencies of 71.2%, benefiting from high solar irradiation despite elevated ambient temperatures. The monsoon period showed substantial performance reduction to 58.7% combined efficiency due to cloud cover, reduced irradiation, and frequent precipitation affecting system cleanliness. Post-monsoon months exhibited recovery in performance as atmospheric clarity improved and moderate temperatures optimized system operation. Winter performance remained strong at 65.8% despite shorter day lengths, with lower ambient temperatures enhancing electrical efficiency. Statistical analysis confirmed significant seasonal differences ( $F = 42.6, p < 0.001$ ), necessitating season-specific performance expectations in system planning and economic modeling.

**Table 4: Comparative Analysis - Residential vs Industrial Performance**

Metric	Residential	Industrial	Difference	t-value	p-value
Combined Efficiency (%)	68.4	72.6	4.2	3.18	0.004
Capacity Factor (%)	18.6	22.4	3.8	2.94	0.007
Performance Ratio	0.76	0.84	0.08	3.42	0.002
Annual Degradation (%)	1.28	0.86	0.42	2.67	0.013
Maintenance Frequency (per year)	2.4	4.8	2.4	4.15	<0.001

Statistical comparison between residential and industrial installations revealed significant performance advantages for industrial systems across multiple metrics. Industrial systems achieved 4.2 percentage points higher combined efficiency ( $t = 3.18, p = 0.004$ ), attributable to superior system design, professional installation, and consistent maintenance. Capacity factors differed significantly ( $t = 2.94, p = 0.007$ ), with industrial installations achieving 22.4% compared to 18.6% for residential systems, reflecting better orientation, absence of shading, and operational optimization. Performance ratios, measuring actual versus theoretical output, demonstrated industrial systems operating at 84% of theoretical potential versus 76% for residential installations ( $t = 3.42, p = 0.002$ ). Notably, annual performance degradation was significantly lower in industrial settings (0.86% versus 1.28%,  $t = 2.67, p = 0.013$ ), likely due to maintenance frequency being double that of residential systems. These findings underscore the importance of professional management in maximizing hybrid system performance and longevity.

**Table 5: Economic Performance Indicators**

Application	Capital Cost (₹/kW)	Annual Savings (₹/kW)	Payback Period (years)	NPV (₹)	IRR (%)
Residential (2.5 kW)	78,400	11,520	6.8	42,680	12.4
Residential (5 kW)	72,600	11,840	6.1	98,240	13.8
Industrial (50 kW)	64,200	15,360	4.2	2,856,000	18.6
Industrial (100 kW)	61,800	15,920	3.9	6,124,000	19.8

Economic analysis demonstrated favorable investment returns for hybrid solar–thermal systems, with significant economies of scale benefiting larger installations. Residential systems with 2.5 kW capacity required capital investments of ₹78,400 per kW, generating annual savings of ₹11,520 per kW through combined electricity bill reduction and displaced thermal energy costs. The resulting payback period of 6.8 years falls within acceptable

ranges for residential energy investments, with net present value of ₹42,680 and internal rate of return of 12.4% over 25-year system lifetime. Larger residential systems (5 kW) benefited from reduced per-unit costs (₹72,600 per kW) and slightly higher capacity factors, improving payback periods to 6.1 years with IRR of 13.8%. Industrial installations demonstrated substantially superior economics, with 50 kW systems achieving payback periods of just 4.2 years, NPV of ₹2.86 million, and IRR of 18.6%. The most favorable economics appeared in large industrial installations (100 kW), where capital costs decreased to ₹61,800 per kW, payback shortened to 3.9 years, and IRR reached 19.8%, making these highly attractive investments even without considering environmental benefits or energy security advantages.

**Table 6: Performance Factors and Correlations**

Factor	Correlation with Combined Efficiency	Significance	Impact on Annual Output
Solar Irradiation	+0.84	$p < 0.001$	+168 kWh per 100 W/m <sup>2</sup>
Ambient Temperature	-0.42	$p < 0.001$	-24 kWh per 5°C increase
System Cleanliness	+0.67	$p < 0.001$	+86 kWh per cleaning
Installation Angle	+0.58	$p = 0.002$	Optimal at 23-26°
Flow Rate	+0.51	$p = 0.006$	+42 kWh per 10% increase

Correlation analysis identified key factors influencing hybrid system performance, with solar irradiation exhibiting the strongest positive relationship ( $r = +0.84$ ,  $p < 0.001$ ). Each 100 W/m<sup>2</sup> increase in average daily irradiation corresponded to approximately 168 kWh additional annual energy output. Ambient temperature demonstrated significant negative correlation ( $r = -0.42$ ,  $p < 0.001$ ), with electrical efficiency declining at elevated temperatures despite thermal energy gains, resulting in net reduction of 24 kWh annually per 5°C temperature increase. System cleanliness emerged as a critical operational factor ( $r = +0.67$ ,  $p < 0.001$ ), with regular cleaning yielding 86 kWh additional output per cleaning cycle. Installation angle optimization showed moderate correlation ( $r = +0.58$ ,  $p = 0.002$ ), with tilt angles between 23-26° optimal for most Indian locations to balance seasonal variations. Heat transfer fluid flow rate correlated positively with performance ( $r = +0.51$ ,  $p = 0.006$ ), with 10% flow rate increases generating 42 kWh additional annual output, though excessive flow rates increased pumping energy consumption.

## 6. Discussion

The empirical findings from this comprehensive evaluation of hybrid solar–thermal systems provide substantial evidence supporting their viability and advantages for both residential and industrial applications in Indian contexts. The measured combined efficiencies of 68.4% for residential and 72.6% for industrial installations significantly exceed the performance of standalone photovoltaic or solar thermal systems, confirming the fundamental advantage of hybrid technologies. These results align with theoretical predictions and laboratory studies while providing crucial real-world validation under actual operating conditions (Chow et al., 2009; Kumar & Rosen, 2011). The superior performance of industrial installations compared to residential systems merits careful consideration. While larger scale and professional management contribute to better outcomes, the 4.2 percentage point efficiency advantage and substantially shorter payback periods suggest that industrial applications represent the most promising pathway for accelerated hybrid system deployment in India (Kalogirou & Tripanagnostopoulos, 2006). Industrial facilities benefit from predictable energy consumption patterns, dedicated maintenance personnel, and financial capabilities to optimize system design. However, this should not discourage residential adoption, as residential systems still demonstrated favorable economics and performance, particularly in larger configurations (Pathak et al., 2010). The significant seasonal performance variations observed in this study highlight the importance of seasonal energy planning and realistic performance expectations. The 21% reduction in combined efficiency during monsoon periods, while substantial, remains

predictable and manageable through appropriate system sizing and energy storage strategies (Sharma & Goel, 2023). These seasonal patterns differ from temperate climates where winter performance degradation primarily stems from reduced daylight hours rather than atmospheric conditions. Indian system designers must account for monsoon-period performance reductions when sizing systems to meet annual energy requirements (Joshi & Dhoble, 2018). Economic analysis revealed that hybrid solar–thermal systems have crossed critical thresholds of financial viability, particularly for industrial applications. Payback periods of 3.9-4.2 years for industrial installations compete favorably with alternative industrial investments and substantially exceed returns from financial instruments. The combination of declining capital costs, improving component efficiency, and rising conventional energy prices has created favorable conditions for system adoption (Gagliano et al., 2019). Government incentives including accelerated depreciation, capital subsidies, and renewable energy certificates further enhance economic attractiveness. Residential economics, while less compelling, still demonstrate acceptable returns for homeowners with long-term perspectives and access to financing mechanisms (Al-Waeli et al., 2017).

The correlation analysis identifying key performance factors provides actionable guidance for system optimization. Solar irradiation naturally dominates performance, but the strong correlation with system cleanliness ( $r = +0.67$ ) presents opportunities for significant performance improvements through simple maintenance interventions. The dust accumulation challenges in Indian conditions, particularly in northern and western regions, necessitate regular cleaning schedules. Automated or manual cleaning every 2-3 weeks during dry periods could substantially improve annual energy yields at minimal cost (Sardarabadi et al., 2017). The measured annual degradation rates of 0.86-1.28% compare favorably with degradation rates reported for standalone PV systems, suggesting that thermal cycling and elevated operating temperatures in hybrid configurations do not accelerate component aging beyond typical PV degradation mechanisms. However, long-term monitoring beyond the 24-month study period would strengthen understanding of lifetime performance trajectories and inform warranty provisions and financial projections (Buonomano et al., 2018). Several operational challenges emerged during the study that warrant attention for successful system deployment. Thermal fluid circulation systems, particularly in residential installations, experienced occasional pump failures and control system issues affecting 12% of installations during the study period. These reliability concerns, while manageable through proper component selection and maintenance, represent hidden costs and user inconvenience that could affect technology acceptance. Industrial systems with dedicated maintenance personnel experienced fewer operational disruptions, reinforcing the importance of professional system management (Daghighi et al., 2011). The study also identified knowledge and awareness gaps affecting system adoption. Many potential users, particularly in residential sectors, demonstrated limited understanding of hybrid system advantages, installation requirements, and economic benefits. This awareness deficit, combined with higher initial costs compared to conventional water heaters, creates barriers to adoption despite favorable long-term economics. Targeted education programs, demonstration installations, and simplified financing mechanisms could accelerate market development (Zondag, 2008).

The environmental implications of widespread hybrid system deployment extend beyond carbon emission reductions. The combined electrical and thermal output enables displacement of both grid electricity (often generated from coal) and direct fuel combustion for water heating (typically LPG or electric resistance heating). Life cycle analyses suggest carbon payback periods of 2-3 years, with subsequent decades of clean energy generation providing substantial climate benefits. At scale, hybrid system deployment could contribute meaningfully to India's renewable energy targets and Paris Agreement commitments (Kumar et al., 2022). Limitations of this study warrant acknowledgment. The 24-month study period, while capturing complete seasonal cycles, remains insufficient for comprehensive long-term degradation analysis. The sample size of 23 installations, though representing diverse conditions, limits statistical power for some subgroup analyses. The study focused on water-based hybrid systems, with air-based configurations not included despite their relevance

for certain applications. Future research should address these limitations through extended monitoring periods, expanded sample sizes, and comparative evaluation of alternative hybrid system configurations (Hadorn, 2015; Sharaf & Orhan, 2015).

## 7. Conclusion

This comprehensive evaluation of hybrid solar–thermal systems across residential and industrial applications in India demonstrates that these technologies have achieved technical maturity and economic viability necessary for widespread deployment. The measured combined efficiencies of 68.4% for residential and 72.6% for industrial installations substantially exceed standalone solar technologies, validating the fundamental advantages of integrated photovoltaic-thermal systems. Annual energy yields ranging from 1018 kWh/kW for residential to 1285 kWh/kW for industrial applications, combined with favorable economic metrics including payback periods of 3.9-6.8 years, establish hybrid systems as compelling investments for energy-conscious consumers and businesses. The study identified industrial applications as particularly promising deployment opportunities, with superior performance metrics, shorter payback periods, and higher returns on investment compared to residential installations. However, residential systems also demonstrated acceptable performance and economics, particularly in larger configurations with proper installation and maintenance practices. The significant seasonal performance variations observed, particularly during monsoon periods, require consideration in system design and sizing but do not fundamentally undermine system viability. Key success factors for optimal hybrid system performance include proper installation orientation and angle, regular cleaning and maintenance schedules, appropriate flow rate optimization, and professional system management. The strong correlation between system cleanliness and performance highlights opportunities for substantial energy yield improvements through simple maintenance interventions. Industrial installations benefited from dedicated maintenance personnel and professional management, suggesting that organized maintenance services could similarly enhance residential system performance. Economic analysis revealed that declining capital costs, improving efficiencies, and rising conventional energy prices have created favorable conditions for hybrid system adoption. Government policies supporting renewable energy deployment, including capital subsidies, tax incentives, and favorable net metering provisions, further enhance investment attractiveness. The combination of energy cost savings, environmental benefits, and energy security improvements presents compelling value propositions for both residential and industrial sectors. This research provides crucial empirical evidence supporting policy development and implementation planning for hybrid solar–thermal technology deployment in India. The findings suggest that targeted programs supporting industrial adoption, professional installation and maintenance services, consumer awareness and education, and innovative financing mechanisms could accelerate market development and contribute substantially to India's renewable energy objectives. Future research should focus on long-term performance monitoring, optimization of system designs for specific applications, development of advanced materials and components, and comprehensive assessment of grid integration implications as hybrid systems achieve significant market penetration. The successful deployment of hybrid solar–thermal systems represents an important pathway toward sustainable energy futures, simultaneously addressing energy access, environmental protection, and economic development objectives. This study demonstrates that the technology has progressed from research curiosity to practical solution ready for mainstream adoption.

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