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TECHNO-ECONOMIC AND SOCIO-ENVIRONMENTAL ASSESSMENT OF A PARABOLIC TROUGH COLLECTOR–PCM SOLAR COOKING AND DRYING SYSTEM FOR RURAL HOUSEHOLDS

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Abstract

Ending dependence on traditional biomass and fossil fuel–based cooking is central to meeting global goals on health, climate mitigation and gender equity. Among the portfolio of clean cooking options, parabolic trough collector (PTC)–based solar thermal systems with phase change material (PCM) storage offer a distinctive value proposition: they can deliver medium-temperature heat for both cooking and agricultural drying, including during evening hours, using relatively simple mechanical and thermal components. However, most research on such systems focuses on thermal performance, with limited attention to integrated techno-economic and socio-environmental implications for real households and community kitchens. This paper provides a scenario-based assessment of an experimentally characterised PTC–PCM indirect solar cooking and drying system, using created but realistic data. Three energy scenarios are compared: (i) LPG-only cooking; (ii) mixed LPG–biomass cooking with simple stoves; and (iii) the PTC–PCM solar system with LPG backup supplying most daily cooking and part of crop drying needs. For a representative rural household, results indicate that the PTC–PCM system can reduce LPG consumption by about 70% and eliminate fuelwood use for cooking, with an estimated discounted payback period of 6.5–7 years over a 15-year technical life and a benefit–cost ratio of roughly 1.6. For a small community kitchen and agro-processing unit, higher utilisation shortens the payback period to about four years and raises the benefit–cost ratio to around 2.1. Annual CO_2-equivalent emissions decline by an estimated 0.8–1.4 tonnes per household and 1.8–2.5 tonnes per community system, alongside substantial reductions in local deforestation pressure and household air pollution. Social co-benefits include time savings in fuelwood collection, improved indoor air quality, enhanced food security through reliable drying, and new livelihood opportunities. The study also highlights key sensitivities—particularly utilisation rate, capital cost and policy support—and situates PTC–PCM systems within the broader landscape of clean cooking pathways such as PV-based e-cooking and advanced biomass stoves. Overall, the assessment suggests that PTC–PCM solar cooking and drying systems, when appropriately designed and supported, can form a robust pillar of clean cooking transitions in sun-rich rural settings.

Keywords: solar cooking; parabolic trough collector; phase change material; techno-economic analysis; clean cooking; rural energy; solar drying

1. Introduction

Clean cooking sits at the intersection of energy access, climate mitigation, public health and gender justice. Around the world, millions of households still rely on fuelwood, charcoal, agricultural residues and dung burned in open fires or rudimentary stoves. The consequences are well documented: high levels of household air pollution linked to respiratory and cardiovascular disease, time poverty associated with fuel collection, environmental degradation from unsustainable wood harvesting, and financial vulnerability where households purchase increasingly expensive fuels. Even where liquefied petroleum gas (LPG) and kerosene have become available, their recurring cost and exposure to price and supply volatility constrain sustained use among low-income households.

These intertwined challenges have motivated a broad search for alternatives: improved biomass stoves, LPG expansion, biogas, ethanol, electrical cooking and solar thermal technologies. Solar cooking stands out because it directly harnesses an abundant and locally available resource—sunlight—at the point of use, without fuel purchases, complex supply chains or local pollution. Field projects across diverse regions show that solar cookers can substantially reduce fuelwood use, cut greenhouse gas emissions, improve indoor air quality and free up time previously devoted to collecting fuel. Yet adoption has often been uneven. Barriers include cultural preferences for particular cooking practices, the need to align cooking times with sunshine, and limitations of early box or panel cookers in achieving high temperatures and year-round reliability.

Within this evolving landscape, concentrating solar thermal systems offer important advantages. Parabolic trough collectors (PTCs) focus beam radiation onto a linear receiver, achieving higher flux densities and operating temperatures than flat-plate or box cookers. Originally developed and commercialised for industrial process heat and power generation, PTCs have since been adapted for lower-temperature applications such as domestic cooking, institutional kitchens and crop drying. Their geometry is particularly well suited to indirect cooking configurations, in which the collector remains outdoors while heat is transported via a working fluid to an indoor or shaded cooking space. This separation improves user comfort and safety, and makes it possible to integrate thermal storage more easily.

However, a purely "sun-following" system cannot fully respond to users' temporal preferences. Households commonly prefer to cook in the early morning and evening, whereas direct normal irradiance peaks around midday. Thermal energy storage is therefore critical. Phase change materials (PCMs) provide a compact and effective way to store solar heat as latent heat over a narrow temperature range. During sunshine hours, the PCM melts, absorbing heat at nearly constant temperature; during off-sunshine hours, it solidifies and releases stored heat, allowing cooking or drying to continue when direct solar input is low or absent. Experimental studies have demonstrated that integrating PCMs into solar cookers or indirect heating units can extend cooking availability well into the evening while maintaining relatively stable temperatures in the cooking chamber.

The thesis research motivating this paper designed and tested a PTC-based solar cooking and drying system with a rectangular PCM thermal storage tank and an indoor cooking/drying chamber. The first paper derived from that work concentrated on thermal, exergy and operational performance: optical and thermal efficiency of the PTC, PCM melting and solidification behaviour, cooking power, and drying temperature profiles under different operating conditions. The present paper deliberately shifts focus. Rather than presenting additional experimental data, it develops a techno-economic and socio-environmental assessment framework and populates it with created but realistic data informed by the characteristics of the tested system and by typical fuel-use patterns in rural contexts.

Three key questions guide the analysis:

1. Under what conditions of utilisation, capital cost and fuel price do PTC–PCM solar cooking and drying systems become economically attractive for rural households and community kitchens?
2. What magnitude of fuel savings and emissions reductions can realistically be achieved, and how sensitive are these benefits to underlying assumptions?
3. How do these systems compare conceptually to other clean cooking pathways such as PV-based electrical cooking and high-efficiency biomass stoves in terms of costs, complexity and social fit?

By addressing these questions, the paper aims to complement the detailed engineering analysis of the original experimental work with a decision-oriented perspective relevant to policymakers, practitioners and community-level stakeholders considering investment in solar cooking technologies.

2. System description and assessment framework

2.1 System configuration and operating principle

The PTC–PCM system considered in this assessment consists of four main subsystems:

1. A parabolic trough collector that focuses solar radiation onto a linear receiver tube through which a heat transfer oil circulates.
2. A rectangular PCM-based thermal storage tank where the hot oil transfers heat to PCM modules.
3. An indoor cooking and drying chamber equipped with a finned heat exchanger through which the same oil circulates to deliver heat on demand.
4. An auxiliary LPG stove retained for backup and specific high-temperature or early-morning tasks.

During sunshine hours, the collector is oriented to track the sun (manually or with a simple mechanical arrangement). The receiver oil temperature rises as it flows through the focus region, then passes into the PCM tank, where it gives up heat to the encapsulated PCM. Once the PCM has reached its melting point, further heat input leads primarily to latent heat storage at nearly constant temperature until the PCM is fully melted. When cooking or drying heat is required, the oil circulates through the indoor heat exchanger, either directly from the collector (when the sun is available) or from the storage tank (during evening or cloudy periods). Airflow in the drying chamber is controlled to maintain desired product temperatures, while the cooking compartment accommodates standard pots and pans.

The experimentally validated prototype demonstrated that, under typical clear-sky conditions, the system can:

- raise cooking-zone temperatures to levels suitable for boiling, simmering and light frying;
- maintain drying temperatures in the 60–80 °C range needed for many fruits, vegetables and spices; and
- extend useful heating several hours beyond sunset when the PCM is properly charged.

This operational profile underpins the techno-economic scenarios described below.

2.2 Functional boundary and service definition

For assessment purposes, the functional boundary is defined as the delivery of *useful thermal energy for daily cooking and seasonal crop drying services* for two archetypal users:

- a single rural household; and
- a small community kitchen with an associated agro-processing unit.

Useful thermal energy refers to heat available at the pot or drying tray, after combustion or solar-thermal conversion and heat transfer. This definition allows comparison across LPG-only, mixed-fuel and solar-integrated options, even though their upstream supply chains and device efficiencies differ.

The boundary includes:

- capital costs of energy appliances (PTC–PCM system, LPG stove, basic biomass stove where relevant), including installation;
- operation and maintenance costs of the PTC–PCM system (cleaning, minor repairs, pump maintenance, PCM inspection);
- recurring fuel purchases (LPG cylinders, purchased fuelwood) or imputed costs of collected biomass;
- direct emissions from fuel combustion and associated local environmental impacts; and
- social variables such as time spent collecting fuel or tending fires, and qualitative health co-benefits from reduced smoke exposure.

Upstream manufacturing emissions and end-of-life disposal are noted qualitatively but not quantified, since the focus is on operational performance and decision-relevant trade-offs for local stakeholders.

2.3 Energy scenarios

Three primary scenarios are constructed for each user type:

Scenario 1 – LPG-only baseline

All cooking is performed on a conventional LPG stove. For households, annual consumption is assumed at nine 14.2-kg cylinders. For community kitchens, annual consumption is set at forty cylinders. Crop drying is conducted via open-sun methods with opportunistic use of small biomass-fired dryers during rainy spells. This scenario represents a modern-fuel baseline with relatively low indoor air pollution but high recurring fuel expenditure and climate-relevant emissions.

Scenario 2 – Mixed LPG–biomass baseline

Cooking is split between LPG and traditional or simple biomass stoves. Households use around five LPG cylinders per year plus 2.5 tonnes of fuelwood, collected and/or purchased. Community kitchens use forty LPG cylinders plus around twelve tonnes of fuelwood for large-pot cooking and ad hoc drying. This scenario reflects common energy-mix realities in many rural and peri-urban settings, where LPG is reserved for quick cooking and emergency use, while biomass remains the default for long-duration tasks.

Scenario 3 – PTC–PCM solar cooking and drying with LPG backup

The PTC–PCM system provides most of the energy for midday and evening cooking as well as a significant portion of crop drying requirements. LPG is retained as a backup fuel for very cloudy days, early-morning cooking and some high-temperature frying tasks. Fuelwood is not used for cooking. Based on the experimentally demonstrated performance of the prototype and realistic utilisation patterns, household LPG use is assumed to fall from nine to 2.7 cylinders per year (70% reduction), while community kitchens experience a 75% reduction in LPG use and elimination of routine cooking-related fuelwood consumption.

3. Techno-economic methodology

3.1 Cost components and financial parameters

The economic evaluation uses a discounted cash-flow framework with a 15-year analysis period, corresponding to a realistic technical life for a properly maintained PTC–PCM system. The key cost components are:

- **Capital expenditure (CAPEX)** on hardware and installation;
- **Annual operation and maintenance (O&M)** costs; and
- **Annual fuel expenditures** for LPG and biomass under each scenario.

A real discount rate of 8% is adopted to reflect the opportunity cost of capital in many developing-country contexts, though this is varied in sensitivity analysis. The principal economic indicators are:

- simple payback period (years);
- discounted payback period;
- net present value (NPV) of the solar system relative to the baseline;
- benefit–cost ratio (BCR); and
- levelised cost of useful thermal energy (LCUTE) in INR per megajoule of pot- or tray-level heat.

Representative cost and technical assumptions for the household and community systems are given in **Table 1**.

Table 1. Representative techno-economic assumptions for PTC–PCM systems and baseline fuels

Parameter	**Household system**	**Community system**
PTC–PCM CAPEX (INR)	50,000	200,000
Annual O&M (% of CAPEX)	2.5%	2.0%
Project life (years)	15	15
Discount rate (real)	8%	8%
Annual LPG use, baseline (cyl/year)	9	40
LPG price (INR per 14.2-kg cylinder)	1,100	1,100
LPG reduction with PTC–PCM	70%	75%
Annual fuelwood use, baseline (t/y)	2.5	12
Fuelwood shadow price (INR/t)	3,000	3,000
Solar performance degradation	0.5% per year	0.5% per year

The shadow price of fuelwood includes both cash payments and the imputed value of time spent collecting and transporting wood. Solar performance degradation captures gradual reflector soiling, minor optical losses and PCM ageing.

3.2 Calculation of levelised cost of useful thermal energy

To compare scenarios, the levelised cost of useful thermal energy is calculated as:

$$LCUTE = \frac{NPC_{capital} + NPC_{O\&M} + NPC_{fuel}}{NPQ_{thermal}}$$

where the numerator aggregates net present costs of capital, O&M and fuel, and $NPQ_{thermal}$ is the net present quantity of useful thermal energy delivered at the cooking pot or drying tray. Device and fuel efficiencies are used to convert input energy (e.g., LPG calorific value) to useful energy, recognising the different conversion efficiencies and losses in LPG stoves versus the PTC–PCM system.

This allows statements such as: *"for the same service level, LCUTE in the PTC–PCM + LPG scenario is 15–20% lower than in the LPG-only baseline."*

4. Results

4.1 Household-scale economics

For the LPG-only household, annual expenditure on LPG in the base year is approximately INR 9,900. In Scenario 3, where the PTC–PCM system supplies most cooking energy, LPG consumption falls to about 2.7 cylinders per year, or roughly INR 2,970 in fuel costs. Adding annual O&M of INR 1,250 yields a total first-year outlay of INR 4,220. The net first-year saving relative to the LPG-only baseline is therefore about INR 5,700.

With flat real fuel prices, the simple payback period (CAPEX divided by annual savings) is approximately 8.8 years. Assuming modest real fuel price escalation of 3% per year, the discounted payback period shortens to about 6.5–7 years. Over the 15-year horizon, the discounted value of fuel savings exceeds the discounted cost of the PTC–PCM system, yielding a positive NPV and a BCR of roughly 1.6.

The LCUTE for the combined PTC–PCM + LPG option is around 15–20% lower than that of LPG-only cooking, assuming the solar system is routinely used when solar energy is available. Under-utilisation would lengthen payback and weaken the economic case.

Table 2. Indicative household-scale economic performance

Indicator	LPG-only baseline	PTC–PCM + LPG
CAPEX (INR)	0	50,000
Annual O&M (INR, year 1)	0	1,250
Fuel cost (INR, year 1)	9,900	2,970
Net savings (INR, year 1)	–	~5,700
Simple payback (years, no escalation)	–	~8.8
Discounted payback (years, 3% esc.)	–	~6.5–7.0
Benefit–cost ratio (15-year horizon)	–	~1.6
LCUTE (INR/MJ useful heat, relative)	baseline	~15–20% lower

4.2 Community-scale economics

Scaling the PTC–PCM system for a community kitchen and agro-processing unit increases CAPEX to about INR 200,000 but also substantially raises utilisation. Baseline LPG consumption is forty cylinders per year, with about twelve tonnes of fuelwood used annually for cooking and drying. Under Scenario 3, LPG demand is reduced by roughly 75% and routine cooking-related fuelwood use is eliminated.

Under these conditions, first-year savings from reduced LPG and fuelwood can exceed INR 80,000, even after accounting for about INR 4,000 in O&M. The simple payback period is around 2.5–3 years; with discounting and fuel price escalation, the effective payback is closer to four years. Over fifteen years, the BCR is approximately 2.1, and LCUTE is significantly lower than in the baseline mixed-fuel scenario.

This underscores the advantage of targeting higher and more continuous demand contexts—schools, community kitchens, hospitals and cooperatives—where fixed capital assets are heavily used.

4.3 Environmental outcomes

At household level, reducing LPG use from nine to 2.7 cylinders per year cuts LPG-related CO_2 emissions by several hundred kilograms annually. If the household previously used a mixed LPG–biomass strategy, eliminating about 2.5 tonnes of fuelwood for cooking further reduces CO_2-equivalent emissions and relieves local forest pressure. Over the 15-year life, cumulative reductions can reach 12–20 tonnes of CO_2-equivalent per system, depending on baselines and utilisation.

For the community system, combined reductions in LPG and fuelwood translate into estimated annual CO_2-equivalent savings of around 1.8–2.5 tonnes and lifetime savings of roughly 25–35 tonnes. These estimates exclude upstream emissions from fuel extraction and transport; including those would strengthen the relative advantage of the solar system.

Beyond CO_2, the sharp reduction in biomass combustion significantly lowers emissions of particulates, carbon monoxide and black carbon—pollutants with serious health and climate impacts. Although not quantified here, these benefits are well-documented in clean-cooking literature.

4.4 Social and livelihood implications

The PTC–PCM system also generates several intertwined social benefits:

- **Time and drudgery reduction:** Eliminating fuelwood collection can free up 100–150 hours per year for a household and substantially more at community scale, easing physical burdens and giving particularly women and children more time for schooling, income-generation or rest.

- **Health co-benefits:** Reduced exposure to smoke lowers the risk of respiratory illness and eye irritation. This is especially relevant in mixed-fuel baselines where biomass fires continue alongside LPG.
- **Food security and livelihoods:** Controlled drying conditions reduce post-harvest losses and improve product quality for chilli, spices and fruits. Evening drying using stored heat increases throughput and stabilises small agro-enterprises.
- **Gender and agency:** Because women are typically primary cooks and fuel collectors, they stand to gain most from time savings and health improvements. Empowering women's groups to own and govern community systems can enhance agency and ensure that design choices reflect local preferences.

These elements are summarised in **Table 3**.

Table 3. Environmental and social indicators for PTC–PCM systems (indicative ranges)

Indicator	Household system	Community system
Annual LPG reduction	~70%	~75%
Annual fuelwood reduction	2.5 t (cooking)	12 t (cooking)
Annual CO_2-e reduction	0.8–1.4 t	1.8–2.5 t
Time savings (fuel collection)	100–150 hours/year	250–400 hours/year
Indoor smoke exposure	Strongly reduced	Strongly reduced
Crop-drying quality	Improved	Improved (larger scale)
Livelihood opportunities	Small-scale	Expanded (co-operative)

5. Comparative and sensitivity analysis

5.1 Position relative to other clean cooking options

PTC–PCM systems are one piece of a larger clean-cooking puzzle. PV-based e-cooking uses electricity from solar PV systems to power induction or resistive cookers. It offers high convenience and can be integrated into multi-service energy systems (lighting, appliances, ICT). However, it generally requires higher upfront capital costs, batteries and more complex electronics, which may pose challenges in remote areas with limited technical support.

Improved biomass stoves remain attractive because they are cheaper and compatible with existing fuels and cooking practices. They typically deliver higher efficiency and lower emissions than traditional three-stone fires but still rely on constant fuel supply and emit more pollutants than gas or solar options.

In this portfolio, PTC–PCM solar systems occupy a niche where:

- direct normal irradiance is strong and reliable;
- cooking and drying loads are substantial; and
- local fabrication and repair capacity exists or can be developed.

They are not best suited to cloudy, high-latitude or heavily shaded areas, but in sun-rich regions they can shoulder a large share of cooking and drying demand while other options provide flexibility and backup. A resilient, realistic clean-cooking strategy is likely to combine multiple options rather than betting on a single “hero” technology.

5.2 Sensitivity to utilisation and capital cost

Two parameters strongly shape the economics:

- **Utilisation rate:** If cultural preferences or perceived inconvenience limit use of the solar system, fuel savings will fall and the payback period may exceed system life. If, however, users consciously align meal timings with sunshine and take full advantage of stored heat and drying capacity, utilisation will be high and economic performance strong.
- **Capital cost:** Local standardisation and moderate-scale production can reduce costs per unit of aperture area and storage capacity by 20–30%, dramatically improving payback and BCR. Conversely, reliance on expensive imported components or overly sophisticated tracking systems can undermine affordability.

5.3 Role of policy and institutions

Policy and institutional design will largely determine whether PTC–PCM systems remain interesting prototypes or become widespread tools. Helpful measures include:

- targeted capital subsidies or vouchers for low-income users;
- concessional loans or revolving funds;
- integration with rural development, agricultural value-chain and women’s empowerment schemes;

- technical standards and training frameworks; and
- access to carbon finance or other performance-based rewards.

Community-based governance—through cooperatives, women's self-help groups or school committees—can pool risks and responsibilities, ensure proper use and maintenance, and embed the technology in local social structures.

6. Limitations and future work

The analysis has limitations:

- All numerical results are based on *created but plausible* data rather than long-term monitored field deployments. Real-world performance will vary with climate, user behaviour, cooking practices and build quality.
- Fuel price dynamics are simplified; more detailed stochastic modelling could explore economic robustness under volatile prices or policy changes.
- Environmental and health benefits are only partially quantified; full life-cycle assessment and health impact analysis would give a richer picture.
- Social analysis is conceptual rather than empirical; grounded fieldwork using mixed methods is needed to understand how gender, norms and institutions shape adoption and sustained use.

Future research paths include:

- long-term field pilots with high-resolution monitoring of technical performance and user behaviour;
- optimisation studies that integrate stochastic solar and demand profiles;
- hybrid configurations combining PTC–PCM systems with PV, biogas or high-efficiency biomass stoves; and
- participatory social research on gender dynamics, livelihood outcomes and policy design.

7. Conclusions

This paper has reconstructed the techno-economic and socio-environmental implications of a parabolic trough collector–based solar cooking and drying system with PCM thermal storage, building on the thermal and exergy analysis of an experimentally evaluated prototype. Framed within realistic household and community-scale scenarios and populated with coherent, plausible data, the assessment yields several key insights.

At household level, a PTC–PCM system that displaces roughly 70% of LPG use and eliminates fuelwood for cooking can achieve a discounted payback period of about 6.5–7 years, a benefit–cost ratio greater than 1, and a lower LCUTE than LPG-only cooking, provided utilisation is robust. At community scale—where utilisation is higher—the payback period can drop to around four years and the benefit–cost ratio can exceed 2.0, especially when drying functions are used intensively for value-added agro-products.

Environmentally, the systems can avoid multiple tonnes of CO_2-equivalent emissions over their life and relieve pressure on local biomass resources, while also slashing indoor smoke exposure. Socially, they promise time savings, health improvements, better food security and new livelihood pathways, particularly if women and marginalised groups are central in design and governance.

Yet PTC–PCM systems are not a universal answer. They are highly sensitive to utilisation, context and policy support. Their strongest role is as part of a diversified clean-cooking ecosystem alongside LPG or biogas, improved biomass stoves and PV-based e-cooking, each addressing different aspects of the cooking and energy puzzle.

In summary, parabolic trough collector–PCM solar cooking and drying systems constitute a technically robust and potentially cost-effective pillar of clean-cooking transitions in sun-rich regions. With thoughtful design, supportive policies, local manufacturing and strong community engagement, they can help reconfigure household energy practices in ways that are healthier, more affordable and more sustainable for the communities that need it most.

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