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Performance Analysis of a PV-BESS-Grid Integrated Fast EV Charging System

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Abstract: This study investigates the optimal integration of fast EV charging stations with photovoltaic (PV) and battery energy storage systems (BESS) in Jaipur, India, focusing on areas with high E-rickshaw usage. Using HOMER software, various hybrid configurations were simulated to minimize the Levelized Cost of Energy (LCOE) while ensuring reliable and sustainable power. Results show a 47% reduction in LCOE—from 13.50 to 7.10 INR/kWh—when combining PV, BESS, and grid connectivity. The findings demonstrate the potential of hybrid systems to enable cost-effective, reliable, and eco-friendly EV charging infrastructure for urban India, offering a strategic model for future sustainable mobility planning.

Keywords: EV charging Station, HOMER, Optimization, BESS, PV system, LCOE, smart grid

1. INTRODUCTION

The global shift toward electric vehicles (EVs) represents a crucial step in achieving sustainable transportation, and India is actively participating in this transition. Faced with severe pollution and a heavy dependence on fossil fuels, the country sees EV adoption as a key strategy to reduce environmental harm and cut down on imported oil. However, a major obstacle to the widespread adoption of EVs is the lack of adequate charging infrastructure. A reliable and efficient charging network is essential to support the growing number of EVs and ensure a smooth transition from internal combustion engine vehicles to electric mobility. In cities like Jaipur, E-rickshaws have emerged as a popular and eco-friendly mode of public transport. These electric three-wheelers offer a cleaner alternative to conventional auto-rickshaws, especially in congested urban areas. Despite their benefits, the growth of E-rickshaws is limited by poor access to charging facilities, often forcing drivers to rely on inefficient and informal charging setups. This not only reduces their operational efficiency but also discourages further investment in the sector. To address these challenges, it is important to explore renewable energy-based EV charging solutions. Solar-powered charging stations, especially when integrated with battery energy storage systems (BESS), offer a sustainable and cost-effective alternative. This study focuses on region in Jaipur, evaluating both grid-connected and off-grid EV charging configurations using HOMER software. The goal is to determine the most reliable and affordable system with a low Levelized Cost of Energy (LCOE), ultimately supporting cleaner urban transport and advancing India's sustainable development goals.

This study adopts a comprehensive approach to optimizing electric vehicle charging infrastructure by integrating renewable energy sources with both grid-connected and off-grid systems. Unlike previous research that primarily focuses on conventional grid-based solutions, this study explores the incorporation of solar photovoltaic (PV) systems and battery energy storage systems (BESS) to enhance sustainability and reliability. It specifically examines the Jaipur region, addressing the unique charging needs of E-rickshaws, a widely used mode of public transportation. By tailoring the analysis to this context, the study provides valuable insights into developing efficient and cost-effective EV charging infrastructure. The findings highlight the potential of renewable energy integration to reduce dependence on conventional electricity sources, lower operational costs, and improve urban mobility. This research serves as a framework for implementing similar solutions in other urban areas, contributing to the broader goal of sustainable transportation and energy management in growing cities.

II. LITERATURE REVIEW

This study employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology to systematically review existing literature on electric vehicle (EV) charging stations. The PRISMA framework facilitated the identification, screening, and selection of relevant research articles, ensuring comprehensive coverage of key aspects. The methodology consists of four primary phases: identification, screening, eligibility, and inclusion. A thorough search was conducted across multiple databases using keywords such as "EV charging stations," "renewable energy integration," "grid-connected systems," "off-grid systems," and "E-rickshaw charging." Duplicate studies were removed, and the remaining papers were evaluated for relevance based on their titles and abstracts. Shortlisted studies were further assessed for eligibility according to inclusion criteria, which focused on EV charging infrastructure, renewable energy integration, and relevance to the Indian context. The final selection of studies provided a solid foundation for analyzing current trends and advancements in EV charging infrastructure.

India's need for a well-developed EV charging network is widely acknowledged, especially in light of the country's commitment to sustainable transportation. Abid et al. (2022) emphasize that integrating renewable energy into EV charging stations can significantly reduce carbon emissions and enhance the sustainability of urban transport. The authors highlight the necessity of establishing an extensive charging infrastructure to support the growing adoption of electric vehicles. Chu et al. (2022) further explore the coordination of EV charging in residential communities, addressing the challenges and potential solutions associated with managing plug-in electric vehicles (PEVs). Their study proposes a multi-agent federated reinforcement learning approach to optimize charging schedules and alleviate peak demand issues.

The role of E-rickshaws as a key mode of public transport in India presents both unique challenges and opportunities. Ekren et al. (2021) analyze the sizing of solar-wind hybrid electric vehicle charging stations using HOMER software, emphasizing the necessity of robust infrastructure to meet the energy demands of small electric vehicles like E-rickshaws. The study highlights the inadequacy of existing charging infrastructure, which restricts operational range and limits convenience for users. Similarly, Ghatak et al. (2021) investigate the optimization of EV charging stations via HOMER Grid, underscoring the economic feasibility and operational efficiency of integrating renewable energy sources. The authors argue that well-planned infrastructure development can significantly enhance E-rickshaw adoption and usability, particularly in urban environments.

The integration of renewable energy into EV charging stations has been a focal point in various studies. Singh et al. (2022) explore the design and evaluation of hybrid renewable energy-based charging stations, showcasing the benefits of combining solar photovoltaic (PV) and battery storage to provide a stable energy supply. Expanding on this, Güven and Yücel (2023) analyze similar systems in Turkey, demonstrating the potential for widespread adoption in major cities. Their study employs HOMER software to model and optimize EV charging station designs, considering cost, reliability, and environmental impact. Other research has assessed the feasibility of diverse EV charging configurations. Shaikh et al. (2022) evaluate a stand-alone hybrid PV-hydrogen-based charging station, highlighting the challenges and advantages of off-grid systems. The study stresses the importance of energy storage and management for maintaining a reliable power supply, particularly in areas with limited grid access.

Infrastructure development plays a crucial role in the transition to clean energy. Bansal et al. (2020) conduct a technical and economic analysis of one-stop charging stations for battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs), reinforcing the significance of renewable energy integration. Several studies focus on optimizing EV charging stations through advanced modeling techniques. Thomas et al. (2020) evaluate grid-connected EV charging stations powered by renewable energy, assessing associated challenges and benefits. Meanwhile, Syed Mohammed et al. (2022) examine the techno-economic feasibility of hydrogen-based EV charging through a case study approach, emphasizing hydrogen's role as a clean energy carrier in sustainable transport infrastructure. Additional studies explore hybrid energy systems for EV charging. Jha et al. (2022) investigate EV design and control using HOMER software, providing insights into optimizing hybrid energy solutions. Mosetlhe et al. (2022) examine off-grid solar and wind-powered hybrid EV-HFCV charging stations, assessing both technical and economic factors. Shafiq et al. (2022) conduct an analysis of grid-connected solar PV-based EV charging facilities, exploring cost and environmental impacts. Similarly, Boddapati et al. (2022) examine the design and evaluation of hybrid energy-based EV charging stations, advocating for a balanced approach to energy management and infrastructure development.

Early studies also offer foundational insights. Hafez and Bhattacharya (2017) provide an initial assessment of optimal EV charging station design, emphasizing renewable energy integration to enhance urban transport sustainability. Al Wahedi and Bicer (2022) investigate the techno-economic optimization of stand-alone renewable energy-based charging stations in Qatar, offering comparative insights from other regions. Aldhanhani et al. (2017) explore the benefits of decentralized energy systems in EV charging station design, advocating for renewable distributed generation. Finally, Nishanthy et al. (2022) conduct a techno-economic analysis of hybrid solar-wind EV charging stations along highways, demonstrating their potential to enable long-distance travel and mitigate range anxiety among EV users.

III. EV SYSTEM ARCHITECTURE

The architecture of the electric vehicle (EV) charging station system was systematically designed and simulated utilizing HOMER software in the current research. Figure 1 presents a schematic diagram detailing the interconnected components of the system, which include the Smart Grid (SMGrid), Solar Photovoltaic (SPV) plant, Battery Energy Storage System (BESS), and the electric vehicle charging load, denoted as basecase_EV. The system includes both an AC and DC distribution network, with the SMGrid supplying alternating current (AC). The SPV plant and BESS are linked to the direct current (DC) network through an EV Converter, serving as the interface between the alternating current (AC) and DC sides. The SPV plant utilizes solar energy to produce electricity, which can be employed directly for EV charging or stored in the BESS for future utilization. The BESS is essential for maintaining a consistent power supply, particularly during times of inadequate solar generation, such as nighttime or overcast conditions.

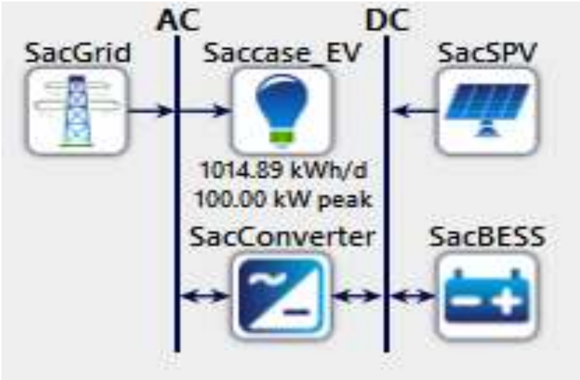

Figure 1 EV Charging Station System Architecture

The EV charging load, referred to as basecase_EV, indicates the daily requirement for EV charging, established in this study at 300 kWh/day, with a peak demand of 35 kW. The system's design facilitates operational flexibility, permitting it to either utilize grid power or function autonomously with renewable energy sources and storage solutions. This hybrid method enhances reliability and efficiency, diminishes dependence on the grid, and optimizes the utilization of clean energy. The application of HOMER software enabled system optimization by permitting simulations across multiple scenarios and the evaluation of the technical and economic performance of various configurations.

IV. SYSTEM COMPONENTS AND MODELING IN HOMER

This study models an EV fast-charging station using HOMER software, integrating key components: Smart Grid (SMGrid), Solar PV (SPV), Battery Energy Storage System (BESS), and EV charging load (basecase_EV). Each component is defined with technical and economic parameters to simulate performance under real-world conditions.

4.1 Component Overview

- **Smart Grid (SMGrid):** Provides backup power and stability. Modeled with electricity tariffs, demand charges, and outage possibilities to assess grid interactions and cost trade-offs.
- **Solar PV (SPV):** Acts as the main renewable source. Location-specific solar data was used to model energy output, accounting for seasonal variations, temperature, and shading.
- **Battery Energy Storage System (BESS):** Stores surplus solar power and supplies energy during peak demand. Key parameters include capacity, efficiency, and lifecycle costs to support load management and enhance reliability.
- **EV Charging Load (basecase_EV):** Represents daily EV energy usage and peak power needs. Load profiles simulate fast-charging behavior and help assess system adequacy.

4.2 System Integration and Optimization

HOMER integrates all components to evaluate technical performance, cost (LCOE, NPC), and environmental impact (emissions). The software tests multiple system configurations to find the most efficient and cost-effective hybrid setup.

V. MODELING APPROACH

The proposed EV charging station design follows a step-by-step modeling process:

✓Define EV charging load profile.
✓Identify available resources (solar, grid, battery).
✓Input technical specs (SPV, BESS, grid).
✓Conduct economic analysis (CAPEX, OPEX, incentives). ✓Optimize system configurations using HOMER.
✓Validate results through simulations.
✓Perform sensitivity analysis to test robustness.

This modeling approach supports a reliable, low-cost, and sustainable EV charging solution using hybrid energy sources tailored for Jaipur's urban context.

VI. RESULTS AND DISCUSSION

6.1 Load Profile Analysis

EV charging stations in Jaipur exhibit peak electricity demand between 12 PM and 10 PM, primarily driven by workplace and commercial E-rickshaw usage. Year-round demand remains steady with slight seasonal shifts. Heatmaps reveal consistent midday peaks, making solar PV a suitable energy source. These patterns support strategic PV and BESS sizing to ensure efficient and reliable energy delivery.

6.2 Base Case (Grid-Only)

The baseline scenario, entirely dependent on the grid, records an annual electricity consumption of **109,500 kWh**. While meeting energy demand, it proves costly and unsustainable:

- **NPC:** ₹17.88 million
- **LCOE:** ₹13.50/kWh
- **O&M Cost:** ₹1.23 million/year
- **Renewable Fraction:** 0%

This setup demonstrates limited environmental benefits and high long-term operational costs.

6.3 Optimized Off-Grid System

The off-grid system uses a **125 kW PV array** and a **20 kW–72 kWh BESS**, generating **183,839 kWh/year**. It ensures energy independence with:

- **NPC:** ₹9.57 million
- **LCOE:** ₹7.10/kWh
- **O&M Cost:** ₹239,504/year
- **Renewable Fraction:** 100%
- **Surplus Energy:** 51,265 kWh

Despite a negligible unmet load, this configuration significantly reduces operational costs and emissions.

6.4 Optimized On-Grid System

This hybrid model combines a **21.9 kW solar PV**, **10 kW EV converter**, and the same BESS, covering the total annual load of **109,500 kWh** using renewable energy. Grid connectivity enhances reliability while supporting solar excess management. It offers:

- High energy autonomy
- Lower LCOE
- Scalability for urban deployment

Table 6 Simulation Optimization Comparison

Description	Base Case	Optimal Case
NPC	₹17.88M	₹9.57M
Initial Capital	₹2.50M	₹21.8M
O&M Cost	₹1.23M	₹239,504
LCOE	₹13.50/kWh	₹7.10/kWh

Integrating solar PV and BESS into EV charging infrastructure leads to a 47% reduction in the Levelized Cost of Energy (LCOE), dropping from ₹13.50 to ₹7.10/kWh, while enabling full or near-complete reliance on renewable energy. Both off-grid and grid-connected hybrid configurations offer scalable, sustainable, and cost-effective solutions for urban mobility needs. This strategy provides a practical and replicable model for advancing green energy adoption and EV infrastructure development in cities like Jaipur. The findings clearly demonstrate the significant economic and environmental advantages of shifting from traditional grid reliance to optimized renewable energy systems. By harnessing solar energy and battery storage, these systems not only reduce operating costs but also enhance long-term energy sustainability and resilience.

7 Conclusion

This study optimizes power management in PV-BESS-Grid integrated fast EV charging stations in Jaipur, emphasizing economic and environmental benefits. Analysis using HOMER software reveals that grid-dependent systems, while stable, incur high costs and lack sustainability. In contrast, an optimized off-grid setup with solar PV and battery storage achieves full energy independence, significantly reducing NPC, LCOE, and operational costs while ensuring surplus renewable energy generation. The findings underscore the feasibility of PV-BESS integration for cost-effective, secure, and eco-friendly EV charging. Future efforts should refine these systems, explore additional renewables, and scale implementation for sustainable urban development.

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