Applied Energy 146 (2015) 11–19

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Plug-in vs. wireless charging: Life cycle energy and greenhouse gas emissions for an electric bus system

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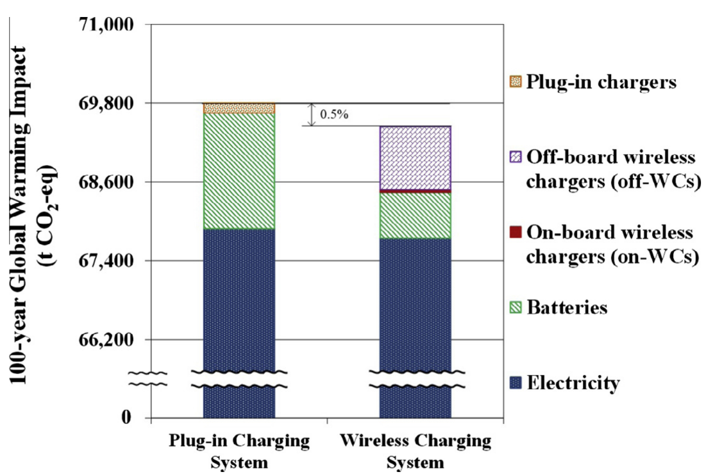
HIGHLIGHTS

- Compared life cycle energy and GHG emissions of wireless to plug-in charging.
- Modeled a transit bus system to compare both charging methods as a case study.
- Contrasted tradeoffs of infrastructure burdens with lightweighting benefits.
- The wireless battery can be downsized to 27–44% of a plug-in charged battery.
- Explored sensitivity of wireless charging efficiency & grid carbon intensity.

GRAPHICAL ABSTRACT

In this study, plug-in and wireless charging for an all-electric bus system are compared from the life cycle energy and greenhouse gas (GHG) emissions perspectives. The comparison of life cycle GHG emissions is shown in the graph below. The major differences between the two systems, including the charger, battery and use-phase electricity consumption, are modeled separately and compared aggregately. In the base case, the wireless charging system consumes 0.3% less energy and emits 0.5% less greenhouse gases than plug-in charging system in the total life cycle. To further improve the energy and environmental performance of the wireless charging system, key parameters including grid carbon intensity and wireless charging efficiency are analyzed and discussed in this paper.



ARTICLE INFO

Article history:
Received 25 August 2014
Received in revised form 6 February 2015
Accepted 8 February 2015

Keywords:
Wireless charging

ABSTRACT

Wireless charging, as opposed to plug-in charging, is an alternative charging method for electric vehicles (EVs) with rechargeable batteries and can be applicable to EVs with fixed routes, such as transit buses. This study adds to the current research of EV wireless charging by utilizing the Life Cycle Assessment (LCA) to provide a comprehensive framework for comparing the life cycle energy demand and greenhouse gas emissions associated with a stationary wireless charging all-electric bus system to a plug-in charging all-electric bus system. Life cycle inventory analysis of both plug-in and wireless charging hardware was conducted, and battery downsizing, vehicle lightweighting and use-phase energy consumption

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http://dx.doi.org/10.1016/j.apenergy.2015.02.031

Plug-in charging
Life cycle assessment
Vehicle lightweighting
Energy
Greenhouse gases

were modeled. A bus system in Ann Arbor and Ypsilanti area in Michigan is used as the basis for bus system modeling. Results show that the wirelessly charged battery can be downsized to 27–44% of a plug-in charged battery. The associated reduction of 12–16% in bus weight for the wireless buses can induce a reduction of 5.4–7.0% in battery-to-wheel energy consumption. In the base case, the wireless charging system consumes 0.3% less energy and emits 0.5% less greenhouse gases than the plug-in charging system in the total life cycle. To further improve the energy and environmental performance of a wireless charging electric bus system, it is important to focus on key parameters including carbon intensity of the electric grid and wireless charging efficiency. If the wireless charging efficiency is improved to the same level as the assumed plug-in charging efficiency (90%), the difference of life cycle greenhouse gas emissions between the two systems can increase to 6.3%.

1. Introduction

The transportation sector is responsible for 27% of U.S. greenhouse gas (GHG) emissions [1] and 28% of total U.S. energy use [2]. Vehicle electrification through electric vehicles (EVs) with rechargeable batteries has the potential to significantly reduce the GHG emissions compared to a fleet of internal combustion engine vehicles (ICEVs) [3]. Conventional EVs are charged through plug-in chargers, but these EVs face challenges including (1) heavy battery packs, (2) high battery costs, and (3) the inconvenience and time requirements for charging. Heavy battery pack is a critical challenge for further improving vehicle fuel economy, especially for all-electric buses that have large batteries. The battery pack can comprise about 26% of the weight of bus, considering the example of a long-range all-electric bus manufactured by BYD Auto Company which has a 324 kW h lithium iron phosphate (LFP) battery (assuming 88 Wh/kg battery pack) and curb weight of 14 t [4,5]. Due to the large size and the high price of lithium material, the LFP battery cost can be as high as 39% of the total cost of a long-range all-electric bus [4,6].

An alternative charging method, the EV wireless charging, an application of the Wireless Power Transfer (WPT) technology, may overcome the problems of plug-in charging. The WPT technology can be traced back to a century ago when Nicola Tesla introduced near-field coupling of two loop resonators based on magnetic resonance [7,8]. With WPT technology, the EV can be charged without a cable and connector. Through the magnetic field between two coil plates, one loaded on the bottom of the vehicle and the other embedded in pavement, the electric energy can be transferred wirelessly. Wireless charging can be classified as stationary or dynamic charging [9]. Stationary wireless charging equipment can be utilized in a garage, parking lot or bus stop. For dynamic charging, the vehicle can be charged in motion through multiple sets of coils and accessories embedded along the road. The charging efficiency of more than 80% has been reported for both stationary and dynamic charging [9–13]. Currently, wireless charging has been mostly demonstrated on vehicles with fixed routes, such as public transit buses [14].

Life Cycle Assessment (LCA) is the methodology to evaluate the potential environmental impacts associated with the total life cycle of a product or system, which encompasses material production, manufacturing, use and retirement stages [15]. LCA can help researchers better understand the wireless charging EV system from energy and environmental perspectives. Life cycle energy demand and GHG emissions are two metrics for evaluation in this study.

Wireless charging provides frequent charging opportunities at transit centers and major bus stops during bus operation hours. This can lead to battery downsizing, which results in vehicle lightweighting and fuel economy improvement, compared with plug-in charging. Associated benefits may include reduced energy consumption and emissions in battery production and potential reduction in use-phase electricity consumption for a pure electric vehicle. However, the wireless charging infrastructure can create additional energy and environmental burdens. Thus, it is meaningful to analyze the tradeoffs and inform future development of wireless charging bus systems.

This paper compares plug-in and stationary wireless charging from a life cycle perspective, based on an existing transit bus system to evaluate the energy consumption and GHG emissions. Although there is significant ongoing research into the engineering side of EV wireless charging [10,13,16–19], research examining life cycle energy and environmental implications is not well established. This study adds to the current development of EV wireless charging by utilizing LCA methods to model the plug-in and wireless chargers, battery downsizing and use-phase lightweighting benefits. In addition, this study highlights key parameters that greatly influence the energy and GHG emissions of a wireless charging bus system.

2. Method

2.1. Goal and scope

The goal of this LCA study is to compare two charging scenarios for an all-electric bus system, plug-in charging and stationary wireless charging, in terms of Cumulative Energy Demand (CED, TJ) [20,21] and 100-year Global Warming Impact (GWI, t CO_2-eq) [22]. CED represents total primary energy requirements of both renewable and non-renewable sources, including fossil, nuclear, biomass, wind, solar, geothermal energy and hydropower. This study models the major differences between the two systems using a process-based LCA approach in order to quantify the burdens associated with each stage of the life cycle, including the material extraction, production and manufacturing burden of chargers and batteries, as well as the use-phase energy consumption. The end-of-life stage is excluded due to lack of data. It is assumed that the buses in each charging scenario are all-electric and made with identical components, except for battery and charger. So the materials and manufacturing of the bus shell and other accessories are not modeled. Stationary wireless charging is considered as the wireless charging method in our model.

An existing transit bus system serving the Ann Arbor and Ypsilanti area in Michigan, USA, called TheRide [23], is used as the basis for our bus system simulation. The total numbers of routes, buses and bus stops for the model are adapted from the current bus system. Only regular transit routes are considered. Altogether sixty-seven buses and twenty-one routes are modeled. The adapted bus system map and the modeling parameters can be found in the Supporting Information (Fig. S1, Table S1 and Table S2). The twenty-one routes are classified into three groups for simplicity: the blue (Ann Arbor city routes), red (Ann Arbor–Ypsilanti intercity routes) and green routes (Ypsilanti city routes), based on their service areas. Thirteen blue routes operate in Ann Arbor downtown and its suburban area, four red routes operate between Ann Arbor and Ypsilanti down-