



REVIEW ARTICLE

RECENT ADVANCES IN SOLAR STEAM GENERATORS: PHOTOTHERMAL MATERIALS, STRUCTURAL ARCHITECTURES, AND ENERGY CONVERSION APPLICATIONS

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ABSTRACT

Solar steam generation has emerged as a highly efficient and sustainable technology for water purification, desalination, and decentralized energy applications, particularly in off-grid and resource-constrained regions. Unlike conventional solar thermal systems that rely on bulk water heating, solar steam generators utilize localized interfacial heating to achieve high solar-to-vapour conversion efficiencies under low solar concentration. This review presented an analysis of recent advances in solar steam generation technologies, focusing on photothermal materials, structural design strategies, performance characteristics, and system integration pathways. Carbon-based materials, plasmonic nanoparticles, semiconductor oxides, and biomass-derived absorbers were examined in terms of optical absorption, thermal management, cost, and scalability. The methodology employed was systematic analytical literature review, drawing on peer-reviewed articles, conference proceedings, and review papers indexed in Scopus, Web of Science and Google Scholar, published between 2010 and 2025. Key findings revealed that carbon-based and biomass-derived photothermal materials can achieve solar-to-vapour conversion efficiencies of 80–93% under one-sun illumination, while interfacial floating and three-dimensional structural designs offer superior salt rejection and heat localization compared to conventional bulk-heating configurations. Integration of solar steam generators with thermoelectric generators and organic Rankine cycle systems was shown to be feasible for off-grid electrification, though long-term durability and techno-economic viability under field conditions remain critical outstanding challenges.

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1.0 Introduction

Solar steam generators represent a promising technology for sustainable energy conversion, particularly relevant for off-grid electricity generation in rural areas. Solar steam generators transform concentrated solar radiation into useable steam for mechanical power conversion (turbine/engine) or for process heat (Harzaz *et al.*, 2024). Solar steam generation is a photothermal conversion process that directly transforms solar radiation into thermal energy for water evaporation without bulk heating of the entire water volume. Unlike conventional solar thermal systems that heat large water bodies, localized solar steam generation concentrates heat at the air-water interface, significantly improving energy conversion efficiency (Gao *et al.*, 2019). The process involves three critical steps: solar absorption, photothermal conversion, and steam generation at the evaporation surface.

The theoretical foundation of solar steam generation rests on the energy balance equation at the evaporation interface. The incident solar energy is partitioned among multiple pathways: absorption by the photothermal material, heat losses through conduction to bulk water, convection and radiation to the ambient environment,

and the latent heat required for phase change from liquid to vapour (Zhao *et al.*, 2020). The solar-to-vapour conversion efficiency ( $\eta$ ) is typically expressed as:

$$\eta = \frac{\dot{m}h_{lv}}{C_{opt}P_0A} \quad 1$$

where  $\dot{m}$  is the mass flow rate of evaporated water,  $h_{lv}$  is the latent heat of vaporization,  $C_{opt}$  is the optical concentration factor,  $P_0$  is the incident solar power density, and  $A$  is the illuminated area (Chen *et al.*, 2017). The complete energy balance at the evaporation interface is expressed as:

$$Q_{solar} = Q_{evap} + Q_{cond} + Q_{conv} + Q_{rad} \quad 2$$

where  $Q_{solar}$  is the absorbed solar energy flux (W/m<sup>2</sup>),  $Q_{evap}$  is the latent heat flux for evaporation,  $Q_{cond}$  is the conductive loss to bulk water,  $Q_{conv}$  is the convective heat loss to ambient air, and  $Q_{rad}$  is the radiative heat loss to the surroundings. The optical efficiency ( $\eta_{opt}$ ) of the photothermal absorber quantifies the fraction of incident solar irradiance converted to useful heat and is defined as:

$$\eta_{opt} = \alpha - \frac{\varepsilon\sigma(T_s^4 - T_{amb}^4)}{G} - \frac{h_c(T_s - T_{amb})}{G} \quad 3$$

where  $\alpha$  is the solar absorptance of the photothermal material (typically >0.90 for high-performance absorbers),  $\varepsilon$  is the thermal emittance,  $\sigma$  is the Stefan–Boltzmann constant ( $5.67 \times 10^{-8}$  W/m<sup>2</sup>K<sup>4</sup>),  $T_s$  is the absorber surface temperature,  $T_{amb}$  is the ambient temperature,  $G$  is the incident solar irradiance, and  $h_c$  is the convective heat transfer coefficient (W/m<sup>2</sup>K). The radiation loss coefficient ( $U_{rad}$ ) characterises net longwave emission from the hot absorber surface and is given by:

$$U_{rad} = \varepsilon\sigma(T_s^2 + T_{sky}^2)(T_s + T_{sky}) \quad 4$$

where  $T_{sky}$  is the effective sky temperature. The convective loss coefficient ( $h_c$ ) is strongly influenced by wind speed and surface geometry; for free convection it is typically 2–10 W/m<sup>2</sup>K, while forced convection under field wind speeds of 1–5 m/s can raise  $h_c$  to 15–30 W/m<sup>2</sup>K, substantially reducing net evaporation efficiency (Zhao *et al.*, 2020; Gao *et al.*, 2019; Harzaz *et al.*, 2024). These loss mechanisms underscore the importance of designing low emittance photothermal surfaces and enclosing or windbreaking the evaporation system in outdoor deployments

Advances have demonstrated solar steam generation efficiencies exceeding 90% under one-sun illumination (1 kW/m<sup>2</sup>), representing a significant improvement over earlier systems that required concentrated solar flux (Xu *et al.*, 2018). More recent studies have further pushed these boundaries: multiscale biomimetic evaporators based on composite fibre structures have achieved efficiencies of 94–96% under one-sun conditions (Sun *et al.*, 2025), while bilayer Janus membrane absorbers have sustained evaporation rates exceeding 2.0 kg/m<sup>2</sup>/h in saline environments over 30-day continuous operation trials (Kim *et al.*, 2024). Advanced three-dimensional cone and origami architectures have demonstrated 15–25% higher evaporation rates than planar designs by exploiting omnidirectional light trapping (Liu *et al.*, 2023). Integration of photothermal materials with thermoelectric generators has enabled simultaneous electricity generation at densities of 0.8–1.5 W/m<sup>2</sup> alongside water purification, opening pathways for multi-functional off-grid systems (Harzaz *et al.*, 2024). These recent advances collectively indicate a technology rapidly approaching the performance thresholds required for practical rural deployment, though durability and scale-up remain outstanding challenges. This breakthrough has been achieved through interfacial heating strategies that minimize heat losses to the bulk water while maximizing solar absorption at the evaporation surface. The aim of this review is to examine recent advances in solar steam generation technologies with particular emphasis on photothermal materials, structural design strategies, and performance optimization under real-world environmental conditions.

Notwithstanding the growing body of literature, several important gaps remain that this review specifically seeks to address. First, the majority of existing reviews focus on laboratory-scale performance of individual photothermal materials without systematically comparing structural design architectures and their suitability for field deployment, particularly in tropical and arid environments such as sub-Saharan Africa (Kim *et al.*, 2024; Harzaz *et al.*, 2024). Second, biomass-derived photothermal materials which offer the most practical pathway to low-cost solar steam generation in rural and resource-constrained settings have received comparatively limited dedicated treatment in systematic reviews, often being discussed only as a subcategory within broader material surveys. Third, the integration of solar steam generation with electricity-generating thermodynamic cycles (thermoelectric and ORC systems) for combined water-energy provision has not been critically synthesised with explicit consideration of the technical and economic constraints applicable to small rural

communities. This review addresses these gaps by providing a structured, critical synthesis that simultaneously covers material advances, structural design trade-offs, operational performance under real environmental conditions, and system integration pathways, with explicit attention to applicability in rural and off-grid contexts.

## 2. Method

This review adopted an analytical literature-based methodology to evaluate recent developments in solar steam generation technologies. Peer-reviewed journal articles, conference proceedings, and authoritative review papers published primarily between 2010 and 2025 were surveyed using major scientific databases, including Scopus, Web of Science, and Google Scholar. Keywords such as solar steam generation, interfacial evaporation, photothermal materials, solar desalination, and solar-driven electricity generation were used to identify relevant studies. Inclusion criteria comprised: (i) peer-reviewed journal articles, conference papers, and authoritative review articles written in English; (ii) studies published between 2010 and 2025; (iii) works reporting original experimental, computational, or review data on solar steam generation, photothermal materials, interfacial evaporation, solar desalination, or solar-driven electricity generation; and (iv) studies providing quantitative performance metrics such as evaporation rate, solar-to-vapour efficiency, or system output power. Exclusion criteria comprised: (i) grey literature, theses, and non-peer-reviewed reports unless they contained primary data not available in peer-reviewed outlets; (ii) studies focused exclusively on large-scale concentrating solar power plants without relevance to low-concentration or interfacial steam generation; (iii) articles with insufficient methodological detail to permit critical appraisal; and (iv) duplicate publications reporting the same dataset. The selected literature was screened based on relevance to material design, structural configuration, performance evaluation, environmental operation, and system integration for water purification and energy generation. Studies were categorized into thematic sections covering photothermal materials, structural design strategies, performance optimization, water quality considerations, and integration with electricity generation systems. The review synthesizes trends, compares design trade-offs, and identifies research gaps to guide future development and deployment of solar steam generators.

## 3. Results and Discussion

### 3.1 Material Design and Innovations

The performance of solar steam generators critically depends on the properties of photothermal materials employed at the evaporation interface. Ideal materials exhibited broadband solar absorption (>90% across the solar spectrum), low thermal conductivity to minimize heat dissipation, appropriate wettability for continuous water supply, and structural stability under prolonged solar exposure (Li *et al.*, 2019).

#### 3.1.1 Carbon-Based Materials

Carbon-based materials have emerged as leading candidates for solar steam generation due to their excellent solar absorption, low cost, and abundance. Graphene oxide (GO) and reduced graphene oxide (rGO) demonstrate near-perfect solar absorptance (>98%) across ultraviolet to infrared wavelengths while maintaining relatively low thermal conductivity (Wang *et al.*, 2022). Carbon black, derived from incomplete combustion of hydrocarbons, offers similar optical properties at significantly lower production costs, making it attractive for large-scale deployment in developing regions (Zhang *et al.*, 2015). Carbon nanotubes (CNTs) arranged in aligned arrays provide both high solar absorption and efficient water transport channels through capillary action (Li *et al.*, 2019). Studies have reported solar steam generation efficiencies of 85-92% using CNT-based systems under one-sun conditions (Zhang *et al.*, 2015). However, the relatively high cost of CNT synthesis remains a limitation for widespread adoption in rural electrification projects.

#### 3.1.2 Plasmonic Nanoparticles

Plasmonic materials exploit the effects of localized surface plasmon resonance (LSPR) to achieve intense light absorption and subsequent heat generation at the nanoscale. For instance, gold and silver nanoparticles demonstrated strong LSPR peaks in the visible spectrum, enabling efficient photothermal conversion (Zhang *et al.*, 2015). The localized heating effect created temperature gradients of several hundred degrees Celsius around individual nanoparticles, dramatically accelerating water evaporation in their immediate vicinity.

Aluminium nanoparticles have gained attention as cost-effective alternatives to noble metal plasmonic materials. Recent research demonstrated that aluminium nanoparticle-based solar steam generators achieved

73% efficiency under one-sun illumination, with the added advantage of earth-abundant material availability (Ishii *et al.*, 2016). This characteristic is particularly relevant for applications in sub-Saharan Africa where material sourcing presents logistical challenges.

### 3.1.3 Semiconductor and Metal Oxide Materials

Transition metal oxides such as  $Ti_2O_3$ ,  $MoO_3$ , and  $WO_3$  exhibit strong solar absorption due to their electronic band structures and can be synthesized through scalable methods. Titanium-based materials demonstrated exceptional photostability and corrosion resistance in aqueous environments, extending operational lifetimes beyond 1,000 hours of continuous solar exposure (Li *et al.*, 2019).

### 3.1.4 Biomass-derived materials

Biomass-derived materials represent an emerging category with significant potential for rural applications. Carbonized wood, agricultural waste, and fungal materials offer natural hierarchical porous structures that facilitate water transport while providing solar absorption (Chen *et al.*, 2017). Some studies in Nigeria demonstrated that carbonized palm fronds and other biomass achieved about 50-68% solar steam generation efficiency, highlighting the viability of locally sourced materials for solar energy applications in West Africa (Ifeanyi-Eze and Okayim, 2022; Okedu *et al.*, 2024).

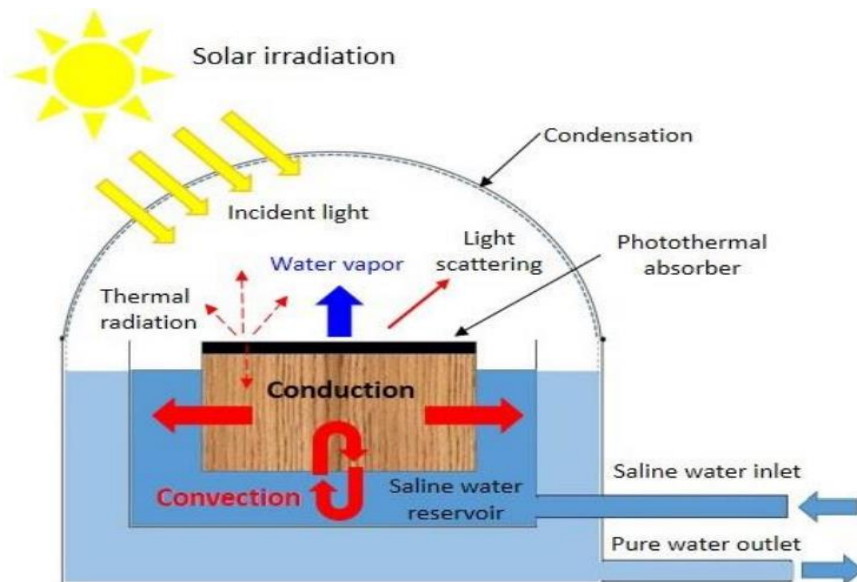
The use of biomass-derived photothermal materials has attracted increasing research attention owing to their low cost, renewability, and alignment with circular economy principles. Carbonized natural wood is among the most studied substrates: its natural micro-channel network provides efficient capillary water supply to the evaporation surface while its carbonized outer layer delivers broadband solar absorptance exceeding 95% across the ultraviolet to near-infrared spectrum (Jia *et al.*, 2021). Evaporation rates of 1.3–1.7  $kg/m^2/h$  under one-sun illumination have been reported for carbonized wood-based evaporators, substantially surpassing the theoretical pure-water evaporation rate of approximately 0.5  $kg/m^2/h$  without solar assistance (Hu *et al.*, 2023). Agricultural residues such as rice husk, sugarcane bagasse, cotton stalks, and corn cob char have similarly been converted into photothermal absorbers through simple pyrolysis or hydrothermal carbonization routes. Rice-husk-derived carbon achieved a solar-to-vapour efficiency of 88.4% under 1-sun conditions, while its low bulk density makes it inherently suitable for floating interfacial applications (Wang *et al.*, 2024). Fungal and bacterial cellulose networks offer additional advantages of tunable pore architecture and high hydrophilicity; bacterial cellulose aerogels carbonized at 800°C demonstrated an evaporation rate of 1.52  $kg/m^2/h$  and a solar-to-vapour efficiency of 91.2% (Zhang *et al.*, 2022). Within the West African context, studies on carbonized palm fronds, coconut shell char, and groundnut-shell-derived carbon have demonstrated efficiencies in the range of 50–68%, affirming the viability of locally abundant feedstocks for solar steam generation without reliance on imported nanomaterials (Ifeanyi-Eze and Okayim, 2022; Okedu *et al.*, 2024). Despite these advantages, challenges remain in controlling pyrolysis conditions for reproducible optical and structural properties at scale, and in ensuring that leachates from biomass-derived materials do not compromise the quality of produced water intended for drinking or irrigation. Future work should focus on standardised carbonization protocols, surface passivation strategies, and long-term field validation of biomass-derived solar steam generators under tropical climatic conditions.

## 3.2 Structural Design Strategies

The architecture of solar steam generators significantly influences their performance through effects on heat localization, water management, and salt rejection. Three primary design configurations have been extensively investigated: floating structures, confined systems, and hybrid designs.

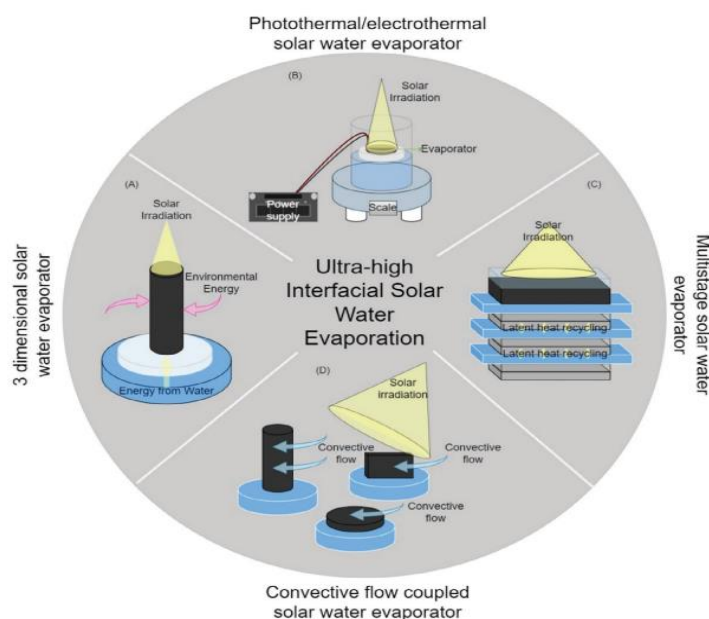
### 3.2.1 Interfacial Evaporation Systems

Floating interfacial solar steam generators position the photothermal layer directly at the air-water interface, supported by thermally insulating substrates such as polystyrene foam, wood, or aerogels (Guo, *et al.*, 2021). Figure 1 provides a schematic overview. This configuration minimizes conductive heat losses to bulk water by maintaining a steep thermal gradient across the insulating layer. The thickness and thermal conductivity of the insulating substrate critically determine overall system efficiency, with optimal insulation thickness typically ranging from 10-30 mm for foam-based materials (Chamsa-ard *et al.*, 2020).



**Figure 1:** Schematic representation of an interfacial solar evaporation system (Chamsa-ard et al., 2020)

Water transport to the evaporation surface occurs through capillary channels within the photothermal layer or through dedicated wicking structures. Natural materials like cotton fabric, cellulose sponges, and bacterial cellulose demonstrate effective water transport rates of 0.2-0.8 kg/m<sup>2</sup>/h while maintaining structural integrity (Zhou et al., 2016). The balance between water supply rate and evaporation rate determines system stability; insufficient water supply leads to dry-out and reduced efficiency, while excessive water supply increases parasitic heat losses. Figure 2 presents various designs for interfacial evaporation systems, where A) is 3D interfacial solar water evaporator, B) is solar interfacial driven water evaporator coupled with joule heating, C) is solar driven interfacial multistage solar distiller and D) is solar interfacial driven water evaporator enhanced with convective flow.



**Figure 2:** Various designs of ultra-high solar interfacial evaporation systems (Kim et al., 2024)

### 3.2.2 Three-Dimensional Architectures

Three-dimensional (3D) solar steam generators employ vertical or conical structures that increase the effective solar absorption area while enhancing water transport through extended capillary pathways (Jiang et al., 2016). Cone-shaped designs with apex angles of 30-60° have demonstrated 15-25% higher evaporation rates compared to flat configurations due to increased light trapping and reduced reflection losses (Sun et al., 2025).

Origami-inspired foldable structures represent an innovative approach that combines high surface area with compact storage and transport characteristics (Liu et al., 2023). These designs are particularly relevant for

deployment in remote areas where logistics constraints favour lightweight, collapsible systems. Field trials in East Africa showed that origami solar steam generators maintained 82% of their initial performance after 500 folding cycles (Lema, 2024).

### 3.2.3 Confined Water Layer Systems

Recent research has explored confined water layer configurations where a thin water film (1-10 mm) is maintained between the solar absorber and a transparent cover. This design reduces convective heat losses to ambient air while maintaining high evaporation rates through reduced pressure or increased temperature in the confined space. Experimental results indicate that confined systems achieve 10-15% higher efficiencies compared to open systems under windy conditions, which is relevant for the Sahel region's climate characteristics (Ahmed *et al.*, 2020). Table I summarises the four principal structural configurations of solar steam generators reviewed in this study. As shown, floating interfacial systems offered the simplest construction and lowest thermal mass, enabling solar-to-vapour efficiencies of 80–90% under one-sun conditions, but remain susceptible to salt accumulation and wind-induced performance degradation. Three-dimensional architectures improved light trapping and evaporation area but involved more complex fabrication and higher convective losses. Confined layer systems attained efficiencies of 82–91% by suppressing convective losses, at the cost of greater system complexity. Hybrid or multi-layer configurations achieved the highest reported efficiencies (85–93%) by combining features of other designs, though their fabrication difficulty and cost remained limiting factors for rural deployment. These trade-offs should guide material and structural selection based on deployment context, available fabrication capacity, and targeted application (Guo *et al.*, 2021; Jiang *et al.*, 2016; Ahmed *et al.*, 2020; Liu *et al.*, 2023).

**Table I:** Comparison of solar steam generator structural configurations

Design Type	Key Features	Advantages	Disadvantages	Typical Efficiency (One-Sun)	Representative Studies
Floating Interfacial	Photothermal layer on insulating substrate (foam, wood) floating at water surface	Simple construction; Low thermal mass; Minimal conductive losses; Easy scalability	Sensitive to wind/waves; Salt accumulation issues; Limited structural stability	80-90%	(Guo <i>et al.</i> , 2021)
3D Architectures	Vertical structures (cones, cylinders, origami) with extended surface area	Enhanced light trapping; Increased evaporation area; Better salt rejection; Improved water transport	Complex fabrication; Higher material costs; Increased convective losses; Difficult to scale	75-88%	(Jiang <i>et al.</i> , 2016)
Confined Layer	Thin water film between absorber and transparent cover	Reduced convective losses; Protection from wind; Higher temperatures achievable	Requires sealed system; Vapor condensation on cover; More complex maintenance; Pressure buildup concerns	82-91%	(Ahmed <i>et al.</i> , 2020)
Hybrid/multi-layer	Combined features (e.g., 3D + confined, bilayer absorbers)	Optimized for multiple functions; Enhanced salt management	High complexity; Expensive fabrication; Difficult optimization; Maintenance challenges	85-93%	(Liu <i>et al.</i> , 2023)

### 3.3 Performance Characteristics and Optimization

Solar steam generation performance was quantified through multiple metrics including solar-to-vapour efficiency, evaporation rate, and energy conversion effectiveness under varying environmental conditions. Understanding these parameters is essential for system design optimization for specific geographic locations.

### 3.3.1 Environmental Factors

Solar irradiance intensity directly correlates with steam generation rates, with most systems demonstrating linear performance improvements from 1 to 10 suns of concentration (Zhang *et al.*, 2015). However, the harsh solar conditions in sub-Saharan Africa (daily solar irradiation of 5-7 kWh/m<sup>2</sup>) also present challenges related to material degradation and thermal management (Ahmed *et al.*, 2020).

Ambient temperature influenced the baseline water temperature and affected heat loss rates. Studies conducted in tropical climates (30-40°C ambient) reported 8-12% higher evaporation rates compared to temperate conditions due to reduced sensible heat requirements. Relative humidity inversely affected evaporation rates, with performance decreasing by 15-25% as relative humidity increases from 30% to 80% (Wang *et al.*, 2022). This factor was particularly relevant during wet season (June-September) when humidity levels rise significantly.

Wind speed presented a complex effect: moderate wind (1-3 m/s) can enhance evaporation by removing saturated vapour from the surface, while strong winds (>5 m/s) increase convective heat losses, reducing overall efficiency. Field measurements in the Sahel region indicated optimal performance occurred at wind speeds of 2-2.5 m/s (Azoumah *et al.*, 2010).

### 3.3.2 Water Quality Considerations

Real-world deployment of solar steam generators must address water quality issues including salinity, biological contaminants, and suspended particulates. Salt accumulation on evaporation surfaces represents a critical challenge, as salt crystallization can block solar absorption and water transport pathways, degrading performance by 40-60% within days of operation in high-salinity water (>3% NaCl) (Xu, 2018).

Self-cleaning mechanisms have been developed to address salt fouling. Strategies include hydrophilic surface modifications that promote salt dissolution during dark periods, edge-preferential salt crystallization designs that keep the central absorption area clear, and periodic flushing systems activated by capillary pressure differentials (Gao *et al.*, 2019). Recent innovations using Janus membranes with asymmetric wettability demonstrated continuous operation for 30 days in 10% brine without performance degradation (Xu *et al.*, 2018).

Biological fouling from algae and bacteria growth on wet surfaces exposed to sunlight poses additional challenges. Antimicrobial coatings incorporating silver nanoparticles or copper compounds have shown effectiveness in inhibiting biofilm formation for periods exceeding six months (Chen *et al.*, 2017). However, the long-term environmental impacts of antimicrobial material leaching require careful evaluation, particularly in water-scarce regions where produced water may be used for irrigation or livestock.

Table 2 presents performance parameters of solar steam generators under various field operating conditions, providing a consolidated reference for system designers targeting rural deployment. The data reveal that start-up times of 2–15 minutes are primarily governed by the thermal mass and insulation quality of the evaporator assembly, with low-thermal-mass designs (<50 g/m<sup>2</sup>) responding most rapidly to intermittent sunshine, an important consideration in climates with variable cloud cover. Salt rejection capability, which ranges from continuous operation to complete fouling within 30 days depending on surface design, emerges as the most critical performance determinant for brackish water applications in the Sahel region. Wind speed effects and dust accumulation are shown to reduce efficiency by up to 40%, underscoring the need for enclosed or wind shielded system designs and self-cleaning surface coatings for long-term outdoor performance. The 2–10+ year system lifetime range reflects the strong influence of material UV-stability and corrosion resistance, parameters that must be prioritised in material selection for cost-effective rural applications.

### 3.4 Integration with Electricity Generation Systems

While solar steam generators are primarily designed for water purification and desalination applications, their integration with thermodynamic cycles for electricity generation represents an emerging research frontier particularly relevant for rural electrification.

**Table 2:** Performance parameters of solar steam generators under various conditions

Parameter	Typical range	Influencing factor	Optimal condition	Impact on rural applications	Reference
Start-up time (min)	2-15	Thermal mass, insulation properties, initial water content	Low thermal mass (<50 g/m <sup>2</sup> ), good insulation	Faster start-up enables better response to intermittent sunlight	(Xu, 2018; Zhou, et al., 2016)
Salt rejection capability	0-30+ days	Surface wettability, flow design, flushing mechanisms	Hydrophobic edges, continuous flushing, Janus membranes	Critical for brackish water sources common in rural Sahel region	(Gao et al., 2019)
Wind resistance	5-40% efficiency loss at 5 m/s	System design (open vs. enclosed), convective losses	Enclosed or semi-enclosed designs, windbreaks	Sahel region experiences frequent winds; protection needed	(Li et al., 2019)
Dust accumulation impact	10-30% efficiency drop over weeks	Surface self-cleaning, tilt angle, coating properties	Hydrophobic coatings, >15° tilt, periodic rain cleaning	Dust storms common in Borno State; self-cleaning essential	(Ahmed et al., 2020; Kumar and Yadav, 2021)
System lifetime (years)	2-10+	Material stability, UV resistance, corrosion protection	UV-stable polymers, corrosion-resistant materials	Long lifetime reduces replacement costs in remote areas	(Chen et al., 2017; Liu et al., 2023)

### 3.4.1 Thermoelectric Conversion

Thermoelectric generators (TEGs) convert temperature gradients directly into electrical power through the Seebeck effect, offering a solid-state, maintenance-free approach to power generation (Giovannelli, 2015). Integration of TEGs with solar steam generators creates hybrid systems where the temperature difference between the hot evaporation surface (70-100°C) and ambient cooling provides the thermal gradient for electricity production (Liu et al., 2023).

Experimental implementations have demonstrated electrical power outputs of 0.8-1.5 W/m<sup>2</sup> under one-sun illumination with commercially available bismuth telluride TEG modules. While power density remains modest, these systems offer continuous low-power generation suitable for sensor networks, LED lighting, and small electronics charging in off-grid settings. Recent work in Kenya deployed solar steam-TEG systems for rural health clinic refrigerators, achieving continuous operation of 15W vaccine coolers (Giovannelli, 2015).

The trade-off between steam production and electricity generation requires careful optimization. Directing heat to TEGs reduces steam output, necessitating design strategies that minimize this compromise. Cascaded configurations where TEGs utilize waste heat from the evaporation process without interfering with the primary steam generation have shown promising results, maintaining 85% of pure steam generator efficiency while producing supplementary electrical power (Yang et al., 2018).

### 3.4.2 Organic Rankine Cycle Integration

For larger-scale applications, organic Rankine cycle (ORC) systems can convert solar steam into mechanical and electrical energy using low-boiling-point working fluids (Zhang et al., 2015). Small-scale ORC systems (1-10 kW) designed for distributed generation in rural areas have achieved electrical efficiencies of 8-12% when coupled with concentrating solar steam generators operating at 150-200°C (De Sá et al., 2018).

The modularity of ORC systems makes them suitable for community-scale installations in rural Africa. A pilot project in rural Tanzania integrated a 5 kW ORC system with parabolic trough solar collectors and demonstrated continuous electricity supply for a 50-household community, with operational costs 30% lower than diesel generators over a five-year period (Ramde et al., 2020). However, the technical complexity and maintenance requirements of ORC systems present challenges in areas with limited technical expertise, necessitating capacity building initiatives.

Practical design patterns that have emerged for solar steam generators intended for rural electrification include modular parabolic dish + small boiler + micro-turbine or Stirling/ORC, linear Fresnel with once-through DSG feeding an ORC, and Scheffler reflectors feeding batch or continuous steam cookers/boilers adapted to electricity generation via small turbines or ORC units. Table 3 provides a comparative summary of six collector-generator configurations applicable to small-scale and rural solar steam electricity systems. Parabolic trough systems with heat transfer fluid (HTF) loops are the most mature technology but introduce HTF handling complexity and additional heat exchanger components that may challenge maintenance in remote settings. Direct steam generation (DSG) in parabolic troughs eliminates the HTF loop and reduces capital

costs, though two-phase flow instabilities complicate control. Parabolic dish systems offer the highest steam temperatures and are best suited to very small, modular units where single-dish-single-power-unit configurations are practical. Linear Fresnel reflectors provide a cost-effective alternative to troughs due to simpler flat-mirror structures, albeit at lower optical efficiency. Scheffler reflectors are particularly appropriate for community-scale, low-pressure steam applications given their low fabrication cost and proven track record in rural contexts across the Global South. Central receiver or micro-tower configurations, while capable of high temperatures and dispatchable generation, are the least suited to micro-scale rural systems due to their high capital and operational complexity. Overall, the parabolic dish and Scheffler configurations present the most promising trade-offs for off-grid rural electrification in sub-Saharan Africa, combining modularity, relative simplicity, and field-proven performance.

**Table 3:** Comparative summary of solar steam generator options for small/rural systems

Collector generator type	Typical steam temp / pressure (feasible small scale)	Suitability for small rural systems	Advantages	Main technical risks / implementation issues	Reference
Parabolic trough with HTF + boiler	Medium: 200–400°C; moderate pressure (up to medium pressure steam)	Moderate — widely proven but needs HTF loop and careful freeze protection	Mature technology, modular fields, well-developed receivers	HTF cost and handling, extra heat exchanger, pumps, more components to maintain	(Seshie, et al., 2018)
Parabolic trough with DSG	Medium: saturated steam up to ~300–350°C depending on design	Good potential — DSG reduces HTF cost, but control is harder	Eliminates HTF and secondary exchanger; potential CAPEX reduction	Two-phase flow instabilities, control complexity, steam quality control	(Zarza et al., 2004)
Parabolic dish (point focus)	High: can reach >400°C and high pressures (depending on receiver)	High suitability for very small, modular units (single dish → single power unit)	High flux and high efficiency per unit; compact modularity	Requires very accurate tracking; receiver durability; higher optical precision	(Giovannelli, 2015)
Linear Fresnel (LFR)	Medium: typically, lower than trough due to lower concentration ratio	Promising for low-cost linear systems and simple fabrication	Flat mirrors, simpler structure; lower capital cost per m <sup>2</sup>	Lower optical efficiency, more shading and blocking, receiver design complexity	(De Sá et al., 2018)
Scheffler reflector (fixed dish with seasonal adjustment)	Low to medium: suitable for steam for cooking or low-pressure generation	Highly suitable for very local, low-cost steam generation (micro-scale)	Low cost, simple fabrication; good for community-scale steam; proven in rural contexts	Limited to lower pressures/temps; single axis/seasonal alignment needed; limited literature for electricity coupling	(Asghar et al., 2023)
Small central receiver / micro-tower	High (if heliostats used)	Less suited to micro rural unless cluster investment exists	Centralized high temp storage possible; dispatchability	High complexity, heliostat control and alignment costs	(Ramde et al., 2020)

HTF-Heat transfer fluid

#### 4. Conclusion

Solar steam generation represents a transformative approach for sustainable water purification and decentralized energy production, offering high efficiency through localized interfacial heating under low solar concentration. This review demonstrated that advances in photothermal materials, particularly carbon-based, semiconductor, and biomass-derived absorbers, have significantly improved solar absorption, thermal localization, and system affordability. Structural innovations such as floating interfacial systems, three-dimensional architectures, and confined evaporation layers further enhance performance by reducing heat losses and improving water transport. Despite substantial progress, practical deployment of solar steam generators faces challenges related to salt accumulation, dust deposition, wind-induced heat losses, and long-term material durability. Recent self-cleaning surfaces, salt-rejection designs, and enclosed architectures show

promise in addressing these limitations. Importantly, the integration of solar steam generators with thermoelectric devices and organic Rankine cycle systems opens pathways for combined water and electricity supply in off-grid communities, although efficiency and maintenance considerations remain critical.

Based on the findings of this review, the following specific recommendations for further studies are advanced. First, given that biomass-derived photothermal materials such as carbonised palm fronds, rice husk char, and wood-based absorbers achieved efficiencies of 50–68% in West African studies, future research should focus on optimising pyrolysis protocols, surface functionalisation strategies, and hybridisation of locally available biomass with low-cost carbon additives to narrow this performance gap. Second, since salt fouling was identified as the most critical operational challenge, degrading performance by 40–60% within days in high-salinity water, research into scalable, durable Janus membrane and edge-crystallisation designs suitable for low-cost fabrication in developing-country settings is urgently needed. Third, because wind-induced convective losses reduced efficiencies by up to 40% under Sahel field conditions, systematic investigations of low-cost enclosure and windbreak designs tailored to these climatic conditions should be prioritised, with performance validated in outdoor field trials rather than solely in controlled laboratory environments.

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