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Hybrid Photovoltaic-Thermal (PVT) Energy Systems for Hotel Operations: A Review of Design Strategies and Implementation Challenges in Tanzania

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REVIEW ARTICLES

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Abstract: Tanzania's hospitality sector faces persistent challenges in providing reliable and affordable hot water because of rising electricity tariffs, grid instability, and reliance on fossil fuel backup systems. Given the country's high solar irradiance, hybrid photovoltaic (PV) and solar thermal (PV/T) systems are a promising option for increasing thermal energy reliability and reducing operational costs and environmental impacts. This review synthesizes global and regional studies on hybrid configurations that integrate photovoltaic electricity generation with solar thermal water heating technologies, focusing on their relevance to hotel operations in Tanzania. We describe system design approaches, control strategies, storage options, and reported operational outcomes, and we summarize performance ranges (notably reported solar fractions of roughly 60–80% in well-designed systems) and typical techno economic indicators. The evidence indicates that hybrid systems can substantially increase solar contribution to hot water loads and reduce grid dependence, but adoption in Tanzania is constrained by limited local performance data, a lack of standardized design practices, and insufficient techno economic evaluations tailored to local conditions. We conclude that hybrid PV/T systems show strong potential for commercial hot water use in Tanzania and recommend targeted field trials, standardized design guidelines, and context specific economic analyses to support wider deployment.

Keywords Hybrid solar PV; Solar fraction; Techno-economic performance; Solar water heating

1. Introduction

Reliable and affordable hot water supply is a critical operational requirement in Tanzania's hospitality sector, where guest comfort, hygiene standards, and service quality depend heavily on continuous access to heated water. However, hotels across the country face persistent challenges due to rising electricity tariffs, unstable grid supply, and high operating costs of diesel-based backup systems (Agoundedemba et al., 2023). These constraints not only increase operational expenditure but also undermine energy security and environmental sustainability. As Tanzania continues to experience rapid urbanization and tourism growth,

the need for resilient and cost-effective thermal energy solutions has become increasingly urgent (Phiri et al., 2025).

Tanzania's geographic location within the global solar belt provides a strong foundation for solar-based energy systems. Solar irradiance levels ranging from 4 to 7 kWh/m²/day make solar technologies particularly attractive for domestic hot water production (Raymond et al., 2022). While solar thermal systems are widely recognized for their efficiency in water heating, and PV systems for electricity generation, their combined use in hybrid configurations offer enhanced performance, higher solar utilization, and improved reliability. Hybrid solar PV and solar thermal energy systems integrate electrical and thermal components to maximize solar resource capture, reduce auxiliary energy consumption, and increase system resilience during periods of fluctuating solar availability (Ajay Kumar et al., 2026).

Despite exciting global progress in hybrid solar technologies, Tanzania is still exploring how best to embrace these innovations. Most studies focus on either PV or solar thermal systems alone, with fewer exploring combined hybrid solutions specifically designed for commercial hot water needs. There's also a gap in shared knowledge about different system setups, how well they work, and what to consider when implementing them in Tanzanian hotels. This review aims to fill that gap by bringing together current research on hybrid solar PV and thermal systems, examining their design, performance, and suitability for improving hot water supply in Tanzania's vibrant hospitality sector (Haji, 2019).

2. Review Methodology

To ensure a systematic, comprehensive, and reproducible synthesis of the existing literature, this review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines.

2.1 Literature Search Strategy and Database Selection

A comprehensive literature search was executed across five primary academic databases: Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar. The search targeted peer-reviewed journal articles and full-length conference proceedings, most of which were published between 2020 and 2026. The search strategy utilized combinations of Boolean operators (AND, OR) and keywords tailored to capture technology, application, and performance evaluation metrics:

$$\text{Search String} = (\text{"PV/T"} \vee \text{"PVT"} \vee \text{"hybrid PV thermal"}) \wedge (\text{"hotel"} \vee \text{"hospitality"} \vee \text{"commercial"}) \wedge (\text{"electricity savings"} \vee \text{"techno-economic"})$$

In addition to database searches, we reviewed reference lists of relevant articles and previous reviews (citation chasing) to identify additional studies for inclusion.

2.2 Eligibility Criteria

Studies were evaluated based on predefined inclusion and exclusion criteria to ensure relevance to commercial and institutional hot water systems:

(a) Inclusion Criteria

Studies were selected for inclusion if they focused on hybrid photovoltaic-thermal (PV/T) systems, solar thermal, or hybrid renewable configurations applied within hospitality or related service-sector operations, provided quantitative empirical or modeled performance data (such as energy savings, thermal efficiency, solar fraction, or payback period), and were published as peer-reviewed journal articles or official technical reports.

(a) Exclusion Criteria

Conversely, studies were excluded if they examined generic or unassisted grid systems without a renewable

integration component, focused exclusively on residential or non-hospitality contexts without transferable operational insights, lacked sufficient performance or techno-economic metrics, or consisted of non-peer-reviewed literature, editorials, and conference abstracts lacking primary data.

2.3 Selection Process and PRISMA Flow

The article selection process followed a two-stage screening approach:

(a) Title and Abstract Screening**:** Duplicate records were removed using reference management software. Titles and abstracts were screened to eliminate clearly out-of-scope records.

(b) Full-Text Assessment: Remaining articles underwent full-text review to evaluate compliance with the inclusion criteria.

A thorough search was conducted across Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar, resulting in 167 initial records. After removing 22 duplicates, we carefully screened the titles and abstracts of the remaining 145 articles, which led to the exclusion of 31 studies that didn't quite fit our main focus. We then reviewed the full text of the remaining 114 papers, and 23 of these were excluded because they were in non-hospitality settings, lacked operational data, or were not peer-reviewed. Ultimately, we included 91 studies in our review, ensuring a comprehensive and relevant selection.

Tanzania lies within the global solar belt, receiving an average solar irradiance of 4-7 kWh/m²/day, making it highly suitable for both PV and solar thermal applications. Regions such as Dodoma, Singida, and Manyara experience long sunshine hours and stable climatic conditions, creating an ideal environment for solar-based hot water systems (Bishoge et al., 2019). This abundant resource forms the foundation for integrating hybrid solar technologies into commercial buildings, particularly hotels with high, continuous hot-water demand (Fathi et al., 2026). The average solar irradiance levels across representative Tanzanian regions are summarized in Table 1, highlighting the country's favorable solar resource for hotel water-heating applications.

Table 1: Average Solar Irradiance in Tanzanian Regions and Implications for Hotel Energy Systems (Okika et al., 2025)

Region	Average Irradiance (kWh/m²/day)	Sunshine Hours (per year)	Notes
Dodoma	6.5	3,000	Stable, high solar potential
Singida	6.2	2,950	Consistent year-round insolation
Manyara	6.8	3,100	Strongest irradiance, ideal for hotels

3.2 Principles of Solar Photovoltaic (PV) Energy Conversion

Photovoltaic systems transform sunlight into electricity using semiconductor materials, primarily crystalline silicon. When sunlight hits a PV cell, it creates electron-hole pairs that generate direct current (DC) (Guerra et al., 2018). In hybrid setups, this electricity can power auxiliary devices such as heating elements, circulation pumps, or thermal controllers that oversee system operation (Mao et al., 2025). The efficiency of PV modules depends on factors such as solar irradiance, temperature, shading, and panel orientation (Richard et al., 2024). Since PV output varies with environmental conditions, hybrid systems often use surplus PV electricity for water heating, enhancing solar energy utilization and decreasing reliance on grid power (Maggu et al., 2025).

3.3 Principles of Solar Thermal Water Heating

Solar thermal systems harness solar radiation and convert it into heat using collectors such as flat-plate or evacuated-tube types (Kalair et al., 2022). The absorbed heat warms water or a heat-transfer fluid, which is then stored in insulated tanks for future use (Haj Zaidan et al., 2018). The system's efficiency relies on factors such as collector performance, heat loss, storage size, inlet water temperature, and daily hot water needs. These systems are especially effective for water heating, often reaching thermal efficiencies of 40% to 70%,

far surpassing the electrical efficiency of PV panels (Singh et al., 2025). Their capacity to produce large quantities of hot water makes them ideal for commercial settings like hotels, where demand is high and consistent (Fadzlin et al., 2022).

3.4 Hybrid Solar PV and Solar Thermal Energy Systems

Hybrid systems combine PV and solar thermal technologies, working together to make the most of solar energy. There are two main ways to set them up:

(a) PV-Assisted Solar Thermal Systems

PV electricity powers an electric heating element or heat pump inside the storage tank. The solar thermal collector remains the primary heat source, while PV provides auxiliary heating when thermal energy is insufficient (Namdar et al., 2025). Figure 1 illustrates the architecture of a PV-assisted solar thermal system in which the solar thermal collector provides the primary source of heat, while electricity generated by the PV array powers the auxiliary heating element whenever the available solar thermal energy is insufficient.

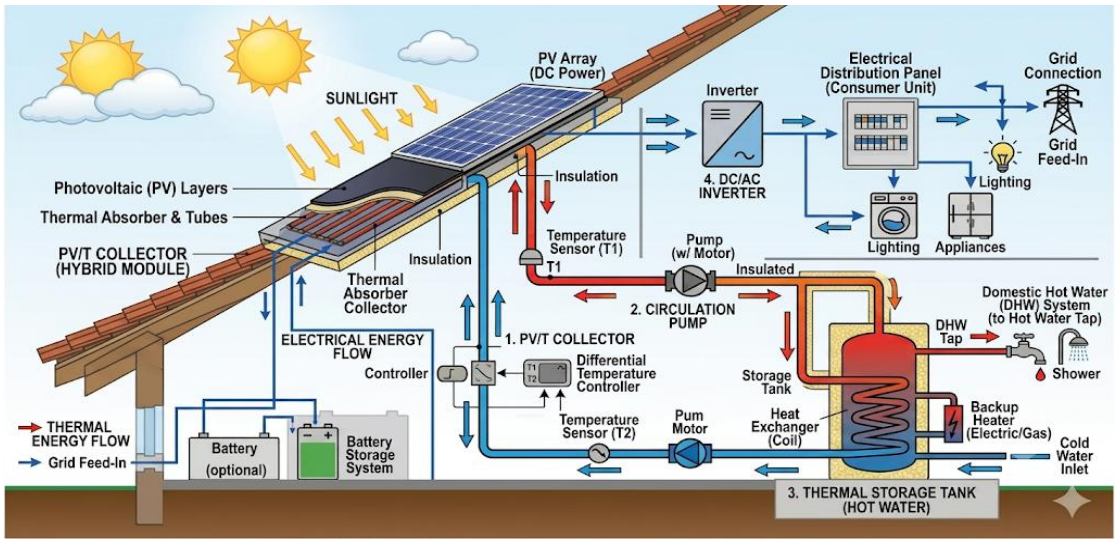

Figure 1: Schematic of PV-assisted solar thermal system (Herrando et al., 2023)

PV/T integrates electrical and thermal energy production by combining photovoltaic layers with a thermal absorber in a single hybrid module. Sunlight generates DC electricity while the thermal absorber captures excess heat, which is transferred via a circulation pump to a storage tank for domestic hot water (Namdar et al., 2025). This integration is managed by a differential temperature controller that uses sensors (T1 and T2) to optimize heat exchange, while an inverter converts the electrical output for household use, battery storage, or grid feed-in. By cooling the PV cells with thermal fluid, the system simultaneously improves electrical efficiency and provides sustainable heating within a compact footprint (Elias Ahmed et al., 2024).

(b) Photovoltaic-Thermal (PV/T) Collectors

PV/T collectors combine PV cells and thermal absorbers into one unit. They generate electricity and capture heat simultaneously, increasing overall system efficiency. Cooling the PV cells with circulating fluid boosts electrical output while also producing usable thermal energy (Herez et al., 2020). Figure 2 presents the operating principle of a photovoltaic-thermal (PV/T) collector, demonstrating how a single collector simultaneously generates electricity and captures thermal energy to improve overall solar energy utilization.

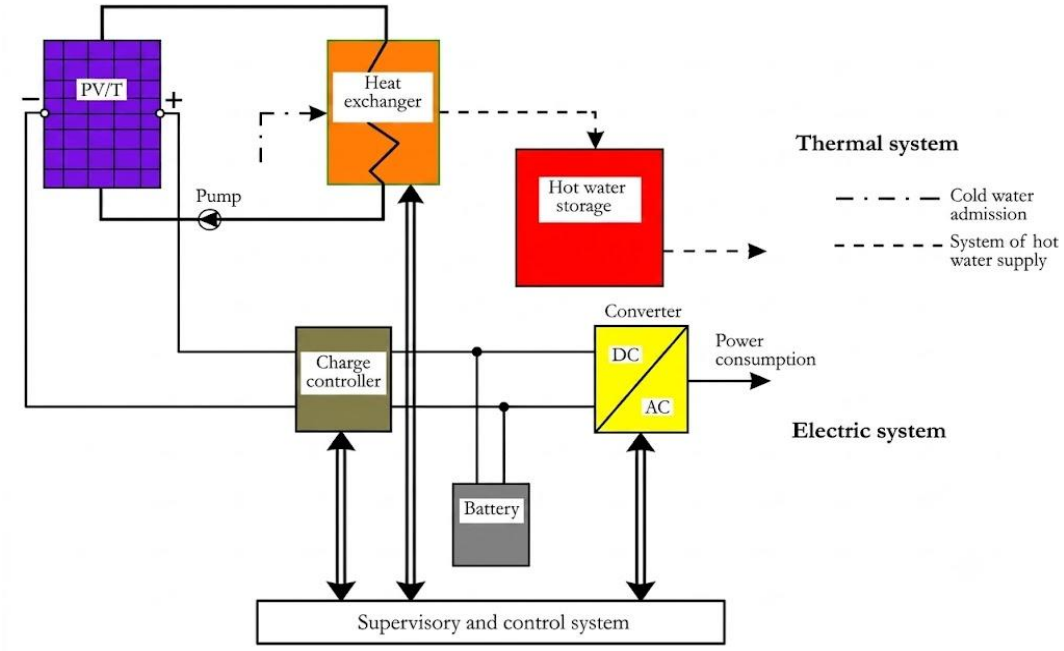

Figure 2: Diagram of PV/T collector showing electricity and heat generation (Herrando et al., 2023)

The PV/T collector serves a dual purpose: its solar cells generate DC electricity, while a cooling fluid circulates behind them to capture excess heat, thereby helping the cells operate more efficiently (Talal et al., 2024). On the electric side, the power flows through a charge controller to be stored in a battery or transformed by a converter into AC power for household use (Brottier & Bennacer, 2020). Simultaneously, on the thermal side, a pump moves the heated fluid through a heat exchanger, warming the water in a storage tank for domestic supply (Li et al., 2024). A supervisory and control system monitors the entire operation, balancing the electrical loads and the water temperature to ensure maximum energy efficiency from both sources (Van Oevelen et al., 2023).

3.5 Control Strategies and System Optimization

Hybrid solar systems rely on intelligent thermal controllers to manage energy flow and ensure stable operation (Handam, 2025). These controllers monitor tank temperature, PV output, collector performance, and hot water demand patterns, enabling them to activate auxiliary heating when necessary and prevent overheating or energy wastage (Znaczko et al., 2025). Effective control strategies improve system responsiveness during peak demand periods and enhance overall reliability. Optimization typically involves selecting appropriate PV array sizes, collector areas, and storage volumes to match daily hot water requirements (Khan et al., 2025). Simulation tools such as TRNSYS, HOMER, and MATLAB/Simulink are commonly used to evaluate system performance under varying climatic and operational conditions, helping designers tailor hybrid systems to specific environments (Alsadi & Khatib, 2018).

3.6 Relevance to Tanzania's Hospitality Sector

The hospitality industry in Tanzania consistently experiences high demand for hot water in guest rooms, kitchens, and laundry services (Sampaio et al., 2024). However, hotels often face challenges such as rising electricity tariffs, unreliable grid supply, and the high operating costs associated with diesel backup systems ("Towards Sustainable Hospitality: Enhancing Energy Efficiency in Hotels," 2024). Hybrid solar PV and solar thermal systems offer a practical solution by improving energy autonomy, reducing electricity consumption, and lowering greenhouse gas emissions (Kundzina et al., 2026). Tanzania's strong solar resource further enhances the feasibility of these systems. Despite their potential, adoption remains limited due to a lack of standardized design guidelines, insufficient local performance data, and minimal

techno-economic assessments tailored to Tanzanian conditions (Lyanda & Mwakitalima, 2025). Addressing these gaps is essential for enabling widespread deployment of hybrid solar technologies in the country's hospitality sector.

4. Review of System Designs

Hybrid solar PV and solar thermal energy systems have been developed in various configurations, each designed to maximize the use of solar resources while providing a reliable hot water supply. Although the fundamental principles are consistent across regions, system designs vary with climate, load profiles, available technologies, and economic factors (Chow, 2010). This section reviews the main design approaches relevant to Tanzania's hotel sector, focusing on system architecture, component integration, and operational strategies.

4.1 PV-Assisted Solar Thermal Systems

One of the most common hybrid setups involves combining a traditional solar thermal collector with a PV-powered auxiliary heating element. In this configuration, the solar thermal collector serves as the primary heat source, while PV-generated electricity drives an immersion heater or heat pump when solar heat alone is insufficient (Iyankumar et al., 2025). This method works well for hotels with predictable morning and evening peaks in hot water demand. The system's effectiveness relies on properly sizing the collector area, storage tank volume, and PV array capacity. A thermal controller manages the switch between solar thermal input and PV-assisted auxiliary heating, ensuring consistent water temperatures throughout the day.

4.2 PV/T (Photovoltaic–Thermal) Collector Systems

PV/T collectors combine PV cells and thermal absorbers into a single unit, enabling the simultaneous generation of electricity and heat (Hosouli et al., 2025). By cooling the PV cells with circulating water or heat-transfer fluid, PV/T systems boost electrical efficiency while capturing useful thermal energy. These systems provide higher overall solar utilization compared to separate PV or thermal collectors. However, PV/T technologies are less common in Tanzania due to higher initial costs, limited local availability, and the need for specialized installation expertise. Their compact design makes them appealing for hotels with limited roof space (Odoi-Yorke, 2025).

4.3 Direct PV-to-Heating Element Systems

Some hybrid systems completely skip solar thermal collectors and rely on PV electricity to power high-efficiency heating elements (Milón Guzmán et al., 2025). Although this setup is simpler and easier to install, it is generally less efficient than systems that include thermal collectors. However, in areas with high solar irradiance and rising electricity prices, PV-direct heating can still significantly reduce grid consumption. This arrangement is often used as a retrofit for hotels that already have electric boilers but want to lower operational costs without replacing their existing infrastructure (Al-Zoubi et al., 2021).

4.4 Hybrid Systems with Smart Thermal Controllers

Modern hybrid systems increasingly incorporate intelligent thermal controllers that optimize energy flow in response to real-time conditions (Madunagu et al., 2026). Table 2 compares the major hybrid solar system configurations, their primary heat sources, auxiliary components, and operational advantages for hotel applications.

These controllers monitor tank temperature, PV output, collector performance, and hot water demand patterns (Meraj et al., 2023). They can focus on solar thermal input, turn on PV-powered auxiliary heating when necessary, and reduce their dependence on grid electricity, making their energy use more efficient and eco-friendlier.. Advanced controllers also prevent overheating, reduce standby losses, and improve system responsiveness during peak demand periods (Haller & Heinz, 2024). For hotels in Tanzania, where grid instability is common, smart controllers significantly enhance reliability and energy autonomy

(Chandrasekaran et al., 2025). As illustrated in Figure 3, smart thermal controllers continuously monitor collector temperature, storage tank conditions, PV power generation, and hot water demand to optimize energy flow between the electrical and thermal subsystems.

Table 2: Hybrid Solar System Types, Heat Sources, and Advantages for Hotel Operations(Herrando & Ramos, 2022).

System Type	Primary Heat Source	Auxiliary Support	Key Advantage
PV-Assisted Thermal	Solar collector	PV-powered heater	Reliable peak demand coverage
PV/T Collector	PV, absorber	Integrated unit	Higher overall efficiency
Direct PV Heating	PV, electricity	Heating element	Simple retrofit option
Smart Controller Hybrid	Solar, PV	Intelligent control	Optimized energy flow

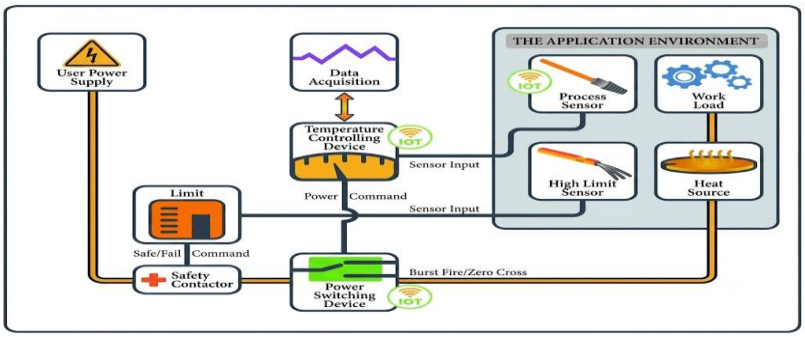

Figure 3: Energy Flow Pathways Managed by Smart Thermal Controllers in Hybrid PV/T Systems (Ullah & Kim, 2017)

4.5 Storage Tank Configurations

Storage design is crucial for the performance and reliability of hybrid solar water-heating systems (Sun et al., 2026). Hotels typically need large, well-insulated tanks to handle peak hot-water demand in the morning and evening. Often, a single-tank system is used in which solar thermal input and PV-assisted auxiliary heating share the same tank (Gaonwe et al., 2026). This simplifies the setup but requires careful control to maintain stable temperatures. In larger hotels, dual-tank systems are common. These systems preheat water with solar collectors into a primary tank, then use a secondary tank with PV-powered auxiliary heating, offering better flexibility and temperature control. Some advanced setups feature stratified tanks that keep different temperature layers separate, reducing mixing losses and increasing efficiency (Han et al., 2009).

The selection of storage type depends on space, demand patterns, solar contribution goals, and the complexity level hotel operators are prepared to manage (Tarragona et al., 2022). The main storage tank configurations commonly adopted in hybrid solar water-heating systems are summarized in Table 3, together with their operational characteristics.

Table 3: Storage Tank Options for Hotels

System Type	Primary Heat Source	Auxiliary Support	Key Advantage
PV-Assisted Thermal	Solar collector	PV-powered heater	Reliable peak demand coverage
PV/T Collector	PV, absorber	Integrated unit	Higher overall efficiency
Direct PV Heating	PV, electricity	Heating element	Simple retrofit option
Smart Controller Hybrid	Solar, PV	Intelligent control	Optimized energy flow

Figure 4 illustrates the temperature stratification within a thermal storage tank. Maintaining distinct temperature layers improves heat storage efficiency and enables the delivery of higher-temperature water during periods of peak demand.

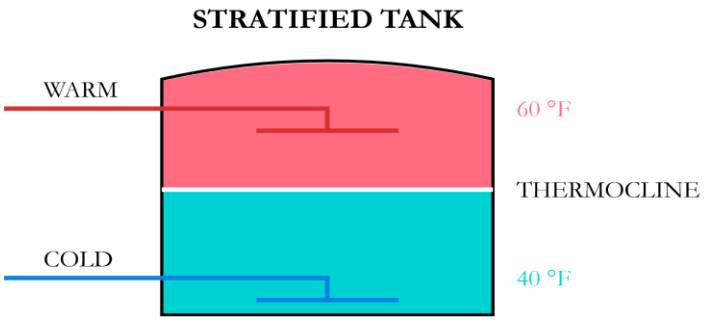

Figure 4: Stratified storage tank diagram showing temperature layers (Barrak et al., 2024)

4.6 System Design Considerations for Tanzanian Hotels

Designing effective hybrid solar systems for Tanzanian hotels requires careful consideration of the country's unique energy challenges and operational conditions (Mwasenga & KamolekaMlela, 2024). Hotels in Tanzania experience consistently high demand for hot water, driven by guest rooms, kitchens, and laundry services, making them ideal candidates for hybrid solar technologies. The country's strong solar resources support high system performance, but rising electricity tariffs and frequent grid instability make reliability and cost savings equally important design priorities (Okika & Musonda, 2026). Hybrid systems that combine solar thermal collectors with PV-assisted auxiliary heating offer a balanced solution by maximizing solar utilization while ensuring a stable hot water supply during cloudy periods or peak demand (Naveenkumar et al., 2025). However, successful implementation depends on proper system sizing, intelligent control strategies, and adequate storage capacity. Limited technical expertise, lack of standardized design guidelines, and minimal local performance data remain barriers to widespread adoption (Efosa Brown Amayo et al., 2025). Addressing these challenges through training, quality assurance, and context-specific design tools will be essential for enabling hotels to fully benefit from hybrid solar technologies (Gaber et al., 2025). Systems that combine solar thermal collectors with PV-assisted auxiliary heating provide the best balance of performance, affordability, and reliability. Proper sizing, smart control, and sufficient storage are crucial for achieving high solar fractions and decreasing dependence on grid electricity or diesel generators (Rosales-Pérez et al., 2023).

5. Performance Outcomes

Hybrid solar PV and solar thermal energy systems have demonstrated strong technical and operational performance across diverse climate zones, particularly in applications with high, steady hot water demand, such as hotels, hospitals, and hostels. This section reviews key performance results reported in the literature, focusing on solar fraction, energy savings, reliability, and system efficiency metrics that are directly relevant to Tanzania's hospitality industry.

Hybrid solar PV and solar thermal energy systems have demonstrated strong technical and operational performance across diverse climate zones, particularly in applications with high, steady hot water demand, such as hotels, hospitals, and hostels (Samykano, 2023). This section reviews key performance results reported in the literature, focusing on solar fraction, energy savings, reliability, and system efficiency metrics that are directly relevant to Tanzania's hospitality industry.

5.1 Solar Fraction and Thermal Contribution

One of the most common indicators of system performance is the solar fraction, which shows the part of the total hot water energy demand supplied by solar energy (Xu et al., 2026). Reported solar fractions from representative case studies are summarized in Table 4, illustrating the performance achieved under different climatic and system conditions.

Table 4: Reported Solar Fractions in Case Studies

Location	System Type	Solar Fraction (%)
Southeast Asia	PV-Assisted	75
East Africa	PV/T	80
Spain	Hybrid mix	65

Studies consistently report solar fractions ranging from 60% to over 80% for well-designed hybrid systems (de Freitas Moscardini Júnior & Rüther, 2020). Systems that combine solar thermal collectors with PV-powered auxiliary heating reach higher solar fractions than standalone solar thermal systems, especially during times of fluctuating sunlight (Kazemian et al., 2023). This improved contribution is especially helpful in regions like Dodoma, where abundant sunlight supports strong year-round performance (Rahaman & Iqbal, 2019).

5.2 Reduction in Grid Electricity Consumption

Hybrid systems greatly reduce reliance on grid electricity by shifting much of the water-heating load to solar energy (Nwagu et al., 2025). PV-assisted auxiliary heating is particularly effective in reducing electric booster use, which typically accounts for the largest share of a hotel's energy expenses(Emadur et al., n.d.). International case studies demonstrate reductions in grid electricity consumption of 30-60%, depending on system size, storage capacity, and usage patterns (Koko, 2022). For Tanzanian hotels facing escalating tariffs and supply instability, these reductions lead to significant operational savings and enhanced energy security (Wu et al., 2022). The comparison presented in Figure 5 shows the percentage reduction in grid electricity consumption achieved by different hybrid renewable energy configurations. The results indicate that integrating battery storage with PV systems substantially increases grid electricity savings.

Grid-connected renewable systems vary in efficiency, with Grid/PV setups providing a baseline of approximately 55% savings by offsetting daytime peak loads, while Grid/Wind typically offers around 40% due to the higher variability of wind speeds compared to predictable solar cycles (Bakić et al., 2016). The addition of Battery Energy Storage Systems (BESS) significantly increases these savings by capturing excess generation for use during non-productive hours, enabling a Grid/PV/Battery configuration to achieve nearly 80% grid independence (Rana et al., 2026). The most robust performance comes from Grid/PV/Wind/Battery configurations, which can achieve savings exceeding 90% by leveraging the complementary nature of solar and wind resources, alongside storage, to maintain a stable, high Renewable Energy Fraction (REF) (Anyanwu et al., 2025).

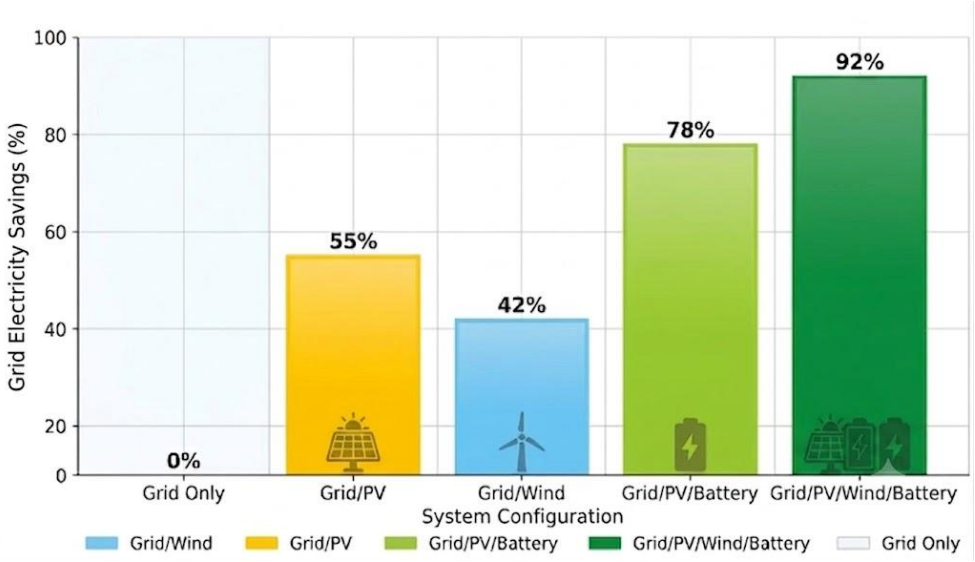

Figure 5: Grid Electricity Savings (%) Across Hybrid Configurations in Hotels(Serat et al., 2024)(Schleifer et al., 2023)

5.3 Improved System Efficiency

By combining PV and thermal components, hybrid systems achieve greater overall solar utilization than standalone technologies (Efzan et al., 2026). PV/T collectors, in particular, achieve combined electrical and thermal efficiencies exceeding 60%, although their adoption remains limited due to cost and availability. Even with simpler PV-assisted systems, using excess PV electricity for water heating enhances the effective efficiency of the PV array and reduces curtailment losses (Clift & Suehrcke, 2021). As shown in Figure 6, PV/T systems achieve higher overall energy utilization than standalone photovoltaic or solar thermal systems because they simultaneously generate electricity and recover useful thermal energy.

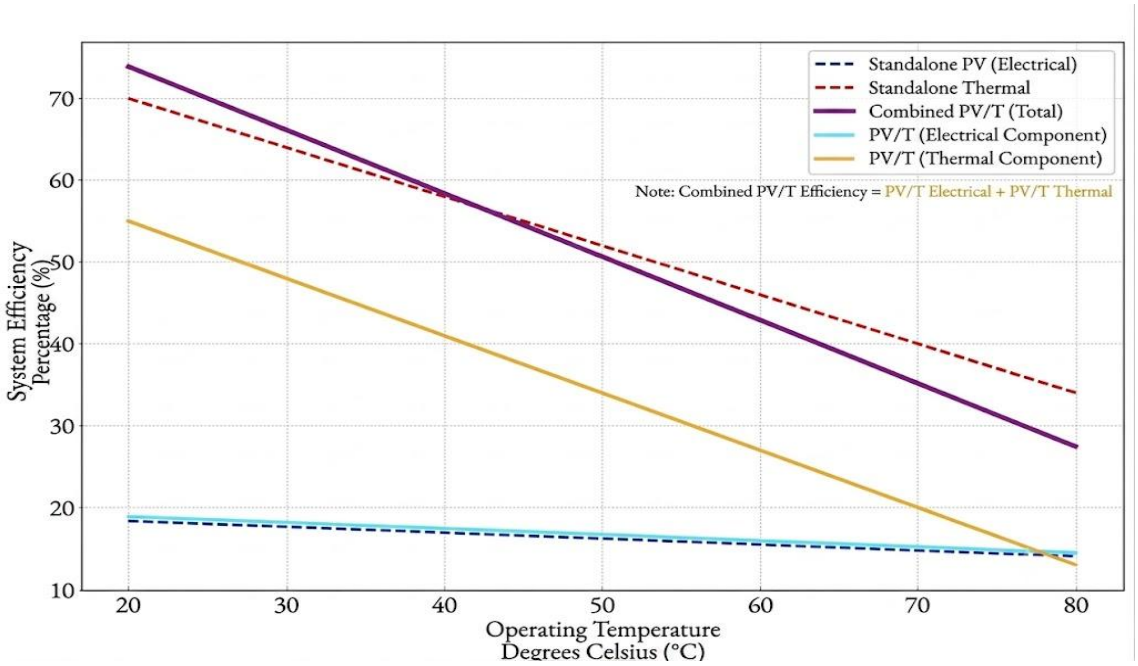

Figure 6: Graph of combined PV/T efficiency vs. standalone PV or thermal systems

5.4 Enhanced Hot Water Reliability

Reliability is a critical performance outcome for hotels, where interruptions in hot water supply directly affect guest satisfaction (Au-Yong et al., 2024). Hybrid systems improve reliability by providing multiple energy pathways: solar thermal as the primary source, PV-powered auxiliary heating as the secondary source, and grid electricity only as a last resort. Thermal controllers maintain stable water temperatures by activating auxiliary heating when needed, reducing the risk of temperature drops during peak-demand periods or cloudy conditions (Misrol et al., 2022).

5.5 Economic Performance

Techno-economic analyses consistently demonstrate that hybrid systems provide favorable lifecycle economics, especially in regions with high solar irradiance and increasing electricity prices. Payback periods usually span from 3 to 7 years, depending on system setup, local tariffs, and financing terms (Thango & Obokoh, 2024)(Karda et al., 2023). The techno-economic indicators reported in previous studies are summarized in Table 5, including payback period, electricity savings, and carbon emission reductions.

Table 5: Economic Indicators of Hybrid Systems

Indicator	Range Reported	Notes
Payback Period	3–7 years	Depends on tariffs
CO_2 Reduction	20–50%	Annual savings
Electricity Savings	30–60%	Hotel case studies

Although initial costs are higher than those of traditional electric heaters, long-term savings from lower electricity use and reduced maintenance make hybrid systems economically beneficial for commercial applications (Rupar-Gadd et al., 2025).

5.6 Environmental Benefits

Hybrid systems significantly reduce greenhouse gas emissions by replacing electricity generated from fossil fuels. Studies show annual CO_2 reductions of 20-50% for hotels using hybrid solar water heating systems (Anvari et al., 2025). These environmental advantages support Tanzania's national goals for expanding renewable energy and fighting climate change.

6. Discussion

The review of hybrid solar PV and solar thermal energy systems demonstrates that these technologies offer significant potential to improve hot water reliability and reduce energy costs in Tanzania's hospitality sector. However, the extent to which these benefits can be realized depends on several contextual, technical, and economic factors (Bdour et al., 2023). This section interprets the performance outcomes in relation to Tanzania's energy landscape and identifies key considerations for effective system deployment.

Table 6 provides a friendly overview of the main hybrid system types, highlighting their combined efficiency, capital costs, roof-space requirements, ease of maintenance, and suitability for different hotel sizes. It brings together key details such as solar fractions, payback periods, and practical insights from the studies we've reviewed, making it easier to understand the key points.

The table shows that PV/T collectors achieve the highest combined efficiency, though they entail higher initial costs and greater technical challenges. PV-assisted systems present a practical, balanced choice for many hotels. Meanwhile, direct PV heating stands out as the simplest retrofit option, though it typically requires a larger PV area to meet thermal demand.

A central finding is that hybrid systems consistently achieve higher solar fractions and greater overall efficiency compared to standalone PV or solar thermal systems (Gyatso et al., 2023). This is particularly relevant for Tanzania, where hotels face high electricity tariffs and frequent grid instability (Okechi Ifeanyi-nze & Erungworo Okayim, 2022). By combining thermal collectors with PV-powered auxiliary heating, hybrid systems reduce dependence on grid electricity and diesel generators, thereby enhancing energy autonomy. The ability of PV to support auxiliary heating during periods of low thermal output also addresses one of the main limitations of conventional solar water heaters: variability in solar availability

Table 6: Comparison of hybrid solar system types for hotel hot-water applications(Mostakim & Hasanuzzaman, 2022)

System Type	Combined Efficiency/Solar Utilization	Typical Capital Cost Range	Roof-space Requirement	Maintenance& Technical Complexity
PV-Assisted Thermal	Solar fraction 60-80%; moderate combined utilization	Low-Moderate	Moderate; thermal collectors and PV array	Low-Moderate; familiar thermal tech; simple electrical integration
PV/T(Integrated PV/T collectors)	Combined electrical and thermal >50–60% reported; highest utilization	High	Low–Moderate; compact integrated panels	High, specialized installation; fluid loops and commissioning
Direct PV-to-Heating Element	Lower thermal efficiency; high PV utilization when direct-coupled	Low	Moderate–High; larger PV area if no thermal collectors	Low; simple electrical retrofit; minimal plumbing changes
Smart-Controller Hybrid(any base architecture)	Improves effective solar utilization; increases reliability	Adds modest cost to the base system	No extra roof area beyond the base system	Moderate; requires sensors, controllers, and commissioning

Despite these benefits, adoption in Tanzania remains limited. A key barrier is the lack of standardized design guidelines tailored to local climate conditions and hotel demand profiles (Cruz Davila et al., 2025). Many installations depend on generic sizing rules that might not maximize performance (Chen, 2012). Additionally, the higher upfront cost of hybrid systems can discourage investment, especially for small and medium-sized

hotels with limited capital (Terkes et al., 2025). While lifecycle savings are significant, the lack of financing options and incentives slows market adoption (Kumar et al., 2025).

Technical capacity poses another challenge; hybrid systems need proper installation, smart control strategies, and regular maintenance to perform at their best (Marinho et al., 2025). Limited local expertise in PV/T technologies and advanced thermal controllers can lead to poor system operation or early failures (Sepúlveda-Oviedo, 2025). Improving local technical training and creating quality assurance standards would help close these gaps (Aguilar-Jiménez et al., 2024).

From a policy perspective, hybrid solar systems align well with Tanzania's renewable energy goals and its efforts to reduce reliance on fossil fuels (Liu et al., 2023). However, current policies do not specifically encourage hybrid setups, and there are no targeted incentives for commercial solar water heating. Implementing supportive measures like tax exemptions, low-interest loans, or performance-based rebates could boost adoption in the hospitality sector (Lyu et al., 2022).

Overall, the discussion highlights that hybrid solar PV and solar thermal systems are technically viable and economically attractive for Tanzanian hotels, but their successful deployment requires context-specific design, supportive policies, and strengthened technical capacity. Addressing these factors will be essential for unlocking the full potential of hybrid solar technologies in the country's commercial hot water market (Herez et al., 2025).

7. Conclusion

Hybrid solar systems that combine PV panels and solar water heaters can help hotels in Tanzania get more reliable hot water and cut electricity use. To move forward, we recommend running field trials in different hotel types for 12–24 months, collecting and sharing the performance data in an open database, and building local cost models that use Tanzanian electricity prices and financing options. These steps will show how the systems perform in real conditions and give hotel owners clear numbers on savings and payback.

For designers and installers, aim for a 60–80% solar contribution and size storage at 50–80 L per guest per day (or about 1.5–2× the hotel's daily hot-water energy need) as a starting point. Use controllers that prioritize PV power, include periodic high-temperature cycles to prevent bacteria, and support remote monitoring and fault alerts. Require proper commissioning (hydraulic balancing and sensor checks) and a 6-month performance acceptance period tied to warranty conditions.

Policymakers and industry should support these efforts with targeted incentives (tax relief or low-interest loans tied to verified performance), national design and monitoring guidelines, and technician training programs focused on PV/T hydraulics, controls, and maintenance. Together, this research, technical, and policy actions will build the evidence, skills, and confidence needed to scale hybrid solar hot-water systems across Tanzania's hotels.

Declaration of Ethical Standards

As the authors of this study, we declare that we comply with all ethical standards.

Credit Authorship Contribution Statement

D. W. Kafumu: Conducted the literature search, reviewed and synthesized relevant studies, drafted the initial manuscript, and prepared figures and tables.

I. J. Mwakitalima: Provided conceptual guidance, contributed to structuring the review, critically revised the manuscript for intellectual content and ensured alignment with academic standards.

M.K. Mlela: Oversaw methodological rigor, offered technical and theoretical insights, reviewed drafts, and refined the final version for clarity and accuracy.

Declaration of Competing Interest

The authors declared no conflicts of interest.

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The authors declare that generative AI was used only for language editing and not for scientific content generation.

Data Availability

No datasets were generated or analyzed during the current study.

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