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# Techno-Economic Analysis of Solar PV–Battery-Based Microgrids for Rural Electrification

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**ABSTRACT**
Access to reliable and affordable electricity remains a persistent challenge in rural and remote regions, where grid extension is often technically difficult and economically unviable due to low population density, scattered habitation, and difficult terrain. Solar photovoltaic (PV)–battery-based microgrids have emerged as a promising decentralized alternative for achieving sustainable and reliable rural electrification. This study presents a techno-economic analysis of a standalone solar PV–battery microgrid designed to meet the electricity demand of a representative rural community. The proposed framework integrates load profiling, PV array and battery bank sizing, and economic evaluation using key indicators such as Net Present Cost (NPC), Levelized Cost of Energy (LCOE), simple payback period, and internal rate of return (IRR). A representative case configuration, developed using assumed load and resource data consistent with values reported in the literature, is analyzed to assess technical feasibility and financial viability, and a sensitivity analysis is carried out to examine the influence of solar irradiance, battery cost, discount rate, and load growth on system economics. The results indicate that solar PV–battery microgrids can provide a technically reliable and increasingly cost-competitive solution for rural electrification, particularly as battery costs continue to decline, although high upfront capital cost and periodic battery replacement remain the dominant economic constraints. The study concludes with recommendations for policy support, system hybridization, and future research directions to enhance the scalability and long-term viability of PV–battery microgrids in rural areas.

**Keywords:** Solar PV, Battery Energy Storage System (BESS), Microgrid, Rural Electrification, Techno-Economic Analysis, Levelized Cost of Energy (LCOE), Net Present Cost (NPC), HOMER Pro, Renewable Energy, Off-grid Systems, Payback Period, Sustainable Development.

## I. INTRODUCTION

Electricity access is a fundamental enabler of socio-economic development, yet a substantial proportion of the rural population in developing regions continues to face unreliable or entirely absent grid supply. Extending the conventional utility grid to sparsely populated, geographically remote, or hilly terrain is frequently constrained by high infrastructure cost, long transmission distances, and low load density, which together make grid extension technically complex and financially unattractive for utilities. In this context, decentralized renewable energy systems, and solar photovoltaic (PV)–battery-based microgrids in particular, have emerged as a technically sound and increasingly affordable pathway to bring reliable electricity to unserved and underserved rural communities.

A solar PV–battery microgrid combines a PV array, a battery energy storage system (BESS), power conditioning units (charge controllers and inverters), and a local distribution network to supply electricity to a cluster of households, institutions, or small enterprises, either in a fully standalone (off-grid) configuration or with limited grid interaction. Because solar irradiance is intermittent and unavailable during the night, battery storage is essential to buffer the mismatch between generation and demand and to ensure a continuous and reliable power supply. The declining cost of PV modules and lithium-ion batteries over the past decade has considerably improved the economic competitiveness of such

systems relative to diesel generation and, in many cases, relative to grid extension itself.

While the technical design of PV–battery microgrids is relatively well established, their long-term viability depends critically on techno-economic feasibility — that is, whether the system can reliably meet the projected load over its operating life at a cost that is affordable to users, financially sustainable for the implementing agency, and competitive with alternative electrification options. Techno-economic analysis therefore combines system sizing and performance simulation with financial evaluation using indicators such as Net Present Cost (NPC), Levelized Cost of Energy (LCOE), payback period, and internal rate of return (IRR), and is commonly supported by simulation and optimization tools such as HOMER Pro.

This paper, titled "Techno-Economic Analysis of Solar PV–Battery-Based Microgrids for Rural Electrification," presents a structured framework for evaluating the technical feasibility and economic viability of such systems. The study reviews recent literature on PV–battery and hybrid renewable microgrids for rural electrification, outlines the limitations of existing electrification approaches, proposes a system design and evaluation methodology, and illustrates the approach through a representative case configuration with sensitivity analysis. The overall objective is to provide planners, researchers, and policymakers with a clear, reproducible methodology for assessing whether a solar PV–battery microgrid is a technically feasible and economically sound option for a given rural context.

## II. LITERATURE SURVEY

### *1. Chaurey and Kandpal (2010) – Solar Home Systems vs. PV Microgrids*

Authors: Akanksha Chaurey, Tara Chandra Kandpal | Year: 2010 | Title: A Techno-Economic Comparison of Rural Electrification Based on Solar Home Systems and PV Microgrids

Chaurey and Kandpal compared solar home systems (SHS) and PV-based microgrids for rural electrification using annualised life-cycle cost as the basis for comparison, across varying numbers of households and distribution network lengths. The study found that a microgrid configuration is generally the more economical option for villages with flat terrain, more than about 500 densely located households, and a modest daily load such as a few low-power CFL lamps used for a few hours each evening, while SHS remains preferable for very sparse or scattered habitations. The work remains a foundational reference for comparing individual versus community-scale solar electrification options.

### *2. Amutha and Rajini (2016) – HOMER-Based Analysis for Southern India*

Authors: W. M. Amutha, V. Rajini | Year: 2016 | Title: Cost Benefit and Technical Analysis of Rural Electrification Alternatives in Southern India Using HOMER

Amutha and Rajini used HOMER software to evaluate multiple rural electrification alternatives, including solar PV, biomass, and hybrid PV-battery-diesel configurations, for unelectrified villages in southern India. The study compared these decentralized options against grid extension on the basis of cost of energy and net present cost, concluding that renewable-based microgrids can be more economical than grid extension for remote villages beyond a certain distance from the existing network, while also highlighting the sensitivity of results to local solar resource and load assumptions.

### *3. Bahramara, Moghaddam, and Haghifam (2016) – Review of HOMER-Based Planning*

Authors: S. Bahramara, M. Parsa Moghaddam, M. R. Haghifam | Year: 2016 | Title: Optimal Planning of Hybrid Renewable Energy Systems Using HOMER: A Review

This widely cited review examined a large body of literature that uses the HOMER (Hybrid Optimization Model for Electric Renewables) tool for sizing and techno-economic evaluation of hybrid renewable energy systems. The authors summarized how HOMER's simulation, optimization, and sensitivity-analysis capabilities are used to determine cost-optimal combinations of PV, wind, diesel, and battery storage, and discussed the strengths and limitations of the tool, including its treatment of component

degradation, dispatch strategy, and uncertainty in resource data.

***4. Ibrik (2019) – Micro-Grid Solar Electrification in Palestine***

Author: Imad H. Ibrik | Year: 2019 | Title: An Overview of Electrification of Rural Areas in Palestine by Using Micro-Grid Solar Energy

Ibrik presented the techno-economic impact of electrifying small rural communities in Palestine using PV-based micro-grids, comparing the approach with diesel-generator-based supply. The study reported that PV micro-grids can meet household and street-lighting loads while substantially reducing CO2 emissions relative to diesel generation, and argued that micro-grid PV systems are a practical solution where grid connection is politically or financially constrained.

***5. Prum, Goh, Zhang, Dai, Kurniawan, and Goh (2024) – Hybrid Systems in Asian LDCs***

Authors: Mengly Prum, Hui Hwang Goh, Dongdong Zhang, Wei Dai, Tonni Agustiono Kurniawan, Kai Chen Goh | Year: 2024 | Title: Optimizing Hybrid Energy Systems for Remote Communities in Asia's Least Developed Countries

Using HOMER-based techno-economic analysis, this study assessed hybrid solar PV–wind–battery–diesel configurations across remote locations in Cambodia, Laos, Myanmar, and Bangladesh. The authors demonstrated that renewable-dominant hybrid systems consistently reduced life-cycle cost and emissions compared with diesel-only supply, and highlighted the importance of site-specific resource data and load profiling in achieving cost-optimal designs for least-developed-country contexts.

***6. Ali, Biswas, Sheikh, Al Mamun, and Hossen (2025) – Battery Technology Comparison for Rural Bangladesh***

Authors: Md. Feroz Ali, Diganto Biswas, Md. Rafiqul Islam Sheikh, Abdullah Al Mamun, Md. Jakir Hossen | Year: 2025 | Title: Techno-Economic Optimization of Battery Storage Technologies for Off-Grid Hybrid Microgrids in Multiple Rural Locations of Bangladesh

This study compared four battery energy storage technologies — ZnBr flow, Li-ion NMC, lead-acid, and LiFePO4 — within PV-wind hybrid microgrids across five rural Bangladeshi locations using HOMER Pro and real hourly load and resource data. The results indicated that flow-battery-based configurations achieved the most favourable techno-economic and environmental performance in several locations, underscoring that battery chemistry choice can materially affect system cost of energy and renewable fraction, and is therefore an important design decision in PV-battery microgrid planning.

***7. Ali, Ali, Biswas, Al Mamun, and Hossen (2025) – Village-Scale Hybrid Microgrid Model***

Authors: Md. Ripon Ali, Md. Feroz Ali, Diganto Biswas, Abdullah Al Mamun, Md. Jakir Hossen | Year: 2025 | Title: Sustainable Energy Solutions for Rural Bangladesh: An Optimized Hybrid Microgrid Model

This study developed and optimized a PV–wind–biogas–battery–grid hybrid microgrid for a rural village, using a bottom-up device-usage load profile and satellite-derived resource data in HOMER Pro. The optimal configuration achieved over 80% renewable penetration at a low levelized cost of energy, and sensitivity analysis showed that PV capital cost and grid sellback price exerted the strongest influence on overall system economics, more so than wind or biogas cost variation.

***8. Raja Sekhar, Chiranjeevi, et al. (2026) – Tribal Village Case Study, India***

Authors: Y. Raja Sekhar, C. Chiranjeevi, et al. | Year: 2026 | Title: Optimising Hybrid Renewable Energy Systems for Remote Tribal Villages: A Techno-Economic Case Study from Central and Eastern India

This recent case study evaluated site-specific hybrid renewable configurations, including solar PV, wind, battery storage, and diesel backup, for two remote tribal villages in Madhya Pradesh and Jharkhand, India, that lack grid connectivity due to dense forest cover. Using NPC, LCOE, and emission metrics alongside sensitivity analysis of resource and demand variability, the authors found that incorporating demand-side management strategies could reduce both LCOE

and NPC by up to 20%, illustrating that load-side interventions, not only supply-side sizing, materially affect the economics of rural PV-battery microgrids.

## III. EXISTING SYSTEM

Rural electrification has traditionally been pursued through three broad approaches: (i) extension of the central utility grid, (ii) diesel-generator-based decentralized supply, and (iii) individual solar home systems (SHS). Grid extension, while offering a stable and familiar supply, requires substantial capital investment in transmission and distribution infrastructure and is often deferred or ruled out for remote, low-density, or difficult-terrain communities due to poor cost recovery. Diesel-generator-based mini-grids can provide reliable power on demand but are burdened by high and volatile fuel costs, logistical difficulty in fuel transport to remote areas, ongoing maintenance requirements, and significant greenhouse gas and local air pollutant emissions. Standalone solar home systems provide basic lighting and mobile-charging services to individual households but typically supply only a small, fixed load, offer limited scope for productive or community use, and do not benefit from the economies of scale available to a shared microgrid. Existing hybrid systems reported in the literature (PV/wind/diesel/battery, PV/biomass/battery, etc.) improve reliability and reduce emissions relative to diesel-only supply, but often introduce additional complexity, multiple technology dependencies, and higher operation and maintenance burden that may not be appropriate for every rural site. There remains a need for a simplified, standardized techno-economic evaluation framework, focused specifically on solar PV–battery configurations, that rural planners and small implementing agencies can apply with locally available data.

## IV. PROPOSED SYSTEM

The proposed work develops a techno-economic evaluation framework for a standalone solar PV–battery microgrid intended to supply a cluster of rural households, along with common community loads such as street lighting, a school, and a primary health sub-centre. The framework proceeds through four stages: (1) load assessment, in which the daily and seasonal electricity demand of the community is estimated from appliance-level or survey-based data; (2) system sizing, in which the PV array capacity, battery bank capacity, and power conditioning unit (inverter/charge controller) ratings are determined to reliably meet the estimated load with an acceptable loss-of-power-supply probability; (3) economic modelling, in which capital cost, replacement cost, and operation and maintenance (O&M) cost are combined with the system's expected performance to compute NPC, LCOE, payback period, and IRR; and (4) sensitivity analysis, in which key uncertain parameters — solar resource variability, battery cost trajectory, discount rate, and load growth — are varied to test the robustness of the techno-economic conclusions. Unlike hybrid diesel- or biomass-integrated systems, the proposed framework focuses specifically on a PV–battery-only configuration, reflecting the growing number of rural sites where battery costs have fallen sufficiently for a fully renewable, fuel-free system to be competitive, while retaining the option to compare against a diesel-backed or grid-extension baseline as an economic benchmark.

## V. SYSTEM METHODOLOGY

### *A. Load Estimation*

The daily electrical load of the target community is estimated by aggregating the power rating and expected hours of use of household appliances (lighting, fans, mobile charging, television) and community loads (street lighting, school, health sub-centre), producing an hourly load profile for a representative day in each season. A system design margin (typically 20–30%) is added to the estimated peak load to account for future load growth and forecasting uncertainty.

### *B. PV Array and Battery Sizing*

The required PV array capacity is estimated from the daily energy demand and the site's peak sun hours (average daily solar irradiance expressed in equivalent full-sun hours), adjusted for system losses (soiling, temperature derating, wiring, and inverter efficiency). The battery bank is sized to provide a specified number of autonomy days

(typically 1–2 days for PV–battery-only systems) at the design depth of discharge appropriate to the battery chemistry (for example, 80% for lithium-ion, 50% for lead-acid), while charge controller and inverter ratings are selected to handle the peak PV output and peak load, respectively.

### *C. Economic Indicators*

The economic viability of the system is assessed using the following standard indicators, consistent with the methodology commonly implemented in tools such as HOMER Pro:

Net Present Cost (NPC): the present value of all costs incurred over the project lifetime, including initial capital cost, replacement cost of components (principally the battery bank), and operation and maintenance cost, minus the present value of any salvage value at the end of the project life.

Levelized Cost of Energy (LCOE): the NPC converted to an equivalent uniform annual cost using the capital recovery factor, divided by the total annual electricity served, expressed as cost per kWh — this is the key metric for comparing PV–battery microgrids against grid tariffs or diesel-based alternatives.

Simple Payback Period: the time required for cumulative savings (or avoided cost relative to the baseline, such as diesel generation or kerosene/candle use) to equal the initial investment.

Internal Rate of Return (IRR): the discount rate at which the net present value of the project's cash flows equals zero, used to assess the project's attractiveness relative to the cost of capital.

### *D. Simulation and Sensitivity Analysis*

Consistent with the approach adopted in the reviewed literature, system simulation and sizing optimization can be performed using HOMER Pro or an equivalent techno-economic simulation tool, using site-specific solar resource data (for example, from NASA POWER or similar databases), local component costs, and the estimated load profile. A sensitivity analysis is subsequently performed by varying solar irradiance (±10–15%), battery capital cost (reflecting the observed and projected decline in lithium-ion battery prices), discount rate, and annual load growth rate, to identify which parameters most strongly influence the resulting LCOE and payback period, and thereby to understand the robustness of the base-case techno-economic result.

## VI. ILLUSTRATIVE CASE STUDY AND RESULTS

To demonstrate the application of the proposed framework, an illustrative case configuration is presented for a representative rural cluster of 100 households plus common community loads, broadly consistent with rural settlement patterns in Telangana and similar solar-resource regions of India (average daily peak sun hours of approximately 5.5 hours). The parameters, cost assumptions, and resulting indicators below are illustrative — based on typical values reported in the literature reviewed in Section II — and are intended to demonstrate the evaluation methodology; they should be replaced with site-measured load data and local, current vendor quotations before being used for an actual investment or publication-grade result.

***Table 1. Illustrative System Configuration***

| Parameter | Assumed Value |
|---|---|
| Households served | 100 |
| Estimated peak load | 18 kW |
| Average daily energy demand | 95 kWh/day |
| Average daily peak sun hours | 5.5 h/day |
| PV array capacity (sized) | 28 kWp |
| Battery bank capacity (Li-ion, 1.5-day autonomy, 80% DoD) | 45 kWh |

| Parameter | Assumed Value |
|---|---|
| Inverter / power conditioning unit rating | 20 kVA |
| System design life | 20 years (battery replacement at year 10) |

***Table 2. Illustrative Techno-Economic Results***

| Indicator | Illustrative Value |
|---|---|
| Total initial capital cost | ≈ ₹ 28–32 lakh (≈ USD 34,000–39,000) |
| Net Present Cost (NPC), 20-year life | ≈ ₹ 45–52 lakh |
| Levelized Cost of Energy (LCOE) | ≈ ₹ 9–12 / kWh (≈ USD 0.11–0.14 / kWh) |
| Simple payback period (vs. diesel baseline) | ≈ 6–8 years |
| Internal Rate of Return (IRR), 20-year horizon | ≈ 10–14% |
| Renewable fraction | 100% |

These illustrative results are broadly consistent with LCOE ranges reported for standalone and hybrid PV-battery rural microgrids in the reviewed literature, where reported values range from below USD 0.02/kWh for large, grid-supported or biogas-supplemented hybrid configurations, up to USD 0.25–0.70/kWh for small, fully standalone systems in high-cost or low-resource locations. The relatively favourable LCOE obtained in the illustrative case reflects the assumption of a reasonably high solar resource and a moderate battery cost per kWh; sites with lower irradiance, higher transport and installation costs, or smaller community size would be expected to show a correspondingly higher LCOE, reinforcing the importance of site-specific assessment rather than generic benchmarking.

***Sensitivity Analysis***

A one-at-a-time sensitivity analysis on the illustrative case indicates the following qualitative trends, consistent with findings reported by Ali et al. (2025) and Raja Sekhar et al. (2026):

- Battery capital cost has the strongest influence on LCOE among the parameters tested, given that the battery bank and its mid-life replacement represent a substantial share of total system cost; a 20% reduction in battery cost per kWh reduces the illustrative LCOE by roughly 8–10%.
- Solar irradiance directly affects the required PV and battery sizing; a 10% reduction in average irradiance increases the illustrative LCOE by approximately 6–9%, underscoring the importance of accurate, site-specific resource data.
- Discount rate has a moderate effect, with higher discount rates (reflecting higher-risk or commercially financed projects) increasing LCOE, while low-cost or subsidized financing markedly improves project economics and shortens payback period.
- Unanticipated load growth beyond the design margin increases both battery cycling stress and the likelihood of load-shedding events, indicating the value of building in a reasonable demand growth allowance at the design stage rather than expanding the system reactively.

## VII. CONCLUSION

This study presented a techno-economic analysis framework for solar PV–battery-based microgrids aimed at rural electrification, combining load estimation, PV and battery sizing, and standard economic evaluation indicators — NPC, LCOE, payback period, and

IRR — within a structured, reproducible methodology. A review of recent literature confirmed that PV–battery and related hybrid renewable microgrids can achieve levelized costs of energy that are competitive with, or lower than, diesel-based and in some cases grid-extended alternatives, particularly as battery costs continue to fall and simulation tools such as HOMER Pro are used to identify cost-optimal system configurations. The illustrative case configuration presented in this paper indicated that a 100-household PV–battery microgrid in a moderate-to-good solar resource region can achieve a payback period of roughly six to eight years and a positive internal rate of return over a twenty-year project life, though battery capital cost and local solar resource remain the dominant drivers of overall project economics. Solar PV–battery microgrids therefore represent a technically viable and increasingly cost-competitive pathway for extending reliable electricity access to unserved and underserved rural communities, provided that system design is grounded in accurate, site-specific load and resource data rather than generic assumptions.

## VIII. FUTURE SCOPE

Future work can extend the proposed framework in several directions. Site-specific validation using measured hourly load profiles and locally sourced component quotations would improve the accuracy of the techno-economic estimates beyond the illustrative values presented here. Comparative analysis against grid-extension cost per connected household, and against hybrid configurations incorporating a small wind, biogas, or diesel-backup component, would help identify the least-cost electrification pathway for a given site. Incorporating demand-side management strategies — as demonstrated to reduce LCOE and NPC by researchers such as Raja Sekhar et al. (2026) — and evaluating alternative battery chemistries, including flow batteries and LiFePO4, as examined by Ali et al. (2025), could further improve system economics and reliability. Finally, integration of productive-use loads (agro-processing, cold storage, irrigation pumping) into the load profile, along with policy and financing mechanisms such as capital subsidies, results-based financing, or pay-as-you-go models, merits further study to strengthen the long-term financial sustainability and developmental impact of rural solar PV–battery microgrids.

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