



OPEN Techno-economic and policy analysis of solar-wind powered EV charging for sustainable E-mobility

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In this study, the techno-economic viability of electric vehicle charging stations using a combination of solar photovoltaic and wind turbine technologies is examined, with specific reference to identifying the optimal configuration of wind turbine, solar photovoltaic, battery, and power conversion equipment. The cost of energy, net present cost, and initial capital cost are examined in varying climatic conditions in India. A total of 26 sites are examined to assess the viability of solar photovoltaic, wind turbine, and battery-based electric vehicle charging stations. Key findings of the study reveal that solar photovoltaic, wind turbine, and battery configurations are the most cost-effective for 11 sites, with the lowest cost-effectiveness in Pune and the highest in Bhopal. For the remaining sites, solar photovoltaic and battery configurations are the most viable, with the highest cost-effectiveness in Jodhpur and the lowest in Srinagar. The study also reveals that wind turbine and battery configurations are not viable for any of the sites, as the cost of energy is high. It is also revealed through sensitivity analysis that higher electric vehicle load makes the systems unreliable, while aligning electric vehicle charging capacity with available resources enhances reliability and cost-effectiveness.

Keywords Electric vehicle, Solar photovoltaic, Wind, Cost of energy

Abbreviations

COE	Cost of energy
PV	Photovoltaic
EV	Electric vehicles
NPC	Net present cost
EVCS	Electric vehicle charging stations
OC	Operating cost
HOMER	Hybrid optimization of multiple energy resources
NASA	National aeronautics and space administration
IC	Initial capital costs
SOC	State of charge
LCOE	Levelized cost of energy
USD	United states dollar
M	Millions
WT	Wind turbine

The growth of electric vehicles has increased the need for sustainable and reliable electric vehicle charging infrastructure. The integration of solar technology with electric vehicle charging stations has been identified as a promising approach to reduce dependence on fossil fuels and minimize greenhouse gas emissions¹. Furthermore, hybrid approaches to renewable energy systems, such as the use of batteries or hydrogen-based storage systems such as reversible fuel cells can also improve the reliability of such systems and increase their share of renewable energy sources^{2,3}. In addition, various advanced planning techniques, such as geographic information system and multi-criteria decision-making, have been widely employed to optimize the location of solar-based electric vehicle charging infrastructure and improve their efficiency and sustainability^{4,5}.

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The global spread of electric vehicles (EVs) has increased significantly owing to their importance in combating the emission of harmful pollutants from the atmosphere^{6,7}. In 2024, EV sales surpassed 17 million units, showing a positive growth trend for the EV industry⁸. In 2023, electric vehicles accounted for 15.8% of newly sold vehicles, showing a 2.8% increase compared to the preceding year⁹. In February 2025, electric vehicle sales globally reached 1.2 million units, showing a 50% increase compared to the same period of the preceding year¹⁰. Therefore, electric vehicle sales are expected to continue this positive growth trend in 2025. According to projections, electric vehicle sales are expected to grow by at least 17–18% in 2025, surpassing a milestone of 20 million units¹¹. According to statistical projections, by the end of 2025, the global electric vehicle market is expected to reach a huge value of 784.2 billion, and it is expected to grow at a compound annual growth rate (CAGR) of 6.01% and reach 990.4 billion by 2029¹².

India encourages the widespread adoption of electric vehicles as part of the broader goal of achieving sustainable development and achieving carbon neutrality. The projection of the electric vehicle market in India suggests that it will have a compound annual growth rate of 19.44%, growing from 54.41 billion USD in 2025 to 110.7 billion USD in 2029¹³. The literature currently suggests that India had 5.6 million electric vehicles in use on the roads in 2024¹⁴. The electric vehicle market in India has also witnessed a surge in sales, with 2 million units sold in 2024 compared to 1.6 million units in 2023, representing a growth of 24%¹⁴. The policies of the government in this regard are expected to enhance the sales of electric vehicles, and the chances of the high oil price levels experienced in the preceding year may also attract the interest of potential customers¹⁵. The widespread distribution of electric vehicle charging stations (EVCS) will facilitate the adoption of EVs, allowing owners to travel long distances confidently with convenient access to charging stations. However, there will be significant challenges in supplying the growing EVCS with the required electricity from the current system. The system will experience an increase in load peaks due to a considerable rise in electrical load demand. This results in breaches of voltage limits, overloads in transformers and feeders at different voltage levels, and adverse effects on the grid¹⁶.

In order to address the energy security dilemma and improve the environment, the imperative is to develop and use renewable energy sources^{17,18}. Powering new energy vehicles using renewable sources, such as solar photovoltaic (PV) and wind, or a mix of the two, might be an appealing solution to the problem of charging new energy vehicles^{19,20}. Several academics have dabbled with EV research, and most new energy vehicles available today are purely electric. Zorlu and Ozcan²¹, Choi and Bhakta²², Thulasigam et al.²³, and Mallikarjun et al.²⁴ focussed different renewable resources in different regions worldwide, for renewable-powered EVCS. It is found that site specific conditions influence economic and feasibility of EV charging stations. The energy management of renewable energy source based EVCS for and performance improvement is reviewed in^{25,26}. Mouli et al.²⁷ consider practical site-specific variations such as seasonal solar availability in Netherlands. Rooftop PV potential is utilized for PV charging. Due to seasonal variation of resources grid connection should be important for charging station. Karmaker et al.²⁸ proposed biogas-PV EV charging stations to reduce grid burden. To evaluate techno economic feasibility HOMER Pro software is used and optimal setup achieved an operating expenditure of \$2540, net present cost (NPC) of \$56,202, and a cost of energy (COE) of \$0.1302/kWh, and CO₂ emissions is reduced by 34.68% compared to grid-based stations. Alghoul et al.²⁹ used HOMER for PV-grid EVCS. It is found that integrating 10 kW solar hybrids set up achieved 2.14% penetration rate. This system offered 6.3 year payback period under feed in tariff scheme followed by 14.7 years of profit. Eom et al.³⁰ investigated the techno-economic performance of grid-connected EVCS installations along highways under different policy scenarios using HOMER software. The authors concluded that enabling the policy mitigation scenario would reduce NPC by 40% and further reduce CO₂ emissions. Different combinations of PV panels, inverter, fuel cell, electrolyzer, hydrogen tank, biomass generator, battery and wind turbine (WT) were analyzed by Guven et al.³¹ for techno-enviro-economic analysis of EVCS using HOMER Pro tool. The combination of PV, electrolyzer, hydrogen tank, biomass generator, inverter, fuel cell and grid was the most favourable with an NPC of \$611,283.50 and an LCOE of \$0.0215, while it proved to be the least favourable in terms of CO₂ emissions. Karmakar et al.³² performed a techno-economic analysis of PV-powered EVCS for highway installations in four metro cities (Mumbai, Chennai, Delhi and Kolkata) in India using the HOMER grid program. The proposed grid-connected PV-based highway EVCS provides electricity at \$0.029/kWh per unit, which is significantly lower than the standard grid cost of \$0.080/kWh. The techno-economic and environmental performance of EVCS consisting of solar PV, WT and battery banks was conducted by Alanazi et al.³³ for Saudi Arabia using Homer Pro software. It was concluded that the integration of PV/wind/battery/converter system provides the best performance in off-grid scenarios for daytime chargers, with an NPC of \$475,110, and of COE of \$0.168. While the on-grid configuration prefers a PV/wind/grid/converters setup for nighttime charging, achieving an NPC of \$150,316 and a COE of \$0.0179. Alshammari et al.³⁴ analyzed economic feasibility of PV/wind/biomass hybrids, with PV-biomass emerging as the most cost-effective option (LCOE: \$0.099/kWh). For optimization by HOMER different studies are given in^{35–37,45–51,58–65}. It is powerful tool which oversimplify real world uncertainties such as demand fluctuations, renewable sources intermittency and dynamic EV user.

From above review following research gap emerges (i) Limited multi-location techno-economic assessments. (ii) Lack of comparative analysis of hybrid system configurations for EV charging stations. (iii) Insufficient investigation of temporal electricity generation patterns (iv) Inadequate assessment of regional cost of energy variations. (v) Limited analysis of load variation impacts on economic indicators (vi) Lack of implications and policy recommendations on solar and wind based EV charging stations for diverse climatic condition.

To fill this gap, the present work performs a comparative simulation of such systems across 26 climatic zones of India. The contributions of this study include:

- Techno-economic feasibility analysis of electric vehicle charging stations for twenty-six different Indian locations with diverse climatic conditions are analyzed.

- Hybrid combinations of WT/Battery, PV/WT/Battery and PV/Battery are investigated for 26 different Indian locations.
- The monthly electricity generated by EVCS at different sites is investigated.
- Cost of energy variation for different sites is computed.
- The effect of load on net present cost and energy cost are computed, and variations are examined for different Indian sites.
- Implications and policy recommendations.

Methodology

Site description and resource data

India spans 3.287 million square kilometres and has six climate zones under Köppen's classification: humid subtropical, tropical wet and dry, arid, semi-arid, tropical wet, and montane³⁸. Table 1 sites are selected to represent diverse geographical regions and solar resource conditions across the study area. The selection was based on the availability of reliable meteorological data (solar irradiation and temperature), regional diversity, and the relevance of these locations for evaluating the feasibility of renewable energy-based hybrid micro grids. This approach allows the analysis to capture variations in climatic conditions and energy demand patterns, ensuring a more comprehensive techno-economic assessment. The NASA prediction of Worldwide Energy Resource (POWER) database³⁹ provides monthly mean wind speeds at 50 m height for 26 regions from January 1981 to December 2021. Figure 1 shows the 41-year wind speed trends, and Table 1 lists the maximum and minimum values.

NASA's POWER database collected average monthly irradiance values for 26 locations over 41 years. Figure 2 displays the average monthly irradiance data for the 26 sites. The monthly average air temperature data for the chosen sites was obtained from NASA's POWER database, covering 41 years from January 1981 to December 2021. Figure 3 illustrates the monthly mean temperature data for 26 selected locations.

Proposed design

Five steps were involved in this study's methodology. The steps involved are proposed design, techno-economic assessment tool selection, designing and simulation, sensitivity and comparative analysis and optimal configuration selection.

Cities	Climatic zone	Lat ($^{\circ}$ N)	Long ($^{\circ}$ E)	Average wind speed	
				From 1981 (m/s)	Up to 2021 (m/s)
Srinagar	Montane	34.08	74.79	2.18 (September)	2.76 (February)
Dehradun	Humid sub tropical	30.19	78.02	2.92 (September)	4.74 (April)
Lucknow		26.45	80.53	3.13 (October)	5.49 (March)
Patna		25.61	85.13	3.08 (October)	5.15 (July)
Shillong		25.34	91.53	2.64 (October)	5.34 (July)
Ranchi		23.35	85.33	3.11 (November)	5.28 (July)
Hamirpur		31.68	76.52	3.02 (September)	4.46 (May)
Port Blair		11.61	92.72	3.40 (March)	8.88 (June)
Bhopal		23.25	77.42	3.66 (October)	6.42 (May)
Varanasi		25.45	82.85	3.45 (October)	5.22 (March)
New Delhi		28.35	77.12	3.50 (October)	4.74 (April)
Kolkata		22.39	88.27	3.46 (October)	6.16 (June)
Vishakhapatnam	Tropical wet and dry	17.43	83.14	4.01 (January)	7.20 (July)
Pune		18.52	73.84	4.31 (January)	8.56 (July)
Nagpur		21.09	79.07	3.86 (November)	6.27 (July)
Chennai		13.081	80.27	4.81 (October)	7.08 (June)
Mumbai		19.07	72.51	3.75 (April)	7.40 (July)
Hyderabad		17.36	78.46	4.30 (December)	7.78 (July)
Thiruvananthapuram		8.5	76.9	3.54 (March)	7.28 (June)
Minicoy	Tropical wet	8.28	73.03	2.87 (March)	8.25 (June)
Panjim		15.49	73.81	3.73 (November)	7.81 (July)
Jodhpur	Semi-Arid	26.18	73.01	3.99 (October)	6.81 (June)
Bangalore		12.57	77.38	4.53 (October)	8.00 (July)
Ahmedabad		23.04	72.38	3.52 (October)	6.47 (June)
Bhavnagar		21.77	72.15	3.95 (October)	7.04 (July)
Jaipur	Arid	26.92	75.82	3.79 (November)	6.10 (May)

Table 1. Selected cities in various climate zones with minimum/maximum average wind speeds.

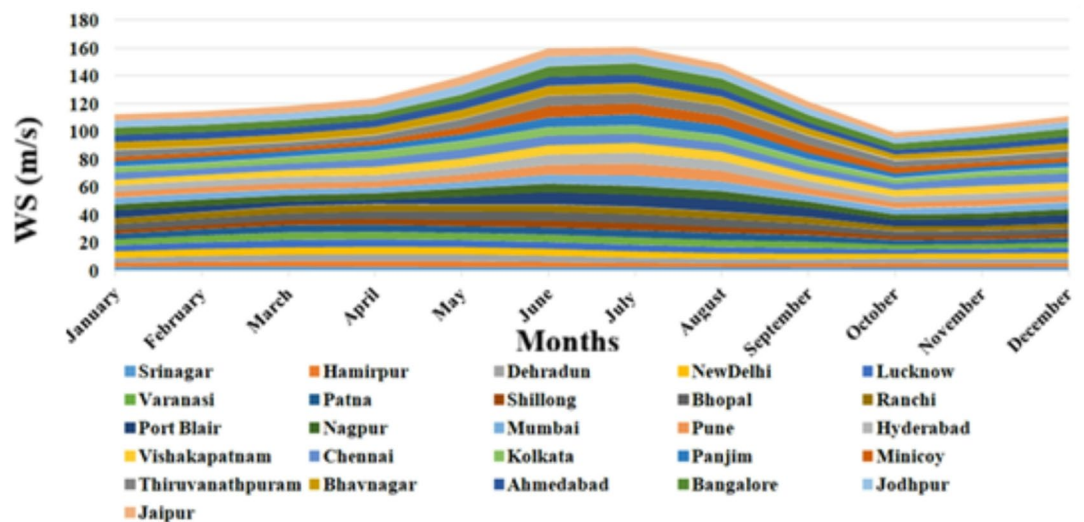


Fig. 1. Data from 26 selected locations on the average monthly wind speed at a height of 50 m.

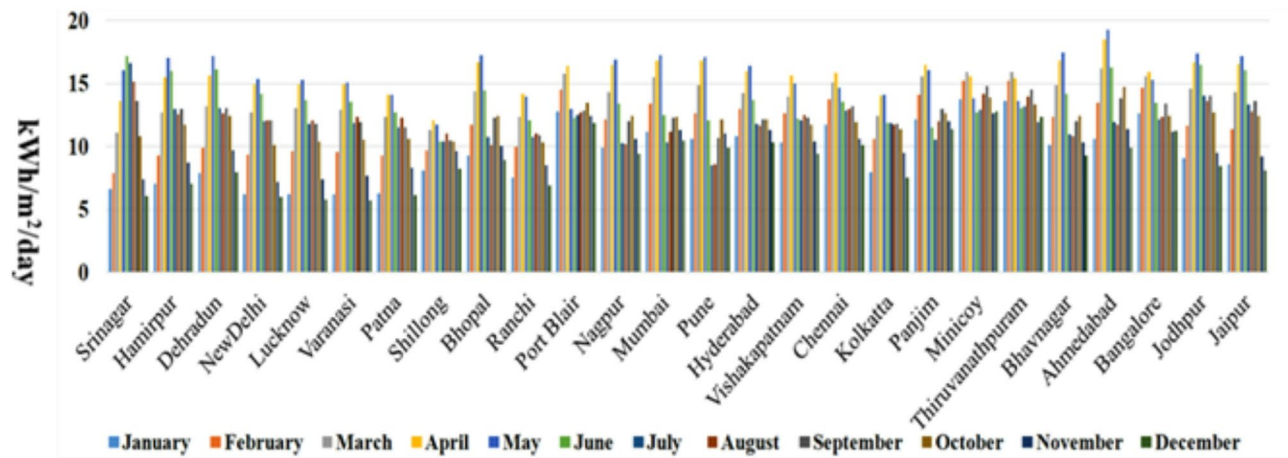


Fig. 2. Monthly average radiation data from 26 chosen locations.

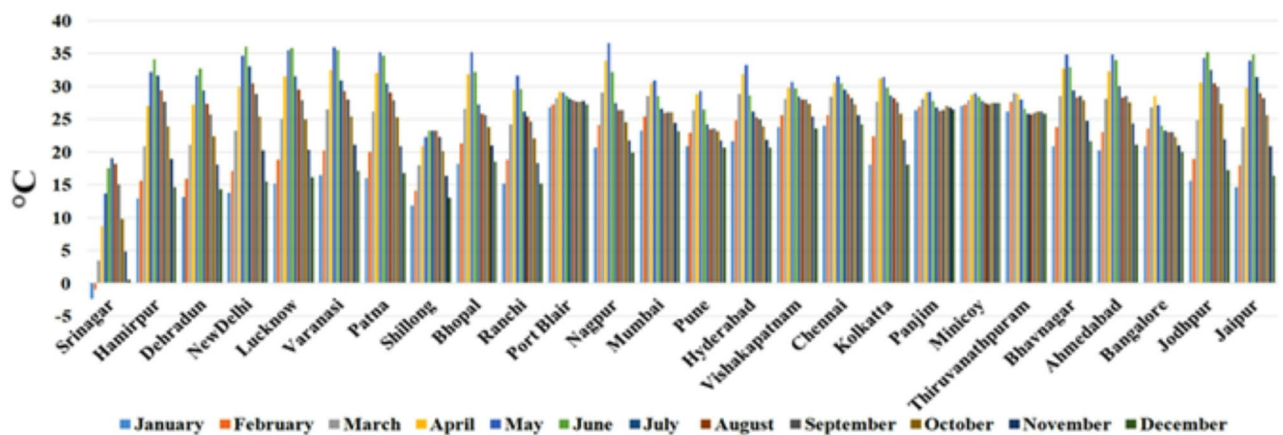


Fig. 3. Monthly average temperature data from 26 selected locations.

Techno-economic and optimization tool selection

The United States National Renewable Energy Laboratory created a microgrid modelling, optimization, and sensitivity analysis program called HOMER⁶⁸. The HOMER Pro program uses grid search to identify the most economically viable solution and works best during the design phase. The HOMER Optimizer utilizes an approach that does not rely on derivatives to determine the most cost-effective system. The HOMER Pro analysis's process flow is shown in Fig. 4. EV charging systems incorporate an energy management system whose main functions are priority-based control, load shifting and demand response, state-of-charge-based battery management, and hybrid control with predictive algorithms. The load-following dispatch strategy in HOMER was adopted, in which renewable sources primarily meet load demand, and the battery supplies the deficit. Limitations include that HOMER does not capture uncertainties in solar radiation, wind speed, load demand, economic parameters, component degradation, and grid instability.

Decision variables, constraints, and objective function

The objective is to fulfil the daily demand for EVCS while selecting the most economical size and operating scenario that minimizes installation and operating costs during the system's lifetime. After HOMER computes the COE and NPC for all potential combinations, sizes, and operating scenarios, the optimal configuration can

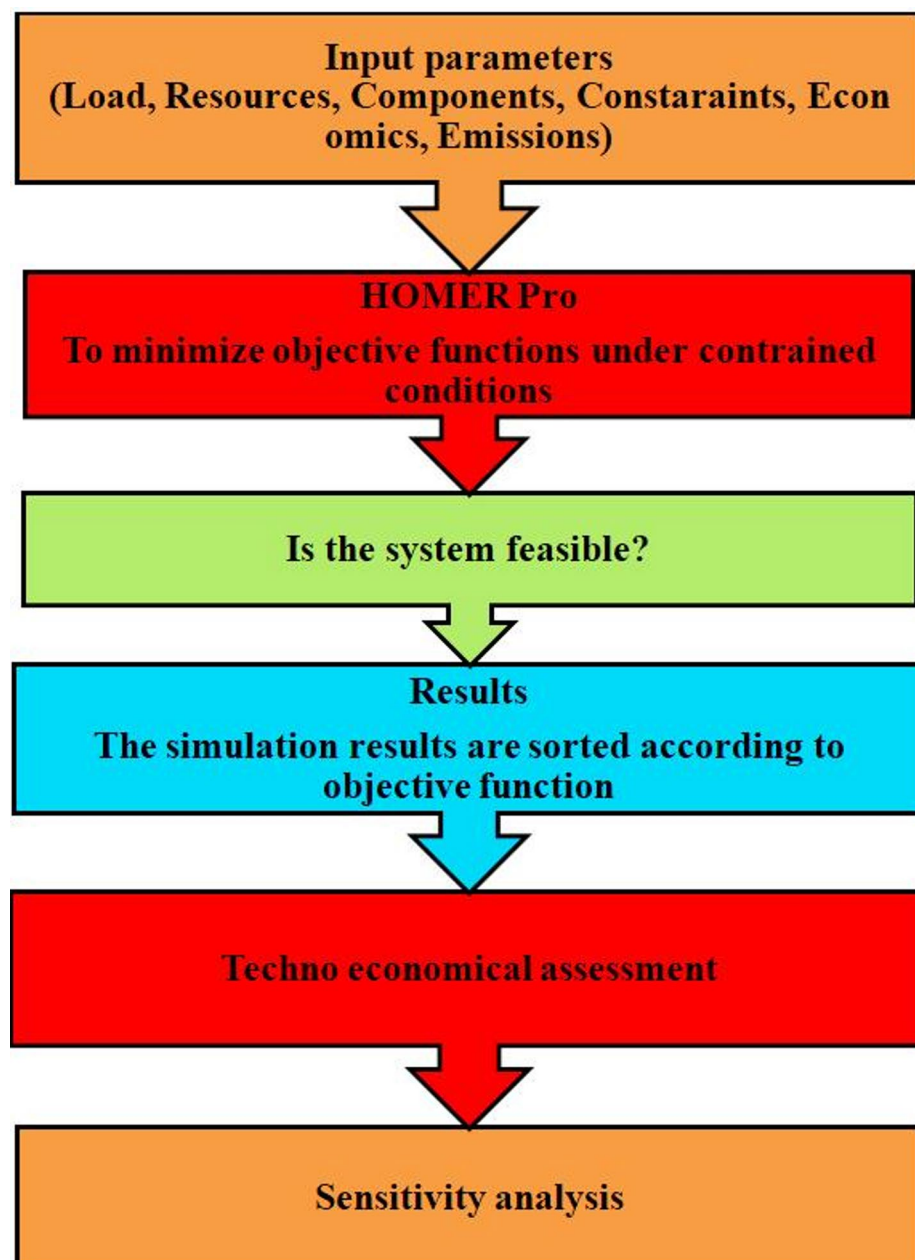


Fig. 4. HOMER Pro analysis flowchart.

Parameter	Range
Discount Rate	6% – 8%
Inflation Rate	2% – 3%
Project Lifetime	20–25 years

Table 2. Economic parameters.

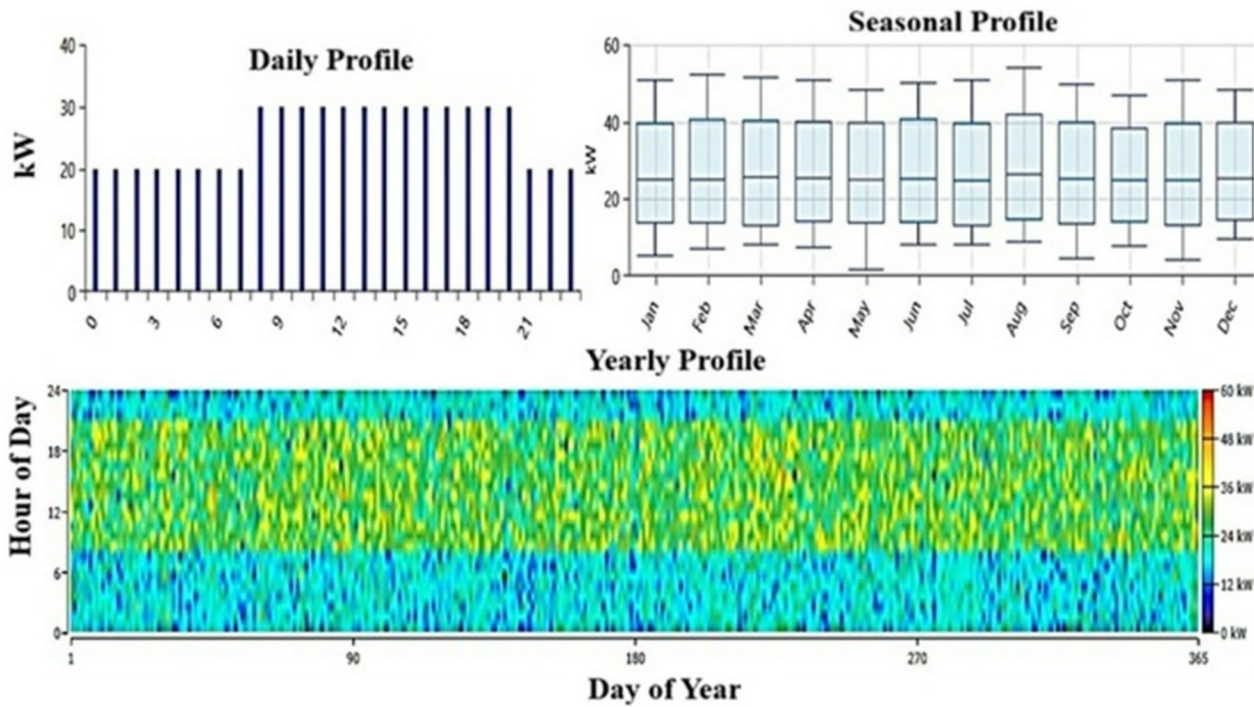


Fig. 5. Profile of the load for the 26 potential charging stations.

be identified by choosing the one with the minimum NPC and COE. The NPC of a component is determined by deducting the present value of all installation and maintenance expenses incurred throughout the project’s duration from the present value of all revenues generated by the component during that timeframe⁴⁰. Net Present Cost (total lifetime cost in present value) i.e. C_{NPC} is given by Eq. 1 and key economic input parameters are shown in Table 2.

$$C_{NPC} = \frac{C_{Annual}}{\frac{i(i+1)^n}{(i+1)^n - 1}} \tag{1}$$

In Eq. 1, C_{Annual} denotes the total yearly cost, n signifies the economic operational lifespan measured in years, and i indicates the real discount rate.

COE is the overall cost of constructing and operating an energy generation facility, divided by the cumulative power output of that plant during its operational lifespan. Equation 2 is used to calculate and denote the average cost per kilowatt-hour of each plan to meet the demand⁴¹.

$$COE = \frac{I_0 + \sum_{t=1}^n \frac{A_t}{(1+i)^t}}{\sum_{t=1}^n \frac{M_{el}}{(1+i)^t}} \tag{2}$$

Where, I_0 = investment expenditure; M_{el} = quantity of electricity produced in the specified year; A_t = total annual costs in year t; i = actual discount rate; n=duration of economic viability in years.

HOMER model

Load data

The potential charging station load profiles at the five locations under consideration are shown in Fig. 5. The evaluated station has an annual energy need of 600 kWh per day, a utilization factor of 0.47, and a maximum power demand of 53.17 kW. The number depends on average EV battery size:

Number of EVs = \frac{Daily Load (kWh/day)}{Battery Capacity per EV (kWh)} \tag{3}

Typical EV battery sizes are small EV (2-wheeler/3-wheeler): 5–10 kWh, small car: 30–40 kWh, medium car: 50–60 kWh, large car / SUV: 70–90 kWh. If 30 kWh EV → 600/30=20 EVs/day. If 40 kWh EV → 600/40=15 EVs/day. If 60 kWh EV → 600/60=10 EVs/day. Thus depend on battery size 10–20 EVs can be charged daily. Renewable energy fraction (REF) is the portion of the total energy supplied to the load that comes from renewable sources (such as solar, wind, hydro). In this study REF=1 (or 100%) which means entire energy comes from renewable sources.

Wind turbine (WT)

For simulation, the common 3 kW WT was selected for many benefits in terms of performance and economy. Each WT is assumed to have capital, replacement expenses of ₹260,000, ₹260,000 respectively. Operation and maintenance cost is 2% to 3%⁴² of capital cost i.e. ₹7800. Based on the HOMER optimizer, the WT’s capacity is optimized. The exponential law model is frequently used in real-world situations to calculate wind speed variations in height and topography. This model calculates wind speed at various altitudes, such as 50 m, the height of anemometers, and the WT hub height. The wind speed at the height of the turbine hub is calculated using the following formula⁴³.

U_{hub} = U_{anem} * \left(\frac{Z_{hub}}{Z_{anem}} \right)^{\alpha} \tag{4}

Where, U_{hub} = wind speed at the hub height of the WT [m/s]; Z_{hub} = The WT’s height at the hub [m]; U_{anem} = wind speed recorded at the height of the anemometer [m/s]; α = power-law exponent; Z_{anem} = Anemometer height [m].

The following formula is used to calculate a WT’s power output⁴³.

P_{WTG} = \left(\frac{\rho}{\rho_0} \right)^{\alpha} * P_{WTG, STC} \tag{5}

Where, P_{WTG} = WT power output [kW]; ρ = real air density; ρ_0 = density of air under ambient conditions; $P_{WTG, STC}$ = The WT’s power output at ambient pressure and temperature [kW].

Power-law exponent (α), ranges from 0.05 to 0.5 and is affected by both the atmospheric stability and the surface roughness. The α is taken as 0.14 for the selected locations. At various wind speeds at hub height, the WT’s power curve shows the features of the energy generation. The system has a rated capacity of 3 kW with an initial capital cost of ₹260,000. The annual operating and maintenance cost is estimated at ₹3,781 per kW so it is equal to ₹ 11,346 per year⁶⁶, while the replacement cost is equal to the initial investment at ₹260,000. The turbine is installed at a hub height of 50 m and is designed to operate over a lifetime of 20 years.

Solar PV panels

The study used the generic flat plate PV. This analysis assumes operating and maintenance expenses are considered to be ₹3500 per year and PV capital and replacement costs to be ₹35,000/kW. Each panel’s rated capacity is 1 kW. The lifetime is 25 years, and the derating factor is 80%. These are provided in Table 3. The proposed design utilizes solar technologies to capture solar energy for electricity production. Additionally, less area is needed for small-scale generation facilities. Other renewable energy solutions also need more time to construct. The efficiency of solar technology has made it a competitive player in recent times. The following equation determines the PV/T output^{43,44}.

Nominal capacity (kWh)	1
Nominal voltage (V)	12
Lifetime	10 years
Initial capital	₹16,750
Replacement cost	₹16,750
Operating and maintenance cost	₹1675/year
Maximum charge rate (A/Ah)	1
Capacity ratio	0.403
Maximum discharge current (A)	24.3
Maximum capacity (Ah)	83.4
Maximum charge current (A)	16.7
Roundtrip efficiency (%)	80
Rate constant (1/h)	0.827

Table 3. Details about the chosen battery’s specifications and price.

$$P_{pv} = Y_{pv} f_{pv} \left(\frac{G_T}{G_{T,STC}} \right) [1 + \alpha_p (T_C - T_{C,STC})] \quad (6)$$

Where, f_{pv} = PV derating factor; Y_{pv} = Rated capacity of PV; G_{STC} = Incident radiation under conventional testing parameters; G_T = PV array's exposure to sunlight; T_C = Temperature of the PV cell; α_p = Power's temperature coefficient; $T_{C,STC}$ = PV cell's temperature during standard testing.

Battery storage

Batteries serve as energy storage components in a hybrid renewable energy system, allowing for the accumulation of surplus power provided by renewable sources and subsequent discharge during power disruptions. During the experiment, a nominal 12 V and 1 kWh nominal lead acid battery capacity was employed. In our estimation, a battery will cost ₹16,750 to buy, ₹16,750 to replace, and ₹1675 to operate and maintain annually. In the analysis lead acid battery allows a more realistic techno-economic comparison with other storage options and reflects solutions that are feasible for practical implementation. The HOMER optimizer is used to maximize the battery's capacity. The battery state of charge (SOC) limits was defined to avoid deep discharge and overcharging. When the battery reached its maximum SOC, excess renewable generation was treated as curtailed energy.

Converter

The converter is expected to cost ₹17,500 for initial investment, replacement, and operation and maintenance. The rated capacity is 1 kW and 15-year lifespan with 95% efficiency using the HOMER optimizer; the converter's capacity is improved.

System configuration

Figure 6 illustrates the composition of the PV/WT/battery hybrid EV charging system, which includes converters, batteries, WT, and other components. Batteries are the primary means of storing energy, and PV and WT power sources generate the bulk of the electricity used to power EV charging stations. The extra electricity will be charged to the battery when the PV arrays and WTs produce more energy than is required for charging. Instead, the batteries will provide the load. The hourly electricity output from renewable energy sources is compared with the hourly demand load during the year-long simulation of the proposed hybrid renewable energy system in HOMER Pro. This is done while considering the integrated components' unit costs, lifespan, and technical specifications. All workable alternatives to satisfy the intended load demand are examined through the simulation process. These solutions consider configurations, sizes, dispatch techniques, and sensitivity characteristics. To find the best setup for the site, HOMER Pro simulates every viable alternative.

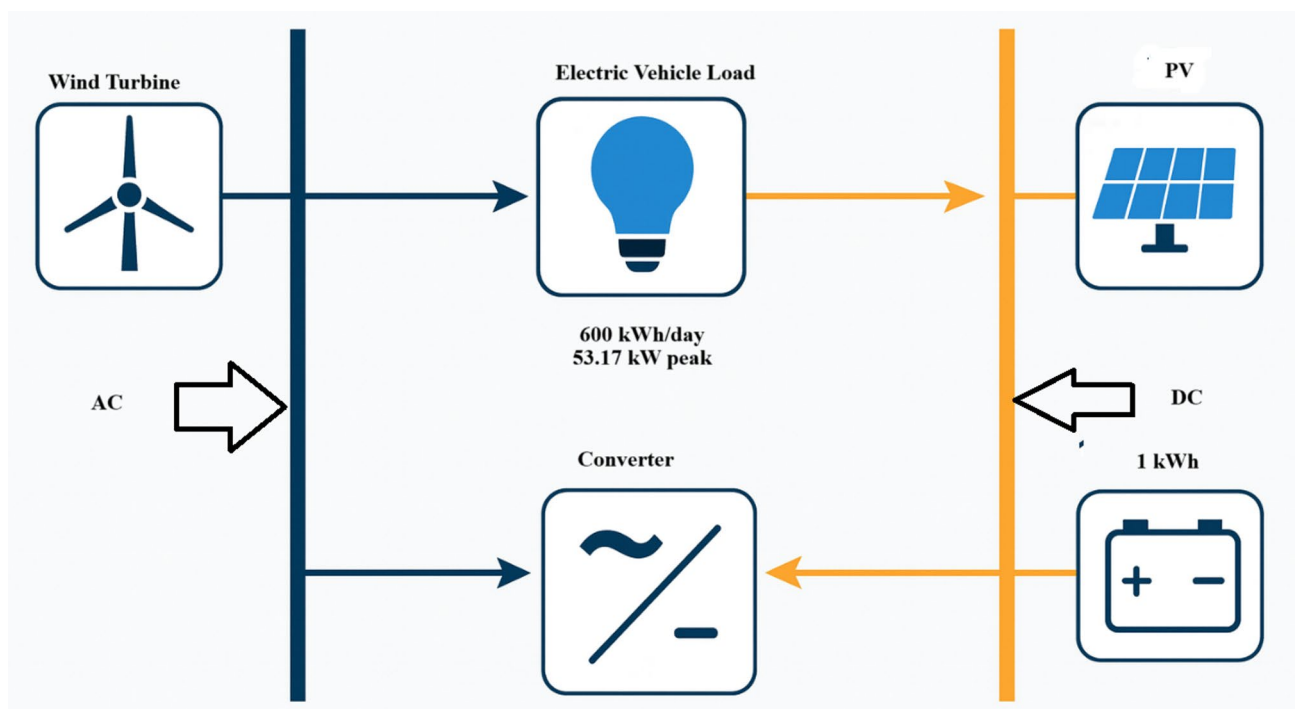


Fig. 6. An off-grid hybrid PV/WT/battery system block diagram.

Results and discussions

Analysis of optimal configuration

The technical and economic aspects of hybrid renewable energy EV charging stations have been analysed across 26 selected locations in India, as detailed in Table 4, where M represents millions. This study examines three unique types of hybrid EV charging stations: WT/Battery, PV/Battery, and PV/WT/Battery. The WT/Battery configuration is found to be not feasible for Dehradun, Hamirpur, Lucknow, Minicoy, Patna, Shillong, and Srinagar because the wind energy potential at these locations is relatively low and highly variable. Due to the insufficient and inconsistent wind resources, the wind turbines are unable to generate adequate electricity to reliably meet the load demand. Moreover, the low and intermittent wind speeds significantly reduce the turbine's capacity factor, resulting in poor overall energy production and making the configuration impractical for these sites. Based on COE and NPC hybrid PV/WT/battery based systems are determined to be the optimal choice for EV charging stations in Ahmedabad, Bangalore, Bhavnagar, Bhopal, Minicoy, Mumbai, Panjim, Port Blair, Pune, Patna, and Visakhapatnam, which accounts for 11 out of the total 26 locations. The most cost-effective PV/battery charging station is in Jodhpur (458 kW PV, 0 WTs, 941 batteries of 1 kW, and 63.3 kW converter), with minimum operating costs (OC), COE, NPC, and initial capital costs (IC) of ₹5.08 M/year, ₹33.39/kW, ₹108 M, and ₹32.9 M, respectively. The least cost-effective charging station is in Port Blair and has a maximum NPC, COE, OC, and IC of ₹1.44B, ₹446/kW, ₹86 M, and ₹172 M, respectively. The system has 0 kW of PV, 354 WTs, 4538 batteries, and a 236-kW converter.

PV-WT power production

Figure 7 presents PV generation is high during summer i.e. March to May and sharp decline during monsoon months i.e. June to August which confirm incorporation of hybrid system for maintaining reliability. Wind peak is observed in July complementing reduced PV output and demonstrating the advantage of PV-WT hybrid systems for powering EV charging applications. Cities with optimum PV configuration face larger fluctuation regions (e.g., Bangalore, Pune, and Visakhapatnam) which achieve more stability showing importance of regionalized planning. Stable solar region such as Jaipur, Jodhpur, Patna require less backup but high variable region such as Shillong, Kolkata, Mumbai demand larger storage capacity and stronger grid integration.

Sensitivity analysis

The sensitivity analysis examines the impact of variations in load (the quantity of EVs) on the NPC (₹) and COE (₹/kWh) across several locations in India. For PV/WT/battery based systems, Ahmedabad, Bangalore, Bhavnagar and Bhopal are shown in Fig. 8a–d, while for other cities are presented in Fig. 1S (supplementary material). Using the optimal design, the figures depict the impact of load demand changes for COE and NPC of EV charging stations at 26 locations. When the electricity use grows from 300 to 900 kWh per day, it is evident that the charging station's NPC likewise increases. NPC steadily increases with load, showing high capital costs when scaling the system. For Ahmedabad, in Fig. 8a, COE is 40.2, but there is a significant drop at 545 kW due to increased renewable energy contribution. This system can be scalable, and more analysis is required to understand the dip in COE. Figure 8b shows COE and NPC variation with load for Bangalore. NPC vary linearly with load, whereas COE drop is observed at 360–420 kW, spikes at 480 kW and peaks near 720 kW. After 780 kW, COE stabilizes but remains on an upward trajectory. This shows that COE exhibits nonlinear behaviour, indicating better infrastructure planning and energy management. From Fig. 8c for Bhavnagar, NPC steadily increases, COE varies from 34.6 to 36.2, and in Fig. 8d for Bhopal, COE varies from 40.6 to 42.2, suggesting it requires a more stable system. Moreover, the key insights from Fig. 1S (supplementary material) are shown in Table 5. Hamirpur, New Delhi, Pune, Patna, and Thiruvananthapuram are more stable and cost-effective, proving the most suitable locations for PV-based EV charging stations. Dehradun, Nagpur and Chennai face COE fluctuations that require storage systems. Hyderabad is stable with minor COE fluctuations. Minicoy, Mumbai, Port Blair, Panjim, Shillong, and Ranchi have COEs of moderate instability, highlighting improvement in energy management.

Table 6 presents a comparative analysis of the COE obtained in the current study with relevant international studies that employed HOMER-based simulations for hybrid renewable energy systems and EV charging stations. The COE values from the present work, which examined 26 sites across India, range between 37.81 and 62.91 ₹/kWh for a daily load of 600 kWh. These results are comparatively higher than those reported in other regions, which can be attributed to differences in resource availability, load assumptions, and system configurations.

CO₂ emission reduction

It refers to lowering in release of CO₂ into the atmosphere. It is a major greenhouse gas responsible for climate change and global warming. For India, the average grid emission factor is commonly taken as: 0.82 kg CO₂/kWh⁶⁷. The reduction in CO₂ due to renewable energy based charging stations are shown in Table 7 and it is calculated by following equation.

$$CO_2\text{reduction} = \text{Energy} \times \text{Emission factor} \quad (7)$$

Implications and policy recommendations

The findings demonstrated the ineffectiveness of a uniform national model for renewable energy-based EV charging. Climate zones, resource profiles, and load behavior all influence the optimal charging architecture. Therefore, India should adopt a location-specific deployment strategy. In this study, the PV/WT/battery system performed best in Ahmedabad, Bangalore, Bhavnagar, Bhopal, Minicoy, Mumbai, Panjim, Port Blair, Pune, Patna, and Visakhapatnam. In several other cities, the PV/battery configuration was found to be more suitable. The most economical PV/battery case was Jodhpur, and the most expensive was Port Blair. This suggests that

Location	Architecture	1 kW WT (No.)	PV (kW)	1 kW Battery (No.)	Converter (kW)	COE (₹/kWh)	COST NPC (₹)	OC (₹/year)	IC (₹) M
Ahmedabad	PV/WT/battery	2	640	998	56.7	40.08	129 M	6.02 M	40.6 M
	WT/battery	139	0	7059	125	267.57	863 M	47.9 M	157 M
	PV/battery	0	701	1000	54.7	40.21	130 M	5.94 M	42.2 M
Bangalore	PV/WT/battery	10	297	818	55.1	35.41	114 M	5.87 M	27.7 M
	WT/battery	92	0	4201	92.6	168.95	545 M	30.5 M	95.9 M
	PV/battery	0	621	1172	87.8	40.21	130 M	5.89 M	42.9 M
Bhavnagar	PV/WT/battery	7	366	901	56.1	35.51	115 M	5.69 M	30.7 M
	WT/battery	100	0	5471	201	200.15	646 M	35.6 M	121 M
	PV/battery	0	687	793	92.1	38.1	123 M	5.70 M	39 M
Bhopal	PV/WT/battery	8	509	966	693	41.17	133 M	6.48 M	37.3 M
	WT/battery	103	0	5629	175	205.8	664 M	36.6 M	124 M
	PV/battery	0	688	1194	61.7	41.95	135 M	6.12	45.1
Chennai	PV/WT/battery	1	528	1000	75.6	36.69	118 M	5.54 M	36.8 M
	WT/battery	97	0	3577	202	164.04	529 M	29.9 M	88.7 M
	PV/battery	0	481	1149	73.6	36.21	117 M	5.39 M	37.4 M
Dehradun	PV/WT/battery	1	554	995	55.1	37.55	121 M	5.69 M	37.3 M
	WT/battery	NOT FEASIBLE							
	PV/battery	0	551	1000	55.5	36.54	118 M	5.49 M	37.01
Hamirpur	PV/WT/battery	1	731	1235	169	45.45	147 M	6.59 M	49.5 M
	WT/battery	NOT FEASIBLE							
	PV/battery	0	734	1221	83.5	43.76	141 M	6.35 M	47.6 M
Hyderabad	PV/WT/battery	1	598	984	55.9	38.16	123 M	5.73 M	38.6 M
	WT/battery	92	0	2920	125	146.84	474 M	27 M	75 M
	PV/battery	0	526	1163	65.5	37.39	121 M	5.53 M	39 M
Jaipur	PV/WT/battery	1	554	972	57.5	37.07	120 M	5.611 M	36.9 M
	WT/battery	158	0	5623	212	262.8	848 M	48.1 M	139 M
	PV/battery	0	551	1000	58.9	36.49	118 M	5.47	37.1 M
Jodhpur	PV/WT/battery	1	426	999	57.5	33.85	109 M	5.18 M	32.9 M
	WT/battery	86	0	7183	177	215.41	695 M	37.3 M	146 M
	PV/battery	0	458	941	63.3	33.39	108 M	5.08 M	32.9 M
Kolkata	PV/WT/battery	1	619	1258	54.7	41.8	135 M	6.17 M	43.9 M
	WT/battery	145	0	5676	145	249.79	806 M	45.5 M	135 M
	PV/battery	0	626	1290	58.5	41.55	134 M	6.07 M	44.5 M
Lucknow	PV/WT/battery	1	479	947	57.5	35.43	114 M	5.46 M	33.9 M
	WT/battery	NOT FEASIBLE							
	PV/battery	0	480	956	57.8	34.72	112 M	5.30 M	33.8 M
Minicoy	PV/WT/battery	4	485	929	65.6	37.26	120 M	5.80 M	34.7 M
	WT/battery	NOT FEASIBLE							
	PV/battery	0	601	1167	54.7	39.36	127 M	5.80 M	41.5 M
Mumbai	PV/WT/battery	8	381	936	59	37.4	121 M	6.01 M	32.1 M
	WT/battery	93	0	5161	161	187.25	604 M	33.33 M	113 M
	PV/battery	0	724	1011	58.1	41.01	132 M	6.04 M	43.3 M
Nagpur	PV/WT/battery	10	488	1000	55.69	43.13	139 M	6.90 M	37.4 M
	WT/battery	100	0	7260	169	231	746 M	40.4 M	151 M
	PV/battery	0	666	1224	54.5	41.71	135 M	6.09 M	44.8 M
New Delhi	PV/WT/battery	1	564	937	58.4	36.88	119 M	5.58 M	36.7 M
	WT/battery	149	0	8098	154	296.15	956 M	52.8 M	177 M
	PV/battery	0	567	945	55.5	36.18	117 M	5.43 M	36.6 M
Panjim	PV/WT/battery	10	301	823	55.9	36.21	117 M	6.03 M	27.9 M
	WT/battery	143	0	5926	349	253.64	818 M	45.8 M	143 M
	PV/battery	0	673	1049	90.9	40.33	130 M	5.93 M	42.7 M
Patna	PV/WT/battery	33	300	833	72.6	59.1	191 M	10.6 M	34.3 M
	WT/battery	NOT FEASIBLE							
	PV/battery	0	570	1262	104	40.05	129 M	5.86 M	42.9 M
Continued									

Location	Architecture	1 kW WT (No.)	PV (kW)	1 kW Battery (No.)	Converter (kW)	COE (₹/kWh)	COST NPC (₹)	OC (₹/year)	IC (₹) M
Port Blair	PV/WT/battery	5	459	937	61.5	36.96	119 M	5.77 M	34.1 M
	WT/battery	354	0	4528	236	446	1.44B	86 M	172 M
	PV/battery	0	681	1401	62.3	44.33	143 M	6.42 M	48.4 M
Pune	PV/WT/battery	8	326	854	56.4	35.02	113 M	5.72	28.8 M
	WT/battery	96	0	2976	222	152.69	493 M	28.1 M	78.7 M
	PV/battery	0	657	1046	108	40.01	129 M	5.88 M	42.4 M
Ranchi	PV/WT/battery	1	597	1547	60	44.5	144 M	6.48 M	48.1 M
	WT/battery	185	0	7568	252	324.87	1.05B	58.9 M	179 M
	PV/battery	0	701	1181	70.4	42.56	137 M	6.22 M	45.5 M
Shillong	PV/WT/battery	1	610	1286	59.9	42.25	136 M	6.25 M	44.2 M
	WT/battery	NOT FEASIBLE							
	PV/battery	0	621	1274	59.8	41.46	134 M	6.08 M	44.1 M
Srinagar	PV/WT/battery	1	863	1873	75.4	57.47	185 M	8.29 M	63.2 M
	WT/battery	NOT FEASIBLE							
	PV/battery	0	855	1891	79.9	56.57	183 M	8.10 M	63.0 M
Thiruvananthapuram	PV/WT/battery	1	580	911	71.2	37.28	120 M	5.65 M	37.1 M
	WT/battery	290	0	5092	160	403.41	1.30B	76.3 M	177 M
	PV/battery	0	573	976	60.9	36.91	119 M	5.54 M	37.5 M
Varanasi	PV/WT/battery	1	595	1049	65	39.25	127 M	5.89 M	39.8 M
	WT/battery	160	0	7052	190	289.62	935 M	52.3 M	163 M
	PV/battery	0	596	1072	66.5	38.66	125 M	5.75 M	40 M
Visakhapatnam	PV/WT/battery	8	429	921	53.8	38.64	125 M	6.19 M	33.4 M
	WT/battery	125	0	5593	169	227.84	735 M	41.1 M	129 M
	PV/battery	0	601	1258	64.9	40.46	131 M	5.92 M	43.2 M

Table 4. The best plans for EV charging stations using renewable energy.

policy support should be based on techno-economic viability rather than being applied consistently across regions.

Prioritize regional deployment over a nationwide rollout

In western and semi-arid regions like Jodhpur, Jaipur, and Ahmedabad, policies should prioritize solar-dominant EV charging infrastructure given their greater solar suitability and lower cost potential. On the other hand, hybrid PV/WT/battery systems are more appropriate in coastal and wind-supportive areas such as Pune, Mumbai, Panjim, Visakhapatnam, and Minicoy, where wind supplements seasonal PV shortfalls. Deployment policies should specifically address storage adequacy and grid-support provisions for more variable eastern and high-rainfall locations like Shillong, Kolkata, and Mumbai, as these sites exhibit greater seasonal variability and thus require stronger balancing capability.

Link capital support to techno-economic performance bands

The results suggested that tiers of public support should be established. Because they have the best short-term demonstration potential, high-performing low-cost sites like Jodhpur and Pune. They should be given priority for early commercial scale-up through capital subsidies, concessional financing, and accelerated depreciation. To increase bankability, moderately priced but strategically significant locations such as Bangalore, Bhavnagar, Bhopal, and Visakhapatnam may require performance-linked assistance. High-cost or high-variability locations such as Port Blair, Srinagar, Ranchi, and Shillong should not be prioritized in the same way as more cost-effective sites. They should receive targeted viability-gap support only when charging access is strategically important for regional inclusion or energy security. This would stop limited public funds from being distributed equally among places with wildly disparate feasibility profiles.

Include complementarities between seasonal resources in planning guidelines

The monthly generation results show a distinct seasonal pattern: PV performance decreases during the monsoon season, while wind output peaks in July. PV output is highest from March to May. This means that seasonal resource matching should be required instead of annual average resource assessment in India's technical standards for renewable EV charging. Planners should ensure there is sufficient battery backup or optional grid support during low-radiation periods in areas that rely on solar power. Because wind generation can partially offset monsoon-related PV reduction, hybridization should be promoted in wind-supportive coastal and western locations. Therefore, future state-level tariff regulations should classify locations based on the seasonal complementarity of solar and wind resources in addition to geographic location.

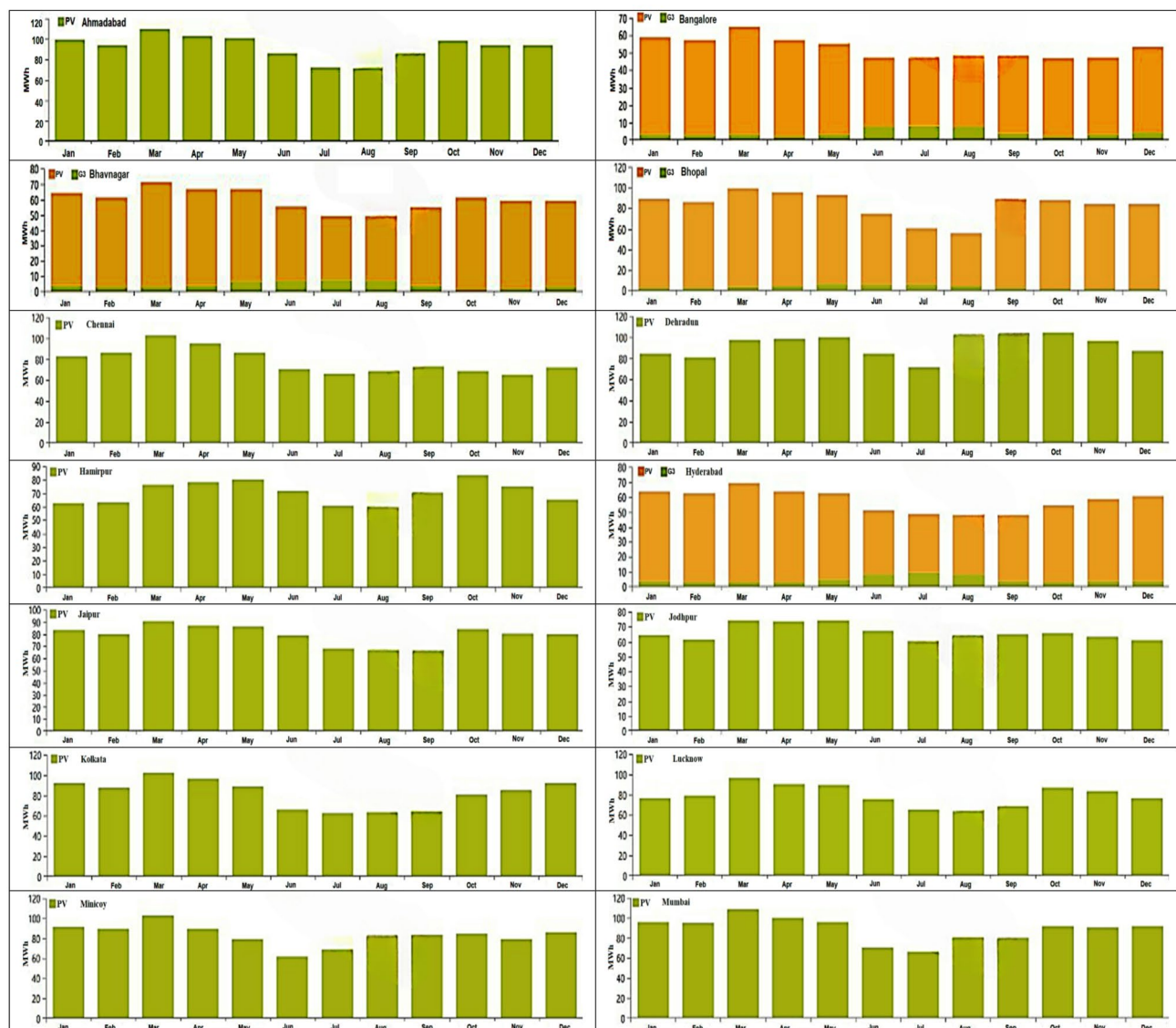


Fig. 7. Comparison of electricity generated monthly by EV charging stations at different sites.

Match the size of charging stations to the rise in local EV demand

According to the sensitivity analysis, COE behavior becomes nonlinear in several cities as load increases, and NPC increases steadily as daily load increases. This implies that both inadequate and excessive charging infrastructure can lower economic efficiency. Therefore, instead of relying on standard station templates, state transportation agencies and urban local bodies should link the deployment of renewable EV charging to city-level EV density, fleet composition, and anticipated growth in charging demand. Cities that showed greater stability under load variation, such as Pune, New Delhi, and Thiruvananthapuram, are excellent choices for broader implementation. On the other hand, areas that exhibit greater volatility or cost instability ought to implement phased capacity expansion with recurring demand evaluations.

Prioritize storage and flexibility in variable-resource locations

The findings showed that the performance of renewable-powered charging is more susceptible to fluctuations in Shillong, Kolkata, Mumbai, Minicoy, Port Blair, and Ranchi. Battery storage should therefore not be considered a secondary add-on in policy. Demand management, converter sufficiency, and storage capacity should be considered fundamental design requirements in such cities. Time-based tariff incentives, staggered charging windows, and managed charging are operational strategies that can increase utilization and ease strain on the local system. This is especially crucial when charging demand may increase in the evening, and renewable output is inconsistent.

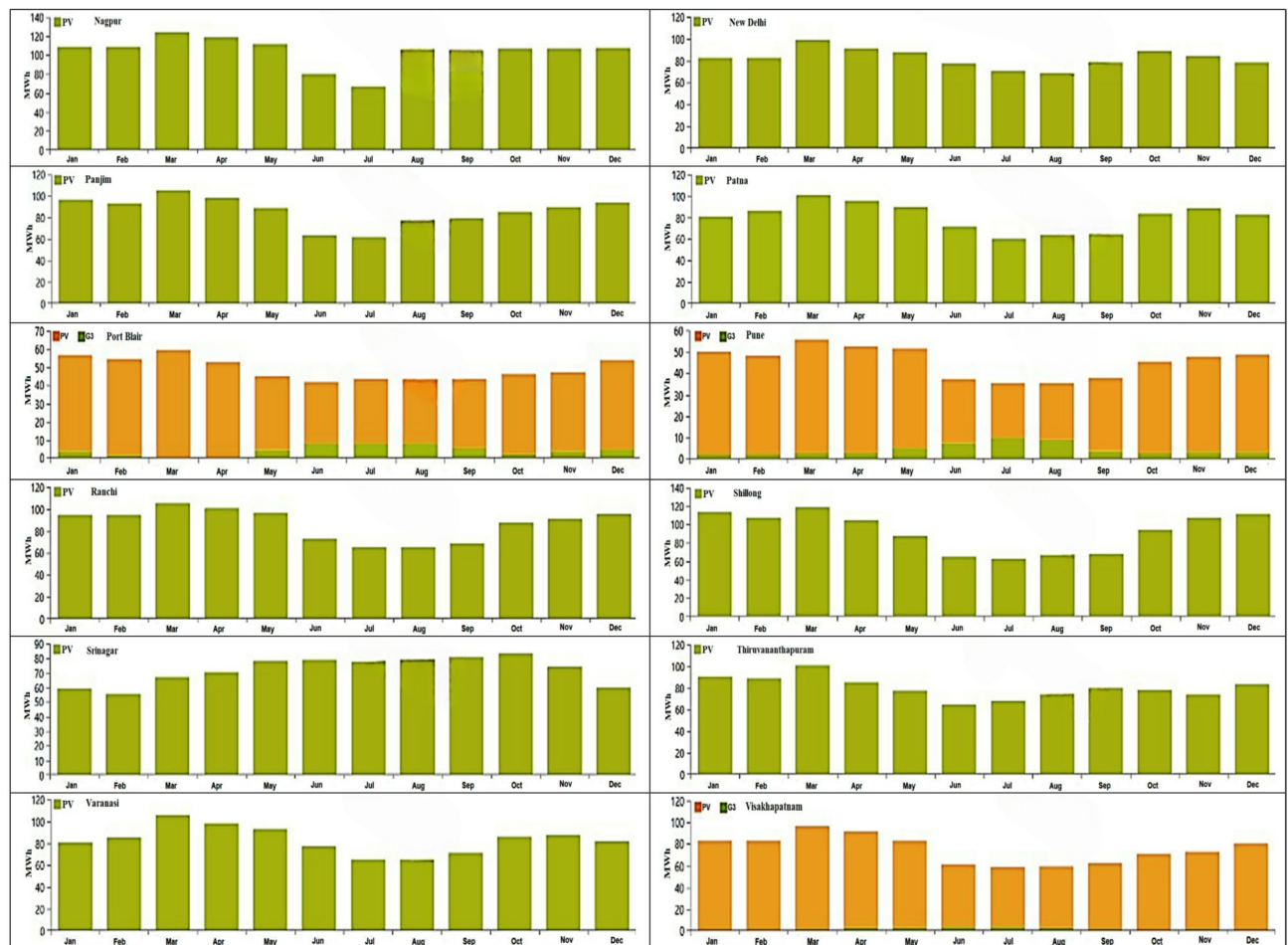


Fig. 7. (continued)

Tailor public-private partnership models to local conditions

Public-private partnership (PPP) models should not be designed in the same way for every location. In commercially promising cities such as Jodhpur, Pune, Bangalore, and Ahmedabad, private investment can be encouraged more easily through measures such as easier access to land, faster approvals, and incentives for renewable energy projects. In contrast, in remote or high-cost locations such as Port Blair and other difficult-resource regions, PPPs may need stronger public participation, including capital co-funding, minimum-revenue assurance, and utility-backed service contracts. This differentiated PPP approach is more consistent with the study's evidence than a single national partnership model.

Target R&D on operational and climatic realities

The study also indicates that future innovation efforts should focus on India-specific hybrid charging design, especially for monsoon-affected, coastal, island, and high-variability regions. R&D should therefore prioritize improved storage sizing, hybrid control strategies, seasonal forecasting, and location-specific energy management for renewable-powered charging stations. Pilot projects should be developed in contrasting site types, such as solar-dominant western cities, hybrid coastal cities, and high-variability eastern or island locations, so that policy evolves from comparative field evidence rather than generic national assumptions.

Therefore, the policy implication of this study is that renewable EV charging in India should be planned through a zonal techno-economic strategy: solar-dominant deployment in strong inland solar regions, hybrid PV/WT deployment in suitable coastal and western regions, and storage-supported or selectively subsidized rollout in climatically volatile or high-cost locations. A location-specific deployment strategy can make renewable EV charging infrastructure more cost-effective and reliable. It can also strengthen its role in supporting India's transition to low-carbon mobility. This case for targeted expansion is reinforced by the study's estimated annual CO₂ reduction potential of 19,872,700 kg in techno-economically favourable locations.

Conclusions

This study comprehensively evaluate EV charging stations fuelled by renewable energy sources, namely PV and wind power. The analysis focuses on 26 meticulously chosen sites throughout diverse climatic condition of India, including technical and economic aspects. The significant techno-economic findings indicate that hybrid PV/

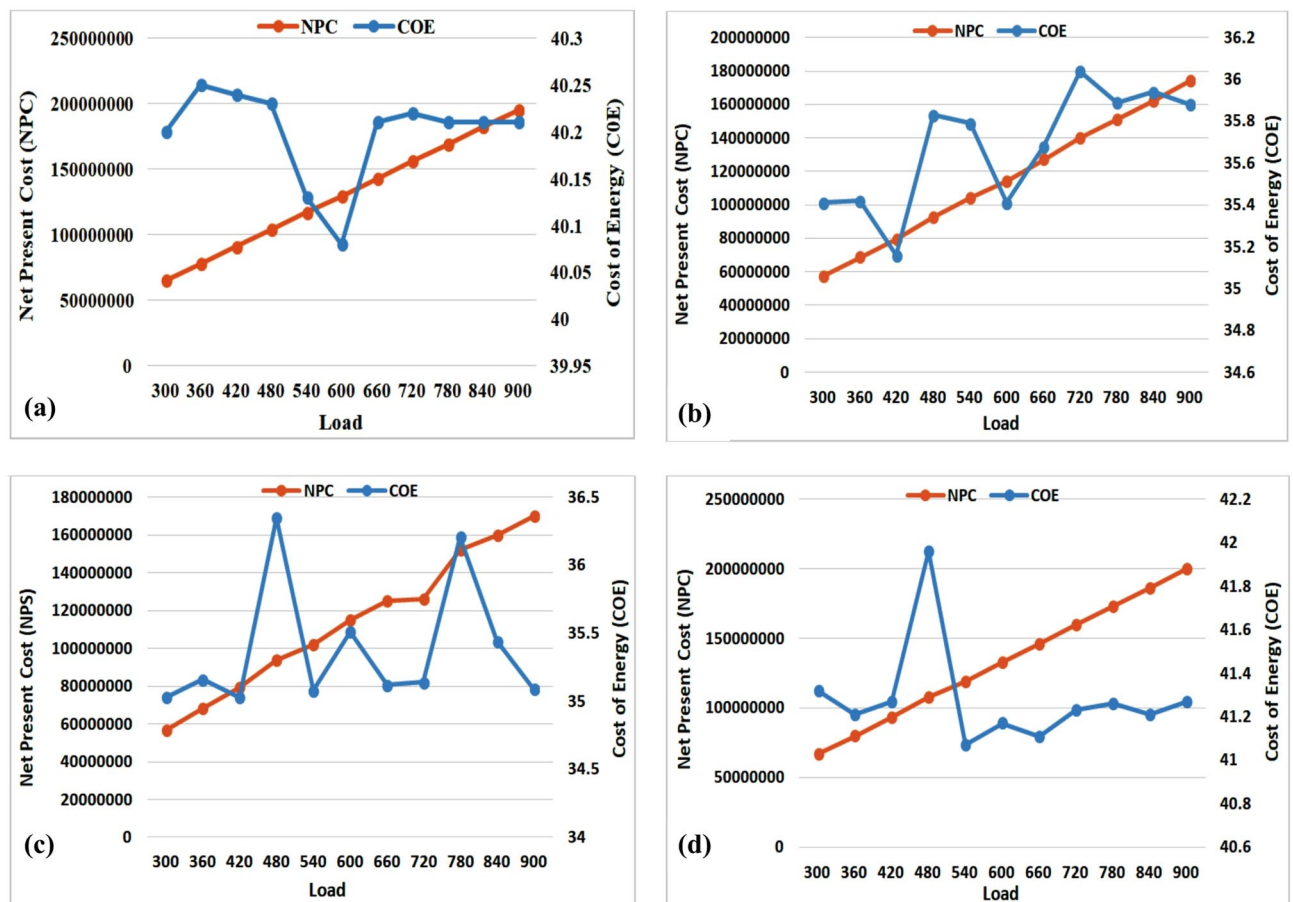


Fig. 8. COE and NPC variation of different Indian sites (a) Ahmedabad, (b) Bangalore, (c) Bhavnagar, and (d) Bhopal.

WT/battery EV charging stations are the best option for EV charging in Ahmadabad, Bangalore, Bhavnagar, Bhopal, Minicoy, Mumbai, Panjim, Port Blair, Pune, Patna, Visakhapatnam and PV/battery EV charging stations are the best option for RE-EV charging stations in Chennai, Dehradun, Hamirpur, Hyderabad, Jaipur, Jodhpur, Kolkata, Lucknow, Nagpur, New Delhi, Patna, Ranchi, Shillong, Srinagar, Thiruvananthapuram.

Hybrid PV/battery charging stations are most cost-effective in Jodhpur, whereas WT/battery is least cost-effective in Port Blair. These charging stations generate 24,235,000 kWh with reduction in CO₂ by 19,872,700 kg.

Among the 26 regions of India, March exhibits the greatest monthly average power output from PV arrays, while July shows the highest monthly average power production from WT arrays. July and October have the lowest monthly average power generation from the WTs and PV arrays. Cities with higher reliance on PV experience seasonal fluctuations. Grid support is crucial in specific cities to maintain energy supply, particularly during months of low solar radiation. Integrating PV with the grid enhances energy stability, especially in regions experiencing significant monsoon impact.

Seasonal fluctuation in PV power is observed for cities with high reliance on PV. Support from the grid is required during low solar radiation months. Grid integration with PV enhances stability in regions experiencing significant impacts from monsoons. The sensitivity analysis's findings indicate that when the daily demand rises from 300 kWh to 900 kWh, the Jodhpur charging station's NPC climbs from ₹53.8 million to ₹162 million. In addition, when the demand increases, the charging station's COE fluctuates by around ₹33.37/kWh. At a charging station load of 600 kWh per day, the COE value reaches a maximum of ₹33.38/kWh and comes to a minimum of ₹33.34/kWh at a charging station load of 660 kWh per day.

Hybrid renewable energy sources of EV charging stations, such as the combination of solar and wind energy with battery power, are technically viable and economically sustainable options to drive the e-mobility revolution in India. The viability of such options is location and demand-driven, and their success will depend on the techno-economic optimization of these options and the implementation of supportive policies and measures, including incentives, R&D, and public-private partnerships.

However, this study is subject to a few limitations. Firstly, the techno-economic analysis is based on site-specific solar and wind power. Therefore, the results might vary for different renewable resource availability. Secondly, the EV charging pattern is considered generic. In practice, this might be different depending on user patterns. Thirdly, the economic analysis is based on certain assumptions related to capital costs, O&M costs, equipment life, and the discount rate. These might vary with technological and market developments. Lastly, this

Sites	NPC trend (M)	COE Range (₹/kWh)	COE stability
Chennai	60–179	36.13–36.22 (Fluctuate)	Unstable
Dehradun	60–180	36.5–36.55 (Moderate fluctuation)	Unstable
Hamirpur	52–210	43.74–43.8 (Decreasing)	Highly stable
Hyderabad	60–180	37.25–37.54 (Moderate fluctuation)	More stable than Chennai
Jaipur	60–180	36.48–36.49 (Fluctuate)	Unstable
Jodhpur	57–160	33.34–33.41 (Moderate variation)	Unstable
Kolkata	52–200	41.5–41.75 (Highly unstable)	highly unstable
Lucknow	60–161	34.71–34.75 (Fluctuate moderate)	More stable than Kolkata
Minicoy	60–180	37.2–38.2 (Fluctuates)	Moderately unstable
Mumbai	60–180	37.2–38 (Highly unstable)	Highly unstable
Nagpur	51–200	41.66–41.74 (Highly unstable)	Most unstable
New Delhi	60–2000	36.13–36.22 (Stable)	Most stable
Panjim	60–180	36–36.25 (Moderate fluctuations)	Moderately stable
Patna	60–180	39.3–40.2 (Highly unstable)	Highly unstable
Port Blair	60–180	36.9–37.15 (Fluctuations present)	Moderate instability
Pune	60–180	34.7–35.2 (Stable trend)	Most stable
Ranchi	51–200	42.45–42.56 (Large fluctuations)	Unstable
Shillong	51–200	41.4–41.48 (Moderate fluctuations)	Moderate stability
Srinagar	100–259	56.47–56.58 (Highly unstable)	Highly unstable
Thiruvananthapuram	60–180	36.91–36.96 (Moderate stability)	Most stable
Varanasi	51–199	38.6–39.3 (Moderate fluctuations)	Stable
Visakhapatnam	60–181	37–40.5 (Moderate)	Stable

Table 5. Key insights for comparison.

Study (Year)	Location	Annual load (kWh/day)	COE/LCOE (₹/kWh)	Software/version
Current study	26 sites in India	600	37.81 to 62.91	HOMER
Minh et al. ⁵²	Vietnam	≈ 500–800 (depending on site)	9.22–13.83	HOMER Pro
Ihm et al. ⁵³	South Korea	≈ 400–600	12.91	HOMER Pro
Oladigbolu et al. ⁵⁴	Nigeria (Africa)	≈ 200–500	19.37–118.06	HOMER Pro
Zhang et al. ⁵⁵	China	Variable (scenarios with EV integration)	24.4436	HOMER Pro (multi-scenario)
Cecchini et al. ⁵⁶	Argentina (Campus, standalone)	≈ 250 (campus EV fleet)	14.75–20.29	HOMER Pro
Rehman et al. ⁵⁷	UAE	24.3 kW peak	11.06–18.44	HOMER Grid/ HOMER Pro

Table 6. COE comparative analysis of different sites.

analysis is focused on techno-economic and policy aspects. It does not take into account detailed power system dynamics, grid stability, voltage regulation, and real-time constraints related to EV charging.

Possible future extensions of this work would be to carry out a multi-site regional analysis for different geographical regions with diverse climate conditions. It would be interesting to see how this method would perform under different site-specific conditions. A more realistic stochastic model for charging would be a good option. In this regard, seasonal variations and various charging modes, ranging from fast charging to ultra-fast charging, would be useful. Advanced energy management using AI/ML techniques would be another direction for future work. In addition, a detailed grid integration and life cycle analysis would be very useful.

S.No.	Sites	Annual energy (kWh)	CO ₂ reduction (kg)
1	Ahmadabad	1,107,000	907,740
2	Bangalore	662,000	542,840
3	Bhavnagar	726,000	595,320
4	Bhopal	1,022,000	838,040
5	Chennai	935,000	766,700
6	Dehradun	1,113,000	912,660
7	Hamirpur	845,000	692,900
8	Hyderabad	715,000	586,300
9	Jaipur	957,000	784,740
10	Jodhpur	799,000	655,180
11	Kolkata	986,000	808,520
12	Lucknow	960,000	787,200
13	Minicoy	1,017,000	833,940
14	Mumbai	1060 000	869,200
15	Nagpur	1,265,000	1,037,300
16	New Delhi	983,000	806,060
17	Panjim	1,030,000	844,600
18	Patna	970,000	795,400
19	Port Blair	648,000	531,360
20	Pune	544,000	446,080
21	Ranchi	1,039,000	851,980
22	Shillong	1,103,000	904,460
23	Srinagar	876,000	718,320
24	Thiruvananthapuram	966,000	792,120
25	Varanasi	995,000	815,900
26	Visakhapatnam	912,000	747,840
	Total	24,235,000	19,872,700

Table 7. CO₂ reduction.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Declarations

Competing interests

The authors declare no competing interests.

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