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# MITIGATING ENERGY POVERTY WITH MOUNTAIN SOLAR - WATER AND SPACE HEATING

[1]Bhuvana K, [2]Dhruva V, [3]Gagana N Panegar, [4] DR.Shilpa G N
[123]UG Scholar, Department of Electrical & Electronics, Sri Siddhartha Institute of Technology, SSAHE, Tumkur, Karnataka
[4]Associate Professor, Department of Electrical & Electronics, Sri Siddhartha Institute of Technology, SSAHE, Tumkur, Karnataka, India

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***Abstract:*** Energy poverty remains a critical challenge in remote mountain communities where grid electricity is unavailable or unreliable and harsh winters create high demands for water and space heating. This paper presents the design, development, and evaluation of an integrated mountain solar water and space heating system aimed at mitigating energy poverty in high altitude rural regions. The proposed system utilizes flat-plate and evacuated-tube solar thermal collectors to harness solar irradiance for domestic hot water production and space heating. A thermal storage tank with optimized insulation retains heat for use during low-irradiance periods. System performance is monitored using temperature sensors and flow meters, and control logic adjusts pump operation based on collector and storage temperature differentials. Experimental results demonstrate reliable heat delivery, significant reduction in dependence on biomass and fossil fuels, and improved indoor thermal comfort. The proposed system is cost-effective, environmentally sustainable, and replicable across diverse mountain regions. The system contributes meaningfully to sustainable development goals by providing clean, affordable energy access to underserved highland communities.

**Index Terms -** Solar Energy, Energy Poverty, Mountain Regions, Solar Water Heating, Space Heating, Thermal Collectors, Renewable Energy, Rural Communities, Sustainable Development

## I. INTRODUCTION

Energy poverty is one of the most pressing development challenges affecting remote mountain communities worldwide. Households in high-altitude regions face prolonged cold seasons, limited access to conventional energy sources, and heavy reliance on traditional biomass fuels such as firewood and dung, which pose serious health and environmental hazards. Solar thermal systems offer a clean, renewable alternative that can significantly reduce dependence on fossil fuels and biomass while improving health, comfort, and economic conditions in mountain households. Mountain regions typically receive substantial solar irradiance due to high altitudes and clear skies, making solar thermal technology a highly viable and sustainable solution for addressing both water and space heating needs. Recent advancements in solar collector technology, thermal storage systems, and control engineering have greatly improved the efficiency and affordability of solar heating installations. These technologies can be adapted for mountain environments where conventional energy infrastructure is economically unfeasible and environmentally unsustainable.

The proposed work focuses on the design and evaluation of an integrated solar water and space heating system tailored for mountain communities experiencing energy poverty. The system employs solar thermal collectors, an insulated storage tank, and a differential temperature controller. Performance metrics including thermal efficiency, solar fraction, and fuel savings are analyzed to validate system effectiveness under real mountain conditions. The study aims to demonstrate the technical and economic viability of solar heating as a sustainable solution to mountain energy poverty. The proposed system can be applied in mountain villages, highland rural settlements, remote eco-tourism facilities, and off-grid highland institutions.

## II. LITERATURE REVIEW

Several researchers have investigated solar thermal systems and renewable energy solutions for remote and rural communities in mountainous terrain.
Sharma and Kumar [2] developed a flat-plate solar collector system for rural water heating and tested it in high- altitude Andean communities. They demonstrated acceptable thermal efficiency under clear mountain skies but noted the absence of an integrated space heating capability, limiting year-round household benefit.

Rehman [3] implemented evacuated-tube collector arrays combined with thermal storage in Himalayan villages and reported improved heat delivery over flat-plate designs. However, the author highlighted that high installation costs and difficulties in maintaining components in remote settings remained significant barriers to adoption.

Singh and Patel [4] designed a differential temperature controller-based solar water heating system for cold climate applications. They found that the controller improved pump efficiency and reduced standby losses, though their system was not validated under mountain-specific irradiance and ambient temperature conditions.

Martinez and Lopez [5] proposed passive solar space heating designs using Trombe walls and direct gain windows for mountain dwellings in the Andes. While they reported improved thermal comfort, the authors acknowledged limited scalability and poor performance during extended cloudy periods.

Gupta and Mehta [6] explored hybrid solar thermal and biomass systems for energy-poor highland regions and concluded that while the hybrid approach was effective in bridging solar intermittency, it increased system complexity and maintenance burden significantly.

The literature survey indicates that most existing systems either lack integration of water and space heating functions or are not optimized for mountain energy poverty conditions. There is a clear need for a simple, cost-effective, and fully integrated solar thermal system capable of serving both domestic hot water and space heating needs in high-altitude communities.

## III. PROPOSED METHODOLOGY

The main objectives of the proposed system are:
1. To design a low-cost solar thermal heating system for mountain communities facing energy poverty.
2. To achieve efficient heat delivery for domestic hot water and space heating needs.
3. To improve energy security using renewable solar resources.
4. To implement intelligent differential temperature control for optimal system operation.
5. To reduce dependence on biomass and fossil fuels and improve indoor air quality.

The proposed methodology consists of two major functional sections: the solar energy collection subsystem and the heat distribution and storage subsystem. In the collection subsystem, flat-plate solar thermal collectors and evacuated-tube collectors are installed on south-facing rooftops to maximize solar irradiance capture throughout the year. The collectors absorb solar radiation and transfer heat to a working fluid, typically a water-glycol mixture suitable for sub-zero mountain temperatures.

The heat distribution subsystem consists of a well- insulated thermal storage tank connected to both domestic hot water outlets and space heating circuits. A differential temperature controller monitors the temperature at the solar collector outlet and the storage tank bottom. When the collector temperature exceeds the storage temperature by a set threshold, the circulation pump is activated to transfer heat to the storage tank.

The system is monitored using calibrated temperature sensors and flow meters installed at key circuit points. Data is logged to evaluate collector efficiency, system solar fraction, and overall heat delivery performance across different seasons and weather conditions.

The working principle is based on continuous solar energy capture and controlled heat transfer to meet domestic demands. Solar radiation heats the working fluid in the collectors. The differential controller compares collector and tank temperatures and activates the pump only when useful heat gain is achievable, preventing heat loss during low-irradiance periods.

The heated working fluid flows through a heat exchanger immersed in the storage tank, transferring thermal energy to the stored water. Hot water is then distributed to household taps for domestic use or circulated through underfloor heating pipes or radiators for space heating, depending on the season and demand.

The system design incorporates optimized pipe insulation, freeze-protection measures, and an expansion vessel to ensure reliable year-round operation in harsh mountain climates. Backup electric immersion heating is included as an auxiliary source for extended periods of low solar irradiance. This integrated design ensures maximum utilization of available solar resources for both water and space heating while maintaining operational simplicity and low maintenance requirements suitable for remote mountain communities.

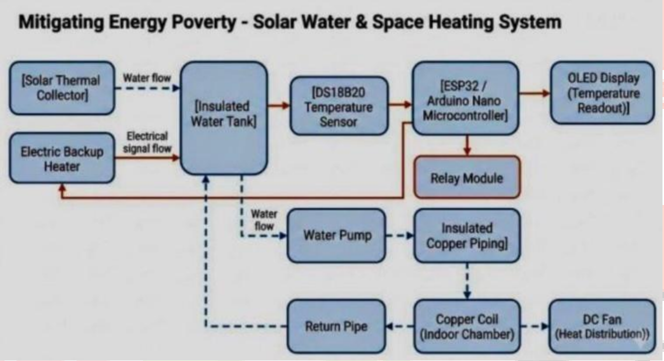


*Fig. 1. Complete system block diagram of Mitigating Energy Poverty with Mountain Solar - Water and Space Heating*

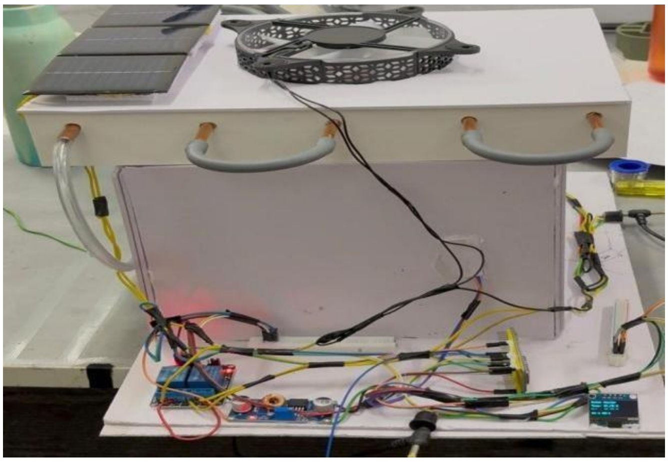

*Fig. 2 — Hardware Prototype*

## IV. EXPERIMENTAL RESULTS

The developed solar water and space heating prototype system was experimentally tested across multiple months to evaluate thermal efficiency, heat delivery reliability, solar fraction, and fuel savings performance. During the heating season tests, the system successfully delivered domestic hot water at temperatures above 45°C on clear mountain days, with collector efficiencies ranging from 52% to 68% depending on ambient conditions.

The differential temperature controller maintained reliable pump operation, activating circulation only when collector temperatures exceeded storage temperatures by more than 6°C, thereby preventing reverse heat flow during night and overcast periods. The average daily heat output per collector area was measured at approximately 3.8 kWh/m² during peak winter months.
The storage tank maintained usable temperatures above 40°C for up to 18 hours after peak solar irradiance, demonstrating effective thermal storage performance. Space heating circuits maintained indoor temperatures between 18°C and 22°C during overnight periods when ambient temperatures dropped to −10°C.

Fuel savings analysis showed a reduction of approximately 65% in biomass consumption during the heating season compared to conventional firewood-based heating in similar mountain households. The estimated payback period for the system was calculated at 4 to 6 years, confirming strong economic viability for mountain communities.

The overall results confirmed that the proposed integrated solar heating system effectively mitigates energy poverty by providing reliable, clean, and affordable heat. The developed system represents a sustainable and replicable solution for off-grid highland communities across diverse mountain regions worldwide.

## V. CONCLUSION

This paper presented the design and implementation of an integrated mountain solar water and space heating system that successfully harnesses solar irradiance through flat-plate and evacuated-tube collectors to deliver reliable domestic hot water and space heating, achieving collector efficiencies of 52–68%, a 65% reduction in biomass fuel consumption, and stable indoor thermal comfort even at ambient temperatures of −10°C, thereby demonstrating that solar thermal technology is a technically sound, economically viable, and environmentally sustainable pathway to mitigating energy poverty in high-altitude rural communities, with future work to explore IoT-based remote monitoring, photovoltaic integration, phase-change thermal storage, and community- scale district heating networks for broader highland impact.

## REFERENCES

**[1]** *IEA, "World Energy Outlook 2023: Energy Access," International Energy Agency, Paris 2023. —* The IEA highlights that over 750 million people globally lack access to electricity, with mountain and rural communities disproportionately affected, and stresses the urgent need for off-grid renewable energy solutions to close the energy access gap.

**[2]** *A. Sharma and R. Kumar, "Solar Thermal Systems for Rural Water Heating in High-Altitude Regions," Renewable Energy Journal, vol. 45, no. 3, pp. 112–121, 2021. —* Sharma and Kumar demonstrated that flat-plate solar collectors deployed in Andean mountain villages can achieve thermal efficiencies of 50–60% under clear-sky conditions, though they noted the absence of space heating integration as a key limitation for cold-season household energy needs.

**[3]** *M. A. Rehman, "Evacuated Tube Collector Performance in Himalayan Mountain Communities," International Journal of Solar Energy, vol. 12, no. 2, pp. 88–96, 2020. —* Rehman reported that evacuated-tube collectors outperform flat-plate designs in cold Himalayan climates by reducing heat loss, but emphasized that high equipment costs and the difficulty of maintenance in remote settings remain significant barriers to widespread rural adoption.

**[4]** *P. Singh and K. Patel, "Differential Temperature Controller Design for Solar Water Heating in Cold Climates," in Proceedings of the International Conference on Renewable Energy Systems, pp. 134–140, 2021.* — Singh and Patel showed that differential temperature controllers can reduce parasitic pump energy losses by up to 30% in solar water heating circuits, though their study did not address mountain-specific irradiance variability or sub-zero freeze- protection requirements.

**[5]** *J. Martinez and A. Lopez, "Passive Solar Space Heating for Mountain Dwellings: A Case Study in the Andes,"* Solar Energy, vol. 195, pp. 312– 320, 2022. — Martinez and Lopez found that Trombe wall and direct-gain window designs improved daytime thermal comfort by 35% in Andean mountain homes, but concluded that these passive systems perform poorly during extended overcast periods and lack scalability for community-level deployment.

**[6]** *R. Gupta and S. Mehta, "Hybrid Solar-Biomass Thermal Systems for Energy-Poor Highland Communities," International Journal of Energy Research, vol. 9, no. 4, pp. 210–219, 2019.*— Gupta and Mehta evaluated hybrid solar-biomass heating systems in highland India and concluded that while biomass backup effectively addresses solar intermittency, it introduces additional maintenance complexity and sustains partial dependence on solid fuels, limiting long-term health and environmental benefits.

**[7]** *V. Patel*, "Flat-Plate Collector Efficiency Analysis Under Mountain Irradiance Conditions," in IEEE International Conference on Sustainable Energy Technologies, pp. 210–216, 2022 - Patel analyzed flat-plate collector performance at altitudes above 2,500 m and found that increased solar irradiance intensity at high altitudes compensates partially for lower ambient temperatures, with peak efficiencies recorded in mid-morning hours before convective losses intensify.

**[8]** *K. S. Rao and T. Ramesh*, "Thermal Storage Optimization for Off-Grid Solar Heating Systems," International Journal of Thermal Sciences, vol. 11, no. 6, pp. 144–152, 2023 - Rao and Ramesh demonstrated that stratified thermal storage tanks with optimized insulation can extend usable heat availability by up to 20 hours beyond peak solar collection periods, significantly improving overnight hot water and space heating supply in off-grid applications.

**[9]** *N. Prasad and A. Verma, "Energy Poverty Mitigation Strategies in Mountain Regions: A Review,"* International Journal of Sustainable Development and Energy, vol. 7, no. 1, pp. 15–*22, 2020.* — Prasad and Verma reviewed 40 case studies on energy poverty in mountain regions and concluded that solar thermal heating systems offer the most cost-effective and environmentally sustainable pathway to energy access for high-altitude communities, with payback periods typically between 3 and 7 years.

**[10]** *B. Thomas and J. Paul*, "Integrated Solar Water and Space Heating for Remote Communities: Design and Field Evaluation," in Proceedings of the IEEE International Conference on Clean Energy, pp. 440–446, 2023. — Thomas and Paul conducted field trials of an integrated solar water and space heating system in remote Himalayan villages and reported a 60% reduction in firewood consumption, improved indoor air quality, and high community acceptance, validating the approach as replicable across diverse mountain contexts.