International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 17, No. 3, September 2026, pp. 2039~2046
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v17.i3.pp2039-2046

Techno-economic optimization of hybrid renewable energy systems for low-carbon EV charging station

Jeyagopi Raman[1], Sudesh Nair Baskara[2], Harpreet Kaur Channi[3,4]
[1]Department of Engineering, INTI International University, Nilai, Malaysia
[2]Department of Civil Engineering, INTI International University, Nilai, Malaysia
[3]Department of Electrical Engineering, INTI International University, Nilai, Malaysia
[4]Eudoxia Research Centre, Mumbai, India, affiliated with Eudoxia Research University, New Castle, United States

Article Info

Article history:

Received Jun 2, 2025
Revised Feb 2, 2026
Accepted Jul 8, 2026

Keywords:

Carbon dioxide emissions
Carbon emissions
Electric vehicles
Energy storage
Renewable penetration
Sustainable development goal

ABSTRACT

The rapid adoption of electric vehicles (EVs) requires charging infrastructure that is sustainable, power-electronically efficient, and grid-compatible. This study presents a techno-economic and environmental optimization of a hybrid renewable energy-based EV charging station near Guru Nanak Dev Engineering College (GNDEC), Ludhiana, India, as a sustainable alternative to conventional petrol stations. Unlike studies based on assumed EV load profiles, the proposed framework integrates real-world e-rickshaw utilization data, inverter efficiency, and sensitivity analysis within a HOMER Pro optimization framework. The system combines solar photovoltaic (PV), battery storage, and grid supply through a bidirectional inverter to manage dynamic charging demand. Local solar irradiance (~5.6 kWh/m²/day) and actual e-rickshaw usage data were used as simulation inputs. Configurations were evaluated using net present cost (NPC), levelized cost of energy (LCOE), inverter efficiency, and CO_2 emissions. The optimal PV-battery-grid configuration achieved an NPC of $28,500, LCOE of $0.11/kWh, inverter efficiency of 95%, and approximately 95% lower CO_2 emissions than grid-connected configuration, with a 6.5-year payback period. The findings highlight the importance of power-electronic efficiency and energy management for economically viable, low-carbon EV charging infrastructure, supporting SDGs 7 and 9.

Corresponding Author:

Harpreet Kaur Channi
Department of Electrical Engineering, INTI International University
Nilai, Malaysia
Eudoxia Research Centre, Mumbai, India
affiliated with Eudoxia Research University, New Castle, United States
Email: harpreetchanni@yahoo.in

1. INTRODUCTION

Despite extensive research on renewable energy–based electric vehicle (EV) charging stations, key limitations persist. Most studies rely on assumed EV load profiles rather than real operational data, reducing practical relevance. Moreover, many HOMER-based techno-economic analyses focus on cost and emissions while neglecting power-electronics factors, such as inverter and charger efficiency. Sensitivity analysis is also often limited, particularly for solar variability and load uncertainty in semi-urban and institutional contexts. These gaps highlight the need for realistic and power-electronics-aware EV charging system designs. The rapid adoption of electric vehicles (EVs) presents a significant opportunity to reduce greenhouse gas emissions and dependence on fossil fuels. However, this potential can only be fully achieved through the development of efficient, reliable, and low-emission charging infrastructure. In areas such as Punjab, India, where urban growth, escalating fuel prices, and power quality being top concerns—sustainable EV charging infrastructure is needed in order to assist green mobility [1], [2]. The conventional petrol filling station near Guru Nanak Dev Engineering College (GNDEC), Ludhiana, Punjab, presents a suitable case study for planning and testing such infrastructure. The area enjoys robust solar potential with average daily solar irradiance levels between 5.4 to 5.8 kWh/m². Coupled with campus-based e-rickshaws and a feasible load profile, GNDEC proves to be an effective and replicable testbed for hybrid EV charging systems [3]-[5].

HOMER Pro, a microgrid simulation and optimization software, allows for modeling hybrid systems of solar photovoltaic (PV), battery energy storage systems (BESS), and traditional grid power. By combining all components, a highly optimized EV charging station can lower operating costs, improve energy resilience, and help meet carbon neutrality targets. The techno-economic and environmental viability of a hybrid renewable energy-driven EV charging station at GNDEC has been examined in this study. The performance parameters like net present cost (NPC), levelized cost of energy (LCOE), and carbon dioxide emissions (CO_2) have been analyzed [6]. Configurations are compared to determine the most economically viable and sustainable solution under local conditions. In addition, the role of battery storage in enhancing system reliability, lowering grid dependence, and maximizing renewable energy utilization is explored.

While several previous studies have used HOMER-based optimization for EV charging stations, few have considered real-world e-rickshaw demand patterns in semi-urban India, or integrated sensitivity analysis and inverter/charger efficiency into the design. This gap motivates the present study, which uniquely benchmarks different configurations, tests their robustness under uncertain parameters, and highlights power electronics considerations. The results provide important recommendations for educational institutions, policymakers, and infrastructure developers aiming to implement decentralized and clean EV charging solutions across South Asia [7], [8]. A comparative summary of existing HOMER-based EVCS studies indicates that while many focus on techno-economic feasibility, they often overlook sensitivity to solar intermittency, battery degradation, and converter efficiency. Table 1 highlights these gaps and demonstrates the distinct contribution of the present study, which integrates local e-rickshaw demand modeling with hybrid-system optimization and power-electronics considerations.

Table 1. Comparative literature review

Authors, year	Location/case	Tool/method	Focus of study	Key findings	Gap/limitation
Rad *et al.* (2025) [9]	85 world capitals	HOMER Grid; techno-economic optimization	Near-zero-emission EV charging	>80% renewable contribution; LCOE varied by city and charging period	No local e-rickshaw demand, biomass integration, or detailed power-electronics analysis
Demirci et al. (2026) [10]	Five European capitals; Ankara case	HOMER Grid; scenario and sensitivity analysis	PV–storage EV charging	Evaluated demand, carbon tax, PV, and ESS cost scenarios	No biomass integration or e-rickshaw-specific demand; V2G left for future work
Veza et al. (2026) [11]	Five Indonesian cities	HOMER Pro; techno-economic optimization	PV–battery–hydrogen EV charging	Identified city-specific optimal PV–hydrogen configurations and LCOE/LCOH	No e-rickshaw demand modeling, PV–biomass integration, or power-electronics analysis
Güven *et al.* (2025) [12]	Çukurova, Adana (Turkey)	HOMER Pro	Six hybrid EVCS scenarios (PV, biomass, H_2, grid)	PV–biomass–H_2–grid mix gave NPC \$611k, LCOE \$0.0215	Complex setup, not easily scalable
Hüner (2025) [13]	Hatay (Turkey)	HOMER Pro	PV–biogas–H_2 hybrid system	NPC \$1.92M, cost \$0.2094/kWh, 95.78% CO_2 reduction	Off-grid only; high capital cost
Zhou *et al*. (2025) [14]	China	HOMER Pro	Wind–solar–storage optimization	Grid-connected (purchase–sale) had lowest NPC (1.87M CNY), 74.7% RE	Grid-focused; limited EV integration
Alhazmi (2025) [15]	Saudi Arabia (Highways)	HOMER Grid	Siting & sizing of fast-charging stations	200–500 kW FCS simulated; 500 kW station gave 3.2 GWh/year; cost \$2.79M	High cost; limited battery/storage integration
Present Work (2025)	GNDEC, Ludhiana (India)	HOMER Pro + sensitivity + benchmarking	Hybrid PV–battery–grid EVCS for e-rickshaws	Achieved 89% solar share, NPC \$28.5k, LCOE \$0.11/kWh, 95% CO_2 reduction; included sensitivity (solar, load, battery) and inverter efficiency	Lacks real-world pilot validation and detailed degradation modeling; scope for V2G and AI-based control in future

The growing demand for EVs in South Asia burdens fossil fuel-reliant grids, particularly where connectivity is not reliable, and thus necessitates decentralized, low-carbon charging infrastructure. Current studies hardly tune hybrid setups that integrate grid supply, solar PV, and batteries for optimal performance or consider real-world factors such as seasonal changes in demand and battery aging. There is also a deficiency of end-to-end techno-economic studies employing indicators such as NPC, LCOE, and payback period [16], [17]. This research bridges these gaps by employing HOMER Pro to design and evaluate a hybrid EV charging station based on cost, reliability, and environmental considerations for scalable, sustainable deployment. The main objectives are: i) To simulate and design a hybrid renewable energy-based electric vehicle (EV) charging station for GNDEC, Ludhiana, using HOMER Pro; and ii) To assess its techno-economic performance in terms of NPC, levelized cost of energy (LCOE), and carbon emissions.

2. METHOD

2.1. Location and data collection

The EV charging station location selected for this study is opposite Guru Nanak Dev Engineering College (GNDEC), Ludhiana, Punjab, India. Local solar irradiance data, with an average value of approximately 5.6 kWh/m²/day, were obtained from the HOMER Pro database. Real EV usage data were collected from campus-operated e-rickshaws, forming the basis for realistic load modeling. Hourly solar availability and EV charging demand profiles were used as inputs for simulation [17].

2.2. System design

The proposed hybrid EV charging system consists of solar photovoltaic (PV) panels, battery energy storage, grid connection, inverter, EV charging units, and an energy management system (EMS), as illustrated in Figure 1 and summarized in Table 2. PV panels generate DC power from solar energy, while battery storage retains surplus energy for use during low solar availability. The grid acts as a backup source to ensure uninterrupted charging. A bidirectional inverter converts DC power to AC for compatibility with EV chargers and the grid. System component sizes were selected based on local solar potential, EV energy demand, and scalability considerations [19].

2.3. Simulation framework

System modeling and simulations were carried out using HOMER Pro software over a full annual period of 8,760 hours. Several configurations—including grid-only, PV + Grid, PV + Battery, and PV + Battery + Grid—were developed and simulated. Hourly dispatch strategies were employed to manage power flow between PV, battery storage, and grid supply to meet EV charging demand [20], [21].

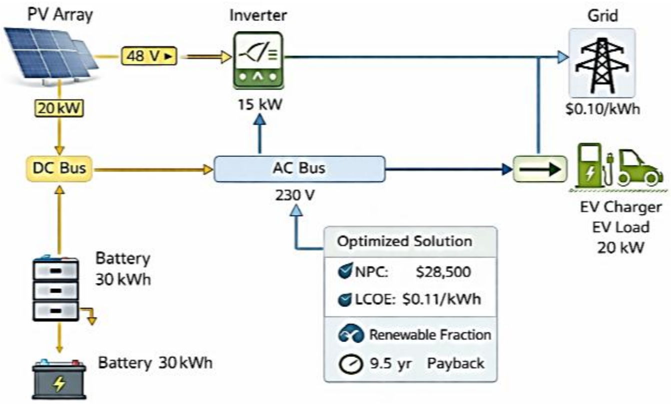

Figure 1. Schematic diagram of an EV charging station

Table 2. Component specification

Component	Value/specification
Number of E-Rickshaws	20
Battery capacity (per e-rickshaw)	4.8 kWh
Total battery capacity	4.8 kWh x 20 = 96 kWh
Daily energy consumption (per e-rickshaw)	1.5 - 2 kWh (per day)
Total daily energy consumption	1.5 kWh x 20 = 30 kWh to 2 kWh x 20 = 40 kWh (per day)
Charging time (per e-rickshaw)	4 - 6 hours (average, typically staggered to avoid simultaneous peak demand)
Total energy requirement (for 1 full charge)	96 kWh (for all e-rickshaws)
PV solar panel system size	20 - 30 kW (to meet daily energy demand, depending on location)
Battery storage (if off-grid or backup required)	30 - 40 kWh (for 1 day's backup energy)
Inverter size	10 kW to 30 kW (depending on charging speed and capacity)
Number of charging stations	1-2 stations (with 10 kW to 20 kW per station for fast charging)
Grid connection (if hybrid)	20% of total system capacity (backup capacity for peak times)

2.4. Optimization criteria

The primary optimization objective was to minimize the NPC while ensuring reliable charging and maximizing renewable energy utilization. Additional performance indicators included levelized cost of energy (LCOE), carbon dioxide (CO_2) emissions, system autonomy, and payback period. Comparative analysis was performed to identify the most cost-effective and environmentally sustainable configuration.

2.5. Sensitivity analysis and power electronics considerations

Sensitivity analysis was conducted to evaluate system robustness under variations in solar irradiance, EV load demand, battery cost, and inverter efficiency. Inverter efficiency (assumed as 95%) and charger characteristics were explicitly incorporated into the HOMER simulations, as they significantly influence system losses and energy cost. This analysis ensures reliable integration of PV, battery storage, and grid supply while maintaining stable charging performance for e-rickshaws [22], [23].

3. RESULTS AND DISCUSSIONS

3.1. Results

This section first presents the quantitative simulation results obtained from HOMER Pro, followed by a focused discussion interpreting the techno-economic, environmental, and sensitivity outcomes. The hybrid renewable EV charging system designed for 20 e-rickshaws consists of a 25 kW solar PV array and 40 kWh battery storage. The total daily energy demand ranges between 35–40 kWh. As shown in Table 3, solar PV supplies approximately 89% of the total energy demand, while the grid contributes around 11%, primarily during periods of low solar availability [24].

The initial capital cost of the system is approximately USD 25,000, and the net present cost (NPC) over the project lifetime is estimated at USD 28,500. The levelized cost of energy (LCOE) is calculated as USD 0.11/kWh, with an estimated payback period of 6.5 years. Annual operation and maintenance costs are approximately USD 1,050. In terms of environmental performance, the hybrid system results in annual CO_2 emissions of approximately 0.35 tons, whereas a grid-only charging system emits about 4.2 tons per year, corresponding to an emission reduction of nearly 95%, as illustrated in Figure 2.

Table 3. Optimization results

Category	Parameter	Value	Explanation
Technical	Solar PV capacity	25 kW	Power generated from solar panels; sized to meet most daily charging needs.
	Battery storage capacity	40 kWh	Stores solar energy for night/cloudy day use; enough for one day of charging.
	Daily energy demand	35–40 kWh/day	Total energy needed to fully charge 20 e-rickshaws daily.
	Solar contribution	~89%	The majority of power comes from solar; reduces grid dependence and emissions.
	Grid contribution	~11%	Backup power source for low solar periods; kept minimal to lower costs.
Economic	Initial capital cost	~$25,000 USD	Total upfront investment for PV, batteries, inverter, and setup.
	Net present cost (NPC)	~$28,500 USD	Total cost over system lifetime, discounted to present value.
	Levelized cost of energy (LCOE)	~$0.11/kWh	Average cost of generated electricity over time; competitive with grid rates.
	Payback period	~6.5 years	Time to recover investment through savings; shorter period means better return.
	Annual O&M Cost	~$1,050 USD	Yearly maintenance and minor replacement costs.
Environmental	CO_2 emissions (hybrid)	~0.35 tons/year	Very low emissions, mostly from occasional grid use.
	CO_2 emissions (grid-only)	~4.2 tons/year	Estimated emissions if the system used only grid power.
	Emissions reduction	~95%	Significant reduction in carbon footprint due to solar-based design.

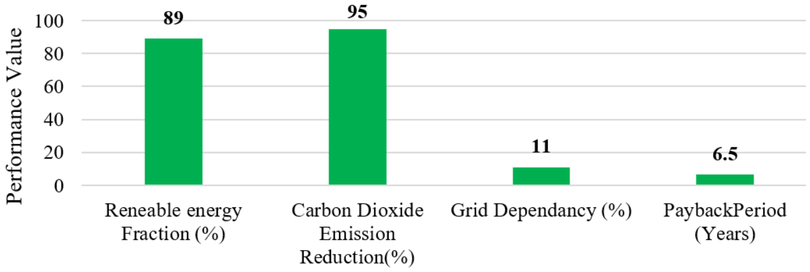

Figure 2. EV charging system performance for 20 E-Rickshaws

Sensitivity analysis was conducted to examine the impact of variations in key parameters on system performance. The weekly heatmap shown in Figure 3 illustrates the aggregate power generation from solar PV, battery storage, and grid supply over a seven-day period. Peak generation occurs during midday due to higher solar availability, while battery and grid sources contribute during early morning and evening hours [25]. Results presented in Table 4 indicate that variations in solar irradiance and EV load demand cause the largest changes in NPC and renewable fraction. Battery cost and inverter efficiency show moderate effects on NPC and LCOE, while changes in discount rate mainly influence long-term economic indicators.

3.2. Discussion

The results indicate that integrating PV generation with battery storage significantly reduces grid dependence and emissions while maintaining acceptable economic performance. The obtained LCOE of USD 0.11/kWh is comparable to values reported in similar EV charging studies conducted in India and Turkey [12]-[14], while the achieved CO_2 reduction exceeds many grid-connected configurations reported in the literature. Sensitivity analysis further indicates that system performance remains stable under variations in solar availability and load demand, highlighting the importance of accurate local data for reliable system design.

The techno-economic outcomes are influenced by power electronics parameters. The assumed inverter efficiency of 95% contributes to lower conversion losses and reduces LCOE by approximately USD 0.01/kWh compared to lower-efficiency scenarios. In addition to economic indicators, system reliability, energy autonomy, and charger utilization metrics (Table 5) provide a broader assessment of system performance beyond cost minimization.

While HOMER Pro is effective for preliminary sizing and techno-economic optimization, complementary tools such as MATLAB/Simulink and RETScreen can support dynamic control validation and financial screening, as summarized in Table 6. Furthermore, policy support through incentives, tariff reforms, interoperability standards, and smart-grid integration can facilitate large-scale deployment of hybrid EV charging systems. Vehicle-to-grid (V2G) integration using fleet-based EVs such as e-rickshaws presents additional opportunities for grid support, subject to suitable regulatory frameworks.

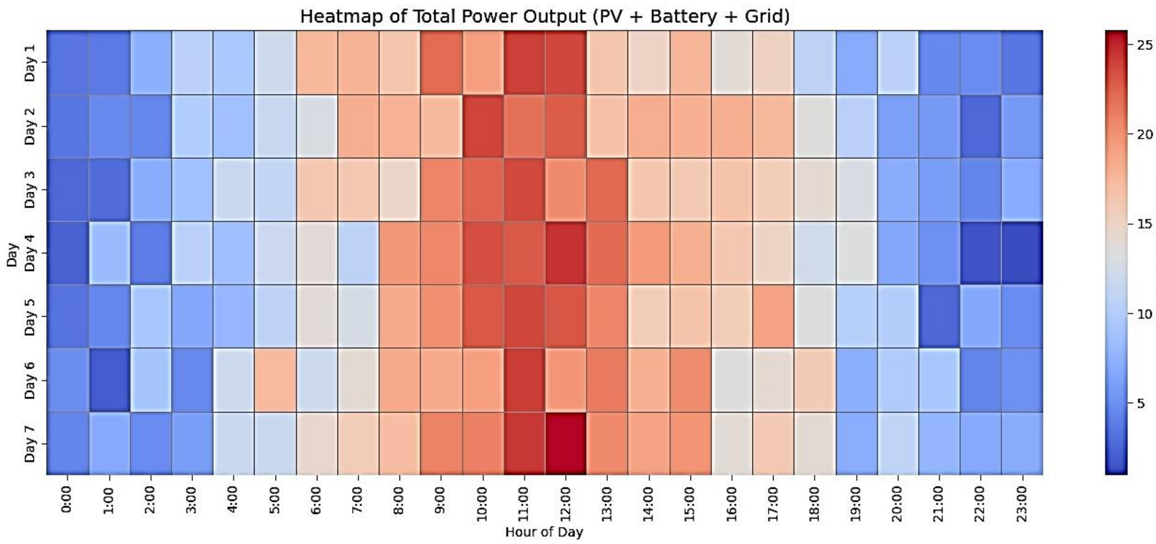

Figure 3. Heatmap of total power output

Table 4. Sensitivity analysis of key system parameters

Parameter varied	Range tested	Effect on NPC	Effect on LCOE	Effect on renewable fraction
Solar irradiance	4.5–6.5 kWh/m²/day	NPC varied by ±12%	LCOE varied from $0.10–0.13/kWh	Renewable fraction 75–92%
Battery cost	–30% to +30%	NPC varied by ±9%	LCOE varied from $0.10–0.12/kWh	Minimal impact
Load demand	±15%	NPC varied by ±15%	LCOE ranged from $0.09–0.12/kWh	Renewable fraction stable at 85–90%
Discount rate	2–6%	NPC increased by 18% at 6%	LCOE varied slightly	No effect
Inverter efficiency	90–97%	NPC reduced by 5% at higher efficiency	LCOE dropped by $0.01/kWh	Renewable fraction unchanged

Table 5. Key performance metrics for the proposed hybrid EV charging system

Metric	Definition	Formula	Insight provided
System reliability (%)	Ability to meet EV charging demand without unmet load	$E_{Reliability} = \frac{E_{Served}}{E_{Demand}} \times 100$	High values indicate dependable charging availability
Energy autonomy index (EAI)	Share of EV charging energy supplied from on-site renewables	$EAI = \frac{E_{PV} + E_{other\ Renewable}}{E_{Total}}$	Higher EAI shows reduced reliance on grid imports
Charger utilization rate (CUR)	Effectiveness of installed chargers	$CUR = \frac{T_{Charging}}{N_{Charger} X T_{Available}}$	Identifies under/over-utilization of charging assets
Renewable fraction (RF)	Portion of system's energy generated from renewables	$RF = \frac{E_{renewable}}{E_{generated}}$	Evaluates sustainability of supply
Round-trip efficiency (RTE)	Efficiency of energy storage cycle	$RTE = \frac{E_{discharged}}{E_{Charged}}$	Captures storage and conversion losses
Net present cost (NPC)	Total lifecycle cost of the system discounted to present value	$NPC = \frac{C_{\mathrm{ann,tot}}}{CRF(i,N)}$	Evaluates overall economic feasibility of the EV charging system over its lifetime
Capital recovery factor (CRF)	Factor used to convert present cost into equivalent annual cost	$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1}$	Accounts for the effect of discount rate and project lifetime in cost calculations

Table 6. Comparative features of simulation tools for EV charging studies

Feature/capability	HOMER Pro	MATLAB/Simulink	RETScreen
Primary strength	Techno-economic optimization, dispatch strategy	High-fidelity dynamic simulation, control validation	Financial feasibility and policy analysis
Temporal resolution	Hourly (default)	Sub-second to hourly (user-defined)	Monthly/daily (built-in datasets)
Battery modeling	Simplified lifetime and replacement	Detailed electrochemical and thermal models	Basic degradation assumptions
Grid interaction	Simplified tariffs, import/export	Full dynamic grid integration and stability	Tariff-based financial screening
Ease of use	GUI-based, moderate learning curve	Requires modeling expertise	Very user-friendly, integrated climate data
Best use case	Optimal sizing, cost evaluation	Dynamic validation, control design	Quick feasibility and financial screening

4. CONCLUSION

This study demonstrates the techno-economic and environmental feasibility of a hybrid renewable energy–based electric vehicle (EV) charging system designed to meet the daily energy requirements of 20 e-rickshaws. The proposed PV–Battery–Grid configuration achieves a renewable energy contribution of approximately 89%, resulting in significant reductions in energy cost and carbon emissions. Among the configurations analyzed, the PV + Battery + Grid system exhibits the lowest net present cost (NPC), the lowest levelized cost of energy (LCOE), the shortest payback period, and a CO_2 emission reduction of over 95% compared to a grid-only charging scenario.

The results confirm that decentralized EV charging infrastructure, when optimally designed using tools such as HOMER Pro and supported by appropriate power-electronics selection, can be both economically viable and environmentally sustainable in solar-rich regions. The key technical contribution of this work is the integration of real-world e-rickshaw charging demand with HOMER-based optimization while explicitly accounting for inverter and charger efficiency, thereby improving the realism and reproducibility of EV charging system design.

From a practical perspective, the proposed framework can be directly adopted by educational institutions, fleet operators, and municipal authorities for deploying cost-effective EV charging stations as alternatives to conventional petrol filling stations. At the policy level, the findings support the need for targeted incentives for solar-integrated EV charging, favorable net-metering and time-of-use tariffs, and standardized power-electronics requirements to accelerate large-scale adoption. The study aligns with sustainable development goal (SDG) 7 (affordable and clean energy) and SDG 13 (climate action) by promoting clean energy access and low-carbon transportation.

Future research should focus on pilot-scale implementation to validate real-time system performance, incorporation of battery degradation and lifecycle modeling, and evaluation of vehicle-to-grid (V2G) operation using bidirectional inverters. Additionally, AI-based energy management and adaptive control strategies can be explored to enhance system efficiency, reliability, and grid interaction under dynamic operating conditions.

ACKNOWLEDGEMENT

We thank Guru Nanak Dev Engineering College, Ludhiana, for their support and resources. We are grateful to our mentors for their guidance and to the team for their valuable inputs. We also acknowledge the use of HOMER Pro software for system simulation and optimization.

FUNDING INFORMATION

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. It was carried out with institutional support and self-resources.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Jeyagopi Raman		✓	✓	✓	✓	✓		✓	✓	✓			✓	
Sudesh Nair Baskara		✓				✓		✓	✓	✓	✓	✓		
Harpreet Kaur Channi	✓		✓	✓	✓	✓	✓			✓	✓		✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state that they have no known conflicting financial, personal, professional, or non-financial interests that might have impacted the research presented in this study. The authors claim there is no conflict of interest.

DATA AVAILABILITY

The simulation data and model parameters supporting the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] A. Shukla, H. Shukla, S. K. Yadav, J. Singh, and R. B. Singh, "Solar powered electric vehicle charging station with integrated battery storage system," *Energy Storage*, vol. 6, no. 8, 2024, doi: 10.1002/est2.70077.

[2] A. Shafiq *et al.*, "Solar PV-based electric vehicle charging station for security bikes: a techno-economic and environmental analysis," *Sustainability (Switzerland)*, vol. 14, no. 21, 2022, doi: 10.3390/su142113767.

[3] P. Stanko, M. Tkac, M. Kajanova, and M. Roch, "Impacts of electric vehicle charging station with photovoltaic system and battery energy storage system on power quality in microgrid," *Energies*, vol. 17, no. 2, 2024, doi: 10.3390/en17020371.

[4] Y. Zhang *et al.*, "HOMER-based multi-scenario collaborative planning for grid-connected PV-storage microgrids with electric vehicles," *Processes*, vol. 11, no. 8, 2023, doi: 10.3390/pr11082408.

[5] B. Deepa, S. Hampannavar, and S. Mansani, "Smart monitoring of microgrid-integrated renewable-energy-powered electric vehicle charging stations using synchrophasor technology," *World Electric Vehicle Journal*, vol. 15, no. 10, 2024, doi: 10.3390/wevj15100432.

[6] A. Syed Mohammed, Anuj, A. S. Lodhi, and Q. Murtaza, "Techno-economic feasibility of hydrogen based electric vehicle charging station: a case study," *International Journal of Energy Research*, vol. 46, no. 10, pp. 14145–14160, 2022, doi: 10.1002/er.8132.

[7] H. C. Chen, C. L. Chen, H. K. Channi, M. Malik, R. Sandhu, and C. Prabha, "A solar-integrated wireless charging system for electric vehicles," *Engineering, Technology and Applied Science Research*, vol. 15, no. 1, pp. 19349–19353, 2025, doi: 10.48084/etasr.8840.

[8] M. S. Islam, A. K. M. A. Shuvo, S. Haque, A. M. Rizvi, and S. Hasan, "Comparative techno-economic feasibility analysis of hybrid renewable energy-based EV charging stations in a developing country," in *2025 International Conference on Electronics and Renewable Systems (ICEARS)*, IEEE, Feb. 2025, pp. 32–37. doi: 10.1109/ICEARS64219.2025.10940582.

[9] M. A. V. Rad, A. Esmaeilpour, F. Rouzbahani, and A. Toopshekan, "Economic optimization of hybrid renewable system for near-zero emission electric vehicle charging stations in the capital cities of the world," *Sustainable Energy Technologies and Assessments*, vol. 82, p. 104546, Oct. 2025, doi: 10.1016/j.seta.2025.104546.

[10] A. Demirci, Z. Ozturk, and M. Terkes, "Sustainable EV charging via scenario-based optimization of hybrid solar-storage systems: A regionally adaptive approach," *Renewable Energy*, vol. 272, p. 126040, Sep. 2026, doi: 10.1016/j.renene.2026.126040.

[11] I. Veza, T. W. B. Riyadi, S. M. N. Rahaju, M. Idris, Irianto, and I. M. R. Fattah, "Techno-economic optimization of multi-city off-grid PV–hydrogen systems for dual EV charging and green hydrogen production," *Frontiers in Energy Research*, vol. 14, May 2026, doi: 10.3389/fenrg.2026.1834349.

[12] A. F. Güven, N. Ateş, S. Alotaibi, T. Alzahrani, A. M. Amsal, and S. K. Elsayed, "Sustainable hybrid systems for electric vehicle charging infrastructures in regional applications," *Scientific Reports*, vol. 15, no. 1, 2025, doi: 10.1038/s41598-025-87985-7.

[13] B. Hüner, "Feasibility and environmental analysis of biogas-based hybrid energy system using homer pro software: a case study for hatay," *Energy Conversion and Management*, vol. 326, p. 119480, Feb. 2025, doi: 10.1016/j.enconman.2025.119480.

[14] D. Zhou, Z. Wang, K. Xi, C. Zuo, and Y. Jia, "Optimization configuration analysis of wind-solar-storage system based on homer," *Energy Engineering*, vol. 122, no. 5, pp. 2119–2153, 2025, doi: 10.32604/ee.2025.061712.

[15] Y. Alhazmi, "Techno-economic design analysis of electric vehicle charging stations powered by photovoltaic technology on the highways of saudi arabia," *Energies*, vol. 18, no. 2, 2025, doi: 10.3390/en18020315.

[16] A. S. M. M. Hasan, "Electric rickshaw charging stations as distributed energy storages for integrating intermittent renewable energy sources: a case of bangladesh," *Energies*, vol. 13, no. 22, p. 6119, 2020.

[17] M. S. Mauludin *et al.*, "Assessing the technological and financial feasibility of PV-wind hybrid systems for EV charging stations on indonesian toll roads," *International Journal of Sustainable Development and Planning*, vol. 20, no. 1, pp. 291–304, Jan. 2025, doi: 10.18280/ijsdp.200127.
[18] M. Sithambaram, P. Rajesh, F. H. Shajin, and I. Raja Rajeswari, "Grid connected photovoltaic system powered electric vehicle charging station for energy management using hybrid method," *Journal of Energy Storage*, vol. 108, 2025, doi: 10.1016/j.est.2024.114828.
[19] P. N. Tiwari, K. P. Tiwari, A. Dixit, A. K. Bohre, N. L. Shah, and S. K. Gupta, "Analysis of microgrids electric vehicles charging stations with hybrid energy storage system algorithm with ai," *Lecture Notes in Electrical Engineering*, vol. 1305, pp. 247–264, 2025, doi: 10.1007/978-981-96-0476-0_19.
[20] L. P. R. Nadimuthu, K. Victor, M. Bajaj, V. Blazek, and L. Prokop, "Solar-thermoelectric mobile storage system integrated with electric vehicles for reducing postharvest and microbial losses in agro produce transportation," *Scientific Reports*, vol. 15, no. 1, 2025, doi: 10.1038/s41598-025-00501-9.
[21] A. Gulraiz *et al.*, "Energy advancements and integration strategies in hydrogen and battery storage for renewable energy systems," *iScience*, vol. 28, no. 3, 2025, doi: 10.1016/j.isci.2025.111945.
[22] H. Knowles, A. Swingler, and L. Swan, "Hybrid battery and sensible thermal energy storage for a microgrid in a remote indigenous Canadian community," *Energy Storage*, vol. 7, no. 3, Apr. 2025, doi: 10.1002/est2.70165.
[23] M. Bai *et al.*, "Comprehensive design of hydrogen-battery hybrid energy storage system in green methanol production from economic, safety, and resilience perspectives," *ACS Sustainable Chemistry and Engineering*, vol. 13, no. 10, pp. 3877–3894, Mar. 2025, doi: 10.1021/acssuschemeng.4c08124.
[24] V. A. Voronin, F. S. Nepsha, and E. E. Kartashova, "Comparative analysis and pre-feasibility study of electric vehicle charging hub architectures," in *2025 7th International Youth Conference on Radio Electronics, Electrical and Power Engineering (REEPE)*, IEEE, Apr. 2025, pp. 1–6. doi: 10.1109/REEPE63962.2025.10971152.
[25] O. Y. Galal, I. Abdelsalam, and M. I. Marei, "Grid-tied three-port converter for enhanced electric vehicle charging with vehicle to grid capability," in *2025 7th International Youth Conference on Radio Electronics, Electrical and Power Engineering (REEPE)*, IEEE, Apr. 2025, pp. 1–6. doi: 10.1109/REEPE63962.2025.10970872.

BIOGRAPHIES OF AUTHORS

Jeyagopi Raman has been a lecturer in the Engineering Department at INTI International University, Nilai, Malaysia, since 2002 and has been a senior lecturer since 2012. He received his B.Eng. degree in Electronic and Electrical Engineering from Robert Gordon University, United Kingdom, in 1998; an M.Sc. degree in mechatronics from De Montfort University, United Kingdom, in 1999; and a Ph.D. degree in electrical power engineering from Universiti Tenaga Nasional, Malaysia, in 2016. He is also a member of the Board of Engineers Malaysia, the Malaysia Board of Technologists, and a Chartered Engineer of The Institution of Engineering and Technology. His research interests include the field of power systems, power quality, power electronics, motor controllers, renewable energy, industrial applications, robotics, artificial intelligence, and intelligent control. He can be contacted at email: jeyag.raman@newinti.edu.my or rjeyagopi@gmail.com.

Sudesh Nair Baskara is currently the Head of Programme (HOP) for Civil Engineering at Inti International University, Nilai. He completed his Ph.D. in Highway and Transportation in 2022. He has been involved in civil engineering for 14 years in both academia and industry. Besides teaching highway and transportation, he also teaches land surveying. He is involved in research on road accident analysis and has published a number of research papers. He can be contacted at email: sudesh.baskara@newinti.edu.my.

Harpreet Kaur Channi has served as an assistant professor at BCET, Ludhiana (July 2008–July 2012), Chandigarh University, Mohali (July 2012–January 2025), and Guru Nanak Dev Engineering College (GNDEC), Ludhiana (January 2025–May 2026). She received her B.Tech. and M.Tech. in electrical engineering from BCET and GNE College, Ludhiana, respectively, and her Ph.D. from Chandigarh University, Mohali. She is the author of 26+ books and has published 140+ research papers indexed in Scopus, Web of Science, IEEE, and other reputed databases. She has 18 years of teaching and research experience and has served on various national and international editorial boards. She has been a research fellow at Eudoxia Research Centre, India, affiliated with Eudoxia Research University, USA, since March 2024. Since March 2025, she has also been a Research Fellow at INTI International University, Malaysia. Her research interests include solar PV systems, smart grids, electric vehicles, energy conversion, and renewable energy integration. She can be contacted at email: harpreetchanni@yahoo.in.