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Digital twin-based mobilized energy storage management for smart parking lot hubs in the deep-decarbonization-aware spatiotemporal transportation-distribution networks nexus

Peyman Zare, SeyedJalal SeyedShenava *, Hossein Shayeghi

Department of Electrical Engineering, Faculty of Technology and Engineering, University of Mohaghegh Ardabili, P.O. Box 179, Ardabil, Iran

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ABSTRACT

Deep decarbonization-aware electric freight operation requires charging and routing decisions to reflect feeder-level carbon conditions rather than distance or average emission factors alone. This study develops a Digital Twin-based mobilized energy storage management framework in which Heavy-Duty Electric Truck (HDET) batteries act as transferable storage resources coordinated through Smart Parking Lot (SPL) hubs across the transportation-distribution networks nexus. The system couples a 35-node transportation network with a modified IEEE 69-bus distribution feeder. Carbon Intensity Tracing (CIT) and time-varying marginal emission rates are embedded in routing and charging decisions, while the Digital Twin synchronizes feeder, traffic, charging, and battery states through receding-horizon updates. Chance constraints capture uncertainty in arrival time, departure time, and traveled distance, and a Bayesian–Stackelberg mechanism coordinates HDET responses, charging prices, congestion effects, and green-electricity allocation. Deep-decarbonization-aware routing reduces the CIT-attributed HDET charging footprint from 9.84 to 7.31 kg, corresponding to a 25.7% reduction, while contractual green-electricity allocation decreases the net HDET footprint to 6.21 kg without implying an equivalent reduction in physical system emissions. Digital Twin feedback reduces mean state-prediction error by 76.1% relative to offline optimization and eliminates feeder-limit violations in the tested case. Benchmark, ablation, sensitivity, and online-offline assessments isolate the contributions of carbon tracing, state correction, probabilistic feasibility, and strategic coordination. Scalability is examined using the IEEE 123-bus feeder and the Anaheim 416-node, 914-link transportation benchmark. The results demonstrate structural transferability to larger coupled systems and establish a reproducible basis for deep-decarbonization-aware mobilized energy storage management through SPL hubs in electric freight networks.

1. Introduction

1.1. Study prelude

Electrification of heavy-duty freight is shifting transport energy demand toward distribution networks, where charging location and timing affect feeder loading and the carbon content of stored battery energy. Deep decarbonization-aware charging can reduce exposure to emission-intensive electricity, but its operational value depends on how accurately carbon responsibility is represented across space and time [1]. Heavy-duty electric trucks add further complexity because their batteries are mobile storage resources constrained by routes, charging windows, and residual state of charge [2]. The mobilized energy storage refers to the traction-battery energy carried by HDETs whose storage location, charging opportunity, SOC, and carbon exposure change endogenously with vehicle movement.

Transport and power networks therefore interact through more than aggregate charging demand. A routing decision determines which charging facilities are reachable, while feeder conditions determine whether those facilities can serve additional load without violating electrical limits. Low-carbon demand response can shift charging toward cleaner periods or locations, yet freight operation must also preserve travel feasibility under changing network conditions [3]. Spatial averaging can obscure feeder-level carbon differences when renewable and thermal generation contribute unevenly to nodal supply. Traffic congestion also changes route impedance and can alter charging opportunities and traction-energy requirements.

* Corresponding author.
E-mail addresses: peymanzare@uma.ac.ir (P. Zare), seyedshenava@uma.ac.ir (S. SeyedShenava), hshayeghi@uma.ac.ir (H. Shayeghi).

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