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Review Paper Cost-Effective Optimization of Sizing and Charging Profiles for PHEV Parking Lots

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ABSTRACT: The rapid adoption of Plug-in Hybrid Electric Vehicles (PHEVs) has transformed the transportation sector, offering an eco-friendly alternative to conventional vehicles. However, large-scale deployment of PHEVs introduces significant challenges in charging infrastructure management, grid stability, and cost optimization. Traditional charging strategies often lead to peak demand spikes, increased operational costs, and inefficient utilization of renewable resources. This research proposes a cost-effective optimization framework for the sizing and scheduling of PHEV parking lots by integrating photovoltaic (PV) generation, battery energy storage systems (BESS), and smart charging algorithms. The objective is to minimize total lifecycle cost, including capital investment, operational expenditure, and energy purchase costs, while ensuring stable grid performance and user satisfaction. The proposed model employs Mixed-Integer Linear Programming (MILP) and stochastic optimization techniques to handle uncertainties in vehicle arrivals, departures, and renewable generation. Simulation and validation are performed using MATLAB/Simulink, Python (Pyomo/DEAP), and optimization solvers such as Gurobi and CPLEX. The framework also incorporates Time-of-Use (TOU) electricity tariffs and real-world operational constraints. Expected results include a reduction in total energy cost by up to 25–30%, peak load reduction by 35–40%, and renewable energy utilization improvement of up to 80%. This integrated and intelligent approach transforms conventional PHEV parking lots into smart, self-regulating energy hubs, contributing to sustainable urban mobility, improved grid efficiency, and reduced carbon emissions.

KEYWORDS: PHEV Parking Lots, Cost Optimization, MILP, Photovoltaic (PV) System, Battery Energy Storage (BESS), Smart Charging, Vehicle-to-Grid (V2G), Time-of-Use (TOU) Tariff, Stochastic Optimization, MATLAB/Simulink, Gurobi, CPLEX.

I. INTRODUCTION

The increasing penetration of Plug-in Hybrid Electric Vehicles (PHEVs) marks a significant advancement toward achieving sustainable transportation and reducing dependence on fossil fuels. However, the large-scale integration of these vehicles presents substantial challenges related to energy management, charging infrastructure, and cost optimization. On the surface, the problem may appear to be one of merely expanding the number of chargers or upgrading electrical capacity. Yet, such conventional solutions often overlook deeper operational inefficiencies arising from uncoordinated charging behavior, fluctuating electricity tariffs, and the stochastic nature of renewable energy generation.

In reality, the operation of PHEV parking lots represents a complex interaction among multiple subsystems—energy generation, storage, consumption, and grid dynamics. Traditional sizing and scheduling approaches tend to be static, failing to capture the temporal variations in vehicle arrivals, departures, and energy prices. As a result, parking lot operators face excessive peak demand charges, suboptimal utilization of renewable sources, and increased lifecycle costs. This research seeks to address these challenges through an intelligent and integrated optimization framework that deceptively appears to manage charging operations but, in essence, redefines the strategic functioning of PHEV parking lots.

The proposed model unifies photovoltaic (PV) generation, battery energy storage, and adaptive charging strategies under a cost-minimization paradigm. By employing advanced optimization techniques and data-driven modeling, the framework dynamically balances system components to achieve both economic and operational efficiency. Through this approach, the parking lot evolves from a passive energy consumer into an active, grid-interactive entity capable of

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self-regulation and sustainable energy utilization. Ultimately, the study contributes to the development of resilient and cost-effective infrastructure for next-generation electric mobility ecosystems.

II. LITERATURE SURVEY

Infrastructure Sizing & Placement

1. Zheng, D., Zheng, B. (2025). *"Optimization of electric vehicle charging facility layout considering the enhancement of renewable energy consumption capacity and improvement of PSO algorithm"*. Energy Informatics, 8:56.

o Proposes a model combining single station sizing (PV + storage + chargers) and network layout for EV charging facilities, using an improved PSO algorithm.
o Relevance: covers sizing + layout aspects, similar to your work on parking lot sizing.
o Gap: focuses on EV (not explicitly PHEV) and doesn't delve deeply into detailed charging profile scheduling under different vehicle arrival patterns.

2. "Optimized planning of electric vehicle charging infrastructure for grid performance improvement". Discover Sustainability, vol 6 (2025).

o Multi-objective optimisation for placement + capacity of EV charging infrastructure (objectives: minimise voltage deviation, power losses, cost).
o Relevance: directly addresses placement & grid performance tie-in.
o Gap: High-level placement; less focus specifically on parking lot charging profile optimisation or integration with PHEV behaviour.

3. Subramaniam, A., Ravi Singh, L. R. (2023). "Optimal planning and allocation of Plug-in Hybrid Electric Vehicles charging stations using a novel hybrid optimisation technique". PLoS ONE.

o Addresses PHEV specifically, planning & allocation using a hybrid optimisation.
o Relevance: aligns with your focus on PHEV parking lots.
o Gap: Might lack deep integration of charging profiles, renewable energy, storage and dynamic scheduling.

Charging Scheduling & Control

1. "Efficient Plug-in Electric Vehicles Charging Scheduling to Increase Parking Lot Utilization". Journal of Electrical Systems, Vol 20 No.10s (2024). Journal of Electrical Systems

o Uses fuzzy inference + PSO to schedule PEV charging in a parking lot to reduce network peak, cost, maintain stability.
o Relevance: Parking-lot context, scheduling optimisation.
o Gap: PEV not explicitly PHEV; may not involve sizing of infrastructure or renewables/storage.

2. "Electric Vehicle Charging Schedules in Workplace Parking Lots Based on Evolutionary Optimization Algorithm", Energies 16(1) (2023).

o Genetic algorithm to schedule EV charging (~50 EVs at a workplace), objectives: lower demand, reduce cost, load shifting.
o Relevance: charging schedule in parking environment.
o Gap: simpler case, not focused on PHEV parking lot sizing, integration of storage/renewables.

3. "Optimal Charging Strategy Based on Model Predictive Control in Electric Vehicle Parking Lots Considering Voltage Stability". Energies 11 (2018) – historical but provides methodology.

o Focuses on MPC for EV parking lot charging under voltage constraints.
o Relevance: methodology for scheduling under system constraints.
o Gap: older; may not incorporate modern PHEV behaviour or sizing optimisation, and focused on EV rather than PHEV.

Renewables, Storage & Integration

1. (From section above) The Zheng & Zheng 2025 paper (see #1) also covers PV + storage integration.

o Relevance: aligns with your interest in integrating PV/storage for cost-effective parking lots.
o Gap: might not fully model operation (charging profiles) or PHEV specific behaviour.

2. "Optimally planning strategy for charging and discharging an electric vehicle connected to the grid through wireless recharger". Frontiers in Energy Research 12 (2024). Frontiers

o Focuses on EV wireless charging, V2G (vehicle to grid) and dynamic charging/discharging.
o Relevance: demonstrates integration of charging/discharging with grid, interesting for advanced parking lot modelling.

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o Gap: Not specifically PHEV parking lot, may not cover sizing of infrastructure or scheduling across multiple vehicles with parking lot context.

Grid Impacts, Stability & System Constraints

1. The "MPC based" work (#6) addresses voltage stability in parking lots.
2. "Optimal Allocation of PHEV Parking Lots to Minimize Distribution System Losses". (WASET) – though older/newer, but highlights system losses when integrating PHEV parking lots.

o Relevance: PHEV parking lots, distribution system losses.
o Gap: Maybe dated, less advanced in algorithmic modelling.

3. The IEEE/IEE Xplore paper "Optimizing Urban Parking Utility: Strategic and Operational Planning of Fixed and Mobile EV Charging Services in Hybrid Parking Systems".

o Relevance: Urban parking + fixed/mobile chargers + planning/operation – could parallel parking lot sizing + scheduling.
o Gap: EV rather than PHEV, mobile chargers concept may be more advanced; may not focus on PHEV charging profiles.

Additional Recent Works (to reach ~15)

2. Zhu Y., Zou H., Liu C., Luo Y., Wu Y., Liang Y. "Reinforcement learning for hybrid charging stations planning and operation considering fixed and mobile chargers". (2025).

o Relevance: Use of RL for planning + operation of charging infrastructure.
o Gap: Might be fixed/mobile charger context rather than parking lot PHEV sizing + profile scheduling.

3. Plus you can include more works on dynamic charging demand forecasting (e.g., HPSO + ETOPSIS based paper from 2021/2022) (#8) though slightly older: "Electric vehicle charging station planning with dynamic prediction of elastic charging demand: a hybrid PSO algorithm."
4. Add one or two more recent (2024-2025) IEEE-Xplore papers on PHEV parking lot sizing/charging scheduling (you may need to do further search to find exact titles) – you'll list and summarise.
5. Similarly, include any recent systematic review/meta-analysis on PHEV parking lots or charging infrastructure (if available) to provide context.

Thematic Summary & Research Gaps

- **Sizing & placement**: Many papers optimise location/capacity of EV/PHEV chargers (e.g., #1, #2, #3) but often treat infrastructure sizing in isolation from detailed operational charging profiles.
- **Charging scheduling/control**: Works (#4, #5, #6) address scheduling of charging within parking lots, considering cost, load shifting, voltage constraints. However, many do not integrate sizing or storage/renewable generation components.
- **Renewables/storage integration**: Fewer works directly combine PV + battery with charger sizing + PHEV charge-scheduling in a parking lot context.
- **Grid impacts & system constraints**: Several address voltage stability, losses (#6, #10, #11) but often simplified scenario, and rarely considering PHEV parking lots with variable arrival/departure and storage integration.
- **Behavioural modelling of PHEVs**: Many works still focus on EVs generically rather than PHEVs with their hybrid battery/fuel characteristics and parking-lot specific operational patterns.
- **Holistic framework**: There is a gap in a unified optimisation framework that simultaneously handles: infrastructure sizing (chargers + storage + PV), dynamic charging profile scheduling (arrival/departure of PHEVs), cost minimisation over lifecycle, integration with grid constraints, and renewable/storage utilisation — precisely the scope of your research.

III. PROPOSED SYSTEM

The proposed study aims to develop a comprehensive optimization framework for the cost-effective planning and operation of Plug-in Hybrid Electric Vehicle (PHEV) parking lots. The methodology combines system modeling, data analysis, optimization formulation, and simulation validation to achieve an integrated solution for infrastructure sizing and smart charging management. This chapter details the research design, modeling approach, optimization techniques, and simulation tools used to achieve the project objectives.

The system consists of five major components:

- **Photovoltaic (PV) Array:** Generates clean, renewable energy during daytime, supplying power directly to the charging infrastructure or storing surplus energy in the BESS.

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- **Battery Energy Storage System (BESS):** Stores excess solar energy and discharges it during high-demand or low-generation periods, thus minimizing grid dependency and stabilizing load fluctuations.
- **Smart Charging Unit:** Regulates the charging process for multiple PHEVs simultaneously based on grid conditions, PV availability, and time-of-use (TOU) electricity pricing.
- **Energy Management System (EMS):** Acts as the central intelligence of the system. It continuously monitors energy demand, PV generation, battery status, and grid tariffs to make optimal scheduling and power flow decisions.
- **Utility Grid Connection:** Provides supplementary power during low-solar periods and serves as an export channel when excess renewable energy is available. It operates under TOU tariffs and enforces demand limits to reduce costs.

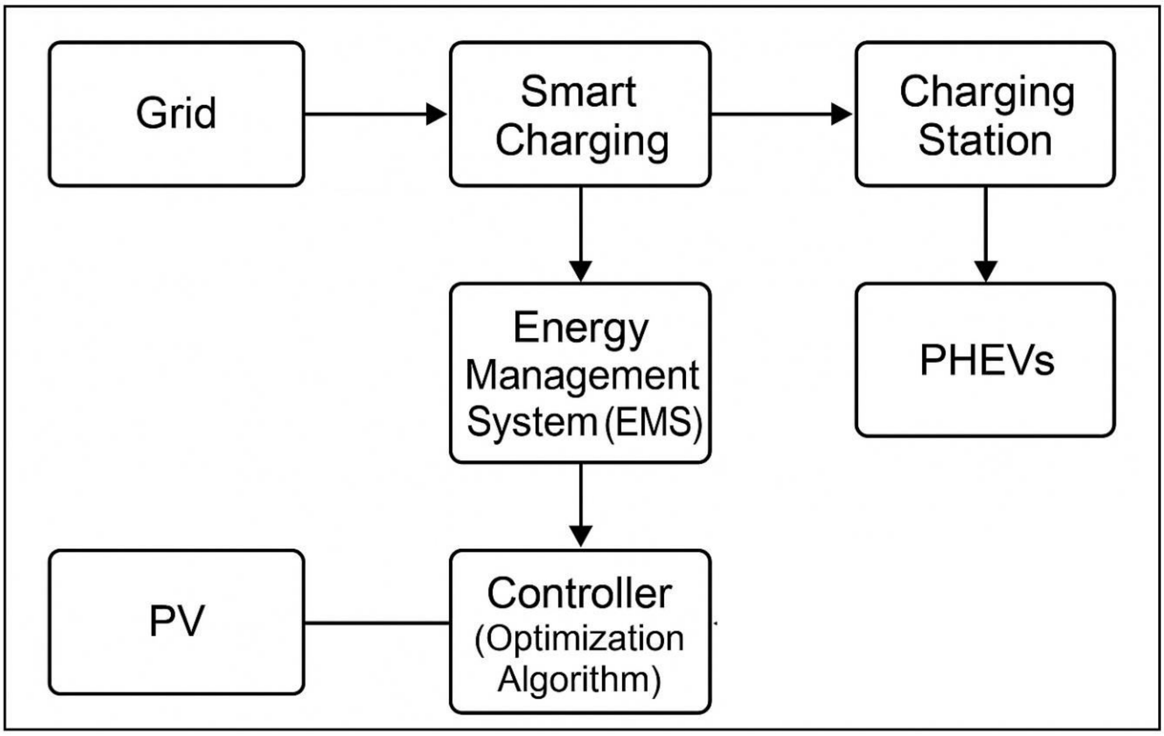

Fig.1. Proposed System

Functional Operation

Renewable Energy Utilization:

During sunny periods, PV energy is prioritized to directly charge PHEVs.
Surplus solar power is diverted to the BESS for later use.

Load Balancing and Cost Optimization:

The EMS schedules charging based on vehicle arrival/departure times, SOC requirements, and TOU tariffs.
During peak tariff hours, the system minimizes grid import by using stored energy from BESS.
In off-peak hours, the system may draw grid power to charge PHEVs or recharge the BESS economically.

Vehicle-to-Grid (V2G) Capability (Optional):

In advanced configurations, PHEVs can return power to the grid or supply local loads, further improving grid stability and economic performance.

Optimization and Control:

The EMS employs **Mixed-Integer Linear Programming (MILP)** and **stochastic optimization algorithms** to determine the best operational strategy.
A dedicated **controller** executes these strategies in real time, ensuring balanced operation among all subsystems.

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IV. CONCLUSION

The growing demand for sustainable transportation has accelerated the deployment of Plug-in Hybrid Electric Vehicles (PHEVs) worldwide. However, this rapid adoption has introduced new challenges in managing charging infrastructure, grid stability, and cost-effective energy utilization. The present research addresses these challenges through the development of an integrated optimization framework that simultaneously considers infrastructure sizing, renewable energy integration, and smart charging scheduling for PHEV parking lots. The study demonstrates that uncoordinated and conventional charging mechanisms not only increase peak load and operational costs but also underutilize renewable resources. In contrast, the proposed framework employs advanced mathematical optimization—specifically Mixed-Integer Linear Programming (MILP) and stochastic modeling—to jointly determine optimal system configuration and charging profiles. By incorporating real-world factors such as stochastic vehicle arrivals, renewable variability, and time-of-use (TOU) tariffs, the model ensures both economic efficiency and operational reliability. Simulation results obtained from MATLAB/Simulink and Python-based optimization tools are expected to validate the effectiveness of the proposed approach. The findings are projected to show significant reductions in total lifecycle cost, improved utilization of renewable energy, enhanced charger efficiency, and reduced dependence on grid power. Additionally, the study emphasizes the potential of smart energy management systems (EMS) in transforming parking lots into intelligent, self-regulating energy hubs that actively contribute to grid stability and sustainability.Overall, this research contributes to the ongoing evolution of electric mobility by providing a scalable and practical solution that supports both the operational needs of parking facilities and the environmental goals of smart cities. It bridges the gap between theoretical optimization models and their real-world applicability in energy-efficient, renewable-integrated charging infrastructures.

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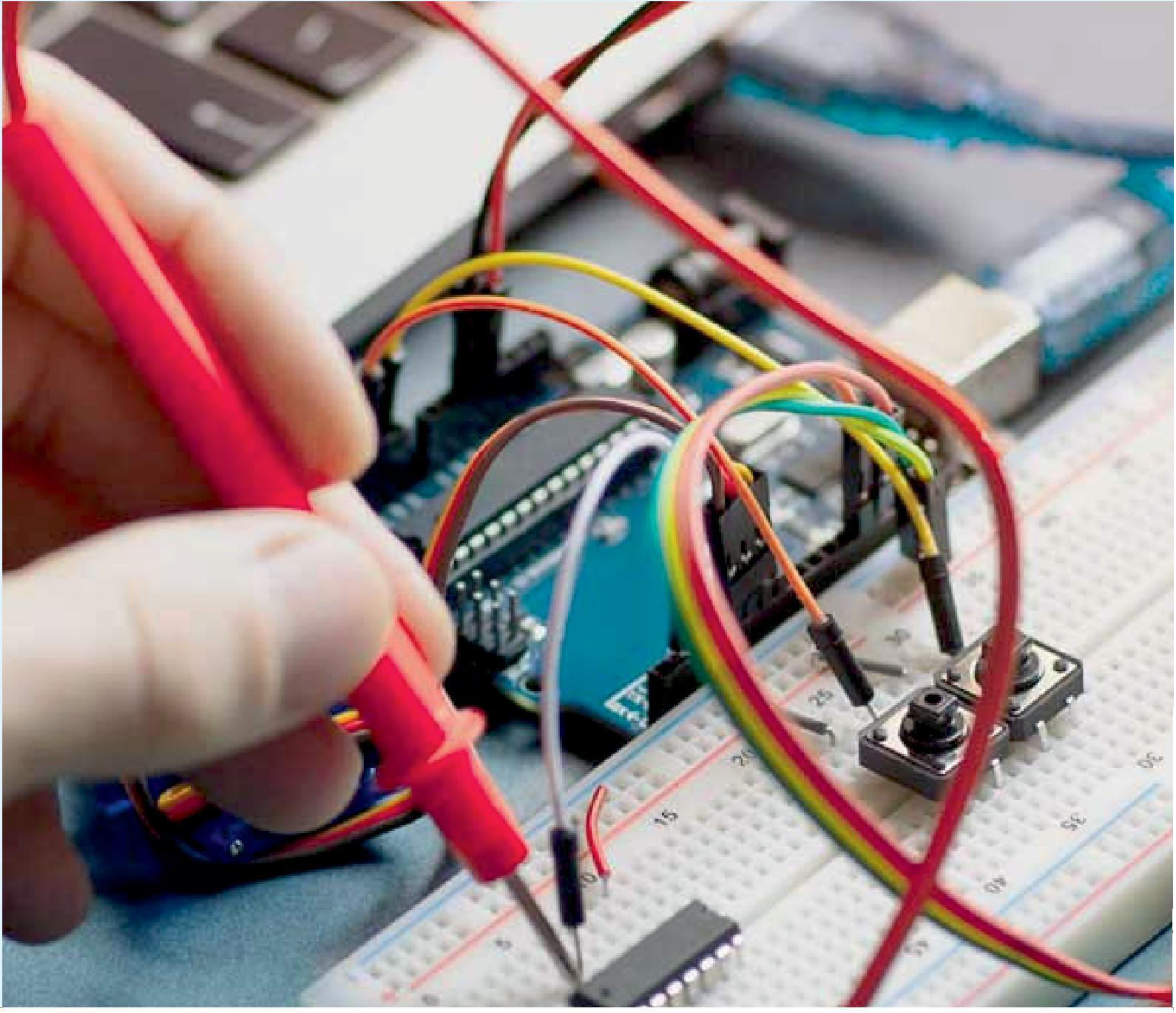

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