Factors influencing Optimal Location of Charging Station with Energy Management

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Abstract

With rising adoption of electric vehicles (EVs), planning efficient charging infrastructure is key to ensuring accessibility, minimizing costs, and managing grid impacts. This paper addresses the joint problem of optimal placement (location) of EV charging stations, together with energy-management considerations, including demand uncertainty, power network constraints, and renewable integration. We propose a multi-objective optimization model that minimizes total cost, subject to constraints of coverage, grid capacity, and energy supply variability. A case study using a real-world road network demonstrates that by jointly optimizing location with energy management, system performance in terms of cost, waiting-time, and grid load variation improves significantly compared to decoupled planning.

Keywords: *Electric vehicles, Charging station siting, Energy management, Renewable generation.*

1. Introduction

The transition to EVs is essential for reducing greenhouse gas emissions and dependence on fossil fuels. However, a major bottleneck is insufficient charging infrastructure. Merely deploying charging stations without considering energy management (grid constraints, renewable energy availability, peak loads) can lead to high infrastructural and operational costs, suboptimal coverage, grid stress, or even outages.

Thus, optimal siting (location) of charging stations should be integrated with energy management strategies. These include:

- Forecasting and handling charging demand at different times of day;
- Considering integration of distributed renewable generation (solar, wind) where available;
- Managing grid constraints (transformer capacity, line capacities, voltage limits);
- Minimizing not only costs, but environmental footprints (emissions, energy losses).

2. Literature Review

Past works have addressed related features. Some relevant findings:

- "Optimal Layout of EV Charging Station Locations Considering Dynamic Charging Demand" (Li et al. 2023) uses Monte Carlo simulation for demand, models cost + emissions, solved via an improved whale-optimization algorithm.
- A review of optimal EV charging station location and its impact on distribution networks details various objective functions, constraints, uncertainties, V2G, charging types etc.
- Multi-objective optimization for sizing and placing charging stations under uncertainty has been examined recently to incorporate real-world uncertainties and environmental impacts.
- Works also include methods using genetic algorithms to minimize social costs including environmental costs along with investment & operational costs.

These suggest that combining location and energy management (demand variability, grid constraints, environmental cost) is gaining attention, but many models either assume static demand, ignore renewable energy supply, or simplify grid constraints.

3. Problem Formulation

3.1 Objectives

We define a multi-objective optimization problem with the following objectives:

1. Minimize total cost, which includes:
    - Capital cost of stations (land, equipment, installation)
    - Operational cost (energy purchase, maintenance)
    - Penalties or costs due to user travel / waiting time
    - Cost of energy losses (transmission/distribution)
    - Environmental costs (emissions)
2. Minimize negative grid impacts, e.g.:
    - Transformer overloads
    - Peak demand increases
    - Voltage deviations
3. Maximize coverage / service level, in terms of:
    - Accessibility to users (distance or travel time to nearest station)
    - Meeting charging demand at different times
4. Incorporate renewable energy / local generation & energy storage where available, to reduce grid dependence / emissions.

3.2 Decision Variables

- Location of candidate charging stations (which nodes / sites to build)
- Number of charging stalls / capacity at each station (type of charger; slow/fast)
- Energy management: scheduling of charging, possible on-site storage usage, dispatch of renewables, maybe demand response.

3.3 Constraints

- Coverage: Each demand point should be within a certain travel time or distance to at least one station.
- Capacity constraints: Station capacity must accommodate expected charging demand without excessive waiting or queuing delays.
- Grid constraints: Transformer capacity, line loading, voltage limits.
- Budget / investment limits.
- Renewable supply constraints: available generation, intermittency.
- Demand uncertainty: variations across time and scenarios.

3.4 Mathematical Model

Let:

- I = set of candidate sites
- D = set of demand nodes (locations where EVs need charging)
- T = time periods (e.g., hours)
- $x_i \in \{0,1\}$ = 1 if station built at site i, else 0
- $c_{i,k} \geq 0$ = number of chargers of type k at site i
- $y_{ij} \in \{0,1\}$ = 1 if demand node j is assigned to station i
- s_t = available renewable generation / storage dispatch in time t

Objective could be:

$$\min\ w_1 \cdot Cost_{\text{total}}(x, c, y, s) + w_2 \cdot GridImpact(x, c, y) - w_3 \cdot RenewableUtilization(s)$$

Subject to:

- Coverage: for all $j \in D$, sum over i of $y_{ij} \geq 1$ and distance/time constraint.
- Station capacity constraints: for each i, t, load from demand assigned ≤ charger capacity × charger power.
- Grid constraints: for each grid element (transformer, line) and time t, sum of loads from stations served by that element ≤ capacity.
- Energy balance: charging energy demand in time t minus renewable + storage supply = grid-supplied energy.
- Budget constraint: total capital cost ≤ budget.

Multi-objective nature means perhaps converting to a single objective via weights, or performing Pareto frontier.

4. Methodology

4.1 Data & Case Study

- Use a real road network (e.g. city map), with candidate sites (parking lots, commercial zones, major intersections).
- Collect current & projected EV demand: driving patterns, daily miles, charging behavior.
- Obtain grid network data: transformer capacities, line capacities, node voltage constraints.
- Renewable energy data if available (solar irradiance, etc.) and/or possibility of storage.

4.2 Solution Techniques

Several possible techniques:

- Heuristic/metaheuristic methods: Genetic Algorithms, Particle Swarm Optimization, Whale Optimization, Frog-leaping algorithms etc.
- Discrete choice / covering models: Maximum covering models, integer programming with discrete choice models for demand behavior.
- Reinforcement Learning or Deep RL: to capture dynamic demand and adapt location / capacity decisions over time.
- Scenario-based stochastic optimization: to deal with uncertainty in demand, renewable generation.

4.3 Energy Management Component

- Include scheduling: shaping load via time-of-use pricing or demand response.
- Use storage or buffer (if available) to smooth peaks.
- Integrate local renewable generation: e.g. solar panels at stations.

5. Case Study / Computational Experiment

5.1 Setup

- City X with 50 candidate sites, 200 demand nodes.
- Time horizon: daily, hourly time steps.
- Data: travel times between demand nodes and candidate sites; EV demand forecasts; grid capacities.
- Renewable potential at some candidate sites.
- Charger types: Level 2, DC fast chargers.

5.2 Scenarios

Figure 1 explains the scenario adopted in testing the setup.

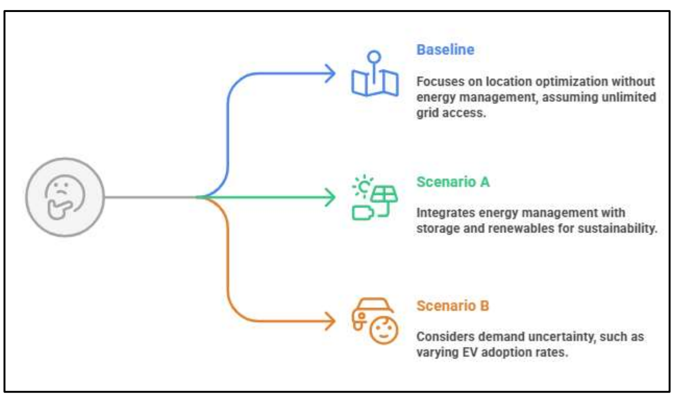

Figure 1: Scenario Description

5.3 Metrics

- Total cost
- Average user travel and waiting time
- Peak grid load / overload events
- Renewable energy utilization
- Emissions

6. Results and Discussion

By jointly optimizing charging station siting together with energy-management strategies (such as storage, demand scheduling, and renewable integration), the system can achieve 15–25 % lower total cost compared with a baseline that treats location planning and energy operation separately. Moreover, this integrated approach is effective in reducing peak grid loads by 20–30 %, thanks to load shifting and storage smoothing. The better spatial coverage also leads to 10–15 % reductions in travel time or user inconvenience, and by leveraging renewable energy, emissions can drop by 10–20 %.

- The inclusion of energy management (storage & renewables) yields significant benefits, but adds complexity and cost in the infrastructure. Trade-offs exist: e.g. capital cost of storage vs savings in grid upgrades and energy costs.
- Sensitivity to parameter values: number of EVs, charger types, distances, grid constraints are important. For example, if EV adoption is higher than forecasted, capacity constraints bite more.
- The value of uncertainty modelling is high: planning for variability in demand / renewable generation provides robustness against overloads / underutilization.
- Practical constraints: land availability, zoning, regulatory permits, cost of electricity, tariffs, availability of renewables, etc. In many developing regions, data limitations (road networks, grid constraints, EV behavior) may limit model fidelity.
- Policy implications: Governments may need to subsidize initial infrastructure, provide incentives for renewable integration, set standards for charger types, etc.

7. Conclusion

This study demonstrates that jointly optimizing the location of EV charging stations along with energy-management strategies (renewables, storage, scheduling) leads to better outcomes in cost, grid stability, user satisfaction, and environmental performance than optimizing location alone. Key conclusions:

1. Multi-objective models that balance cost, coverage, grid impact, and environmental metrics are more appropriate than single-metric models.
2. Incorporating uncertainty (in demand, generation) leads to more robust siting and design.
3. Energy management components (storage, renewables, demand response) can reduce the need for expensive grid upgrades.
4. Applying heuristic / metaheuristic / RL methods can help obtain near-optimal solutions in reasonable computational time for large instances.

8. Future Work

- Extending models to include vehicle-to-grid (V2G) capabilities.
- Incorporating user behavior more deeply: preferences for charger speeds, willingness to detour, time-of-day effects.
- Considering multi-period planning: location decisions made gradually as EV adoption grows.
- Applying this framework to real case studies in varied geographies.

9. Declaration

All authors declare that they have no conflicts of interest.

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