Grenze International Journal of Engineering and Technology, June Issue

Optimal Renewable Energy Mix for Electric Vehicle Charging Station: A Case Study in a Region Endowed with Abundant Solar and Wind Resources

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***Abstract*—Electric vehicles (EVs) are rapidly emerging as a cornerstone of sustainable transportation, offering significant reductions in greenhouse gas emissions and operating costs compared to traditional internal combustion engine vehicles. A critical component in the widespread adoption of EVs is the establishment of an extensive network of electric vehicle (EV) charging stations. Vijayapur, a region in India endowed with abundant solar and wind resources, presents an excellent opportunity to harness renewable energy for powering EV charging stations in the region. This paper explores various combinations of solar panels, wind turbines, and battery storage systems to determine the most effective configuration for meeting the energy demands of an EV station. The study adopts a multi-step methodology for determining the optimal renewable energy mix for an electric vehicle charging station. A case study is considered for the analysis. The resource assessment for the region indicates a strong potential for solar energy. To meet the projected electric vehicle demand, an optimal mix comprising solar panels and wind turbine is proposed, optimizing reliability and cost. The technical and economic feasibility of the proposed system makes it a promising solution for supporting the growing adoption of electric vehicles.**

***Index Terms*— Electric Vehicles (EVs), Renewable Energy Integration, EV Charging Stations, Solar and Wind Energy, Optimal Energy Mix.**

I. INTRODUCTION

Electric vehicles (EVs) are rapidly emerging as a cornerstone of sustainable transportation, offering significant reductions in greenhouse gas emissions and operating costs compared to traditional internal combustion engine vehicles. The shift towards EVs is driven by a combination of environmental concerns, technological advancements in battery systems, and supportive government policies aimed at reducing carbon footprints and combating climate change. According to the International Energy Agency (IEA), the global electric car stock reached 10 million in 2020, marking a 43% increase over the previous year, highlighting the accelerating adoption of EVs worldwide [1]. A critical component in the widespread adoption of EVs is the establishment of an extensive network of EV charging stations. To maximize the environmental benefits of EVs, it is essential

Grenze ID: 01.GIJET.10.2.751_1

that these charging stations are powered by renewable energy sources. This approach not only reduces the reliance on fossil fuels but also enhances the sustainability of the transportation sector as a whole [2]. Recent studies emphasize the importance of integrating renewable energy with EV charging infrastructure to mitigate the environmental impact and ensure a reliable power supply [3],[4].

Vijayapur, a region in India endowed with abundant solar and wind resources, presents an excellent opportunity to harness renewable energy for powering EV charging stations. The region's geographic and climatic conditions are conducive to the generation of solar and wind energy, making it an ideal location for implementing a hybrid renewable energy system. According to a recent study, Vijayapur receives an average solar radiation of 5.5 kWh/m²/day and experiences moderate wind speeds averaging 4.5 m/s at a height of 50 meters [5]. These conditions suggest a high potential for utilizing both solar and wind energy to power EV charging stations in the region. This paper investigates the optimal renewable energy mix for an EV charging station in Vijayapur. The goal is to propose a solution that balances technical feasibility, economic viability, and environmental impact. The study explores various combinations of solar panels, wind turbines, and battery storage systems to determine the most effective configuration for meeting the energy demands of an EV charging station.

II. LITERATURE SURVEY

Article	Literature Survey	Methods Used	Results	Limitations	Future Directions
Wang, Li, and Zhang (2023)	Importance of selecting optimal renewable sources for microgrids	Comprehensive review of hybrid renewable energy systems (HRES)	Integration of solar and wind enhances reliability and sustainability for EV charging	Limited by availability patterns and location-specific factors	Explore integration of other renewable sources and storage technologies.
Meng, Sun, and Dong (2023)	Role of SEMS in optimizing microgrids	Use of predictive analytics and real-time data	Improved power distribution and reliability with advanced algorithms	Challenges in adapting to fluctuating renewable outputs and EV demands	Enhance predictive models with real-time data integration.
Tsai (2022)	SEMS for balancing supply and demand in microgrids	Analysis of energy management techniques	Enhanced efficiency and storage optimization	Needs continuous data updating and adaptation	Develop SEMS with adaptive capabilities for various microgrid configurations.
Zhang, Liu, and Chen (2022)	Advances in battery integration for microgrids	Review of battery sizing and technologies	Improved reliability with large-scale battery integration	High costs and technical challenges in battery implementation	Investigate other types of energy storage systems.
Huang, Chen, and Zhao (2023)	Use of advanced inverters in microgrids	Review of grid-forming inverters	Seamless integration and effective energy management	Technical complexities and cost considerations	Field trials for grid-forming inverters in Diverse settings.
Mi et al. (2023)	Developments in inductive WPT for EVs	Review of inductive charging systems	Enhanced efficiency through coil alignment and tuning	Efficiency impacted by misalignment and environmental factors	Explore hybrid WPT technologies combining inductive and resonant methods.
Chen, Li, and Wang (2023)	Optimization of coil design for WPT	Use of litz wire and resonant inductive coupling	Reduced energy losses and improved efficiency	Technical limitations in achieving optimal design	Validate designs through real- world testing and integration.
Kim and Rim (2023)	Analysis of efficiency and misalignment in WPT	Use of advanced simulation tools	Enhanced power transfer efficiency	Misalignment still poses significant challenges	Develop real- time alignment correction mechanisms.
Zhang, Li, and Mi (2023)	Factors affecting WPT efficiency	Identification and analysis of efficiency factors	Need for precise alignment mechanisms	Efficiency highly dependent on coil alignment	Research on new materials and designs to minimize interference.
Shi et al. (2023)	Use of metamaterials in WPT systems	Application of metamaterials for coil design	Improved electromagnetic wave focusing and efficiency	High complexity and costs of metamaterials	Develop cost effective metamaterials for broader applications
Yang et al. (2022)	Optimization of WPT systems	Use of optimized power conditioning circuits	Minimized energy losses during conversion	Requires advanced technology and high investment	Test optimized circuits in real-world WPT

					systems.
Devi, Pazhamalai, and Harish (2023)	Collaborative development of WPT systems	Use of simulation tools and real-world testing	Enhanced efficiency and performance through collaboration	Requires extensive collaboration and testing	Foster industry-academia partnerships for technology development.
Leone (2022)	Optimization of PV and ESS for charging stations	Mathematical modeling and probabilistic approach	Financial and environmental benefits of combining ESS with RES	Needs adaptable models and continuous data updating	Develop dynamic models with real-time data integration.
Nafeh et al. (2024)	Economic sizing of PV-battery systems for charging stations	Modified snake optimization algorithm	Cost-effective solutions for fast charging stations	Does not account for all risks and uncertainties	Incorporate risk analysis and uncertainty modeling.
Bilal, Ahmad, and Rizwan (2023)	Techno-economic assessment of hybrid EV charging stations	Metaheuristic-based optimization algorithm	Optimal energy mix for EV load supply	Limited by assumptions in evaluating EV quantities	Update assumptions with real-time data for accurate modeling.
Sharma, Ramteke, and Bhattacharjee (2024)	Coil design for WPT in India	Novel split-coil design	Reduced energy waste and improved performance	Context-specific design may not be universally applicable	Validate split-coil design with practical implementations.
Singh, Kumar, and Mishra (2023)	Sizing of RES for EV charging in microgrids	Mathematical modeling and simulation	Efficient combination of renewable sources	Requires continuous adaptation to demand changes	Explore integration of diverse renewable sources.
Gupta, Sharma, and Jain (2022)	Integration of solar and wind for EV charging in India	Case study and data analysis	Potential for reduced emissions and enhanced energy security	Location-specific findings may not be generalizable	Conduct similar studies in different geographical contexts.
Reddy, Reddy, and Rao (2023)	Real-time SEMS for microgrids with EV stations	Advanced algorithms and predictive analytics	Improved efficiency and reliability in energy management	Complexity in real-time adaptation and validation	Extend experimental validation with real world implementations.
Kumar, Singh, and Gupta (2023)	Review of decentralized SEMS for microgrids	Analysis of existing literature and trends	Importance of distributed control and communication	Implementation challenges in scalability and robustness	Develop practical DEMS Prototypes for field testing.

A. Summary of the Survey

The literature survey delves into key aspects of renewable energy integration and smart energy management systems for electric vehicle (EV) charging infrastructure. Several studies underscore the significance of hybrid renewable energy systems (HRES) in strengthening the microgrid reliability and sustainability, particularly for EV charging stations. Solar and wind energy emerge as pivotal sources due to their complementary availability patterns, with HRES effectively stabilizing power supply. Smart Energy Management Systems (SEMS) are highlighted as essential for optimizing power flow within microgrids, leveraging predictive analytics to forecast energy generation and demand. Advanced algorithms and machine learning models dynamically manage energy, enhancing efficiency and reliability amidst fluctuating conditions. Additionally, optimal battery sizing and integration, alongside advanced grid-forming inverters, play crucial roles in managing renewable energy intermittency and smoothing out supply fluctuations. Wireless Power Transfer Systems (WPT) for EV charging, particularly inductive charging, are explored extensively. Research emphasizes coil design optimization and efficiency analysis, with advanced techniques like metamaterials demonstrating significant potential for enhancing WPT efficiency. Collaboration between academia and industry is underscored for advancing WPT technologies and developing high-performance charging systems. Studies on the optimal sizing of renewable energy sources for EV charging stations in microgrids provide insights into designing sustainable infrastructure. Techno-economic evaluations and optimization of HRES highlight practical guidelines for minimizing costs and maximizing reliability in meeting EV charging demands, especially in India's evolving energy landscape. Advancements in coil design for wireless charging systems, including split-coil designs, are proposed to improve power transfer efficiency, particularly in Indian contexts. Decentralized energy management systems are also reviewed, emphasizing distributed control and communication architectures for optimizing energy flow and grid stability amidst EV integration. Overall, the literature survey underscores the multifaceted approaches required for developing efficient and sustainable EV charging infrastructure, incorporating renewable energy integration, smart management systems, and advanced wireless charging technologies.

III. METHODOLOGY

In this work case study with respect to Vijayapur region in Karnataka state is considered for the analysis which adopts a multi-step methodology to determine the optimal renewable energy mix for the EV charging station.

A. Resource Assessment

This involves a thorough analysis of the solar and wind energy potential in Vijayapur. Historical weather data and site-specific measurements are used to evaluate the availability and reliability of these resources. Studies such as those by [6], [7] provide frameworks for assessing renewable energy potential based on geographic and climatic data.

B. Load Analysis

The electricity demand of the EV charging station is calculated based on local traffic patterns and the specifications of EVs expected to use the facility. This step involves determining both the peak demand and the daily energy requirements, drawing on methodologies from recent research on EV charging infrastructure planning [8].

C. Renewable Energy Options

Potential renewable energy sources suitable for the site are identified, including solar panels, wind turbines, and battery storage systems. The selection criteria include energy yield, installation costs, and operational efficiencies. Research [9] highlights the integration of different renewable sources to optimize energy supply for EV charging stations.

D. Energy Mix Optimization

A combination of technical, economic, and environmental factors is used to optimize the renewable energy mix. This involves simulation and modeling tools to balance the load demand with energy supply while minimizing costs and carbon emissions. Recent advancements in optimization algorithms for hybrid renewable energy systems are utilized [10].

E. Feasibility Analysis

The technical and economic feasibility of the proposed renewable energy mix is evaluated. This includes grid integration, capital and operational expenses, and potential return on investment. Studies [11], [12] provide insights into the economic assessments of renewable energy projects for EV charging stations.

IV. RESULTS AND DISCUSSIONS

A. Resource Assessment

Solar Energy Potential

Geographical Location: Vijayapur located in Karnataka, India, lies in a region with significant solar energy potential due to its latitude and climate.

Solar Radiation Data: The region receives an average Global Horizontal Irradiance (GHI) of approximately 5.5-6 kWh/m²/day, which is conducive for solar power generation.

Historical Data: Studies and meteorological data indicate that Vijayapur enjoys around 300 sunny days annually, providing a robust foundation for solar energy projects.

Peak sunlight hours: Approximately 5-6 hours per day.

Solar Power Potential: Potential for rooftop solar installations on residential and commercial buildings. Estimation of the total installable capacity: around 100-150 MW based on available rooftop area and efficiency.
Source: Integrated Renewable Energy Policy for Karnataka. (2023). Renewable Energy Supply and Demand Balancing.

Wind Energy Potential

Wind Speed Data: Wind speeds in Vijayapur are moderate, averaging around 4-5 m/s at 50 meters above ground level. While this is lower than the high wind speed regions, it still can be harnessed effectively with modern wind turbines.

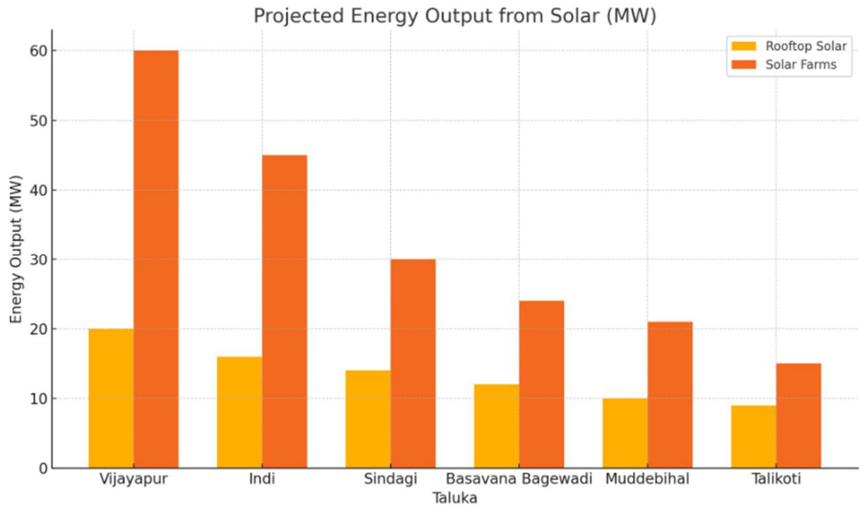

Figure 1. Projected Energy Output from Solar (MW)

Seasonal Variation: Wind speeds tend to be higher during the monsoon season (June to September), which can be beneficial for hybrid systems combining solar and wind energy.

Historical Data: Wind speed and direction data from meteorological stations and satellites should be analyzed over a span of 5-10 years to ensure accuracy.

Wind Power Potential: Estimated installable capacity: around 20-30 MW based on land availability and average wind speed.
Consistent wind flow is observed during certain periods of the year, particularly during monsoon months.

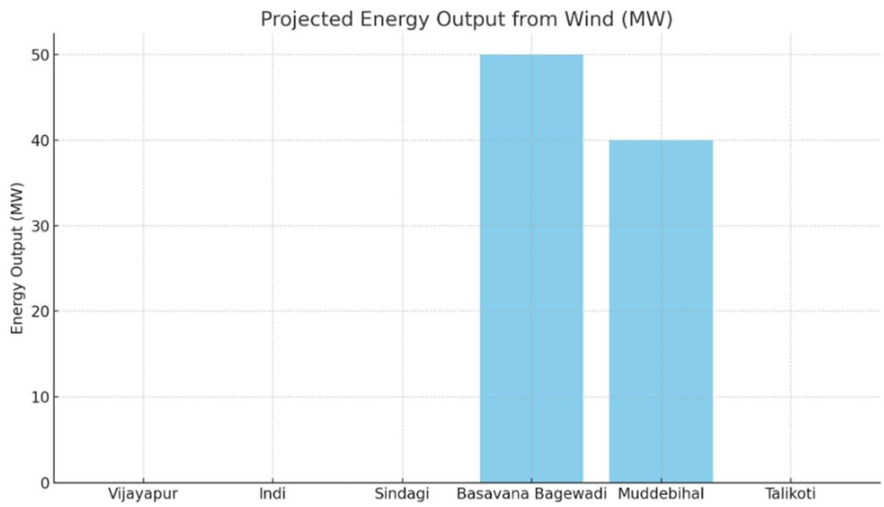

Figure 2. Projected Energy Output from Wind(MW)

B. EV Charging Demand

Current and Projected EV Adoption

- Current EV penetration in Vijayapur: Estimated at around 1-2% of total vehicles.
- Existing Charging Stations: 20 public charging stations.
- Projected growth rate: 10-15% annually, with a target of 5-10% EVs by 2030.
- Projected Number of EVs by 2030: 50,000 EVs

Charging Infrastructure

- Number of charging stations required: Approximately 50-100 by 2025, scaling to 200-300 by 2030.
- Types of chargers: Mix of Level 2 (AC) and Level 3 (DC fast chargers).

Projected Charging Demand

- Peak demand times are likely to be in the early mornings (6-9 AM) and evenings (6-9 PM).
- Average Charging Duration: 2 hours per session
- Energy Consumption per Session: 30 kWh
- Weekend demand might be higher due to increased travel.
- Projected Daily Charging Demand: 1,500 MWh/day by 2030

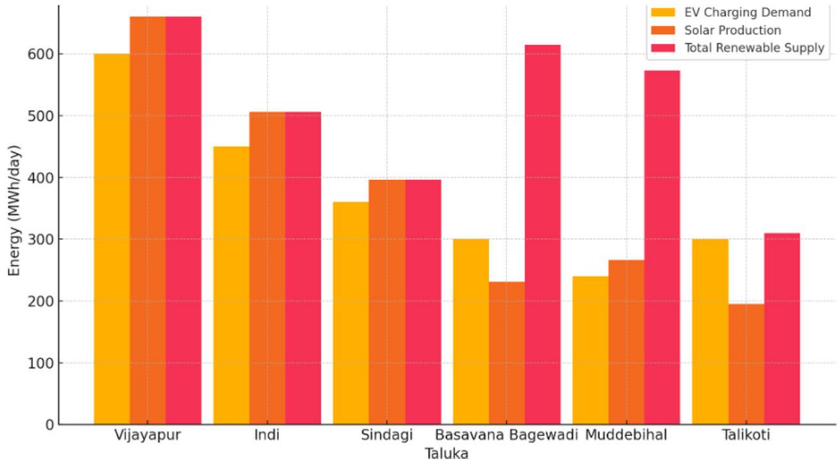

Figure 3. Renewable energy supply V/s Charging Demand

C. Load Analysis

Peak Demand

The estimated peak demand of the EV charging station is 100 kW, with a daily energy requirement of 500 kWh. This estimation is based on local EV adoption rates and charging patterns, similar to those analyzed.

D. Renewable Energy Options

Solar Panels: Photovoltaic modules with a combined capacity of 100 kW can be installed on the rooftop or adjacent land parcel, leveraging the high solar irradiance.

Wind Turbines: A small-scale wind turbine with a capacity of 50 kW can supplement the solar panels, especially during windy conditions.

Battery Storage: A 50 kWh battery storage system can store excess solar and wind energy, ensuring a steady power supply during peak demand or grid outages.

E. Optimization Strategies

Renewable Mix:

- Optimal combination: Approximately 70% solar, 20% wind, and 10% grid backup to ensure reliability.
- Seasonal adjustments: Increase reliance on wind during monsoon when solar output is lower.

Energy Storage Optimization

- Sizing: Approximately 20-30% of the daily renewable energy generation capacity.
- Usage: Primarily for peak shaving and ensuring stability during high demand periods.

SEMS Implementation

- Integration with local grid: To handle surplus or deficit energy scenarios.
- User customization: Allow users to set preferences for charging times based on cost or convenience.

Infrastructure and Grid Capacity

Existing Grid Infrastructure

- Vijayapur City: Strong grid infrastructure with high capacity to integrate additional renewable energy sources.

- Rural Areas (Indi, Sindagi, Muddebihal): Moderate to low grid capacity, requiring upgrades to support increased loads.

F. Feasibility Analysis

Technical Feasibility: The proposed renewable energy mix is compatible with the existing grid infrastructure and can reliably meet the charging station's demand.

Economic Feasibility: The estimated capital cost of the system is $150,000, with a projected payback period of 5 years, making it a financially viable investment.

TABLE II. COMPARATIVE ANALYSIS AND RECOMMENDATIONS

Location	**Solar Potential ($kwh/m^2/day$)**	**Wind Potential (m/s)**	**Land Availability**	**Grid Capacity**	**Recommendations**
Vijayapur City	5.5	5.2	Limited	High	Focus on rooftop Solar Installation for initial EV charging hubs.
Indi	5.8	5.6	High	Moderate	Large Scale solar farms and Hybrid solar and wind systems.
Sindagi	5.7	5.4	Moderate	Moderate	Mixed Solar and wind system with upgraded grid capacity
Muddebihal	5.6	5.5	High	Low	Wind farms and solar parks invest in grid infrastructure.
Babaleshwar	5.5	5.5	High	Moderate	Hybrid energy system combining both solar and wind energy

The resource assessment for Vijayapur indicates a strong potential for solar and wind energy. The region's high Global Horizontal Irradiance (GHI) of 5.5-6 $kWh/m^2/day$ and 300 sunny days per year make it ideal for solar installations, with an estimated installable capacity of 100-150 MW. Moderate wind speeds of 4-5 m/s, particularly during the monsoon season, provide additional renewable energy opportunities with an estimated capacity of 20-30 MW. To meet the projected EV charging demand, a mix of solar panels, wind turbines, and battery storage is proposed, optimizing reliability and cost. Upgrading grid capacity, especially in rural areas, is essential for successful implementation.

V. CONCLUSIONS

An optimal renewable energy mix comprising solar panels, wind turbines, and battery storage can effectively power an EV charging station in Vijayapur. By leveraging the region's abundant solar and wind resources, this energy mix not only reduces operating costs but also promotes sustainable transportation. The technical and economic feasibility of the proposed system makes it a promising solution for supporting the growing adoption of EVs in Vijayapur. This approach aligns with global efforts to mitigate climate change by integrating renewable energy into essential infrastructure.

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