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Design and Performance Analysis of a Solar Thermal Energy System for Rural Applications: A Comprehensive Review

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ABSTRACT

Solar thermal energy systems (STSs) represent a sustainable and scalable technological pathway to address the dual challenges of energy poverty and environmental degradation in rural regions. This review evaluates the engineering design and thermal performance of diverse solar thermal technologies, from low-cost portable water heaters to large-scale concentrating solar power (CSP) systems. Key performance enhancements, including square-shaped riser tubes, selective metafilm coatings, and Phase Change Material (PCM) storage, are analyzed through numerical simulations and field data. Findings indicate that optimizing collector geometry and integrating latent heat storage can improve system efficiency by 10–15%, making STSs economically competitive with conventional fossil fuels in energy-poor communities.

1. INTRODUCTION

Energy is the fundamental driver of industrial and social development, yet rural communities in developing economies frequently suffer from unreliable grid electricity and high fuel costs (Ritesh, Neha, & Mohan 2025). Traditional reliance on biomass and Liquified Petroleum Gas (LPG) contributes significantly to greenhouse gas emissions and poses localized health risks (Aggarwal 2023). Solar thermal systems (STSs) offer a viable alternative by converting solar radiation directly into heat for domestic, agricultural, and industrial processes (Panchal et al. 2024). For rural applications, engineering designs must prioritize high efficiency, low maintenance, and cost-effectiveness to ensure widespread adoption (Sahoo et al. 2014; Aggarwal 2023).

2. Collector Technology and Geometry Optimization

The efficiency of any solar thermal system is primarily governed by its collector design, which serves as the heat exchanger between solar flux and the working fluid (Ritesh, Neha, & Mohan 2025).

2.1 Flat-Plate Collectors (FPCs)

FPCs are the most common technology for domestic heating due to their simplicity (Islam et al. 2023). Engineering research has focused on the riser tube geometry to maximize heat extraction (Fig.1).Numerical analyses using ANSYS FLUENT demonstrate that square-shaped riser tubes provide a larger contact area with the absorber plate compared to traditional circular tubes, resulting in an 8.1% higher heat exchange rate (Islam et al. 2023). While square tubes experience higher pressure drops, they achieve a Performance Evaluation Criterion (PEC) of 2.65, indicating superior overall thermal-hydraulic performance (Islam et al. 2023).

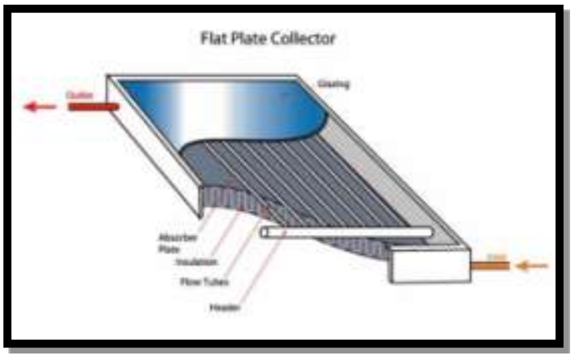

Fig. 1: Schematic Representation of Flat-Plate Collectors

2.2 Evacuated Tube Collectors (ETCs)

ETCs utilize vacuum insulation to minimize convective and conductive heat losses, making them highly effective in cold or high-altitude rural regions (Panchal et al. 2024). They typically achieve thermal efficiencies of 70–85%,

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significantly outperforming FPCs (50–70%) in maintaining the high temperatures required for industrial process heating (Fig. 2).

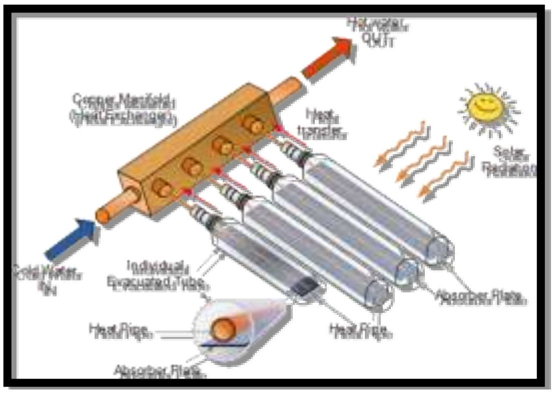

Fig. 2: Schematic Representation of Evacuated Tube Collectors

2.3 Concentrated Solar Power (CSP) Systems

For community-scale applications, CSP technologies like solar towers and Scheffler dishes are utilized to achieve temperatures between 150°C and 600°C (Aggarwal 2023; Vennila et al. 2024). A 10 MW solar tower plant simulated for the high-DNI Leh region demonstrated a Capacity Factor (CF) of 56.9% and a levelized cost of electricity (LCOE) of $0.1202/kWh (Vennila et al. 2024). In the Himalayan foothills, a community system of 22 solar dishes successfully replaced 33,600 kg of LPG annually for student meal preparation (Fig. 3).

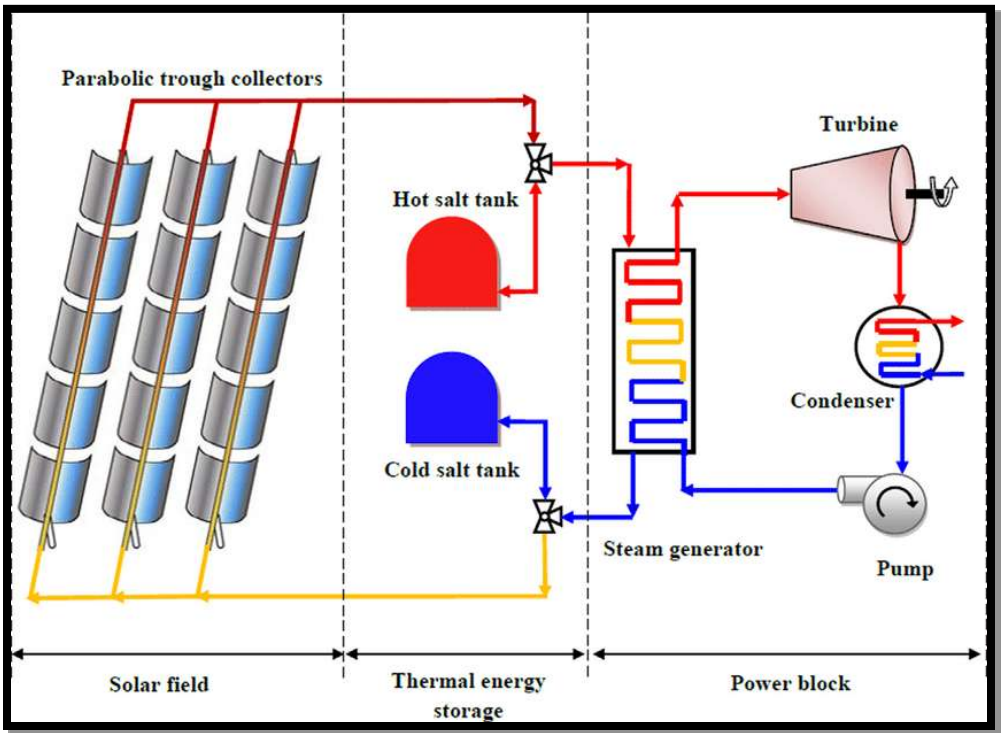

Fig. 3: Schematic Representation of Concentrated Solar Power (CSP) Systems

3. Advanced Materials for Efficiency Enhancement

3.1 Selective Absorber Coatings and Metafilms

Spectral selectivity is critical for reducing radiative losses at high temperatures. Multilayer metafilm absorbers (e.g., W-SiO_2-W stacks) exhibit high solar absorptance (0.942) and low total emittance (0.153) at 500°C (Alshehri et al. 2019). These coatings remain stable up to 700°C and, when deposited on flexible stainless steel foil, offer a cost-effective alternative to commercial paints, costing approximately $2.23/m² (Fig. 4).

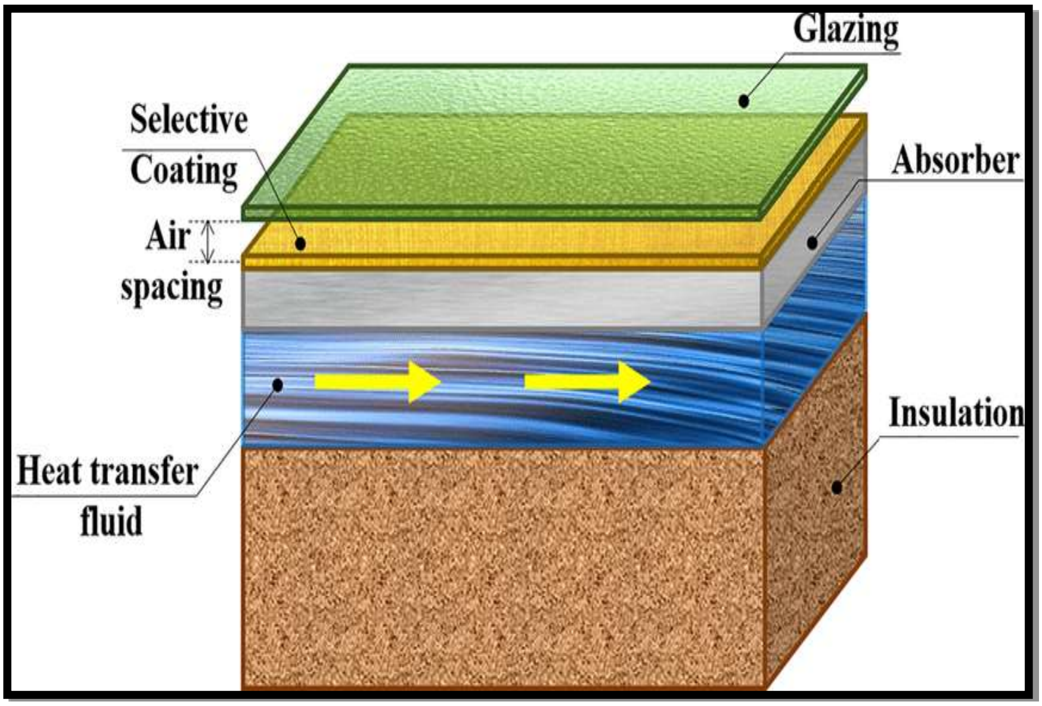

Fig. 4: Schematic Representation of Selective Absorber Coatings and Metafilms

3.2 Engineered Nanofluids

Conventional working fluids like water or oil are limited by their thermal properties. The dispersion of nanoparticles into base fluids can improve thermal conductivity by 10–15% (Ritesh, Neha, & Mohan 2025). An innovative rural solution involves engineering solar selective nanofluids from "used engine oil", which achieves steady-state temperatures 5% higher than conventional systems due to efficient volumetric absorption.

4. Thermal Energy Storage (TES) Solutions

Thermal Energy Storage (TES) plays a crucial role in addressing the intermittent nature of solar radiation, particularly in rural settings where energy reliability is vital. By storing excess thermal energy during peak sunshine hours and releasing it during low or no sunlight periods, TES ensures continuous and stable energy supply (Jani, 2023; Rai, Thakur, & Sharma, 2023).

4.1 Latent Heat Storage using Phase Change Materials (PCMs)

PCMs like paraffin wax or gallium store energy at a constant temperature during phase transition (Jani 2023; Rai, Thakur, & Sharma 2023.). Gallium is particularly effective due to its high thermal conductivity (32 W/m-K) compared to paraffin (Rai, Thakur, & Sharma 2023.). Engineering simulations show that integrating rectangular fins into PCM cavities further optimizes heat transfer rates by increasing the surface area (Rai, Thakur, & Sharma 2023.).

4.2 Applications in Night-time Heating

Solar air heaters equipped with PCM storage can increase outlet air temperatures after sunset, providing sustainable residential space heating (Jani 2023). However, challenges such as high fluid circulation costs and system noise must be addressed through optimized flow control (Jani 2023).

5. Rural Applications and Case Studies

5.1 Himalayan Portable Water Heaters

In remote Himalayan regions where commercial systems have less than 1% market penetration, portable solar water heaters have been developed (Sahoo et al. 2014). These 12.5-liter units utilize polycarbonate thin-sheet glazing, which is virtually unbreakable and achieves a thermal efficiency of 74%, reaching water temperatures of 69°C within five hours (Sahoo et al. 2014).

5.2 Solar Crop Drying

Postharvest losses in rural farming are often due to poor moisture control (Runganga & Kanyarusoke 2018.). Enclosed solar crop dryers protect produce from dust and infestation while reducing drying times to less than two days (compared to over a week for open-air drying) at a material cost under ZAR 2000 (Runganga & Kanyarusoke 2018) (Fig. 5).

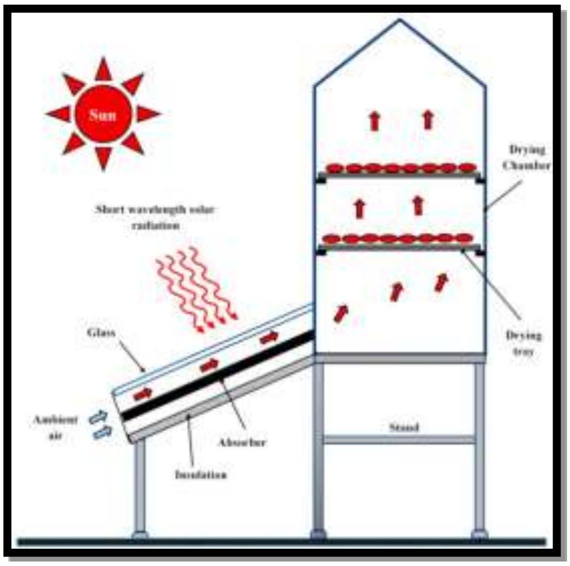

Fig. 5: Schematic Representation of Solar Crop Drying

5.3 Sustainable Jaggery Production

The energy-intensive production of non-centrifugal sugar (Jaggery) traditionally relies on bagasse combustion (Marie et al. 2020). Integrating solar thermal pre-heating and freeze concentration can reduce the specific energy required by 91.3%, saving more than 2 kg of bagasse per kg of jaggery produced (Marie et al. 2020).

6. Performance Analysis and Engineering Modeling

Reliable performance estimation is crucial for stakeholder investment (Jensen & Kong 2022). Engineering experts utilize the Quasi-Dynamic Testing (QDT) method, according to ISO 9806, to derive performance coefficients through multiple linear regression of field data (Jensen & Kong 2022). Software tools such as TRNSYS allow for the modeling of complex systems, including solar-fossil hybrid cycles and transient "capacity" effects during system start-up (Schwarzbözl et al. 2002).

7. Economic and Environmental Impact

The transition to high-efficiency solar thermal systems contributes significantly to Sustainable Development Goals (SDGs) 7 and 13 (Aggarwal 2023).

- Cost Reductions: LCOE values for solar tower systems have reached as low as 0.04–0.07/kWh, with payback periods for community cooking systems often under 3 years (Aggarwal 2023; Panchal et al. 2024).
- Contextual Challenges: Real-world efficiency in arid regions can be reduced by 15–20% due to dust deposition, necessitating regular maintenance or the use of anti-dust coatings (Ritesh, Neha, & Mohan 2025).

8. CONCLUSION

Solar thermal energy conversion is a mature technology with profound potential for rural empowerment. The engineering perspective emphasizes that optimizing collector geometry (e.g., square riser tubes), utilizing selective metafilm coatings, and integrating PCM-based storage are the most effective strategies for maximizing performance. While portable designs provide domestic relief in remote terrains like the Himalayas, large-scale systems such as solar towers and multi-dish steam cookers are essential for community services and industrial processes. Future research should prioritize the long-term stability of nanofluids and the development of smart control systems to further reduce operational costs in emerging economies.

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