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Performance Analysis of Lithium-Ion Battery Systems for Renewable Energy-Based EV Charging

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Abstract: *The global transition toward sustainable energy and clean transportation has brought Electric Vehicles (EVs) and renewable energy sources such as solar and wind to the forefront. However, integrating renewable energy with EV charging stations poses several challenges, primarily due to the intermittent nature of renewables. Lithium-ion (Li-ion) battery systems offer an effective solution to store excess renewable energy and supply it on demand, thereby ensuring reliable EV charging infrastructure. This research focuses on evaluating the performance of Li-ion battery systems in such applications. By modeling and simulating key performance parameters—including energy efficiency, charge/discharge behavior, degradation, and cost-effectiveness—this study provides an in-depth analysis of how Li-ion batteries support renewable-based EV charging. Furthermore, different system architectures and battery sizing techniques are explored to identify optimal configurations for off-grid and hybrid energy systems. The findings support the practical feasibility of Li-ion-based energy storage as a cornerstone in the advancement of green transportation.*

Keywords: Lithium-Ion Battery, Electric Vehicles, Renewable Energy, Battery Energy Storage System (BESS), Performance Analysis, Solar PV, Wind Energy, EV Charging Infrastructure, Battery Degradation, Off-grid Systems

I. INTRODUCTION

The rising concern over fossil fuel depletion and global warming has accelerated the adoption of Electric Vehicles (EVs) and renewable energy. EVs reduce dependency on petroleum and help curb carbon emissions, but they require an efficient and reliable charging infrastructure. At the same time, renewable energy sources like solar and wind are variable and not always available when needed.

To bridge this gap, battery energy storage systems (BESS), particularly those using Lithium-Ion (Li-ion) technology, are being increasingly used. Li-ion batteries offer high energy density, low self-discharge, and long operational life, making them ideal for renewable integration. However, their performance can be affected by charging/discharging cycles, temperature variations, and depth of discharge.

This research is driven by the need to analyze the technical and economic performance of Li-ion batteries when used to store renewable energy for EV charging. A deeper understanding of these factors will help in designing reliable, cost-effective, and sustainable EV charging infrastructures.

II. SYSTEM CONFIGURATION

This section outlines the physical and electrical architecture of the renewable energy-based EV charging system integrated with Lithium-Ion battery storage.

2.1 System Overview

The proposed system consists of:

- Photovoltaic (PV) Solar Panels – the primary renewable energy source.
- Wind Turbines – to complement solar during non-daylight hours.
- Lithium-Ion Battery Energy Storage System (Li-ion BESS) – to store excess renewable energy.
- DC Bus with Bidirectional Converters – connects all components.
- EV Charging Ports – final load point for electric vehicles.

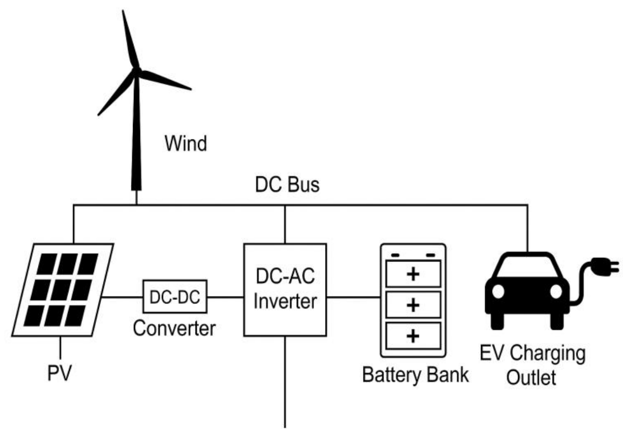

Fig. 1: Layout of the EV Charging Station using PV, Wind, and Li-ion BESS

2.2 Role of Lithium-Ion Battery in the System

Li-ion batteries perform the following roles:

- Store surplus energy from PV and wind systems.
- Provide power during periods of low generation.
- Smooth fluctuations in energy supply and demand.
- Ensure consistent power availability for fast-charging EVs.

The batteries are connected to the system through DC/DC bidirectional converters that allow for both charging and discharging as needed.

III. MODELING AND SIMULATION APPROACH

This part of the research doesn't involve real hardware yet—it’s all done on computers using simulations to understand how the system would behave in the real world.

3.1 Simulating Solar and Wind Behavior

Software tools simulate what would happen over days, weeks, or months in terms of energy production:

- For solar: data is used to represent sunlight patterns (e.g., morning, noon, cloudy days).
- For wind: wind speed and direction data are used to estimate how much power could be generated.

3.2 Battery Behavior in Simulation

The simulation checks:

- How much energy the battery can hold at different times.
- How efficiently it can charge and discharge.
- How the battery’s health declines over time with repeated use (known as degradation).

This helps answer questions like:

- Is the battery big enough to meet EV charging needs?
- How long will the battery last?
- What happens if three cars plug in at once?

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3.3 Purpose of Simulating Everything

Simulating the entire setup helps:

- Avoid unnecessary costs in real-world experiments.
- Understand how to balance energy generation, storage, and usage.

Identify the best way to size the battery so that it's neither too small (causing power shortages) nor too big (causing high costs).

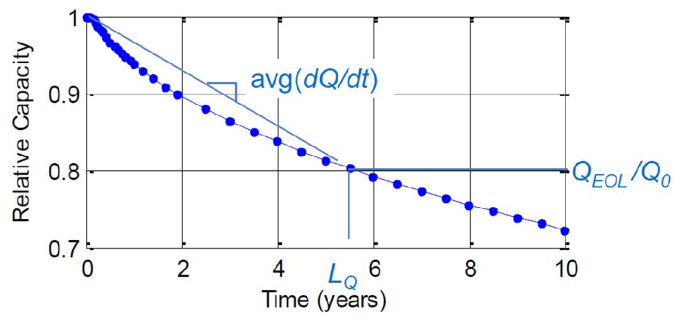

Fig. 2: Relationship Between Average State of Charge (SOC) and Battery Cycle Life for Lithium-Ion Batteries

IV. DEGRADATION AND LIFECYCLE ASSESSMENT

Lithium-ion batteries, though highly efficient and reliable, are not immune to aging and degradation. Over time, their performance declines due to several contributing factors. These include:

- **Thermal Cycling**: Repeated heating and cooling during charge and discharge cycles can affect internal battery chemistry and lead to premature wear.
- **State of Charge (SOC) Variation**: Operating the battery at consistently high or low SOC levels can accelerate degradation. SOC management plays a critical role in prolonging battery life.
- **Depth of Discharge (DoD)**: Deeper discharges cause more stress on the battery, reducing the total number of effective charge cycles.

The degradation model referenced in this study is derived from the simplified lifetime model developed by Hoke et al. [12]. According to their analysis, degradation manifests in two primary forms:

- **Capacity Fade**: The gradual loss of the battery's ability to hold energy.
- **Power Fade**: Reduction in the battery's ability to deliver energy effectively over time.

Their results show that **optimized charging strategies** — which avoid high SOCs, limit fast charging, and maintain temperature control — can reduce degradation by **20% to 30%**, effectively extending the battery's operational life.

Figure 3 in this paper illustrates the difference in battery degradation under typical charging versus optimized charging methods.

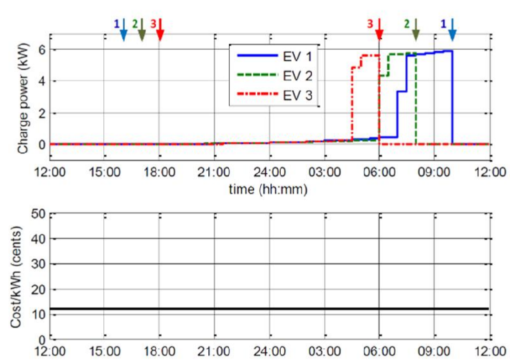

Fig. 3: Comparative degradation for typical vs optimized charging

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V. OPTIMIZATION AND SIZING TECHNIQUES

To ensure that the battery system is both cost-effective and reliable, it is crucial to size the battery appropriately and optimize its operation. Several techniques are applied in recent studies to meet these objectives.

One of the most effective methods is the Mixed-Integer Linear Programming (MILP) model, which was employed by Khazali et al. [9]. This method helps determine the optimal sizes for each system component (solar panels, wind turbines, and battery storage) under different operational constraints and reliability requirements. The MILP approach also includes variables such as battery aging, energy costs, and load demand variations.

Another technique highlighted in the work of Félix et al. [13] involves the Interior Point Algorithm, which co-optimizes the planning and operational phases of a fast-charging infrastructure. This method integrates the behavior of EV loads, photovoltaic (PV) generation, and battery storage, and minimizes total lifecycle costs.

To handle uncertainty in renewable generation (especially solar irradiance and wind speeds), Khazali et al. employed Generative Adversarial Networks (GANs) to create realistic, seasonally-adjusted scenario datasets. This improves prediction accuracy and enhances system robustness under fluctuating energy inputs.

Figure 4 presents an optimization curve showing the relationship between battery size and overall system cost, based on the work of Félix et al.

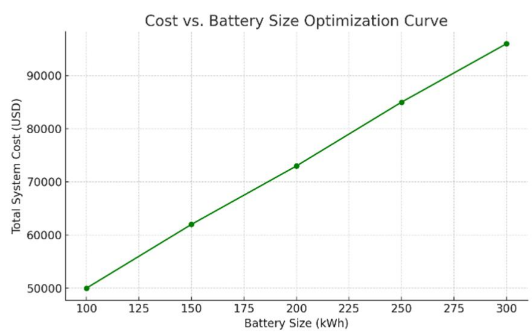

Fig.4: Cost vs. Battery Size Optimization Curve

VI. RESULTS AND DISCUSSION

The simulation and analysis conducted in the reviewed studies reveal several key insights into the performance and economics of lithium-ion battery systems for renewable energy-based EV charging:

- Cost Efficiency: Hybrid systems that combine solar, wind, and lithium-ion battery storage (referred to as Hybrid RES-BESS systems) reduce the overall cost of energy for EV charging stations by approximately 21% compared to systems that rely on a single battery type [9].
- Second-Life Batteries: Reusing lithium-ion batteries from retired EVs — often referred to as second-life batteries — can significantly reduce initial capital expenditures. These batteries, although not suitable for high-demand vehicular use, still retain enough capacity for stationary storage in microgrids and charging stations [9, 11].
- Remote Area Applications: Off-grid systems that integrate PV and lithium-ion BESS are shown to be effective in powering EV charging stations in rural or remote areas where grid extension is economically or logistically impractical [10].
- Improved Battery Life with Smart Charging: Intelligent energy management and optimized charging schedules not only enhance energy utilization but also extend the usable lifespan of batteries by reducing thermal stress and degradation [12].

These findings support the practical viability of integrating lithium-ion battery systems in green EV infrastructure and reinforce the importance of strategic planning and control

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VII. CONCLUSION

Lithium-ion battery systems play a pivotal role in enabling sustainable EV charging infrastructure powered by renewable energy. Their high efficiency, relatively long life, and ability to handle high power demands make them well-suited for this application. However, to unlock their full potential, several key factors must be managed:

- Proper System Sizing: To balance costs and ensure reliability.
- Effective Energy Management: To optimize the use of renewable resources and battery cycles.
- Battery Health Monitoring and Degradation Modeling: To extend lifespan and reduce replacement costs.
- Adoption of AI-based Forecasting and Optimization Algorithms: Such as GANs and MILP for improved performance and adaptability.

Future research should continue exploring the integration of second-life batteries, enhanced thermal management techniques, and decentralized control systems. Together, these efforts can contribute to the development of resilient, scalable, and eco-friendly EV charging networks.

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