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Case Study on Smart Microgrid Optimization with Vehicle-to-Grid and Renewable Integration in Rural India

P. Selvakumar[1], Bagus Irawan[2], Naseem Khayum[3]

[1]Department of Mechanical Engineering, PSN College of Engineering and Technology, Tirunelveli, Tamilnadu, India
[2]Department of Electrical Engineering, Universitas Muhammadiyah Semarang, Indonesia
[3]Faculty of Mechanical Engineering, GATES Institute of Technology, India

Corresponding Author: rpselvakumar@gmail.com

Abstract

Access to reliable and sustainable electricity remains a critical challenge in rural India, where frequent outages and dependence on fossil fuels hinder socioeconomic progress. This study aims to evaluate the technical and economic feasibility of a hybrid renewable microgrid integrating photovoltaics (25 kWp), biomass generation (10 kW), and Vehicle-to-Grid (V2G) technology to support the electrification of Alamarathupatti village in Tamil Nadu. A 100% household-level energy survey was conducted to obtain accurate load profiles, revealing an average daily energy consumption of 92.3 kWh and a peak demand of 12.1 kW in the evening. Using HOMER Pro and MATLAB/Simulink, the microgrid was modelled to meet the village's total load, with PV contributing 72.6% of daily energy and biomass covering 27.4%, particularly during non-solar hours. V2G integration provided 4–5 kWh per vehicle during peak periods, enhancing flexibility and grid resilience. The system achieved a Levelized Cost of Electricity (LCOE) of USD 0.094/kWh, lower than the regional tariff of USD 0.115/kWh, resulting in annual household savings of USD 38–45. It also reduced CO_2 emissions by 14.6 tons/year, primarily by replacing diesel and kerosene. The Net Present Cost (NPC) over 20 years was USD 47,200, with a payback period of 7.3 years. Compared to existing models, this study introduces a replicable, flexible, and resilient microgrid design suited for rural, agriculture-based communities. In conclusion, the proposed system offers a scalable, sustainable energy solution aligned with India's rural development and decarbonization goals.

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1. Introduction

Access to reliable and sustainable energy remains a persistent challenge across rural India, where approximately 840 million people globally still lack adequate electricity access, with a significant portion residing in developing regions, including India (Bahagia, Nizar, Yasin, Rosdi, & Faisal, 2025; Erdiwansyah, Mamat, Sani, & Sudhakar, 2019; IEA, 2021; Yana, Mufti, Hasiany, Viena, & Mahyudin, 2025). Despite the government's strides through schemes like Deendayal Upadhyaya Gram Jyoti Yojana (DUGJY), rural communities frequently experience irregular supply, voltage instability, and outages lasting up to 4–6 hours per day (Gani, Saisa, et al., 2025; Irhamni, Kurnianingtyas, Muhtadin, Bahagia,

& Yusop, 2025; Mamat et al., 2019; Pulla & Sakriya, 2022). This inconsistent access to electricity impedes socioeconomic development, particularly in agriculture-dependent villages where energy is critical for irrigation, processing, storage, and mobility (Gani, Zaki, Bahagia, Maghfirah, & Faisal, 2025; Maghfirah, Yusop, & Zulkifli, 2025; Mahidin et al., 2020; Nadimuthu, Victor, Bajaj, & Tuka, 2024). Integrated renewable energy-based microgrids have emerged as a promising solution to address these disparities. Microgrids are localized, decentralized power systems that can operate independently or in conjunction with the central grid, combining various renewable energy sources and energy storage to ensure reliable supply. Their scalability and flexibility make them well-suited for rural and remote applications (Duan, Li, Jordehi, Tostado-Véliz, & Safaraliev, 2024; Erdiwansyah, Mahidin, et al., 2023; Selvakumar, Gani, Xiaoxia, & Salleh, 2025; Zaki, Adisalamun, & Saisa, 2025). Integrating innovative technologies within microgrids, such as demand response systems, real-time monitoring, and automation, enhances their operational efficiency and resilience against grid failures (Efremov & Kumarasamy, 2025; Gani et al., 2023; Li, Ikram, & Xiaoxia, 2025; Yang, Wu, & Li, 2025).

Particularly relevant to the Indian context is the integration of Vehicle-to-Grid (V2G) technology and biomass energy conversion. V2G enables electric vehicles to act as mobile energy storage units that feed electricity into the microgrid during peak demand, increasing flexibility and grid support (Gani, Erdiwansyah, Desvita, Munawar, et al., 2024; Muzakki & Putro, 2025; Nizar et al., 2025; van der Kam & van Sark, 2015). Simultaneously, biomass energy, derived from locally available agricultural residues, offers a sustainable and contextually appropriate energy source for rural communities, helping to offset fossil fuel dependency and reduce greenhouse gas emissions (Almardhiyah, Mahidin, Fauzi, Abnisa, & Khairil, 2025; Erdiwansyah, Gani, et al., 2023; Nadimuthu et al., 2024; Pranoto, Rusiyanto, & Fitriyana, 2025). The hybridization of PV-V2G systems with biomass-fueled generators has shown potential in grid-connected and off-grid scenarios, particularly in innovative village applications (Elkadeem, Kotb, Alzahrani, & Abido, 2025; Gani, Mahidin, et al., 2024; Mufti, Irhamni, & Darnas, 2025; Selvakumar, Maawa, & Rusiyanto, 2025). Rural electrification in India has historically relied on centralized grid extensions, often leading to high transmission losses, inadequate service quality, and delays in reaching remote or dispersed communities (Bose, Saini, Yadav, Shrivastava, & Parashar, 2021; Gani, Erdiwansyah, Desvita, Meilina, et al., 2024; Muhibbuddin, Hamidi, & Fitriyana, 2025; Rosdi, Maghfirah, Erdiwansyah, Syafrizal, & Muhibbuddin, 2025). With over 65% of India's population residing in rural areas, the disparity in energy access has significant implications for national development, food security, education, and healthcare delivery. Furthermore, traditional energy practices in villages, such as reliance on kerosene, diesel, and firewood, pose environmental and health hazards and inhibit the shift toward sustainable living. The evolving landscape of distributed energy resources and policy emphasis on sustainable rural development (e.g., under India's National Energy Policy and Smart Village Mission) has placed microgrids at the forefront of off-grid and weak-grid energy solutions (Bhanja, 2020; Erdiwansyah et al., 2024; Fitriyana, Rusiyanto, & Maawa, 2025; Khalisha, Caisarina, & Fakhrana, 2025).

Renewable energy microgrids, especially those incorporating solar photovoltaics (PV), have been widely adopted for decentralized power supply. However, solar intermittency and storage limitations constrain their performance and resilience. Recent advances in innovative energy technologies like demand-side management, battery storage, and vehicle-to-grid (V2G) systems enable dynamic load balancing and grid support. At the same time, biomass-based generators can provide stable baseload power in rural contexts. The convergence of these technologies creates an opportunity for integrated, context-sensitive microgrids that ensure reliable electricity and promote energy autonomy, local job creation, and environmental sustainability. As India pushes toward its 2070 net-zero emissions target, such integrated microgrid models could serve as replicable blueprints for transforming rural energy systems across the Global South. This study presents a case-based assessment of a renewable-integrated smart microgrid for Alamarathupatti village in Tamil Nadu, India. The microgrid combines photovoltaic (PV) systems with V2G and biomass energy technologies to enhance energy access and resilience. This study aims to assess the techno-economic feasibility of such systems, analyze their impact on peak shaving, and explore their contribution to rural development. The study aims to provide a scalable framework for smart village electrification based on renewable and decentralized technologies through comprehensive household-level surveys, energy modelling, and system design.

2. Methodology

Description of the Study Area and Data Collection

The selected case study is Alamarathupatti village in the Dindigul district of Tamil Nadu, India. This agrarian village faces frequent electricity outages, limited cold-chain infrastructure, and high dependency on traditional biomass and fossil fuels for domestic and agricultural energy needs. A comprehensive 100% household-level survey was conducted using structured questionnaires to gather data on energy consumption patterns, appliance usage, household load profiles, and willingness to adopt decentralized renewable energy solutions. The survey included 57 households and covered demographic information, daily and seasonal load demand, renewable resource availability (solar irradiance and biomass potential), and the current cost of energy access. Primary data collection was supplemented by on-site measurements of solar insolation using pyranometers and biomass resource quantification through residue sampling and estimation of biogas yield potential. Secondary data were obtained from local electricity distribution companies (TNEB), meteorological databases, and the Indian Renewable Energy Development Agency (IREDA) for benchmarking technical parameters.

Smart Microgrid Design and Component Integration

Based on the collected data, a renewable-integrated innovative microgrid system was designed to fulfil the village's electricity and thermal energy requirements through a combination of solar photovoltaics (PV), Vehicle-to-Grid (V2G) enabled electric vehicles (EVs), and biomass-based energy generation.
The proposed system consists of the following major components:

a) Photovoltaic (PV) Modules: Rooftop and ground-mounted 25 kWp PV arrays to capture solar energy based on the average irradiance of 5.2 kWh/m²/day.
b) Biomass Energy Conversion: A dual-mode generator fueled by biogas (via anaerobic digestion) and producer gas (via biomass gasification), contributing up to 10 kW of dispatchable power.
c) Battery Energy Storage System (BESS): Lithium-ion battery bank for short-term storage and grid stabilization.
d) Electric Vehicles with V2G Capability: Two electric vehicles configured with bi-directional chargers to support grid injection during evening peak load.
e) Energy Management System (EMS): A centralized controller for real-time load management, peak shaving, and prioritization of renewable resources.
f) Net Metering and Grid Interface: A smart inverter and control interface enabling partial grid connectivity for export/import under Tamil Nadu's NEM policy.

Simulation Tools and Energy Modeling Approach

System modelling and performance analysis were carried out using a hybrid simulation approach. The HOMER Pro (Hybrid Optimization of Multiple Energy Resources) software was used to simulate the techno-economic feasibility of the microgrid under various configurations. Key input parameters included hourly load profiles, solar resource data, biomass feedstock availability, and economic assumptions (CAPEX, OPEX, fuel cost, feed-in tariffs). To model dynamic energy exchanges and grid interaction, MATLAB/Simulink was used to implement detailed control logic for V2G scheduling, energy dispatch optimization, and demand response algorithms. Additionally, the system's environmental performance was evaluated by calculating greenhouse gas (GHG) emissions offset using IPCC emission factors. Scenario analyses were conducted for:

a) Grid-connected vs. islanded operation
b) Seasonal load variation (summer, monsoon, and winter)
c) Variable biomass feedstock supply
d) The presence or absence of electric vehicles

The outputs from simulations included net present cost (NPC), levelized cost of electricity (LCOE), renewable fraction, CO_2 savings, and grid dependency ratio, providing a holistic picture of system feasibility and scalability.

3. Results and Discussion

Analysis of Load Demand and Renewable Contribution

The load profile derived from household surveys in Alamarathupatti village indicated an average daily energy consumption of 92.3 kWh, with a peak demand of 12.1 kW occurring between 6:00 PM and 9:00 PM, primarily due to concurrent use of residential lighting, water pumps, fans, and essential appliances during evening hours. To address this demand pattern, a hybrid microgrid was designed comprising 25 kWp of photovoltaic (PV) capacity and 10 kW of biomass-based generation. Simulation results revealed that the proposed system could meet 100% of the village's daily load under normal conditions. Specifically, solar PV provided around 72.6% of the total energy, reliably covering daytime consumption. In comparison, the remaining 27.4% was generated from biomass, which is especially crucial during early morning and late evening when solar output is minimal.

The inclusion of Vehicle-to-Grid (V2G) capability proved highly beneficial. Each V2G-enabled electric vehicle could inject an average of 4–5 kWh per evening back into the microgrid during peak demand hours. This helped reduce the load on biomass generators and added a layer of operational flexibility that allowed the system to respond effectively to solar intermittency, such as during cloudy weather or seasonal variability. V2G technology in this setting illustrates a novel approach to peak shaving in rural contexts, where traditional battery storage can be cost-prohibitive or capacity-limited. Furthermore, the ability to mobilize and repurpose EV battery energy aligns with the growing emphasis on multi-functional energy assets in decentralized energy planning.

From a planning perspective, these findings underscore the importance of load profiling as a foundation for hybrid system sizing. Understanding daily consumption patterns enables more precise matching of generation and storage resources to demand, avoiding overinvestment and energy shortfalls. Moreover, the synergy between intermittent (PV) and dispatchable (biomass + V2G) sources in this system represents a resilient model that can be adapted to various village settings, provided EVs' mobility and energy behaviour are correctly forecasted and managed.

Economic and Environmental Performance

The proposed hybrid microgrid system's Levelized Cost of Electricity (LCOE) was calculated at USD 0.094/kWh, significantly lower than the prevailing regional grid tariff of USD 0.115/kWh. This translates to approximately USD 38–45 annual household savings, depending on individual consumption tiers. These savings are particularly impactful in rural settings where income levels are often constrained, and energy affordability directly affects quality of life. Furthermore, the system's Net Present Cost (NPC) was estimated at USD 47,200 over a 20-year life cycle, with a simple payback period of 7.3 years. This calculation includes revenues from biogas utilization and savings from reduced diesel generator operation, major contributors to operating expenditure in conventional rural electrification models. From an environmental standpoint, the system demonstrated a commendable performance by achieving a net carbon dioxide (CO_2) emissions reduction of 14.6 tons annually. This is due primarily to replacing diesel-based generation and kerosene lamps, which are still widely used in rural India for lighting and backup power. Mitigating these high-emission sources through clean PV, biomass, and V2G integration aligns with international climate commitments and India's targets under the Nationally Determined Contributions (NDCs).

These results are consistent with previous academic findings. For instance, Yang et al. (2025) reported a 12–16% reduction in GHG emissions in PV-biomass hybrid microgrids deployed in Northern China, while (Elkadeem et al., 2025) noted a 4% reduction in a PV-EV system implemented in Saudi Arabia. The higher emission reduction observed in the present study may be attributed to substituting more carbon-intensive energy sources, particularly diesel and kerosene, which are commonly used in off-grid Indian villages. Additionally, including V2G as an energy balancing mechanism enhances the overall carbon efficiency by minimizing over-reliance on biomass during peak loads.

The economic and environmental metrics combined suggest that the proposed system is cost-effective and ecologically sound, making it a strong candidate for scalable deployment across similar rural geographies. However, financial support schemes and carbon credit mechanisms could further reduce the payback period and enhance adoption rates to maximise its impact. Future work should also consider the integration of dynamic tariff modelling, allowing communities to monetize surplus energy exported to the grid under Net Energy Metering (NEM) schemes.

Feasibility and Limitations

The hybrid microgrid designed for Alamarathupatti village has shown strong technical feasibility, particularly due to its integration of biomass as a dispatchable energy source and the application of Vehicle-to-Grid (V2G) technology for managing evening peak loads. Combining intermittent solar energy with locally sourced biomass and flexible V2G contributions creates a resilient and contextually appropriate energy system for rural India. This layered approach ensures base-load reliability and dynamic load balancing, especially during high-demand periods or weather-induced PV generation dips. The intelligent energy management system further enhances system efficiency by coordinating these diverse energy flows in real-time.

Despite its promising performance, the system presents several notable challenges that could affect long-term sustainability and replicability. First, feedstock variability, particularly for biogas and producer gas generators, poses a considerable risk. During dry agricultural seasons or crop failure, the availability of organic waste and biomass residues becomes inconsistent, potentially disrupting generator operations. Second, while the levelized cost of electricity (LCOE) is competitive with regional tariffs, the high initial capital investment required for components such as PV arrays, biogas plants, smart inverters, and V2G-compatible infrastructure presents a financial barrier for self-funded implementation by rural communities. This highlights the necessity for government subsidies, public-private partnerships, or CSR-driven funding models to enable adoption at scale. Third, the operation of such a hybrid system requires ongoing technical maintenance, particularly for the bi-directional inverters used in V2G and the upkeep of anaerobic digesters. Reliance on external experts may increase operational costs and affect system uptime without adequate capacity building and local technical training.

These limitations suggest that while the model is technically sound and socioeconomically aligned with rural needs, its scalability and sustainability depend heavily on institutional support mechanisms, community engagement, and the establishment of rural energy service networks. Future deployments should incorporate robust maintenance training, modular financing schemes, and seasonal feedstock planning to mitigate these challenges and enhance long-term viability.

Replicability and Comparative Insights

Compared with previous implementations of smart microgrids in rural areas, the findings of this study align well with several benchmark models yet also highlight unique advantages. The case study by (Nadimuthu et al., 2024) demonstrated that PV-biogas-V2G systems can effectively reduce grid dependency and meet the high energy demand of agricultural communities. However, their study also noted a marginally higher Net Present Cost (NPC), primarily due to topographic and logistical challenges in hilly terrain. Similarly, (Wang, Wang, Ni, & Zhang, 2025) presented a fully isolated 100% renewable microgrid model for smart buildings, emphasizing demand response as a mechanism to enhance operational profitability and reliability. While their system achieved commendable energy autonomy, it lacked the real-time flexibility and peak-shaving capacity that V2G systems offer. In another notable contribution, The introduced a multi-layered control framework integrating smart homes, EV charging, and hydrogen fueling stations in reconfigurable microgrids (Jordehi et al., 2025). While technically robust, their model is primarily suited to peri-urban or high-tech regions and may not translate effectively to the constraints of rural agrarian settings.

These comparative insights underline the contextual importance of tailoring microgrid architectures to local needs and resource profiles. Unlike the models mentioned earlier, the proposed system in Alamarathupatti demonstrates a balance between cost efficiency, energy flexibility, and ease of deployment in a rural environment. V2G capability enhances load balancing during peak hours and introduces a mobile energy reserve that can be reallocated dynamically a feature absents in many fixed-generation models. Moreover, locally sourced biomass ensures cultural and economic relevance, which is critical for long-term community ownership and sustainability. Thus, while prior studies have made significant strides in advancing intelligent microgrid design, this case study contributes an adaptable and replicable framework particularly suited for the decentralized, rural energy landscape in India and comparable regions.

In summary, the proposed system for Alamarathupatti balances cost, resilience, and sustainability, providing a scalable blueprint for other rural Indian villages with similar climatic and socio-economic characteristics. With targeted policy incentives and community engagement, such hybrid microgrids could significantly advance the Smart Village mission under India's renewable energy roadmap.

4. Conclusion

This study assessed the technical, economic, and environmental feasibility of a hybrid renewable microgrid system for Alamarathupatti village in Tamil Nadu, integrating 25 kWp solar PV, 10 kW biomass generation, and Vehicle-to-Grid (V2G) technology. The results indicate that the proposed system successfully meets 100% of the village's average daily load of 92.3 kWh, with PV supplying 72.6% and biomass covering the remaining 27.4%, effectively managing the peak demand of 12.1 kW. V2G integration contributed 4–5 kWh per electric vehicle per evening, enhancing peak load flexibility and resilience during intermittency. Economically, the system proved viable with a Levelized Cost of Electricity (LCOE) of USD 0.094/kWh, lower than the regional grid tariff of USD 0.115/kWh, resulting in annual household energy savings of USD 38–45. The Net Present Cost (NPC) was calculated at USD 47,200, with a simple payback period of 7.3 years, factoring in savings from reduced diesel consumption and biogas revenue. Environmentally, the system achieved a CO_2 emission reduction of 14.6 tons per year, aligning with India's sustainable energy and climate goals. Despite its strong feasibility, the system's replicability depends on managing biomass feedstock variability, securing initial investment through government or CSR support, and building local technical capacity, especially for V2G and biogas systems. This model offers a more integrated and flexible solution tailored for rural, agriculture-based communities compared to previous studies. In conclusion, the hybrid PV-biogas-V2G microgrid presents a cost-effective, low-emission, and technically adaptable framework for intelligent village electrification. With appropriate policy support and stakeholder collaboration, this model can be scaled to address rural energy poverty while advancing India's broader decarbonization and energy security objectives.

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