AI-Enabled Virtual Resilience Assessment Framework for Community-Managed Rural Hybrid Microgrids: A Case Study Approach

Dr Anurag S D Rai[1], Prof. (Dr.) Shashi Kant Gupta[2*]

[1]Post Doctoral Researcher, [2]Supervisor
[1](pdf.anuragrai@lincoln.edu.my), [2](shashigupta@lincoln.edu.my),
Lincoln University College, Petaling Jaya, Selangor Darul Ehsan-47301, Malaysia

Abstract

Reliable electricity access in remote tribal regions of India remains constrained by weak grid infrastructure and seasonal supply interruptions. This paper presents an AI-assisted virtual resilience assessment framework for community-managed rural hybrid microgrids using three real-world deployments in Central India: Harshdiwari, Kanarkheda, and Mudpar. The deployed 3 kW off-grid systems integrate solar photovoltaic generation, battery storage, and biogas-based auxiliary backup under a decentralized Rural Energy Bank model.

Operational field data, HOMER Pro-based virtual modelling, and AI-assisted analytical methods were used to evaluate system resilience under varying climatic and load conditions. Key indicators such as photovoltaic generation, renewable fraction, battery state-of-charge, unmet load, and generator dependency were analyzed along with socio-economic parameters including kerosene reduction and productive load utilization.

Results show that all systems satisfied more than 98% of annual energy demand, with renewable energy fractions between 97.9% and 100%, and unmet load below 1.05%. The systems maintained nearly 1.5 days of battery autonomy despite monsoon-induced variability. The proposed framework transforms operational rural hybrid microgrids into AI-assisted virtual resilience models for developing scalable and repeatable decentralized energy systems.

Keywords— Rural Microgrids, Hybrid Renewable Energy Systems, Resilience Assessment, Rural Electrification, AI-Assisted Framework.

---

1. Introduction

Reliable electricity access remains a major challenge in remote tribal and rural regions of India due to weak grid infrastructure, difficult terrain, and seasonal supply interruptions. Although decentralized renewable energy systems, particularly solar photovoltaic (PV)-based microgrids, have emerged as viable alternatives for rural electrification, their long-term sustainability and resilience under diverse climatic conditions remain critical concerns.

Hybrid microgrids integrating solar PV, battery storage, and auxiliary backup systems offer localized power generation with improved operational flexibility compared to conventional grid extension approaches. However, system performance is significantly influenced by solar intermittency, seasonal variability, battery degradation, and limited maintenance support in remote areas.

Recent studies on rural microgrids primarily focus on techno-economic optimization and simulation-based system sizing. Limited work has been reported on resilience-oriented assessment using real operational deployments, especially in community-managed rural energy systems. Similarly, the application of AI-assisted and Digital Twin-inspired approaches in decentralized rural microgrids remains at an early stage.

To address these gaps, this paper presents an AI-assisted virtual resilience assessment framework based on three operational rural hybrid microgrids deployed in distinct agro-climatic regions of Central India. The framework integrates operational datasets, virtual modelling, and resilience indicators for evaluating system reliability and scalability under varying operating conditions.

The major contributions of this work include:

1. Development of a virtual resilience assessment framework for rural hybrid microgrids.
2. Integration of real operational data from three community-managed deployments.
3. AI-assisted analysis of load behavior and resilience indicators.
4. Comparative evaluation of technical and socio-economic performance.
5. Proposal of a scalable framework for decentralized rural electrification.

---

2. Case Study and Methodology

The study is based on three operational 3 kW community-managed rural hybrid microgrids deployed in Harshdiwari (Madhya Pradesh), Kanarkheda (Madhya Pradesh), and Mudpar (Chhattisgarh). The selected villages represent diverse agro-climatic and socio-economic conditions including hilly terrain, semi-arid plains, and forested regions.

Table 1. Key Characteristics of Study Villages

Parameter	Harshdiwari	Kanarkheda	Mudpar
Terrain	Hilly/Forested	Semi-Arid Plains	Dense Forest
Avg. Solar Irradiance	~5.25	~5.35	~5.3–5.4
Population (HH)	~680 (125)	~940 (162)	~740 (137)
Grid Supply	Unreliable	Unreliable	Very Poor
Major Occupation	Farming/NTFP	Farming/Livestock	Agriculture/Crafts

The deployed systems integrate solar PV generation, battery storage, biogas-based auxiliary backup, productive loads, and decentralized Rural Energy Bank operational structures.

The proposed methodology follows:

Existing Deployment → Data Collection → Virtual Modelling → AI-Assisted Analysis → Resilience Assessment → Scalable Framework

Operational datasets including PV generation, battery SOC, load served, unmet load, generator runtime, and seasonal variations were collected and analyzed. Virtual system models were developed using HOMER Pro. The AI-assisted analytical framework focused on load trend analysis, seasonal variability assessment, and operational pattern evaluation for resilience-oriented performance analysis.

---

3. Performance and Resilience Assessment

The deployed systems were monitored over a 12-month operational period to evaluate technical and resilience performance.

Table 2. Annual Performance Indicators

Parameter	Harshdiwari	Kanarkheda	Mudpar
PV Generation (kWh/year)	2936	3071	2920
Load Served (kWh/year)	2013	1895	2021
Renewable Fraction (%)	98.7	100	97.9
Unmet Load (%)	0.72	0.36	1.05
Generator Runtime (h/year)	125	0	142

All systems fulfilled more than 98% of annual energy demand. Kanarkheda demonstrated the highest renewable contribution due to relatively stable climatic conditions, while Mudpar experienced greater seasonal variability because of dense forest cover and prolonged monsoon conditions.

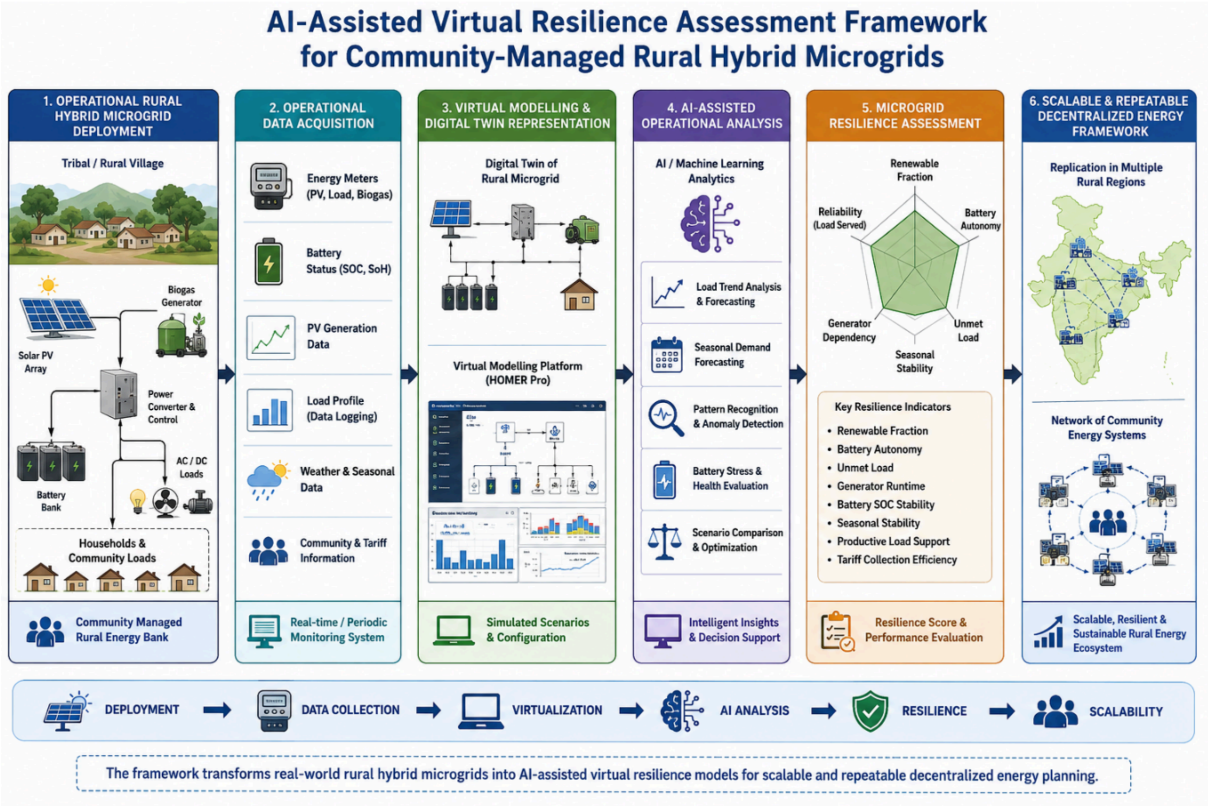

Figure 1.Proposed AI-assisted virtual resilience assessment framework for community-managed rural hybrid microgrids.

Battery autonomy remained close to 1.5 days across all locations, indicating adequate backup capability under fluctuating operating conditions. Seasonal analysis further showed noticeable reductions in photovoltaic generation during monsoon periods due to cloud cover and reduced irradiance availability.

Table 3. Microgrid Resilience Indicators

Parameter	Resilience Impact
Battery Autonomy	Backup capability
Renewable Fraction	Sustainability
Unmet Load	Reliability
Generator Runtime	Backup dependency
Seasonal Stability	Climate adaptability
Productive Loads	Socio-economic sustainability

The resilience framework combines operational monitoring, virtual modelling, and AI-assisted analysis for evaluating system adaptability under varying climatic and load conditions. The proposed approach enables comparative resilience evaluation without requiring physical modification of deployed systems.

The deployed Rural Energy Bank model additionally contributed to improved tariff collection, productive load utilization, women's SHG participation, and reduction in kerosene dependency across all villages.

---

4. Conclusion

This paper presented an AI-assisted virtual resilience assessment framework for community-managed rural hybrid microgrids using real-world deployments from three tribal villages in Central India. The deployed systems demonstrated reliable operation with renewable energy fractions between 97.9% and 100% and unmet load below 1.05%.

The integration of operational field data, virtual modelling, and AI-assisted analytical methods enabled resilience-oriented evaluation of decentralized rural energy systems under diverse climatic conditions. The study also demonstrated the importance of community-managed Rural Energy Bank models in improving operational sustainability and productive energy utilization.

"The proposed framework transforms operational rural hybrid microgrids into AI-assisted virtual resilience models for developing scalable and repeatable decentralized energy systems."

The developed framework provides a practical pathway for scalable and resilient decentralized rural electrification in geographically diverse regions of India.

References

[1] H. Lund, "Renewable energy strategies for sustainable development," Energy, vol. 32, no. 6, pp. 912–919, 2018.
[2] A. Hirsch, Y. Parag, and J. Guerrero, "Microgrids: A review of technologies, key drivers, and outstanding issues," Renewable and Sustainable Energy Reviews, vol. 90, pp. 402–411, 2018.
[3] S. Bahramirad, W. Reder, and A. Khodaei, "Reliability-constrained optimal sizing of energy storage system in a microgrid," IEEE Transactions on Smart Grid, vol. 3, no. 4, pp. 2056–2062, 2017.
[4] M. Shahidehpour and Y. Wang, Communication and Control in Electric Power Systems. Wiley-IEEE Press, 2019.
[5] A. Rai et al., "Community-managed rural hybrid energy systems for decentralized electrification in tribal regions," Internal Project Report, 2024.
[6] HOMER Energy LLC, "HOMER Pro Microgrid Analysis Tool," Boulder, Colorado, USA, 2023.
[7] IEEE PES Task Force, "Definition and classification of power system resilience," IEEE Power and Energy Society Report, 2021.
[8] S. M. Amin and B. Wollenberg, "Toward a smart grid: Power delivery for the 21st century," IEEE Power and Energy Magazine, vol. 3, no. 5, pp. 34–41, 2020.
[9] J. Guerrero, P. Loh, T. Lee, and M. Chandorkar, "Advanced control architectures for intelligent microgrids," IEEE Transactions on Industrial Electronics, vol. 60, no. 4, pp. 1254–1262, 2019.
[10] International Energy Agency (IEA), "World Energy Outlook," Paris, France, 2023.