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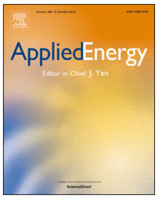

Wireless charger deployment for an electric bus network: A multi-objective life cycle optimization

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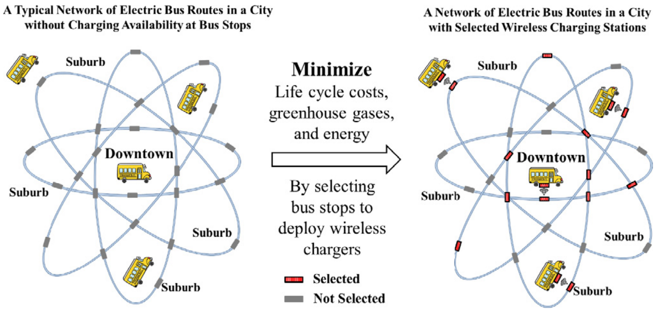
HIGHLIGHTS

- Life cycle optimization of wireless charging infrastructure for electric buses.
- Multi-objective optimization of life cycle costs, GHG emissions, and energy.
- Application of optimization to a case study of the University of Michigan buses.
- Characterization of trade-off of infrastructure burden vs. battery-sizing benefits.
- Sensitivity analysis of battery price, charge rate, and infrastructure costs.

GRAPHICAL ABSTRACT



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ABSTRACT

Deploying large-scale wireless charging infrastructure at bus stops to charge electric transit buses when loading and unloading passengers requires significant capital investment and brings environmental and energy burdens due to charger production and deployment. Optimal siting of wireless charging bus stops is key to reducing these burdens and enhancing the sustainability performance of a wireless charging bus fleet. This paper presents a novel multi-objective optimization model framework based on life cycle assessment (LCA) for siting wireless chargers in a multi-route electric bus system. Compared to previous studies, this multi-objective optimization framework evaluates not only the minimization of system-level costs, but also newly incorporates the objectives of minimizing life cycle greenhouse gas (GHG) emissions and energy consumption during the entire lifetime of a wireless charging bus system. The LCA-based optimization framework is more comprehensive than previous studies in that it encompasses not only the burdens associated with wireless charging infrastructure deployment, but also the benefits of electric bus battery downsizing and use-phase vehicle energy consumption reduction due to vehicle lightweighting, which are directly related to charger siting. The impact of charger siting at bus stops with different route utility and bus dwell time on battery life is also considered. To demonstrate the model application, the route information of the University of Michigan bus routes is used as a case study. Results from the baseline scenario show that the optimal siting strategies can help reduce life cycle costs, GHG, and energy by up to 13%, 8%, and 8%, respectively, compared to extreme cases of "no charger at any bus stop" and "chargers at every stop". Further sensitivity analyses indicate that the optimization results are sensitive to the initial battery unit price ($/kWh), charging power rate (kW), charging infrastructure costs, and battery life estimation methods.

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1. Introduction

The large-scale penetration of electric vehicles (EVs) is an important strategy to mitigate the greenhouse gas (GHG) emissions, environmental impacts as well as energy consumption [1] of the transportation sector that is responsible for 27% of U.S. GHG emissions [2] and 28% of total U.S. energy use [3]. However, there are critical challenges that slow down the penetration and limit the potential for sustainability performance of EVs, stemming from: (1) the lack of accessibility and convenience of charging stations limiting the range of EVs that leads to range anxiety; and (2) the high upfront cost of EVs limiting the economic performance mainly because of the expensive and large onboard rechargeable battery [4]. Wireless power transfer (WPT) for EVs, more commonly known as the wireless charging technology [4], is an emerging charging method alternative to plug-in charging for EVs and can eliminate the two aforementioned bottlenecks of EVs. The electric energy is transferred wirelessly through an air gap from the transmitter coils embedded on the ground to the receiver coils installed on the bottom of vehicles via an electromagnetic field. Deploying wireless charging infrastructure at bus stops, traffic intersections, congestion areas as well as highways enables convenient and widespread charging accessibility [5] without the need to plug in for charging, and also enables significant downsizing (1/3–1/5 of original weight) of the heavy and expensive onboard EV battery because of multiple "opportunity charges" en route while the vehicle still fulfills the range requirements [6]. Battery downsizing has significant implications for lightweighting the vehicle and improving fuel economy [6] so as to reduce the cost of purchasing and driving an EV. Based on the charging mode, wireless charging can be classified as stationary charging, i.e., charging while the vehicle is not moving, and dynamic charging, i.e., charging when the vehicle is moving on the roadway. Transit buses, for example, can be wirelessly charged when picking up or dropping off passengers at bus stops in stationary status. Currently, there are several wireless charging electric bus routes under test in different countries and the grid-to-battery energy transfer efficiency is typically higher than 80% [4], which shows electric buses as a promising application of wireless charging technology.

Although WPT has the potential to enhance the sustainability performance of EVs by downsizing the battery and lightweighting the vehicle, the large-scale deployment of wireless charging infrastructure poses critical sustainability trade-offs in terms of economic, environmental, and energy burdens. Therefore, a comprehensive assessment framework is needed to evaluate the sustainability performance of WPT EV systems. Life cycle assessment (LCA) and life cycle cost analysis (LCCA) have been widely used to evaluate the environmental impacts, energy use, and economic performance of a product or system, which encompasses not only the use-phase burdens, but also the upfront production and manufacturing stages and end-of-life burdens. Authors of this article have previously applied LCA and LCCA to compare the life cycle energy consumption, GHG emissions, and costs of a wireless charging electric bus system with a plug-in charging electric bus system, using the bus routes in Ann Arbor, Michigan in the U.S. as a case study [6,7]. A wireless charging electric bus system was found to have comparable life cycle burdens (costs, GHG, and energy) as an electric bus system using plug-in charging, because the additional burdens from the larger-scale wireless charging infrastructure compared to plug-in charging can be canceled out by the benefits of smaller batteries and vehicle lightweighting. Note that this conclusion is obtained when the deployment of wireless charging infrastructure at existing bus stations is not yet optimized, so this conclusion may be conservative and may underestimate the benefits of wireless charging. An optimal (or near-optimal) deployment and allocation of wireless charging infrastructure at existing bus stops would be expected to further reduce the life cycle burdens of a wireless charging electric bus system and enhance its sustainability performance.

Therefore, this study aims to investigate the reductions of life cycle burdens (costs, GHG, and energy) when optimally siting wireless charging infrastructure at existing bus stops and compare these with extreme cases of "no charger at any bus stop" and "chargers at every stop", by using a multi-objective (costs, GHG, and energy) life cycle optimization (LCO) framework. This optimization problem is a subset of facility location optimization problems. Optimization is a common tool used by researchers to explore the siting of public charging infrastructure for electric vehicles [8,9]. Several researchers have optimized the siting of wireless charging stations for a single electric bus route [10,11], but they lacked a comprehensive life cycle scope and only evaluated the economics of a single bus route, not incorporating other sustainability metrics, such as emissions and energy consumption and not considering the utility of a charging station and route overlapping if used in a network of routes. Systematic assessment and optimization utilizing a life cycle framework is required to effectively evaluate and understand the trade-offs between the economic, environmental, and energy burdens of large-scale WPT infrastructure deployment and the benefits of battery downsizing and fuel economy improvement.

To the best of the authors' knowledge, this is the first study to optimize the deployment of wireless charging infrastructure for a network of bus routes based on a multi-objective life cycle framework. The novel contribution of this work compared to previous studies is threefold:

- This multi-objective optimization framework evaluates not only the minimization of system-level costs, but also newly incorporates and minimizes the two key sustainability indicators of life cycle GHG emissions and energy consumption that are often evaluated in sustainability analysis of emerging technologies [6,12].
- The LCA-based optimization framework is more comprehensive than previous studies in that it encompasses not only the burdens associated with wireless charging infrastructure deployment, but also the benefits of electric bus battery downsizing and use-phase vehicle energy consumption reduction due to vehicle lightweighting, which are directly related to charger siting.
- The multi-route setting enables evaluation of the impact of charger siting at bus stops with different route utility and bus dwell time on battery life. To exhibit the application of this model framework, the route information of the University of Michigan transit bus system (also known as the Blue Buses) is used as a case study.

This multi-objective LCO model is developed to inform research, development, and deployment of wireless charging technologies. The model formulas in the method section and the different scenario analyses in the discussion section will inform the adaptation of this model framework to other real-world scenarios in different cities with different characteristics of bus system size and vehicle miles traveled.

The rest of paper is organized as follows. Section 2 describes methods of constructing the optimization model framework. Section 3 presents first the optimization results when solving for each objective individually, then the multi-objective results. Section 4 discusses the results based on several sensitivity, uncertainty, and scenario analyses. Finally key conclusions and takeaways are summarized in Section 5.

2. Methods

2.1. Overview of the optimization model

A multi-objective optimization model based on life cycle metrics is established to inform decision makers to strategically deploy wireless charging infrastructure at bus stations, based on the existing route network of the Blue Bus system at the University of Michigan as an example of model application. The model aims to solve for the minimal life cycle impacts in terms of costs, GHG emissions, and energy use, by selecting the best bus stations from 83 candidate stops shared by seven different bus routes with a total of 29 buses. The dwell time data from a four-day operation (2015-09-29 to 2015-10-02) were collected and