

Plug-in vs. Wireless Charging: Life Cycle Energy and Greenhouse Gas Emission Analysis of an Electric Bus System

by

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Preface

This thesis is a detailed comparative analysis of the energy and greenhouse gas emissions of two electric vehicle charging technologies: the emerging wireless charging and conventional wired charging. This work first compares the production burdens and component differences between these two chargers and conducted a life cycle inventory analysis. The transit bus system operating in Ann Arbor, Michigan is used as the basis for a case study. The bus fleet is assumed to be all-electric and two charging scenarios are compared: (1) the plug-in charging scenario and (2) the wireless charging scenario. Finally, the thesis highlights the tradeoffs of lightweighting energy savings versus the charging losses in the use phase and quantifies the life cycle energy and environmental burdens.

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List of Abbreviations

CED: Cumulative Energy Demand

DTD (km): daily travel distance

ECR: energy consumption rate (kWh/km)

EV: electric vehicle

GHGs: Greenhouse Gases

GWI: Global Warming Impact

ICEV: internal combustion engine vehicle

LCA: Life Cycle Assessment

LFP: lithium iron phosphate

LMO: LiMn_2O_4

NOR: No Operation Region

off-WC: off-board portion of the wireless charger (installed on the ground)

on-WC: on-board portion of the wireless charger

OR: Operating Region

OSM: Overcharge Safety Margin

PC: plug-in charger

RSC: Reserved Storage Capacity

SOC: state of charge (%)

SOCR (%): the percentage of the *OR* (kWh) relative to the whole capacity of a new battery

(kWh)

WPT: Wireless Power Transfer

Abstract

Vehicle electrification through implementation of electric vehicles (EVs) with rechargeable batteries has the potential to significantly reduce the greenhouse gas emissions compared to a fleet of internal combustion engine vehicles (ICEVs). 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 thesis 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 are 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 is comparable to the plug-in charging system in terms of life cycle energy consumption and greenhouse gas emissions. 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 wireless charging system would emit 6.3% less greenhouse gases than the plug-in charging system.

Keywords: Wireless charging; Plug-in charging; Life cycle assessment; Vehicle lightweighting; Energy; Greenhouse gases

1. Introduction

1.1 Motivation

The transportation sector is responsible for 27% of U.S. greenhouse gas (GHG) emissions (U.S. EPA 2013) and 28% of total U.S. energy use (Davis et al. 2013). 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) (Hawkins et al. 2012). 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 kWh lithium iron phosphate (LFP) battery (assuming 88 Wh/kg battery pack) and curb weight of 14 t (BYD Auto Company 2013; Majeau-Bettez et al. 2011). 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 (BYD Auto Company 2013; Reikes 2014).

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 (Tesla 1905, 1914). 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 (Suh and Kim 2013). 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 (Suh and Kim 2013; Nguyen et al. 2014; Wu et al. 2011; Onar et al. 2013; Wu et al. 2012). Currently, wireless charging has been mostly demonstrated on vehicles with fixed routes, such as public transit buses (Suh and Gu 2011).

1.2 Objective

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.

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 (ISO 2006). 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.

This research aims to compare 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 (Ning et al. 2013; Lee et al. 2013; Li and Mi 2014; Wu et al. 2012; Budhia et al. 2013; Nguyen et al. 2014), 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.

This research has been published in the journal *Applied Energy* 146 (2015) 11–19, entitled “Plug-in vs. Wireless Charging: Life Cycle Energy and Greenhouse Gas Emissions for an Electric Bus System” (Bi et al. 2015).

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) (Hischier et al. 2010; PRé Consultants 2014) and 100-year Global Warming Impact (GWI, t CO₂-eq) (IPCC 2013). 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 this study.

2.2 Bus System Simulation

An existing transit bus system serving the Ann Arbor and Ypsilanti area in Michigan, USA, called TheRide (Ann Arbor Area Transportation Authority 2014), 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 is shown in Figure 1. 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 downtowns and their suburban areas, and four green routes operate in Ypsilanti downtown and its suburban area. Routes in the same group are assumed to have the same parameters, such as travel distance in each loop. It is assumed that about one quarter of bus operation time (from the beginning to end of daily duty) is dwell time at bus stops and transit centers, which is based on a study for a typical route in the TheRide bus system (Batterman et al. 2012). Route details and charger deployment information are summarized in Table 1 and Table 2. Please note that the plug-in chargers and wireless

chargers do not exist in reality currently and it is only a hypothesized plan of charger deployment.

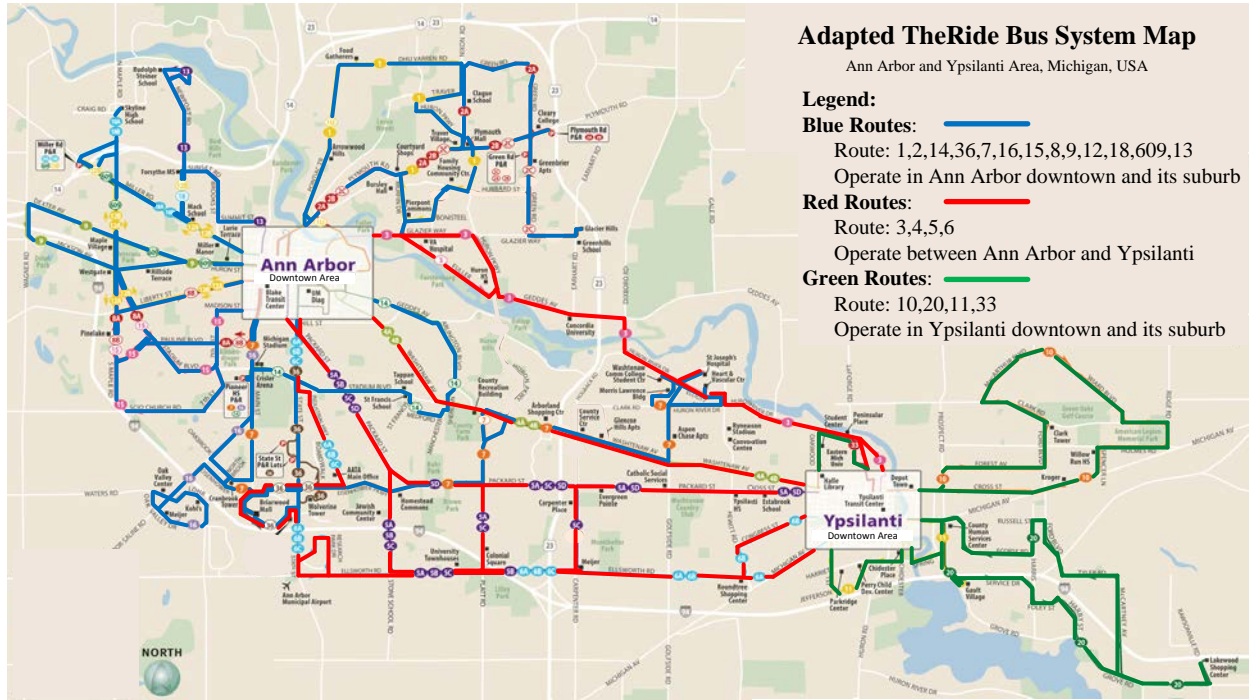


Figure 1. Adapted TheRide bus system map, based on the bus system map from the Ann Arbor Area Transportation Authority.

Table 1. Bus system simulation: route details.

| Route Group | Route Details (Downtown + Suburb) | | | | | | | Suburb Details | | |
|--------------|-----------------------------------|------------|------------|----------------|------------------|-----------|-------------|---------------------------------|----------------------------------|----------------------|
| | How many routes | miles/loop | stops/loop | loops/week day | loops/Sat or Sun | hour/loop | buses/route | stops (both directions) / route | off-WCs (both directions)/ route | charging time (hour) |
| Blue | 13 | 9 (14km) | 42 | 13 | 7 | 1 | 3 | 28 | 8 | 0.008 |
| Red | 4 | 13 (21km) | 64 | 9 | 5 | 1.5 | 4 | 32 | 10 | 0.008 |
| Green | 4 | 9 (14km) | 42 | 13 | 7 | 1 | 3 | 28 | 8 | 0.008 |

Notes: Take the blue routes as an example. There are 13 blue routes, and each route has 3 buses. Each bus travels 9 miles (14 km) in each loop (round trip). One loop has 42 stops deployed and takes 1 hour. Each bus travels 13 loops on weekday and 7 loops on Saturday or Sunday. Of the 42 stops in each loop, 28 stops are in suburb and 8 stops out of those 28 stops are equipped with off-board wireless chargers (off-WCs). In suburb, the bus charges 0.008 hour at each off-WC.

Table 2. Bus system simulation: details of downtown, transit centers and parking lot.

| Downtown Details | Ann Arbor downtown | | Ypsilanti downtown | | |
|---------------------------------------|--------------------|------|--------------------|-------|-----|
| Number of bus stops | 160 | | 80 | | |
| Number of off-WCs | 80 | | 40 | | |
| Time of charging/charging stop (hour) | 0.01 | | 0.01 | | |
| Transit Center Details | | | | | |
| | BTC | CCTC | Hospital | Union | YTC |
| Number of off-WCs | 10 | 4 | 4 | 2 | 6 |
| Time of charging (hour) | 0.1 | 0.01 | 0.01 | 0.01 | 0.1 |
| Parking Lot Details | | | | | |
| Number of plug-in chargers | 67 | | | | |
| Number of off-WCs | 67 | | | | |

Notes: BTC = Blake Transit Center; CCTC = Central Campus Transit Center; YTC = Ypsilanti Transit Center.

Two charging scenarios of this bus system are modeled: 1) plug-in charging scenario and 2) stationary wireless charging scenario. For the plug-in charging scenario, the plug-in chargers are assumed to be only located at the parking lot for buses to charge overnight. The wireless charging scenario is constructed, assuming the wireless charging infrastructure is deployed across the bus service area located at those popular bus stops where the buses stop more frequently, all of the transit centers, as well as the overnight parking lot. It is expected that the downtown areas have greater charging infrastructure density than the suburban areas. A longer charge time is assumed at each transit center (e.g. 6 minutes) and key bus stop (e.g. 36 seconds per charging stop) in downtown than the suburban areas (e.g. 29 seconds per charging stop) because the ridership is assumed to be lower in suburb. The result is that about one quarter of the operation time is dwell time for wireless charging.

The functional unit for this study is providing transit services for Ann Arbor and Ypsilanti area for 12 years with 67 buses, equivalent to 48,034,407 vehicle kilometers in total (on average 716,932 vehicle kilometers per bus). The 12-year horizon is often used as an

estimate for bus life in transit agency reports, such as U.S. Federal Transit Administration (Clark et al. 2007), and used by a previous LCA study modeling electric public transportation buses (Cooney et al. 2013).

2.3 Data Sources and Model Description

2.3.1 Production Phase: Inventory Analysis of Chargers

Figure 2 depicts and compares the wireless charger (WC) and plug-in charger (PC) components. The charger components are modeled based on a 6 kW wireless charger currently under development in Professor Chris Mi's laboratory at the University of Michigan-Dearborn (Nguyen et al. 2014). The plug and cable of a plug-in charger are modeled based on a 2013 Chevrolet Volt charger. The mass of charger components was measured and then modeled using the LCA software SimaPro 8 (Goedkoop et al. 2013). To transmit 60 kW of power to charge the bus, it is assumed that 10 sets of 6 kW chargers are installed and the material burden is scaled up proportionally. A 60 kW wireless charger is separated into on-board portion (on-WC) and off-board portion, i.e., those installed on the ground (off-WC). In total, there are 67 buses operating on 21 routes, with 67 batteries and 67 on-WCs installed on buses. A total of 428 off-WCs (60 kW each) located at major bus stops, transit centers and the parking lot are modeled. Both wireless and plug-in chargers are assumed to last 24 years, thus half of the burdens are allocated to the future and not considered in our 12-year horizon.

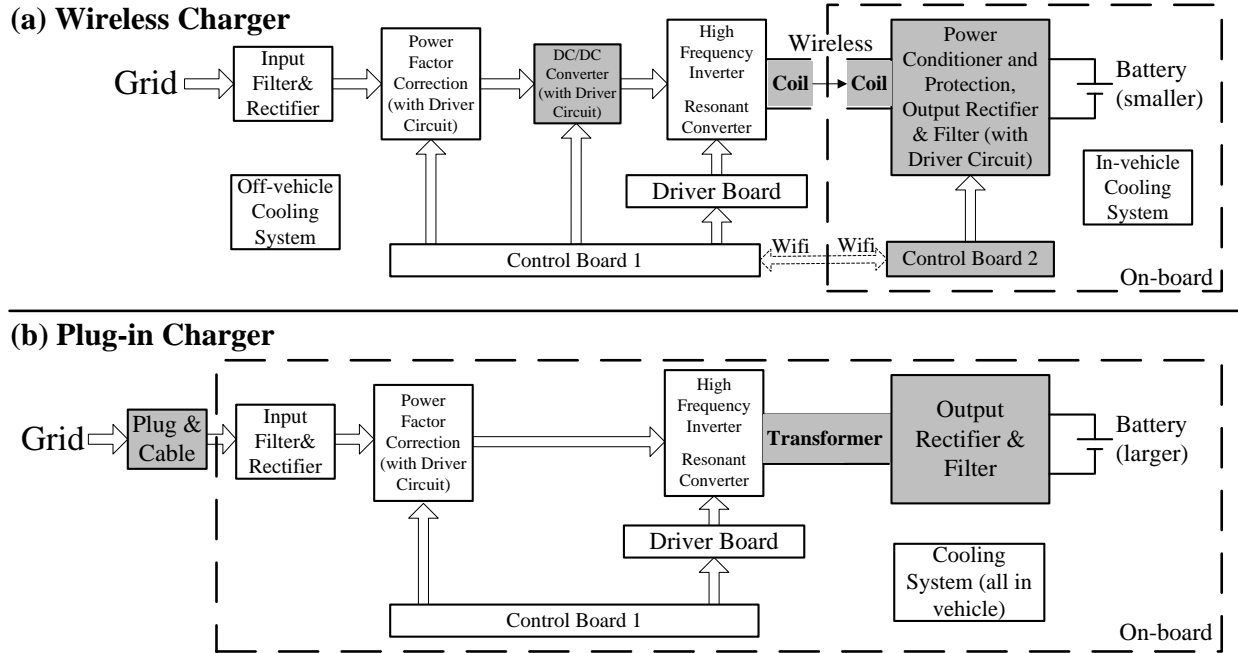


Figure 2. Comparison of (a) wireless charger and (b) plug-in charger for electric vehicles. Component difference is marked in grey. On-board portion of each charger is in the dashed box, and the rest is outside the vehicle.

The charger components of a 6 kW on-board portion of wireless charger (on-WC), off-board portion of wireless charger (off-WC) and plug-in charger (PC) are summarized in Table 3. For the details on the mass of each of the components, please refer to the Appendix. Note that the mass and quantity data shown in the inventory tables are on the basis of 6 kW, not 60 kW. To transmit 60 kW of power to charge the bus, it is assumed that 10 sets of 6 kW chargers are installed and the material burden is scaled up proportionally.

Table 3. Summary of charger components.

| Charger Type | Name | Quantity | Unit | |
|---|---|----------------|--------|---|
| On-board portion of 6 kW wireless charger (on-WC) | <i>Main components:</i> | | | |
| | Coil Plate | 1 | piece | |
| | Power Conditioner and Protection, Output Rectifier & Filter (with Driver Circuit) | 1 | piece | |
| | In-vehicle Cooling System | 1 | piece | |
| | Control Board 2 | 1 | piece | |
| | <i>Accessories:</i> | | | |
| | Aluminum sheet | 1701 | g | |
| Off-board portion of 6 kW wireless charger (off-WC) | <i>Main components:</i> | | | |
| | Input Filter & Rectifier | 1 | piece | |
| | Power Factor Correction (with Driver Circuit) | 1 | piece | |
| | DC/DC Converter (with Driver Circuit) | 1 | piece | |
| | High Frequency Inverter/Resonant Converter | 1 | piece | |
| | Coil Plate | 1 | piece | |
| | Off-vehicle Cooling System | 1 | piece | |
| | Control Board 1 | 1 | piece | |
| | Driver Board | 1 | piece | |
| | <i>Accessories:</i> | | | |
| | | Aluminum Sheet | 1701 | g |
| | | Steel Case | 5000 | g |
| | Extra Cables Connecting the Grid | 5 | meters | |
| | LCD Flat Screen | 1 | piece | |
| 6 kW Plug-in charger (PC) | <i>Main components:</i> | | | |
| | Plug & Cable | 1 | piece | |
| | Input Filter & Rectifier | 1 | piece | |
| | Power Factor Correction (with Driver Circuit) | 1 | piece | |
| | High Frequency Inverter/Resonant Converter | 1 | piece | |
| | Transformer | 1 | piece | |
| | Output Rectifier & Filter | 1 | piece | |
| | Control Board 1 | 1 | piece | |
| | Driver Board | 1 | piece | |
| | Cooling System (all in vehicle) | 1 | piece | |
| <i>Accessories:</i> | | | | |
| | LCD Flat Screen | 1 | piece | |

2.3.2 Production Phase: Battery Downsizing and Lightweighting Calculation

The wireless battery can be downsized due to multiple charges during daily operation, which leads to a reduction of bus weight. The battery downsizing and lightweighting calculation for the wireless charging scenario relative to the plug-in charging scenario is illustrated in Figure 3. The capacity of a plug-in charged battery can be divided into four regions: Overcharge Safety Margin (OSM), Operating Region (*OR*), Reserved Storage Capacity (RSC) and No Operation Region (NOR) (Marano et al. 2009). The electricity amount represented by *OR* (kWh) indicates the minimum battery energy requirement at the start of each day for a bus to fulfill its daily duty. The State of Charge Range (*SOCR*, %) is defined as the percentage of the *OR* (kWh) relative to the whole capacity of a new battery (kWh). The RSC serves two functions: as an energy reserve for unexpected energy demand during daily operation, as well as battery capacity fade in the future. The electricity in a plug-in charged battery depletes at an energy consumption rate (ECR) of k_1 (kWh/km).

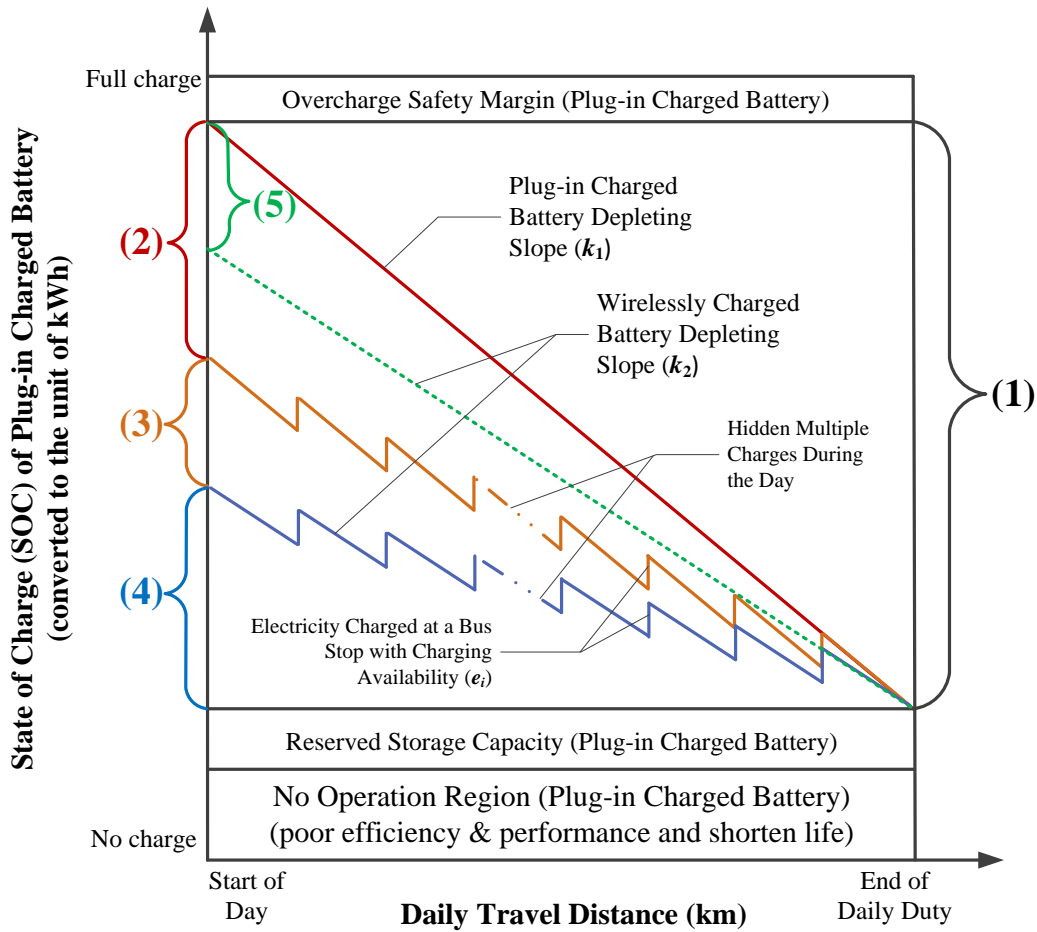


Figure 3. Battery downsizing calculation. Note: The calculation starts from a plug-in charged battery to quantify the minimum electricity needed at start of day for a wirelessly charged battery. (1) Operating Region (kWh) of plug-in charged battery; (2) Primary capacity reduction (kWh) due to wireless charging availability; (3) Secondary capacity reduction (kWh) due to fuel economy improvement; (4) Minimum electricity needed (kWh) at start of day for a wirelessly charged battery (not yet including its own Overcharge Safety Margin, Reserved Storage Capacity and No Operation Region); (5) Daily energy saving (battery-to-wheel) due to wireless charging (kWh).

The plug-in charged battery can first be downsized due to wireless charging availability at charging stations. Since the bus can charge at each of those stations, it is reasonable for the bus to carry a smaller battery to travel the same distance than the plug-in charging scenario, which

results in the primary capacity reduction. The battery capacity after primary capacity reduction (C_1 , kWh) can be calculated from Eq. (1) and Eq. (2), where E_1 (kWh) is the total amount of electricity charged during operation hours, e_i (kWh) is the amount of electricity charged at charging stop i , N is the total number of stops where the bus stops for charging during the operation, η (%) is the average charging efficiency, P (kW) is the charging power and T (hour) is the total amount of charging time at charging stops during the day. The *SOCR* for the wirelessly charged battery is the same as that of the plug-in charged battery (60%). The battery weight (kg) can be calculated by dividing the battery capacity (kWh) by the battery specific energy (0.13 kWh per kg of Li-ion battery) (Dunn et al. 2012a). Therefore, the percentage of vehicle mass reduction due to primary downsizing can be determined, relative to a bus of 15 t, comprising the assumed curb weight of 14 t (BYD Auto Company 2013) and the constant average weight of 1 t for driver, passengers and cargo (U.S. Department of Transportation 2013). Fluctuation in ridership is not considered.

$$E_1 = \sum_{i=1}^N e_i = \eta PT \quad (1)$$

$$C_1 = \frac{OR - E_1}{SOCR} \quad (2)$$

Vehicle lightweighting due to the primary battery downsizing will improve the fuel economy, which means the electricity in a wirelessly charged battery will deplete more slowly than a plug-in charged battery ($|k_2| < |k_1|$). The ECR of a wirelessly charged bus, k_2 (kWh/km), can be determined by the lightweighting correlation. For a sedan, 10% vehicle mass reduction results in a 6-8% use-phase energy reduction for an Internal Combustion Engine Vehicle (ICEV) and 4-7% for many EV types and models (Kim 2014; Kim and Wallington 2013). The EVs are

less sensitive to the mass-induced energy consumption reduction due to the regenerative braking and higher powertrain efficiency (Lewis et al. 2014), so the percentage change in energy consumption of EV is slightly lower than that of ICEV. For a bus, 10% vehicle mass reduction results in about 5% energy reduction for a conventional bus in the Autonomie model (Argonne National Laboratory 2009). However, the lightweighting correlation of an all-electric bus is not available. The percentage change in energy consumption of an electric bus is assumed to be 10% lower than that of a conventional bus, thus 4.5% energy reduction per 10% vehicle mass reduction for a pure electric bus is assumed for the baseline case. This assumption is further analyzed in the sensitivity analysis section. A lighter bus will consume less energy to cover its daily travel distance, which results in the secondary downsizing of the battery. The energy saving (E_2 , kWh) related to secondary downsizing can be calculated from Eq. (3), where DTD (km) is the daily travel distance.

$$E_2 = |k_1 - k_2| DTD \quad (3)$$

Deducting primary (E_1 , kWh) and secondary (E_2 , kWh) capacity reductions from the OR (kWh) of the plug-in charged battery, the minimum electricity needed at the start of day for a wirelessly charged battery can be quantified. Dividing this value by the $SOCR$ (60%), the capacity of a wirelessly charged battery (C_2 , kWh), including the OSM, RSC and NOR, can be quantified. Dividing the battery capacity C_2 (kWh) by the battery specific energy (kWh/kg), the final weight (kg) of the wirelessly charged battery can be determined. The fuel economy can be further improved, which will further downsize the battery. Further iterations of fuel economy and battery downsizing are smaller compared to primary and secondary effects, and so are ignored in this model, which results in a conservative estimate for the wirelessly charged battery.

The lithium-ion battery with LiMn_2O_4 (LMO) cathode material is used to model both plug-in and wirelessly charged batteries. LMO was chosen because of its well established life cycle inventory, lower cost and abundance of manganese in nature (Dunn et al. 2012b; Notter et al. 2010). The cradle-to-gate energy and GHG emissions are modeled as 75 MJ/kg battery and 5.1 kg $\text{CO}_2\text{-eq/kg}$ battery, according to a process LCA study of LMO batteries for electric vehicles that is specific to the United States (Dunn et al. 2012a). When the OSM is 5%, RSC is 15% and NOR is 20%, the *SOCR* is 60% with the state of charge (SOC, %) assumed to swing around 35% to 95% for both plug-in and wirelessly charged batteries (Marano et al. 2009). The cycle life of battery is assumed to be 3000 cycles, based on the general performance of lithium-ion batteries (Xu et al. 2013; Cooney et al. 2013; Majeau-Bettez et al. 2011). For a wirelessly charged battery, the multiple wireless charges during daily operation, however, are assumed to have negligible effect on the battery life. Therefore, for both plug-in and wirelessly charged batteries, energy depleting from 95% to 35% SOC during the operation and charging back to 95% overnight are assumed to represent one cycle.

2.3.3 Use Phase: Electricity Consumption

The life cycle energy and GHG emission intensities of electricity are from U.S. Life Cycle Inventory's (USLCI) low-voltage grid average data for the United States. The Cumulative Energy Demand (CED) is 10.9 MJ/kWh of electricity delivered and the 100-year Global Warming Impact (GWI) is 0.784 kg $\text{CO}_2\text{-eq/kWh}$ of electricity delivered (National Renewable Energy Laboratory 2004). In the base case, the same CED and GWI intensities for the electric grid are used for both nighttime and daytime charging. The variation in electricity carbon intensity between day and night is further explored in a sensitivity analysis.

The life cycle energy demand is calculated based on a series of energy transmission and conversion efficiencies illustrated in Figure 4. Energy is converted and transmitted from resource energy to wheels, with energy losses at each step. At the first step, from resource energy to bus stop, there assumes to be an efficiency of 33%, including extraction, transport, generation and delivery through electric grid, calculated from 10.9 MJ/kWh mentioned in the previous paragraph (National Renewable Energy Laboratory 2004). The plug-in charger efficiency for an electric bus is assumed to be 90% (Cooney et al. 2013). The wireless charging efficiency is assumed to be 85% (Suh and Kim 2013; Nguyen et al. 2014; Wu et al. 2011; Onar et al. 2013). The wireless charging efficiency includes the energy losses due to potential misalignment of on-board and off-board charging pads and the charger design itself. The lithium-ion battery charge/discharge efficiency is assumed to be 90% (Majeau-Bettez et al. 2011; Zackrisson et al. 2010). The battery-to-wheel energy consumption rate of the plug-in charged bus (k_1) is assumed to be 1.46 kWh/km (=2.35 kWh/mile), estimated from several trial and demo operations of the BYD all-electric bus (BYD Auto Company 2013). The ECR of the wirelessly charged bus (k_2 , kWh/km) can be quantified by the battery downsizing calculation. Finally, with the lifetime kilometers traveled, the life cycle energy demand can be quantified.

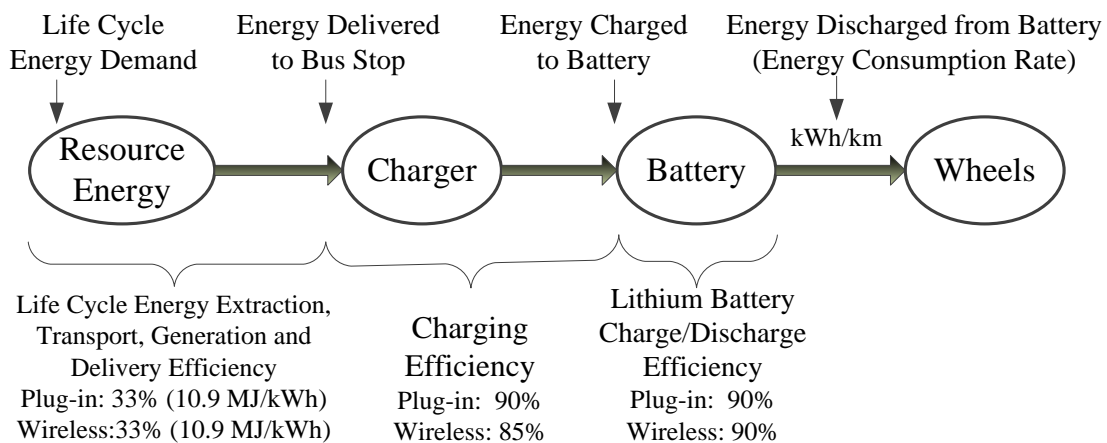


Figure 4. Life cycle energy transmission and conversion cascade.

Finally, the model inputs are summarized in Table 4.

Table 4. Summary of model inputs.

| Model input name | Value | Unit | References |
|--|--------------|-------------|--|
| Life of bus | 12 | years | (Cooney et al. 2013; Clark et al. 2007) |
| Life of plug-in charger | 24 | years | Model parameter |
| Life of wireless charger | 24 | years | Model parameter |
| Days of operation/year | 365 | days/year | Model parameter |
| Curb weight of plug-in charged bus | 14,000 | kg | (BYD Auto Company 2013) |
| Average weight of passengers, driver and cargo | 1,000 | kg | (U.S. Department of Transportation 2013) |
| Battery-to-wheel energy consumption rate of plug-in bus | 1.46 | kWh/km | (BYD Auto Company 2013) |
| SOC Range (<i>SOCR</i>) | 60% | percent | (Marano et al. 2009) |
| Battery specific energy | 0.13 | kWh/kg | (Dunn et al. 2012a) |
| Plug-in charging efficiency | 90% | percent | (Cooney et al. 2013) |
| Wireless charging efficiency | 85% | percent | (Suh and Kim 2013; Nguyen et al. 2014; Wu et al. 2011; Onar et al. 2013; Wu et al. 2012) |
| Base charging power | 6 | kW | Charger from Prof. Chris Mi's lab in UM Dearborn |
| Plug-in charging power | 60 | kW | (BYD Auto Company 2013) |
| Wireless charging power | 60 | kW | Model parameter |
| Lightweighting correlation: % energy reduction/10% electric bus mass reduction | 4.5% | percent | Model parameter |
| Battery cycle life | 3000 | cycles | (Xu et al. 2013; Cooney et al. 2013; Majeau-Bettez et al. 2011) |
| Plug-in battery: cycle/day | 1 | cycle/day | Model parameter |
| Wireless battery: cycle/day | 1 | cycle/day | Model parameter |
| Battery charge/discharge efficiency | 90% | percent | (Majeau-Bettez et al. 2011; Zackrisson et al. 2010) |
| Extra off-WCs deployed to avoid loss of charging time due to missing charging stations | 10% | percent | Model parameter |

3. Results

3.1 Cumulative Energy Demand and Global Warming Impact

The CED and GWI results for the base case are shown in Figure 5 (a) and (b), respectively. The graphs show the life cycle energy demand and GHG emissions of the whole bus system across the service area, either with plug-in charging or wireless charging, within a

12-year period. The plug-in and wireless charging systems are comparable from the perspectives of CED and GWI. Wireless charging system consumes 0.3% less energy and emits 0.5% less GHGs than plug-in charging system in the total life cycle. The tradeoffs of increased energy and GHG burdens from wireless charging infrastructure and benefits from battery downsizing are clearly illustrated.

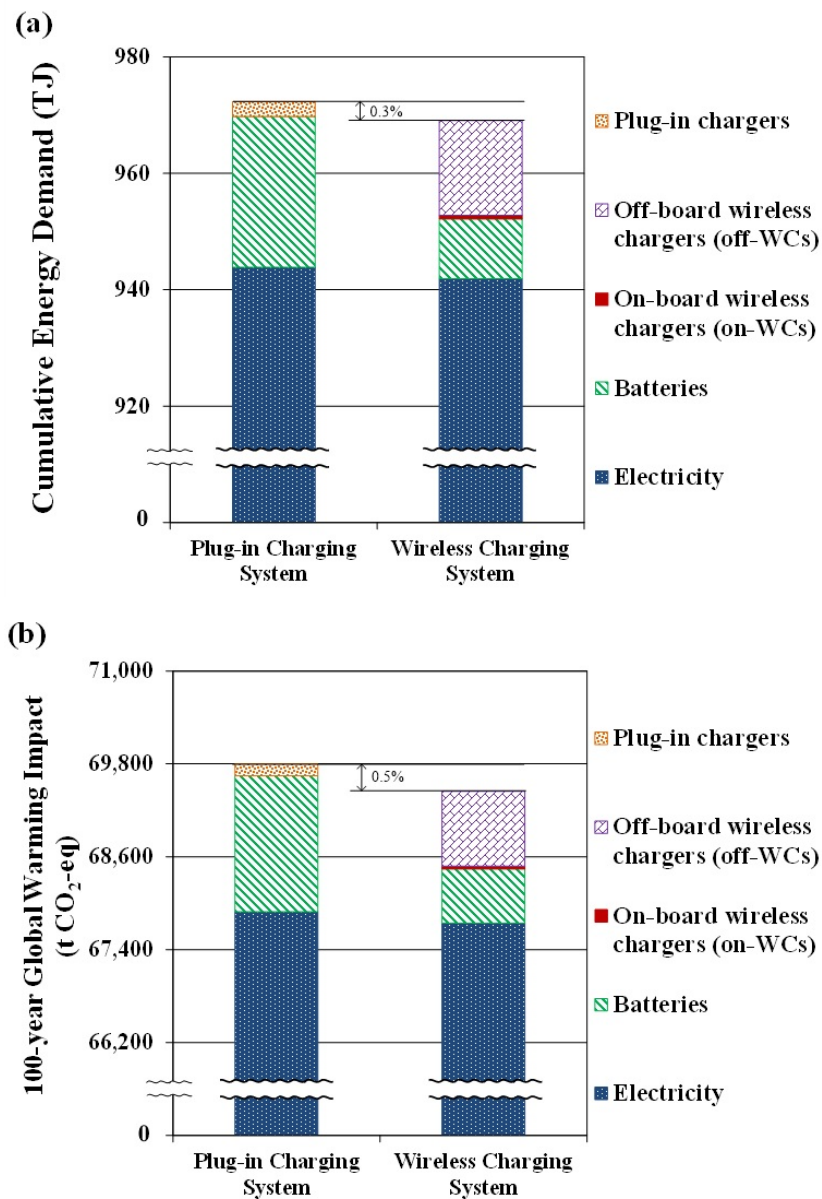


Figure 5. (a) Cumulative Energy Demand and (b) 100-year Global Warming Impact of plug-in and wireless charging electric bus systems.

For charger production, one 60 kW plug-in charger consumes 0.075 TJ life cycle energy and emits life cycle GHGs of 4.56 t CO₂-eq. One 60 kW on-WC consumes 0.018 TJ and emits 1.03 t CO₂-eq and one 60 kW off-WC consumes 0.076 TJ and emits 4.53 t CO₂-eq. Based on the assumptions of the bus system, there are 428 off-WCs and 67 on-WCs deployed for the wireless charging system, while the plug-in charging system only requires 67 plug-in chargers for charging each bus overnight. As a result, the energy and GHG emissions from all chargers (on-WCs and off-WCs) in the wireless charging scenario are respectively 6.7 and 6.6 times greater than from all plug-in chargers in the plug-in charging scenario.

The weights of both plug-in and wireless batteries as well as the corresponding ECRs are shown in Figure 6. It is assumed that each bus travels the same distance each weekday. Based on the daily energy requirement (kWh) and *SOCR* (%), the battery weight of a plug-in charged bus is quantified as 3,525 kg (458 kWh). For a wireless bus, the more charging is available during the day, the more the battery could be downsized. Results show that the buses in the red routes (Ann Arbor-Ypsilanti intercity routes) have potential to carry smaller batteries and have lower ECR, because they have longer charging time during operation than the blue and green routes. The battery can be downsized to 27% of the plug-in charged battery for the red routes, and 44% for the blue and green routes. Based on the cycle life of the battery, the batteries are replaced about every 8 years for both types of buses, so the energy and environmental burden of one and a half batteries is counted in the 12-year lifetime. As shown in Figure 4, after aggregating all the batteries in the whole bus system and taking into account the battery replacement, the energy demand and GHG emissions related to battery material production and manufacturing in the wireless charging system are about 40% of those in a plug-in charging system.

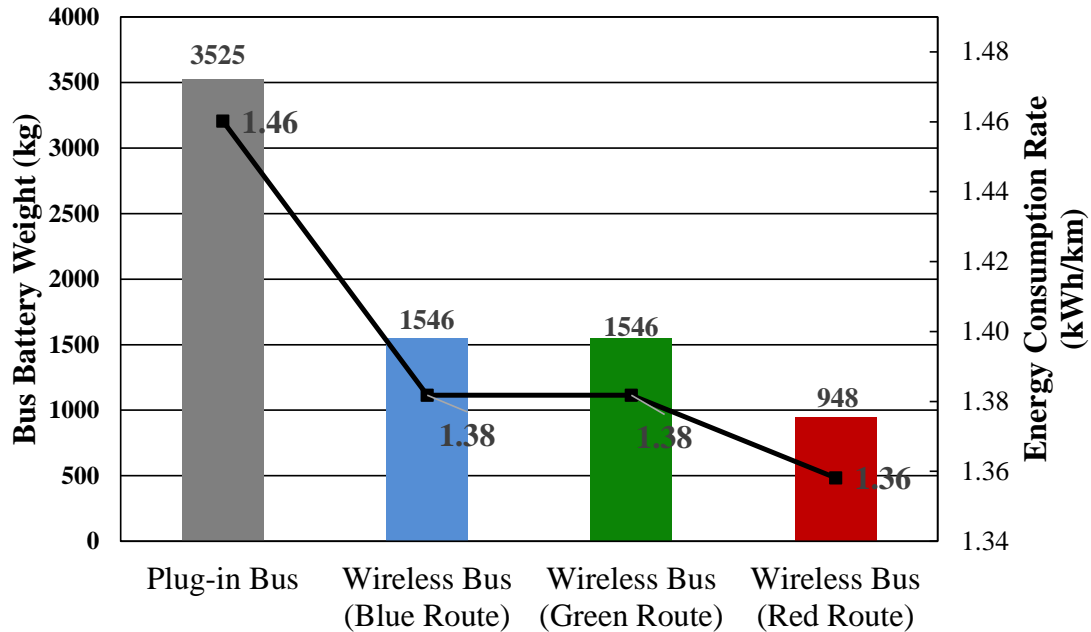


Figure 6. Battery weights and energy consumption rates for plug-in and wirelessly charged buses (the columns are in primary y-axis on the left and the line is in secondary y-axis on the right). Blue routes = Ann Arbor city routes; red routes = Ann Arbor-Ypsilanti intercity routes; green routes = Ypsilanti city routes.

The use-phase electricity consumption dominates the life cycle energy demand and GHG emissions, accounting for about 97-98% of CED and GWI. The lightweighting benefit of wireless charging can be offset by its current relatively poorer charging efficiency, so there is not much difference in electricity consumption between the plug-in and wireless charging systems from the perspectives of CED and GWI. A reduction of 12% to 16% in bus weight for the wireless buses induces a reduction of 5.4% to 7% in battery-to-wheel energy consumption rate. However, the wireless charging efficiency is assumed to be 85%, compared to 90% for a plug-in charger. Therefore, though the battery-to-wheel ECR (kWh/km) is smaller for a lightweight bus, the electricity charged to the bus will not necessarily be smaller and is highly dependent on the charging efficiency.

3.2 Sensitivity Analysis of Key Parameters

Results of sensitivity analysis are summarized in Figure 7. Of all the parameters tested, the results are most sensitive to the wireless charging efficiency and least sensitive to the wireless battery charge/discharge cycle per day.

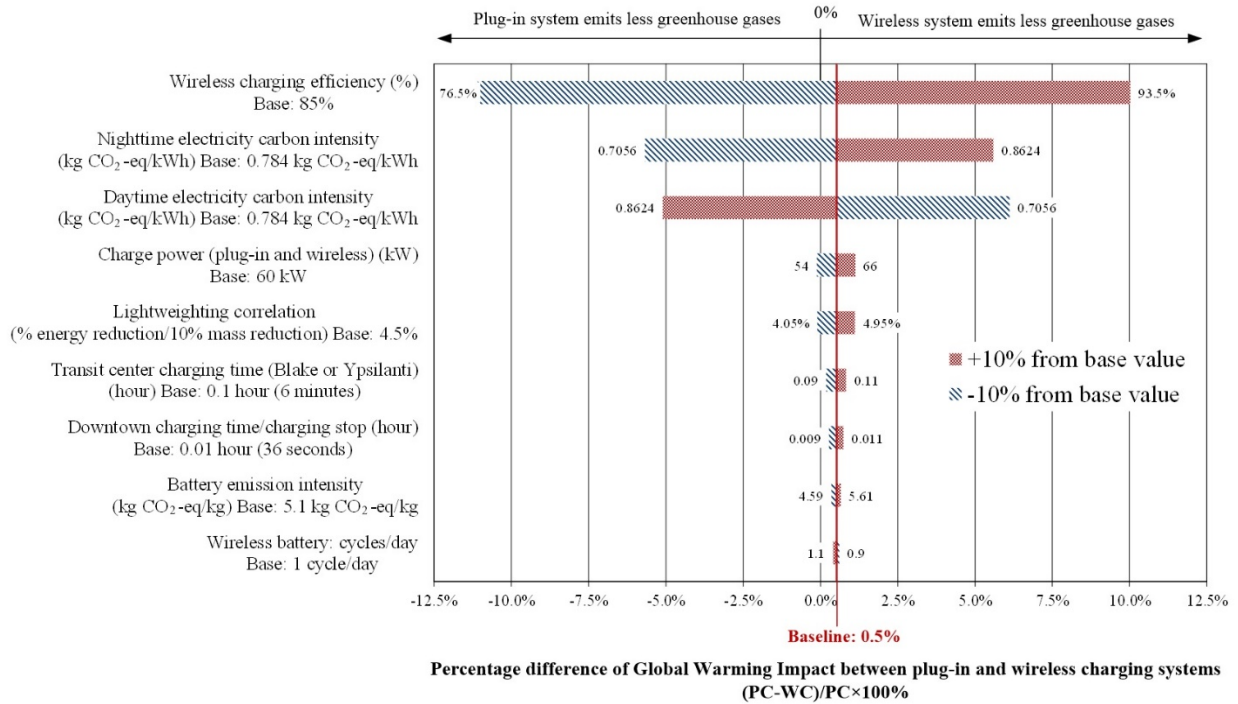


Figure 7. Sensitivity analysis of key parameters. Parameters are ranked according to sensitivity. (PC = greenhouse gas emissions from plug-in charging system; WC = greenhouse gas emissions from wireless charging system)

Improving wireless charging efficiency is a very effective way to improve the environmental performance of the wireless charging system from a GWI perspective. If it is improved to the same level as the assumed plug-in charging efficiency (90%), the life cycle GHG emissions difference between the two systems will be increased to 6.3%.

Results are also sensitive to the carbon intensities of electric generation during the day and night. Based on the model assumptions, the plug-in bus is only charged overnight, but for a wireless bus, about 58% of the use-phase electricity consumption is charged during operation and about 42% is charged overnight. The electricity carbon intensity is assumed to be 0.784 kg CO₂-eq/kWh regardless of day and night in the base case. However, due to the different electricity demand between day and night, the fuel profile used for generation changes, resulting in different grid carbon intensities between day and night. Thus, changes in grid carbon intensity are explored separately for day and night in the sensitivity analysis. If daytime electricity carbon intensity decreases by 10%, the wireless charging system emits 6.1% fewer GHGs than the plug-in charging system. Although the difference in life cycle GHG emissions between the two charging systems is sensitive to the difference of daytime and nighttime grid carbon intensities, it is insensitive to simultaneous increase or decrease in grid carbon intensity for both day and night. For example, in some states in the U.S. or some European countries, the grid carbon intensity may be as low as 300-400 g CO₂-eq/kWh or even lower due to more renewable energy integration (Doucette and McCulloch 2011; Cooney et al. 2013). If 0.3 kg CO₂-eq/kWh is used as both day and night grid carbon intensity instead of the U.S. average of 0.784 kg CO₂-eq/kWh, the difference in life cycle carbon emissions between the plug-in charging and wireless charging systems only increases from 0.5% to 0.9%. Therefore, it is the relative value of the difference in day and night grid carbon intensities rather than the absolute value of the overall level of grid carbon intensity that differentiates the life cycle GHG emissions of the two charging systems.

Parameters including charge power, charging time, life cycle carbon intensity associated with battery production and lightweighting correlation also affect the life cycle GHG emissions.

However, the results are less sensitive to these parameters compared with the wireless charging efficiency and electricity carbon intensity.

The wireless battery is charged and discharged more frequently than the plug-in battery, while *SOCR* is kept constant for both batteries (60%). With the same SOC window, frequent charge and discharge may have negative impact on battery life. However, the extent of the impact is not yet found in literature. The wireless battery may degrade more quickly and battery replacement may be more frequent. To analyze this impact, it is assumed that a plug-in battery has one charge and discharge cycle per day, while wireless battery may have an equivalent of more than one cycle per day, such as 1.1 cycles per day. However, the results are less sensitive to this parameter than other parameters.

The sensitivity analysis evaluates key input parameters by changing their values individually. If these parameters were changed simultaneously, the wireless charging system could emit considerably less GHG emissions than the plug-in charging system. For example, the wireless charging system would emit 18.6% less GHGs than the plug-in charging system when the following conditions are met simultaneously: 1) a wireless charging efficiency of 93.5%; 2) the daytime carbon intensity is 10% lower than nighttime; 3) a charging rate of 66 kW; 3) a lightweighting correlation of 4.95% fuel reduction per 10% vehicle mass reduction, 4) a 10% longer dwell time at charging stations in downtown and transit centers.

4. Discussion

Implementing wireless charging for electric buses or other EVs may pose challenges for the electric grid. On one hand, due to the convenience of wireless charging, EVs can be charged during the daytime when the grid faces peak load demand, which requires extra grid supply.

Thus, wireless charging during daytime may not help ease the peak load power burden of the grid. On the other hand, the life cycle GHG difference between the two systems depends on the fuel mix dispatch of generating assets. If daytime electricity carbon intensity decreases, the wireless charging system emits fewer GHGs than the plug-in charging system. Thus, considering the grid mix difference between day and night, there may be the potential for further reductions in life cycle GHG emissions for the wireless charging EV system.

The battery can be further downsized if more wireless charging infrastructure is implemented. Stationary wireless charging is modeled in this study, which shows a potential of downsizing the battery to about one-third the weight of a plug-in charged battery. If one percent of the buses' routes are covered by off-board wireless charging infrastructure, the battery can be reduced to less than one-fifth the size of the one in a conventional pure electric bus, according to a real world test in Gumi City in Korea (Thornton 2014). Additionally, the battery SOC swings from 40-60% for dynamic charging (i.e. charging while in motion) (Suh and Gu 2011), instead of 35-95% as modeled in this study for stationary charging. Although the battery can be further downsized, the battery cannot be too small in order to maintain a low C-rate for battery health. C-rate is the rate at which a battery is discharged relative to its maximum capacity. For example, 1C rate means one full battery will be discharged in one hour. If the battery is too small, the C-rate will be high and the battery will degrade faster. Maintaining a low C-rate, such as less than 1C, ensures the battery health and service life (Xu et al. 2013). Another reason to limit the battery downsizing is to make sure that there is enough reserved storage capacity for the battery as a precaution for unexpected situations, such as a bus passing over a charging station without stopping to pick up passengers.

There is potential to further reduce the energy and GHG emissions of the wireless charging system by improving the utilization rates of off-WCs. The yearly utilization rate (%) and theoretical life (year) of chargers are summarized in Table 5. A wireless charger is assumed to have the same working hours in the total life as a plug-in charger. Based on experience that a typical plug-in charger could work 8 hours per day for 20 years, 58,400 hours is used as the total working hours for both plug-in and wireless chargers. The techno-economic life of on-WCs, off-WCs and plug-in chargers is assumed to be 24 years, though the theoretical life could be longer. Beyond this time frame, there assumes to be technical innovation and better chargers could retire the old ones. The yearly utilization rates of off-WCs located at key bus stops in downtown and suburb are 2% and 1%, respectively, which are much lower than the off-WCs located at other places like transit centers. In the model, the off-WCs are exclusively used by TheRide bus system. However, the off-WCs can be shared by other fleets, such as the school buses at the University of Michigan commuting between the Central Campus near Ann Arbor downtown and the North Campus in the suburban area. If the charger life is still 24 years, some of the energy and environmental burdens of off-WCs can be allocated to other fleet systems. Future work is planned to study life cycle costs and investigate the optimal deployment of off-WCs. Additionally, a further sensitivity analysis on the charger techno-economic life shows that if both plug-in and wireless chargers are retired after about 17 years of service, there is no difference found in the total GWI between the two systems.

Table 5. Charger yearly utilization and theoretical life.

| Charger category | <i>On-board Wireless Charger</i> | <i>Off-board Wireless Charger</i> | | | | | <i>Plug-in Charger</i> |
|---------------------------|--|-----------------------------------|---------------|------------------------|------------|------------|----------------------------|
| | | <i>Downtown</i> | <i>Suburb</i> | <i>Parking lot</i> | <i>BTC</i> | <i>YTC</i> | |
| Operating hours in a year | 1789 | 182 | 96 | 726 | 2065 | 1589 | 1796 |
| Yearly utilization rate | 20% | 2% | 1% | 8% | 24% | 18% | 21% |
| Theoretical life (years) | 33 | 320 | 606 | 85 | 28 | 37 | 33 |

Notes: BTC = Blake Transit Center in Ann Arbor; YTC = Ypsilanti Transit Center; Yearly utilization rate = operating hours in a year/8760 hours; Theoretical life (years) = life of a charger (hours)/operating hours in a year.

Future studies could include the bus shell and subsystems in the model boundary to further examine the weight reduction. Secondary vehicle weight reduction, or the vehicle weight reduction due to subsystem resizing, including powertrain, can provide further lightweighting benefits (Lewis et al. 2014; Lewis 2013; Shiau et al. 2009; Wohlecker et al. 2007). However, the compounding effect of secondary weight reduction is not included due to lack of data on the subsystem of an electric bus. Further studies could also investigate the alternative battery chemistries, such as lithium iron phosphate (LFP), instead of LiMn_2O_4 (LMO) in our model. LFP has a long cycle life expectancy of 6,000 cycles at 80% depth of discharge (Majeau-Bettez et al. 2011), which may extend the battery life. If available, it can be beneficial to use a U.S.-specific life cycle inventory of LFP. Moreover, the effect of frequent SOC fluctuations on wireless battery life needs to be investigated. A battery/ultracapacitor hybrid energy storage system is recommended for future studies to isolate the battery from frequent charges and extend battery life (Cao and Emadi 2009). Furthermore, the wireless and plug-in battery electricity depleting rates, k_1 and k_2 (kWh/km), are assumed to be constant. However, in reality there is variation in energy consumption in different seasons. Additional energy consumption to maintain comfortable cabin temperatures in the winter and summer would increase the battery electricity depletion rates and this would require a bigger battery to maintain the increased daily energy

demand. Future studies can model the actual battery electricity depletion if the battery discharge data for buses in different seasons are available.

5. Conclusions

A comparative life cycle analysis highlighting the major differences between a plug-in charging electric bus system and a wireless charging electric bus system was conducted in this research. In the production and installation stage, the differences in charger components, number of chargers deployed across the bus service region and the battery sizes were compared. In the use phase, the differences in the life cycle electrical energy consumption were compared.

Although there are additional environmental and energy burdens from the large-scale deployment of wireless charging infrastructure, wireless charging will provide extra charging time during bus operation which significantly reduces the battery size and weight. The battery downsizing leads to vehicle lightweighting and reduction in battery-to-wheel energy consumption. Due to the lower current wireless charging efficiency than the plug-in charging efficiency, the lightweighting benefit of battery-to-wheel energy consumption reduction is offset by the difference in charging efficiency. Therefore, the use phase energy consumption is comparable for both systems.

The life cycle energy consumption and greenhouse gas emissions of these two charging systems are comparable for the base case. A sensitivity analysis was conducted to evaluate the uncertainties in assumptions and sensitivity of results to the key parameters. To further improve the life cycle performance of wireless charging system, it is important to focus on key parameters such as the wireless charging efficiency and grid carbon intensities of day and night. Improving the wireless charging efficiency and “greening” the grid during daytime are key strategies to enhance the energy and environmental benefits of the wireless charging system.

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Appendix

Detailed component inventories of a 6 kW on-board portion of wireless charger (on-WC), off-board portion of wireless charger (off-WC) and plug-in charger (PC) are summarized in the tables below.

Table A1: Inventory of Input Filter & Rectifier.

| Name | Weight (g) |
|---------------------------|-------------------|
| Cables | 15.8 |
| Printed circuit board | 39.0 |
| Fuse | 4.7 |
| Capacitors (film) | 18.0 |
| Cement for RES anti-surge | 17.5 |
| Connector | 3.9 |
| Copper wires | 45.4 |
| Diodes | 22.6 |
| Iron | 251.1 |
| Resistor (metal film) | 1.4 |
| Resistors (unspecified) | 50.2 |
| Power sockets (alloy) | 13.2 |
| Transformer | 31.6 |
| Total Weight | 514.2 |

Table A2: Inventory of Power Factor Correction (with Driver Circuit).

| Name | Weight (g) |
|---------------------------------------|-------------------|
| Cables | 28.5 |
| Printed circuit board | 129.6 |
| Capacitors (electrolyte, <2cm height) | 3.6 |
| Capacitors (electrolyte, >2cm height) | 604.5 |
| Capacitors (film) | 28.7 |
| Capacitors (SMD type) | 0.8 |
| Connectors | 9.1 |
| Diodes | 24.9 |
| Inductor | 0.05 |
| Integrated circuits | 6.5 |
| Iron | 1234.8 |
| Light emitting diode (LED) | 0.005 |
| Litz wires | 529.2 |
| Resistors (SMD type) | 0.2 |
| Power sockets (alloy) | 7.4 |
| Transistors | 24.6 |
| Total Weight | 2632.3 |

Table A3: Inventory of DC/DC Converter (with Driver Circuit).

| Name | Weight (g) |
|---------------------------------------|-------------------|
| Cables | 28.5 |
| Printed circuit board | 124.9 |
| Fuse | 3.6 |
| Capacitors (electrolyte, >2cm height) | 265.2 |
| Capacitors (film) | 21.3 |
| Capacitors (SMD type) | 1.0 |
| Connectors | 8.5 |
| Diodes | 24.6 |
| Inductors | 0.2 |
| Integrated circuits | 27.6 |
| Iron | 562.8 |
| Light emitting diodes (LED) | 0.02 |
| Litz wires | 241.2 |
| Resistor (metal film) | 0.7 |
| Resistors (SMD type) | 0.2 |
| Power sockets (alloy) | 11.8 |
| Transistors | 24.6 |
| Total Weight | 1346.6 |

Table A4: Inventory of High Frequency Inverter/Resonant Converter.

| Name | Weight (g) |
|-----------------------|-------------------|
| Cables | 28.5 |
| Printed circuit board | 112.2 |
| Capacitors (film) | 28.7 |
| Connectors | 4.6 |
| Resistors (SMD type) | 0.02 |
| Power sockets (alloy) | 6.6 |
| Transistors | 24.6 |
| Total Weight | 205.1 |

Table A5: Inventory of Coil Plate (Either On or Off Board)

| Name | Weight (g) |
|--------------------------|-------------------|
| <i>Litz wire:</i> | |
| Pure Copper Wire | 2444.7 |
| Enamel | 24.7 |
| Polyester | 54.5 |
| <i>Other components:</i> | |
| Capacitors (film) | 169.9 |
| Printed circuit board | 80.0 |
| Ferrite bars | 4680.0 |
| Total Weight | 7453.8 |

Table A6: Inventory of Power Conditioner and Protection, Output Rectifier & Filter (with Driver Circuit).

| Name | Weight (g) |
|------------------------|-------------------|
| Printed circuit board | 57.5 |
| Fuse | 3.6 |
| Capacitors (film) | 73.7 |
| Connector | 3.9 |
| Diodes | 49.4 |
| Current Sensor | 16.5 |
| Resistors (metal film) | 1.0 |
| Resistors (SMD type) | 0.04 |
| Power sockets (alloy) | 8.1 |
| Transformer | 37.3 |
| Transistors | 12.4 |
| Total Weight | 263.4 |

Table A7: Inventory of Control Board 1.

| Name | Weight (g) |
|---------------------------------------|-------------------|
| Cables | 15.8 |
| Printed circuit board | 132.1 |
| Fuse | 1.5 |
| Capacitors (electrolyte, <2cm height) | 2.6 |
| Capacitors (SMD type) | 2.6 |
| Connectors | 47.6 |
| Diode | 0.01 |
| Inductors | 0.4 |
| Integrated circuits | 104.7 |
| Light emitting diodes (LED) | 0.1 |
| Resistors (SMD type) | 1.0 |
| Resistors (unspecified) | 19.1 |
| Power sockets (alloy) | 1.5 |
| Switches | 1.8 |
| Transistors | 0.2 |
| Total Weight | 331.1 |

Table A8: Inventory of Driver Board.

| Name | Weight (g) |
|-----------------------------|-------------------|
| Cables | 15.8 |
| Printed circuit board | 38.8 |
| Capacitors (SMD type) | 0.9 |
| Connectors | 5.8 |
| Diodes | 0.04 |
| Inductors | 0.2 |
| Integrated circuits | 9.2 |
| Light emitting diodes (LED) | 0.02 |
| Resistors (SMD type) | 0.1 |
| Total Weight | 70.8 |

Table A9: Inventory of Output Rectifier & Filter.

| Name | Weight (g) |
|-----------------------|-------------------|
| Printed circuit board | 40.0 |
| Fuse | 3.6 |
| Capacitors (film) | 73.7 |
| Connector | 3.9 |
| Diodes | 24.6 |
| Current Sensor | 16.5 |
| Resistor (metal film) | 0.7 |
| Resistors (SMD type) | 0.04 |
| Power sockets (alloy) | 8.1 |
| Total Weight | 171.0 |

Table A10: Inventory of Plug & Cable.

| Name | Weight (g) |
|--|-------------------|
| Cables | 1017.0 |
| Electronic components (unspecified) | 227.0 |
| Glass fiber reinforced plastic (polyamide) | 33.5 |
| Glass fiber reinforced plastic (polyester) | 556.7 |
| Magnetic materials | 15.0 |
| Plug (connecting grid through socket) | 42.6 |
| Polycarbonate materials | 537.5 |
| Polymethyl methacrylate materials | 7.3 |
| EPDM foamed cord | 2.8 |
| Printed circuit board | 56.8 |
| Silicone materials | 27.0 |
| Steel | 35.0 |
| Tellurium copper | 38.2 |
| Thermoplastic Elastomer Compound | 58.3 |
| Total Weight | 2654.6 |

Table A11: Inventory of other components.

| Name | Weight (g) |
|--|-------------------|
| <i>In-vehicle Cooling System of Wireless Charger:</i> | |
| Heat dissipation panel (Aluminum) | 1814.4 |
| Electric fan | 140.0 |
| <i>Off-vehicle Cooling System of Wireless Charger:</i> | |
| Heat dissipation panel (Aluminum) | 7257.5 |
| Electric fan | 560.0 |
| <i>Cooling System of Plug-in Charger:</i> | |
| Heat dissipation panel (Aluminum) | 9071.9 |
| Electric fan | 700.0 |
| <i>Transformer (Plug-in Charger):</i> | |
| Transformer | 1122.0 |
| <i>Control Board 2:</i> | |
| Control Board 2 (Scale down from Control Board 1) | 30.8 |