ABSTRACT

To develop sustainable and livable cities, public transportation systems such as buses are being rapidly electrified worldwide. Due to the significant initial investment costs, Electric Bus (eBus) systems are typically designed in a cost-optimal fashion using Opportunity Charging (OC), in which an eBus is recharged while stationary at a terminal between trips. Since the time between trips is limited, any changes to the charging process can pose new challenges for the operation of an eBus system, leading to delays and disruptions. This study presents a cost-effective approach to addressing uncertainties in the energy supply of an eBus system. The research is divided into three distinct objectives based on the nature of the uncertainty, with the aim of creating a reliable eBus system.

Focusing on the probability of energy supply disruptions due to individual charger failures, the first objective presents a two-stage Stochastic Mixed Integer Program (SMIP) to create a reliable eBus system that limits the average trip start delay. The first stage designs a cost-optimal OC eBus system with charger sharing between routes. Using the first stage design, charger failure probabilities are determined based on the number of chargers at a terminal and the charger utilization rate. This framework makes it decision-dependent uncertainty, reflecting the stochastic nature of charger failure based on wear and tear of charging infrastructure components.

Since the second stage of the framework involved integer variables due to the recourse action of providing additional chargers, the problem was solved using the ancestral Benders decomposition. The proposed methodology was applied to the real-life bus network of Delhi, India. The results demonstrated that the OC infrastructure is sensitive to charger failures and that additional chargers would be required at the terminals to keep the average trip start delay within reasonable limits. Sensitivity analysis showed that at low charger failure probabilities, the model could withstand most charger failure scenarios with acceptable delays in the system. However, as the failure probability increases, the ability to limit delays decreases, requiring substantial changes to the charging infrastructure. The model was able to handle the charger failure probability, thereby limiting

average trip start delays with a small increase in total system cost.

The second objective of the study considers the possibility of spatial failures in the city's power grid and proposes a design framework that guarantees the worst-case trip loss thresholds observed in the system. The problem is formulated as a two-step optimization framework in which the first step creates a cost-optimal OC eBus system for the network. The total system cost obtained in the first step is later used to limit the budget for achieving the required reliability. The second step is formulated as a min-max Mixed Integer Linear Program (MILP) that minimizes the maximum trip loss in the system in the event of spatial power grid disruptions, subject to the limited budget from the first step and an additional buffer. This model uses strategic terminal-substation connections to distribute the energy demand of the eBus system spatially, reducing load and, in turn, reducing the critical nature of individual power grid and eBus system infrastructure.

When this method was applied to a real bus network in Delhi, India, a small increase in budget led to a significant reduction in worst-case trip losses relative to the cost-optimal design. From the case study, the higher trip losses in the cost-optimal design can be attributed to the way terminals and substations are connected. The cost-optimal design resulted in concentrated power demand points, which were spatially distributed using the proposed method. Sensitivity analysis by budget increment revealed that the model is most effective with a small increase in the budget, after which decreasing benefits were observed as the budget increased, indicating its cost-effectiveness.

The third objective addresses multiple uncertainties that can arise simultaneously in the energy supply process: charger efficiency uncertainty and spatiotemporal power grid load shedding. Given that charging efficiency can vary with each charging event, this was addressed using a robust formulation. Meanwhile, spatially correlated load shedding was considered a relatively rare event and modeled stochastically, resulting in a hybrid robust-stochastic framework. Given time-varying electricity prices, Energy Storage Systems (ESS) were installed at terminals to reduce costs while simultaneously increasing reliability.

A case study of a bus network in Delhi, India, showed that the model could design a reliable eBus system that accounts for multiple sources of energy supply uncertainty at only a small cost increase over a cost-optimal design for the same network. The results indicated that reliability against charging efficiency uncertainty required significant changes to the charging infrastructure. In contrast, dealing with load shedding resulted in significant changes to the battery capacity selection for the eBus fleet. Due to an increase in the charging power and battery capacity, the reliable design for both uncertainties required less ESS capacity than the deterministic case. The model also monitored the energy levels of ESS installed at terminals to determine their usage patterns during the operational period. The designed eBus system was able to deal with varying electricity prices and energy supply uncertainties very effectively.

In conclusion, this study proposes a significant deviation from deterministic cost-optimal designs to achieve reliability against energy supply uncertainties, which can help operators maintain advertised schedules when adopting eBuses. This study proposes strategies for cost-effectively designing reliable OC eBus systems within cities. As cities around the world move towards sustainable modes of transport using eBuses, this study can help them achieve their goals while maintaining public transport reliability amid technological changes.

Keywords: Sustainable transportation systems, electric buses, charging infrastructure design, charging scheduling, grid integration, energy supply uncertainty, charging efficiency uncertainty, load shedding, charger failure, stochastic design, hybrid robust-stochastic framework, reliable system.