ECONOMIC FEASIBILITY AND ENVIRONMENTAL IMPACT OF WIRELESS CHARGING TECHNIQUES FOR ELECTRIC GROUND FLEET IN AIRPORTS

By

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ABSTRACT OF THE THESIS

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Balancing environmental, economic, and social issues is challenging for industry sectors and government agencies. According to the Environmental Protection Agency (EPA) of the United States (U.S.), the transportation sector was responsible for 29% of greenhouse gas (GHG) emissions in the U.S. in 2017. Electric mobility is an alternative to mitigate this issue by substituting fossil fuels for electricity. In addition, the use of energy from a renewable source will increase even more environmental benefits. Charging these vehicles can be wireless or wired, stationary, or in-motion.

Many airports are converting the conventional ground fleet to electric vehicles to reduce greenhouse gas (GHG) emissions and increase airport operations sustainability. It is necessary to understand the economic feasibility and environmental impacts of this change to justify the decision. This study first used life cycle cost analysis (LCCA) to compare electrified ground fleet's economic performance compared to conventional fossil fuel option. Three different charging systems (plug-in charging, stationary wireless charging, and dynamic wireless charging) for pushback tractors and inter-terminal buses at a major hub airport were considered in the analysis. Although the conventional fossil fuel options present the lowest initial cost for both fleets, it costs the most in a 30-year analysis period. Among three electric charging infrastructures, the plug-in charging station shows the least accumulative present value of cost. Although the electric ground fleet is proved to show economic benefits, the most cost-effective charging infrastructure may vary depending on driving mileage and system design. The use of LCCA to analyze new systems and infrastructures for decision-making is highly recommended.

Life-cycle assessment (LCA) is then used to quantify the environmental impact of electric fleet compared to conventional fossil fuel vehicles. The assessment was analyzed for energy consumption and emission of $CO_{2\text{-eq}}$ respectively to assess Cumulative Energy Demand (CED) and Global Warming (GW) potential. The results show that the operation phase outweighs any initial impact from manufacturing and charger construction phases; the operations phase accounts for both the highest CED and GW values. For both pushbacks and buses, the electric options are shown to have very similar impacts. The lower impact option can quickly change depending on the design. On the other hand, the conventional vehicle system presented the highest impact on the two studied categories for both fleets. The discrepancy between conventional buses and all three electric options is even higher on the bus fleet study, suggesting that electric buses are environmentally better than conventional.

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DEDICATION

Para meus pais, Vânia de Oliveira Marques e José Edgard Soares Júnior, e para minhas avós Maria José de Oliveira Marques e Mafalda Cotta de Vasconcellos.

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Chapter 1 Introduction

1.1. Background

According to the Environmental Protection Agency (EPA) of the United States (U.S.), the transportation sector is responsible for 29% of GHGs in the U.S. in 2017. Fossil fuel emissions also affect human health, thereby increase the incidence of diseases like asthmas, high blood pressure, lung cancer, diabetes, Alzheimer's disease, dementia, and premature deaths (Requia et al., 2018). Fossil fuel consumption has encountered an economic downturn: fuel price volatility and foreign oil dependency. In this situation, electric mobility is a promising transportation option due to its capability of reducing CO2 footprint, pollution, and becoming less dependent on foreign oil and fuel price (Deloitte, 2010). Electric mobility coupled with low-carbon electricity sources is a transportation alternative that provides reduced greenhouse gas emissions (Hawkins et al., 2012). Electric vehicles do not produce tailpipe pollution (Luin et al., 2019). The pollution generated exclusively depends on the electricity source. The environmental benefits are high when the energy source is sustainable, such as solar, wind, hydropower, and geothermal. Electric mobility using non-renewable energy also has an advantage compared to conventional vehicles; a fossil fuel-fired power generator has concentrated emission that can be treated more efficiently and effectively (Cai and Xu, 2013).

Electric vehicles are becoming more common and are expected to significantly penetrate the market by the year 2020 (Gill et al., 2014). In addition to the possibility of using renewable energy sources, other benefits of electric vehicles (EVs) are government tax credits, emission regulation accordance, improved fuel economy, and vehicle maintenance economy (Deloitte, 2010). Although there are many benefits with EVs, there are also drawbacks preventing using EVs on the existing roadway. Some of those are high vehicle prices, long charging time, range anxiety, battery size, cost and weight, few charging stations, safety issues concerning charging in the rain and snow, and reliability (Deloitte, 2010, Gill et al., 2014, and Kalwat et al., 2015). According to a study conducted by Deloitte Consultant, the six potential barriers to the mass adoption of EVs are familiarity, brand, range, charging, infrastructure, and price. Dijik et al. (2013) claim that electric mobility's future depends on developments in infrastructure, mobility, car manufacturing industry, energy prices, and the electricity sector (Dijk et al., 2013). EVs will penetrate with a high market rate when the infrastructure is prepared to provide convenient charging facilities for consumers. Charging facilities consist of recharge points in charging stations, battery swapping stations, and electric roads. Currently, battery electric vehicles are usually limited to light-duty vehicles due to the battery's low energy density (Connolly, 2017).

Electric roads (eRoads) could be a key factor in accelerating EVs' market penetration by increasing the drive range and eliminating waiting time for charging. The eRoad is the charging infrastructure itself, and the price of vehicles will also reduce since fewer battery will be required. Therefore, an integration of Electrified Road infrastructure into the current transportation network can be a promising solution to promote EVs' popularity and enhance the sustainability of the road transportation sector (Cheng et al., 2015). An Electrified Road (eRoad) is defined as a transportation infrastructure that can ‘‘deliver the electrical power to charge EVs efficiently while stationary or even in motion, using specific conductive or contactless charging systems’’ (Cheng et al., 2015). For the eRoad to be sustainably implemented and used, a combination of multidisciplinary aspects must be studied. The eRoads demand different building methods as compared to traditional roads and require more complex operations and elaborate maintenance plans.

1.2. Problem of Statement

The aviation sector faces sustainability challenges not only in the air but also in ground transportation and airport infrastructure. There are several paths to increase sustainability in the aviation sector, such as aircraft engine technology to improve efficiency, utilizing biofuels, promoting electric aircraft development, migrating ground fleet to electric power, and other green initiatives. Airports have been implementing electric vehicles in their ground fleet as one initiative to mitigate environmental impacts and decrease operational costs. In the United States, the San Diego Airport launched ten electric airport shuttles in May 2019. JetBlue introduced an electric ground service fleet (totaling 59 baggage tractors and 59 belt loaders) at the John F. Kennedy International Airport. In the United Kingdom, Birmingham Airport and Glasgow International Airport implemented electric bus fleets, and Heathrow Airport added more than 50 vehicles to its ground fleet. Additionally, Munich Airport in Germany, Budapest Airport in Hungary, and Soekarno-Hatta International Airport in Indonesia all implemented similar measures.

Charging infrastructure is required to facilitate the use of electric vehicles at the airport. The decision to substitute conventional vehicles with electric vehicles can be impeded by the high investment cost and long payback time of charging infrastructure. Understanding the lifetime cost of each option can add value to decision making. Although transportation agencies usually have an annual budget, it is important to analyze the investment option with a high initial cost and great return in the life cycle. Therefore, it is needed to analyze the life-cycle costs of charging infrastructure for electric vehicles to make better decisions.

The Guidebook for Developing a Zero- or Low-Emissions Roadmap at Airports by Morisson et al. (2020) provides information and resource to create a zero or low-emission roadmap from start to finish. Among different strategies such as support the use of sustainable aviation biofuels and build on-site renewable energy, the guidebook also suggests supporting infrastructure for electric Ground Service Equipment (GSE). The use of electric GSE is an appropriate fit, as the functional use of these vehicles is confined to the local airport area, mitigating many issues regarding the driving range that have hampered electric vehicle adoption in other areas. One promising new technology in wireless power transfer charging would further reduce that concern and potentially alleviate time spent refueling. However, no studies have been conducted to evaluate the sustainability benefits brought by the electrification of GSE at airports. This process-based Life Cycle Assessment (LCA) aims to quantify the impact of electric GSE compared to conventional diesel operations in terms of energy demand and global warming.

This initial study will focus on two representative vehicles of GSE at airports: pushback tractors and inter-terminal buses. After a technical visit to Newark International Airport, which included interviews and follow-up consultations with airport operations managers and vehicle experts, one of the focus vehicle selected is the 'super tugs' or pushbacks, specifically the highest capacity tug that can move the largest aircraft. The main reason for this is that pushbacks are in high demand around the clock in airport operations; optimizing its use, by avoiding stops and refueling time, will benefit the entire airport operation (Lanieri, 2020). Furthermore, pushbacks represent a specific challenge when it comes to implementing electric vehicle operations at airports. They require a greater amount of power and are a more specialized vehicle than a typical baggage truck or other ground equipment to which typical electric vehicles can be more easily modified.

Figure 1 Pushback tractor or "Super tug" at Newark Liberty International Airport

Inter-terminal buses were also selected for this study. Electric buses are already a reality in many airport operations. Additionally, buses are present in a few studies about wireless charging techniques. Combining these two technologies in an airport environment can be extremely beneficial and easier to implement, compared to other GSE. Quantifying the costs and environmental impact of substituting conventional buses for electric buses is a crucial part of the decision-making process, and it is presented in this work.

Figure 2 Inter-terminal buses in Dulles Airport, VA

1.3. Objective and Scope

This study aims to analyze the economic feasibility and environmental impacts of charging infrastructure for an electric ground fleet in airports. Life-Cycle Cost Analysis (LCCA) was conducted for implementing two types of electric ground fleet in airports: pushback tractors and inter-terminal buses. Three electric charging infrastructures were considered in the analysis in comparison to the conventional fossil fuel system. The initial investment, as well as operation and maintenance costs over the analysis period were analyzed and compared for fossil fueled station, and three electric charging infrastructures. The analysis results can be used for better decision making in terms of implementing electric vehicles in an airport environment.

The study also performed a Life-Cycle Analysis (LCA) to analyze the environmental impacts. The fleets and scenarios studied were the same used for the LCCA. The life cycle inventory was compiled for energy consumption and greenhouse gas emissions, respectively, to assess the life-cycle Cumulative Energy Demand (CED) and Global Warming (GW) potential. The analysis results can assist in the decision-making in terms of implementing electric vehicles in an airport environment.

Chapter 2 Literature Review

2.1 Traditional Charging Infrastructure for Electric Vehicles

2.1.1 Battery Swapping Station

In a battery swapping facility, electric vehicle drivers can swap the depleted batteries for a fully charged one (Tan et al., 2019). This process is very short, around five minutes, and is much faster than charging the vehicle in a charging station (Laurischkat, 2016). Some challenges of this technology are battery standardization (Hou et al., 2016 and Yang et al., 2014) and customer acceptance. This last one occurs due to customers being apprehensive of swapping a battery in good condition for one that is depreciated. A solution for this problem is to have the batteries owned by the battery swapping station (BSS) leased to the driver. This solution can also increase the market penetration of EVs by decreasing the cost of the vehicle (Tan, 2018). Another challenge that needs to be overcome is to select an optimized location for the battery swapping station to be cost-efficient and profitable.

EV owners will benefit from reduced vehicle price; and fast charging and do not need to upgrade household infrastructure for charging (Mahoor et al., 2019). BSS owners can increase profits by charging the empty batteries in energy low cost hours and having a partnership with the power utility, which can use the BSS as a large and flexible resource to reduce network congestion and peak load (Mahoor et al., 2019). The joint venture with SunMobility and SmartE performed field trials of battery swap stations for electric two- and three-wheelers in Delhi, India (SunMobility, online). SunMobility developed a modular battery that is easily removable from the vehicle replaced with a fully charged battery at the BSS. According to Mahoor et al. (2019), the battery capital cost is $200/kWh, and the daily operational cost varies between $45.56 and $166.11.

2.1.2 Stationary Charging Station

There are three types of Electric Vehicle Supply Equipment: Level 1 is home-based 120V AC, it charges in 10 to 20 hours, and the cost goes from $300 to $1000. Level 2 is a 240V AC charger, and it can be commercial or home-based. The time to charge is between 4 to 8 hours, and the cost is between $2000 and $4800. Level 3 is considered a "fast charging station", which charges in 20 minutes for 170 miles and 75 minutes for 330 miles. Its cost varies from $14,000 to $51,000 (He et al., 2019; Bansal, 2015).

A stationary charging station can also provide energy through wireless techniques, in that case, the vehicle stops over a wireless charging pad that will charge the battery by inductive power transfer. The charging time depends on the power and the efficiency of the system; the last has on its parameters the electric design and air gap. The efficiency increases when the design includes a capacitor on each coil or includes parallel or series circuit designs that cause equal resonance on both windings. The air gap can also be decreased to increase efficiency by placing the transmitter pad above the pavement.

Plug-in charging is an already well-known technology. In the U.S. there are more than 21,000 charging stations in which around 2,200 are DC fast charging stations (Fueleconomy.gov, online). A few companies are developing technologies for wireless charging stations. For example, WiTricity uses coupled resonators, which are coils with impedance matching network in which the source produces a magnetic field that induces an electric current on the receiver. The efficiency is between 90% and 93%, charging ranges from 3.6 to 11 kW, and this technology allows a little misalignment (WiTricity, online).

2.2 In-Motion Charging on eRoads

2.2.1 The principle of eRoads

The fundamental principal of an Electric Road is that electric vehicles can use energy directly from the power grid and do not need to rely on a storage medium such as a battery (Connolly, 2017). When the energy source is decarbonized, eRoads are also a solution for mitigating CO2 emission. An electric road can be wired using conductive technology or wireless, and the most used technology, among the wireless charging pilot projects in the world, is inductive power transfer.

The charging elements of in-motion charging are installed in the road and charge the vehicle battery while driving, avoiding parking and waiting. Besides convenience, in-motion charging also addresses concerns like driving range (Panchal et al., 2018) and safety because costumers do not need to handle cables. In-motion charging can be conductive or wireless. Conductive charging can be overhead, from the side or underneath, which is usually used for buses and trucks due to the high wire placement (Connolly, 2017).

For the successful implementation and use of charge-while-driving technologies, three important factors are cited: (i) acceptable charging solutions, (ii) successful integration into the practical road infrastructure, and (iii) good functionality and cost-effective maintenance management over the lifetime (Cheng et al., 2015).

Besides theoretical research, tests and prototypes are being studied as well. In 2018, an in-motion conductive charging road, or electric road, was inaugurated in Sweden. It consists of a 2-km embedded track with a rail located underneath vehicles (eRoadArlanda, online).

2.2.2 Conductive Charging in an eRoad

The conductive technique to charge EVs requires a physical connection between the vehicle and the eRoad. This technique is very similar to known developments such as electric trains, trams, and trolleybuses (Connolly, 2017, and Viktoria Swedish ICT on behalf of Volvo GTT and Scania CV, 2014). The physical connection can occur from underneath the vehicle, from the side, or even from above.

The overhead conductive method consists of two supply lines placed above the road and a vehicle equipped with a connection device capable of compensating vertical and horizontal movements (Domingues-Olavarria et al., 2018). Road Bound Conductive is the method used when the vehicle contains a conductor arm equipped with a magnetic contact. When the vehicle is situated above the power conductor in the road, the electric field would charge the battery (Asplund and Rehman, 2014). Road Side Conductive has the power conductors placed on the side of the road, allowing trucks, buses, and passenger cars to use this technology. Another benefit of this method is that the road is untouched, which provides lower maintenance and installation complexity (Domingues-Olavarria et al., 2018).

Weather conditions can influence the operation of conductive charging road. In the case of snow, the cars will keep the snow out of the rail when the traffic density is high; however, in low-density traffic or high-volume snowstorm, plowing will have to be performed for the eRoad to function properly. A special device needs to be used to plow not only the road but also inside the rail. Another important eRoad device for cold regions is electrical heating to avoid ice in the rail, which will block the conductor from the contact (Asplund and Rehman, 2014).

2.2.3 Wireless Charging in an eRoad

In-motion wireless charging charges EV's battery while it is in transit with no physical contact (Jang, 2018). The three main requirements for an effective wireless power transfer (WPT) technology are high power, high efficiency, and large air gap (El-Shahat et al., 2019), to ensure the minimal distance between the road and bottom of the vehicle. These three main requirements are also the biggest challenges of this charging method. The eRoad for wireless charging (Jang, 2018) consists of a transmitter embedded in the pavement and a receiver onboard of the vehicle that captures the transmitted energy. This method is a promising solution due to increased driving range, decreased battery size, and improved convenience (Sun et al., 2018).

Wireless charging is not affected by harsh water conditions since no plug is required (Kalwar et al., 2018). Plug-in charging has losses from 20% to 30% due to wires (Das et al., 2018), which does not occur in wireless techniques. However, wireless charging has a much higher installation cost for infrastructure and safety/shielding requirements.

2.2.4 Comparison between different charging methods for eRoad

Implementing wireless charging for EVs while driving has many challenges, such as large upfront capital costs, relatively immature technology. It requires a high level of communication and collaboration between stakeholders, complex operations and maintenance, and the use of clean electricity (Gill et al., 2014; and Bateman et al., 2018). Rescue teams also need different training to operate in electric roads due to the risk of car accidents when there is human or animal presence under the car or bus. Another risk factor is the electromagnetic field exposure, which will have to be under limited range as prescribed by safety regulatory authorities (Kalwar et al., 2015).

Conductive charging is a more mature technology. It provides higher levels of power and does not impact the pavement when placed overhead or on the roadside. However, when placed overhead, there is a high visual impact; it could affect emergency response with a helicopter, and it is only suitable for bus and heavy-duty vehicles (Panchal et al., 2018). When the conductive charging is underneath as a rail, the drawbacks are road user safety once the conductor is accessible. It is also susceptible to wear and corrosion due to its exposure to the environment. Wireless charging is safer for road users since it is embedded in the pavement, making this technology less vulnerable to damage and vandalism. The conductive technology is known and has been used for years in other transportation modes: trains, trams, and trolleybuses. Therefore, it is more mature than wireless charging. The project called eRoadArlanda, part of the Swedish Transport Administration's pre-commercial procurement of innovation, is based on conductive technology that uses an electric rail installed in roads to power driving vehicles. It estimates that electrifying 20,000 kilometers of roads in Sweden would cost about SEK 80 billion, approximately USD 800 million (eRoadArlanda, online) USD 40,000 per kilometer in a large-scale project.

Stationary charging stations have a few drawbacks. The plug-in charging station must have an interrupting device that shuts off the electric supply when there is a risk of shock. Incontrast, the wireless charging method can detect the presence of ferrous or magnetic material near it and stop the charging to prevent fires or short-circuit hazard (Bansal, 2015). Both plug-in and stationary wireless stations can be very inconvenient due to the time of charging, which does not occur for the in-motion charging method. Another big inconvenience is high demand in a charging station, forming a line that leads to longer waiting time. When using charging stations as the main source of energy, the only option to increase vehicle mileage is to increase onboard battery's size. This solution will increase the price and weight of the battery, charging time. Table 1 summarizes the characteristics of stationary and in-motion charging technologies, while Table 2 points out their advantages and disadvantages.

Table 1 Characteristics of different charging technologies for eRoad

	Charging Technology	Charging Efficiency	Power	Air Gap	Charging Time	Technology Readiness Level (TRL)
Stationary Station	**Swapping Station** (Manhoor et al., 2019 and Khan et al., 2019)	~100%	36 kW - 240 kW *DC fast charging	0 cm	8 min	9
	Wireless – ICPT (Bansal, 2015, Machura and Li, 2019, Panchal et al., 2018)	> 90%	3.3 kW - 25 kW	10 - 30 cm	6.5 - 3 h	7
	Plug-In DC Fast Station (Bansal, 2015, Khan et al., 2019, Channegowda et al., 2015)	93%	36 kW - 240 kW	0 cm	10 - 15 min	9
In-Motion	**Overhead Conductive** (Panchal et al., 2018)	90%	100 - 240 kW	0 cm	Heavy Vehicle: 1.2 - 2.8h Passenger Car: 0.1 - 0.3 h *calculated	7
	Road Bound Conductive (Viktoria Swedish ICT, 2013)	90%	2 - 10 MW/km	0 cm	Heavy Vehicle: 1.7 – 8.3 min Passenger Car: < 1 min *calculated	8
	Roadside Conductive (Domingues-Olavarria et al., 2018, and Suul and Guidi, 2018)	N/A	180 kW	0 cm	Heavy Vehicle: 1.4 h Passenger Car: 8 min *calculated	6
	Wireless – ICPT (Panchal et al., 2018, and Vaka and Keshri, 2017)	71% - 96%	1 kW - 100 kW	7.5 - 50 cm	Passenger Car: 15 min *calculated for 100kW with 96% efficiency	9

*calculated values assumed a heavy vehicle with an energy storage capacity of 250 kW and a passenger car with 24 kWh

Table 2 Advantages and disadvantages of different charging technologies for eRoad

	Charging Technology	Advantages	Disadvantages
Stationary Station	**Swapping Station**	Possibility of partnership with utility company (can be used to optimize the power grid), decrease vehicle price (batteries would be owned by the SS), fast and convenient charging	Battery standardization, operation complexity (battery fully charged for demand pick and battery logistics between SS)
	Wireless - ICPT	Safer perception and convenience for consumer (no need for wire manipulation)	Not easily accessible for maintenance. New technology. Electromagnetic field exposure.
	Plug-In DC Fast Station	Components easily accessible for maintenance, mature technology	Safety hazard due wire manipulation specially during rain and snow, susceptible to damage and vandalism
In-Motion	**Overhead Conductive**	Increase drive range, decrease battery size and range anxiety, mature technology, no pavement impact, easy components access for maintenance	Visual impact, only suitable for trucks and buses, could impede helicopter emergency rescue, susceptible to damage and vandalism
	Road Bound Conductive	Increase drive range, decrease battery size and range anxiety, mature technology, easy components access for maintenance	Impact on the pavement, safety hazard (accessible open conductor), susceptible to damage and vandalism
	Road Side Conductive	Increase drive range, decrease battery size and range anxiety, mature technology, no pavement impact, easy components access for maintenance, suitable for passenger vehicles and heavy-duty vehicles.	Visual impact, safety hazard (accessible open conductor), susceptible to damage and vandalism
	Wireless - ICPT	Increase drive range, decrease battery size and range anxiety, no visual impacts	Impact on the pavement, not easily accessible for maintenance, produces electromagnetic field

2.3 Advancements in Wireless Charging Techniques

Several wireless charging techniques were studied in the past century. Nikola Tesla accomplished the first power transferring in 1904 using radio waves at 150 kHz. Sixty years later, Brown invented a laser where power can be transferred by converting electrical current into a laser beam (Ahmad et al., 2018). Nowadays, the demand for wireless charging as a more convenient and reliable battery recharger gets even higher as the EV market grows (Qiu et al., 2013). The main goal of wireless power transfer is to substitute the conductive charging method and eliminate inconvenience and hazards while maintaining the comparable power level efficiency (Qiu et al., 2013).

2.3.1 Microwave Power Transfer

Microwave Power Transfer consists of the microwave launcher and microwave receiver. This method consists of a microwave launcher connected to the grid and a receiver installed in any low voltage products. Using this technology is possible to transfer power and information by using waves with wavelength range that falls into microwaves category. A DC converted from the grid feeds the microwave generator. The current that passes in the resonating cavities in the microwave generator produces the microwave electromagnetic radiation. When the antenna receives the microwave energy, it converts it back to DC, charging the product (Kalwar et al., 2015). In a study carried out by Shinohara and Nissan Motors, a road-to-vehicle wireless power transfer system at 2.45 GHz was developed. It used slot antennas and magnetron to reduce the cost and a microwave to charge the battery at 76% efficiency. This efficiency is appropriate to charge EVs wirelessly using the microwave (Ahmad et al., 2018). According to Qiu et al. (2013), Microwave Power Transfer has high power, high range, and high efficiency. However, it needs a direct line-of-sight transmission path, large antennas, and complex tracking mechanisms. Kalwar et al. (2015) pointed out that the disadvantage of this technology is the high cost and antenna size, which can be overcome using a waveguide that provides a path for microwaves and does not allow the microwaves' diffusion.

2.3.2 Capacitive Wireless Power Transfer

Capacitive Wireless Power Transfer (CWPT) uses coupling capacitors to transfer power from the source to the receiver instead of coils and magnets. The transmitter and receiver are realized by metal plates where two plates are used at the primary side as a power transmitter, and two plates at the secondary side act as a power receiver (Electreon, online). This technology operates for both high voltage and low current. Additional inductors are added in series with the coupling capacitors to reduce the impedance between transmitter and receiver sides at the resonant arrangement. CWPT has a low cost and is a simple technology compared to other technologies. However, it is useful for low-power applications, such as portable electronic devices, cellular phone chargers, and rotating machines (Chen et al., 2017). The application of CWPT for EVs has been limited due to large air gaps and high-power level requirements (Panchal et al., 2018). According to Qiu et al. (2013) this technology has high efficiency; however, it does not apply to EV charging because it has low power.

2.3.3 Magnetic Gear Wireless Power Transfer

This technology consists of two synchronized permanent magnets positioned side-by-side differently from other wireless charging methods based on coaxial cable. The main power current source is applied to the transmitter winding to produce a mechanical torque on the primary permanent magnet. The mechanical torque causes the permanent magnet to rotate and induce a torque on the second permanent magnet. In this system, the primary permanent magnet works as a generator, and the secondary receives the energy that will charge the battery through a power converter and battery magnetic system (Panchal et al., 2018). According to Qiu et al. (2013), the magnetic gear wireless power transfer has high power, medium-range, and high efficiency leading to a capable technology for EV charging. Another positive fact is that this technology is relatively forgiving of misalignments (Li, 2009). However, the power transfer capability is inversely proportional to the axis-to-axis separation between the primary and secondary permanent magnets as the coupling between the two synchronized windings reduces abruptly, making this method very challenging for dynamic charging (Panchal et al., 2018).

2.3.4 Inductive Power Transfer

The concept of this technology is to transfer power from the primary coil to the secondary coil installed in the car without any wire (Ahmad et al., 2018). It consists of transferring power from one conductive circuit to another using alternating magnetic fields (Requia et al., 2018). The air-core transformer with primary and secondary coils is separated through a small space and transfers power through electromagnetic induction phenomena (Cheng, 2016). This phenomenon is based on Lenz's law and Faraday's law. A time-variant current in a conductor creates the magnetic field around the conductor, and a secondary loop (receiver) gets voltage generated due to time-variant magnetic flux (Ahmad et al., 2018). IPT is already a technology used to charge EV; it has high power transfer when the air gap is small. However, this performance can decrease drastically when the space between the primary and secondary coils increases due to leakage inductance (Kalwar et al., 2015). This method has high power, high efficiency, but a low range (Qiu et al., 2013). Despite being a used technology for EV charging in this low range due to the air gap, is a restraint in several applications. This method is not recommended for dynamic charging; however, it is a great solution for static charging once it eliminates the contact metal to metal of a traditional plug-in charger. Its frequency ranges from 15 to 100 kHz (Kalwar et al., 2015).

2.3.5 Inductive Coupled Power Transfer

Inductive Coupled Power Transfer is very similar to Inductive Power Transfer. However, it employs capacitors connected to both the primary and secondary coils to compensate for the leakage flux due to the increased air gap. Both transmitter and receiver windings consist of electric circuits composed of an inductor and a capacitor connected working on resonance phenomena to enable effective energy transfer at resonant frequency (Kalwar et al., 2015). The value of the coupling coefficient between coils depends on both axis orientations of each coil, the distance between them and magnetic permeability of the mean (García-Vázquez et al., 2017). This technology had been used on stationary charging and dynamic charging. In the second case, the primary coil is embedded in the pavement at spaced locations allowing the vehicle to be charged at several spaced locations across the roadbed. This technology is the most promissory for dynamic charging because it has high power, medium-range, high efficiency (Qiu et al., 2013), and frequency between 20 and 200 kHz. Even though it has a great initial cost to prepare the infrastructure, it also has a big potential to elude this cost by decreasing the electric vehicle battery size (Kalwar et al., 2015).

2.3.6 Resonant Inductive Power Transfer

The Resonant Inductive Power Transfer is another technology that uses inductivity and has power electronics and wireless transformer coils. In the same way as other inductive power transfers, the AC voltage is converted into the AC source and supplied to the primary coil. Following that, the secondary coil receives power via a varying magnetic field, and this power is converted to DC to charge the battery from EV. Different from traditional IPT, to improve efficiency, this technology has additional compensation networks in the series and/or parallel configurations are added to both the primary and secondary windings to create the resonant case. When the resonant frequencies of the primary and secondary coils are matched together, efficient power transfer is possible (Panchal et al., 2018). Besides boosting the power transfer capability, employing resonant circuits in the primary and secondary coils minimizes the voltage and current ratings of the source power supply (Kar et al., 2018).

2.3.7 Potential of wireless charging technologies for eRoad

Wireless charging technologies differ in technical characteristics; however, they all provide an increase in drive range and decrease in battery size compared to stationary technologies, in addition to a decrease in driver's range anxiety, and it does not cause visual impacts on the highway. On the other hand, wireless charging is a new technology, that was not vastly tested and explored. In addition, it has a great impact in the pavement; it is not easily accessible for maintenance and produces electromagnetic field.

Table 3 summaries the efficiency, power, cost, technology maturity level, applicability for EV Charging, of different wireless charging technologies. Technology Readiness Level is based on the NASA criteria (Mankins, 1995), from level 1 as being more preliminary studies until level 9. Level 1 is defined as basic principles observed and reported, while level 9 is assigned when the studied product has proven to be successfully operated in a real-life scenario. Level 4 is attributed to prototypes validated in the laboratory, and for level 5 the validated happened in a relevant environment. The comparison results indicate that the most successful solution in wireless charging of EV is the Inductive Coupled Power Transfer (Kalwar et al., 2018). This technology achieves high efficiency and high power with an air gap suitable for electric vehicle dynamic charging.

Table 3 Comparisons of Characteristics of Wireless Charging Technologies

Charging Technology	Charging Efficiency	Power	Air Gap	Charging Time	Technology Readiness Level (TRL)	Applicable for EV Charging
Microwave (Qiu et al., 2013, and Shinohara et al., 2013)	76%	1.4 kW	10 cm	Passenger Car: 22.6 h *calculated	4	Yes
Capacitive (Panchal et al., 2018, Vaka and Keshri, 2017, and Lu et al., 2017)	83% - 90%	3 kW	15 - 30 cm	Passenger Car: 8.9 h *calculated for 90% efficiency	4	No
Magnetic Gear (Li, 2009)	81%	1.6 kW	15 cm	Passenger Car: 18.5 h *calculated	6	No
Inductive Coupled (Panchal et al., 2019, Vaka and Keshri, 2017, Oak Ridge - ieee, 2018)	71% - 97%	1 kW - 120 kW	7.5 - 50 cm	Passenger Car: 15 min *calculated for 100 kW power and 97% efficiency	9	Yes
Resonant Inductive (Panchal et al., 2018)	90%	N/A	15 - 30 cm	N/A	4	Yes

*calculated values assumed passenger car with energy storage capacity of 24 kWh

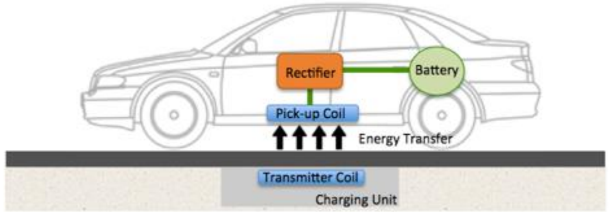
2.4 Design and Construction of eRoad using ICPT

2.4.1 ICPT Design

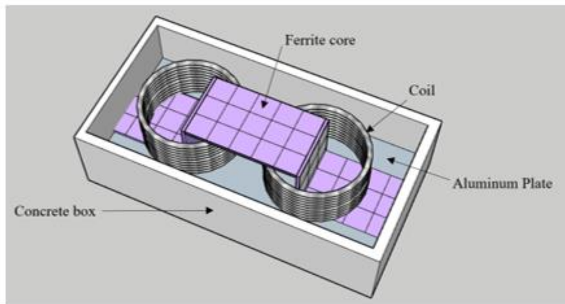
The most studied wireless technology is ICPT due to its cost efficiency and high-power transfer efficiency on the eRoad. This technology consists of onboard and off-board components, as shown in Figure 3 (a). Onboard components are installed in the car and are made of pick-up coil and the current transformer. Off-board is divided into three parts: power supply, converter, and transmitter (primary coil).

An ICPT Wireless Transformer is compounded by coil, shielding material (ferrite and aluminum plate), and protective and supportive layers, as shown in Figure 3(b) (Panchal et al., 2018). The ferrite core, where the cables lay, can have different shapes impacting the magnetic coupling factor. A high permeability ferrite core enhances the coupling coefficient by providing a low reluctance path for magnetic flux (Mohammad et al., 2018). Some common types are U-core, E-core, H-core, I-core, and S-core. The first OLEV generation had an E-core. To increase the efficiency of the system, an I-core was used for the fourth generation (Choi et al., 2015) and an S-type core for the fifth generation (Suul and Guidi, 2018).

One important parameter of ICPT design is the coil shape. Squared and rectangular coils are suitable for arrangement in an array due to aligned sides. However, inductance is increased for these shapes because the sharp corner edges generate an eddy current and increase impedance and hot spot. For that reason, these coil shapes are not good options for high-power applications. Hexagonal coils have the maximum power transfer efficiency at the central position of the primary and secondary coils, but power reduces significantly at the edge of the coil (Panchal et al., 2018). Mecke and Rathge (2004) investigated different coil shapes; the circular shape presented good coupling, however, the power decreased significantly with misalignment. In an attempt to solve the issue, oval shaped-coil was presented, and although it allowed more misalignment, it showed not to be suitable for high power applications such as electric vehicle charging, once it did not transfer high power as efficient as the circular-shaped coil.



(a)



(b)

Figure 3 Illustration of eRoad structure using inductive coupled power transfer: (a) system design; and (b) layout of charging unit

The ICPT system can be installed in segments or as a single-long-coil track. A single-long-coil track can be inefficient in low traffic roads. The whole track is activated, causing a lot of lost energy since the receiver only occupies a small part of the track (Sun et al., 2018). In a segmented design, the length of the segment and the distance between the coils can vary. As a result, there is great flexibility in how the ICPT system can be installed. For every segment of coils installed adjacent to each other, an inverter should also be installed as well to guarantee the appropriate high-frequency AC current supply. The smaller the segments, the greater the number of segments and inverters, which can increase the cost of the system significantly. To avoid the higher cost, the longer segments are preferable (Stamati and Bauer, 2013).

Yilmaz et al. (2012) analyzed both long wire loop and segmented loops. The second one he divided into two: sectioned wired loop – length of the loop is about the size of the vehicle and gaps between loops are smaller (0.2m); and spaced loop – the loop (0.5 m) is much smaller than the car, and the gaps are larger (1 m). He computed the magnetic properties, mutual, and leakage inductance in a 3D finite element analysis. The result is that the smaller loop sizes can reduce the supply voltage requirements and the magnetization reactive power.

The authors (Yalmaz et al., 2012) also conclude that the system's geometry impacts the efficiency due to the coupling coefficient. The efficiency of a magnetic resonance wireless power transfer is given as follows [1], where *n* is efficiency, Z_l is the load impedance, R_p and R_s are the resistance of primary and secondary coils respectively, L_p and L_s are the self-inductance, w_o is the resonance frequency, k is the coupling factor, and μ_0 is the effective permeability with core. It depends on the core material and geometry. The system's efficiency is quadratic in k, the coupling factor, showing the high impact of this factor in the efficiency.

$$n = \frac{Z_l}{(R_s+Z_l)(1+\frac{R_p(R_s+Z_l)}{\left(\frac{w_0}{\mu_0}\right)^2 k^2 L_p L_s})} \quad [1]$$

To determine the length of an eRoad section, there are two important parameters: transmitted power and speed limit. The energy transmitted to the EV from the e-Road is the product of the power generated through the ICPT system and the time the vehicle is exposed to the primary coils. The exposer time is determined by the vehicular speed and the length of the e-Road section (Stamati and Bauer, 2013). Knowing the power of the ICPT system, the next step is to define the energy transfer goal of the system, determine the speed limit following the state legislature, and calculate the needed length. To maintain a constant speed in a highway, it is estimated that the required power transfer from an eRoad with a wireless system is between 20kW to 40kW for passenger vehicles, and between 100kW and 180kW for trucks and buses (Highways England, 2015). The estimation was calculated using a high-level model with sensitive analysis considering traffic density by the time of day. For passenger cars, the used car model was a

Nissan Leaf, and the wheel to grid efficiency was assumed to be 73%. To maintain 50 mph speed, the vehicle requires 12 kW from the grid, while for 70 mph, the value almost double. For a Scania R-series truck at a 55-mph speed, the grid's power demand is 175 kW.

2.4.2 Construction of eRoad

The eRoads are designed to provide energy power to charge EVs dynamically; however, they also need to perform as a traditional road ensuring structural capacity and surface function for conventional and electric vehicles. There are two main construction technique categories for embedding a wireless charging system in the pavement: (1) Prefabrication-based construction method, which has a short period of in-situ implementation because the concrete slab with charging unit can be prefabricated in the factory; (2) In-situ construction method, in which all construction and installation are made on the site, from excavation to placement of charging module (Cheng, 2016).

The precast construction method is preferred for eRoad with concrete pavement due to the advantage of the accelerated construction period and factory quality (Nguyen et al. 2014; Dinh et al. 2014). The precast concrete slab has been used as pavement rehabilitation technology by many highway agencies (Bush, 2017; and Bull and Woodford, 1997). The critical issues that affect the performance of the precast slab are the site preparation, installation method, and load transfer through dowel connection (Tayabji et al., 2012). In-situ construction can be trench based or full lane construction with respect to the existing pavement. The trench method may only be applicable for asphalt pavement, while full-lane reconstruction can be used for concrete pavement. Structural integrity is the most concern when the trench method is used for construction. Table 4 summaries advantages and disadvantages of different construction methods of eRoad about construction method (Highways England, 2015).

Table 4 Advantages and Disadvantages of Construction Methods of eRoad

	Construction Method	Process	Advantages	Disadvantages
In-Situ	**Trench**	Create a trench in the existing pavement to install charging unit, and backfill and lay asphalt surfacing layer	Quickest and cheapest option	Reflective cracking at pavement surface at transverse joints of charging units
	Full-lane Reconstruction	Remove the full depth of pavement layers, install the charging unit with concrete slab	Alignment of charging unit with concrete slab	More time consuming and expensive construction compared to the trench method
Prefabricated	**Full-lane Prefabricated Construction**	Replace the pavement with a full lane width prefabricated concrete slab containing charging unit	Accelerated construction period, factory construction quality (which reduces future maintenance)	Likely to be the highest capital cost option

Chapter 3 Life Cycle Cost Analysis of Wireless Charging Techniques

3.1 LCCA Principle

LCCA evaluates the economic performance of charging infrastructure over its life by analyzing the initial investment cost as well as the long-term expenses of operation and maintenance. Additionally, the analysis adjusts for the discount rate to equalize all cost-bases by bringing costs to their present values. LCCA is an efficient decision-making tool to help compare infrastructure design options, analyze tradeoffs between low initial investment and long-term savings, identify the most cost-effective system, and determine system "payback" time. Figure 4 schemes the process flow of LCCA.

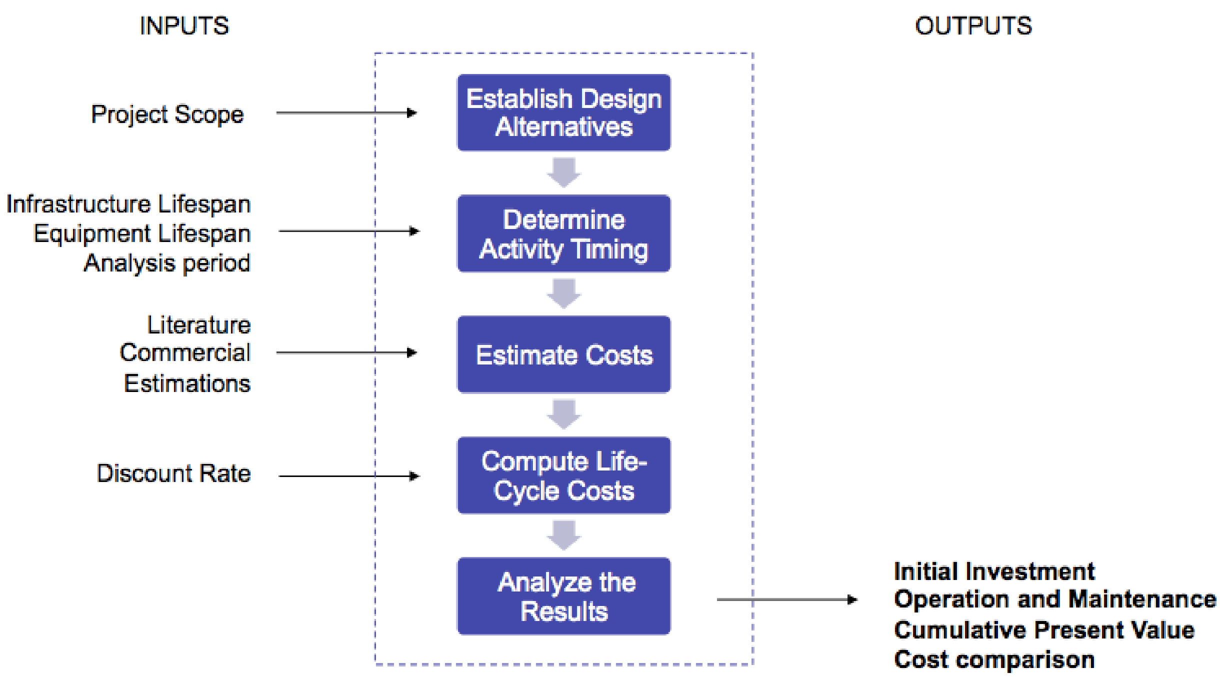


Figure 4 Flowchart of LCCA

The analysis period and discount rate are the two most important factors affecting the life-cycle cost. The analysis period should be selected to review the longest-lived subsystem. This study selected a 30-year analysis. The discount rate used in this study accounts for fluctuations in both investment interest rates and inflation rate. In this study, the updated real discount rate used is 0.4%, based on a 30-year average from 2021 of OMB released data. The discount rate used to convert values to present value is 0.4%. Equation 1 is used to calculate the present value.

$$PV = \frac{Cost}{(1+r)^N} \quad (1)$$

Where PV is the present value, r is the discount rate, and N is the number of years in the future in which the cost is invested.

The LCCA was used in this study to provide comprehensive cost comparisons between the four types of systems: conventional diesel fueled, plug-in electric charged, stationary wireless electric charged, and dynamic wireless electric charged. Two case studies were conducted, one for electrified pushback tractors and the other for inter-terminal buses used in the ground options of airports. This study assumes to charge electric vehicles plug-in charging and ICPT system for stationary and dynamic wireless charging. Compared to other technologies, ICPT has high power transfer efficiency and performs with a medium air gap, large enough to accommodate the distance pavement surface and vehicle.

3.2 Case Study for Pushback Tractors

3.2.1 Analysis Assumptions

The first case study is conducted for the pushback tractor, one of the ground support equipment at airports. Pushback tractors are vehicles used to push aircraft from gate to taxiway, other gates, or maintenance shed. These machines are critical, operating 24/7 and seeing fleet usage of close or equal to 100%. Substituting the conventional diesel fueled equipment with electric versions can increase or decrease the fleet efficiency, depending on the charging method.

The airport characteristics used in this study were estimated based on Newark Liberty International Airport. The airport has three terminals and three runways and handles about 1,000 flights per day. Furthermore, it is assumed that the airport operates with 50 pushbacks, a combustion motor vehicle with 120 liters' diesel fuel capacity. Each vehicle travels 40 miles per day on average, with a fuel efficiency of 1.5 L/km (0.4 gallons/mile). These values were obtained from a technical visit to Newark Liberty International Airport, which included interviewing aeronautical operations managers, the ground fleet maintenance manager, and the ground fleet move team leader.

For electric pushbacks, the assumed power capacity is two batteries of 180 kWh each. The electricity consumption for all-electric pushbacks is assumed to require the same amount of energy to operate, regardless of the power source. The motor combustion efficiency is estimated to be 21%, and the battery efficiency to be 90%. According to the U.S. Energy Information Administration (EIA), 1 kWh contains 3,412 Btu, and one gallon of diesel contains 137,381 Btu. The equipment energy consumption is 11.54 Btu/mile, in which electric consumption represents 3.76 kWh/mile. The total energy required for pushback to operate a full day is 150.4 kWh for electric vehicles and 60 liters of diesel for internal combustion engine vehicles. The time required for refueling and recharge using different methods is calculated below.

Scenario 1: Conventional Diesel Fuel

Each pushback is refueled every 48 hours at a fuel farm in the airport apron. Refueling takes 6 minutes on average. These include 1.5 minutes to park and connect the diesel pump, 3 minutes to fuel (rate of 40 liters/minute), and 1.5 minutes to disconnect and restart the pushback.

Scenario 2: Plug-in Charging

Each pushback is recharged in a 500-kW charging system for 39 minutes every 48 hours. These include 36 minutes to charge 300.8 kWh batteries, 1.5 minutes to park and connect, and 1.5 minutes to disconnect and start the vehicle. Although the two-180kWh battery has 360kWh capacity, in order to operate 48 hours, the pushback requires 300.8 kWh power. Pushbacks are used 24/7, and to avoid any risk of waiting to charge, this study assumed one plug-in charger per vehicle.

Scenario 3: Stationary Wireless Charging

Each pushback is recharged in a 120-kW charging system with 97% efficiency for 2.6 hours. These mainly include charging time except one minute to park and start the vehicle. Because pushbacks are highly required in operation, like the plug-in charger, one stationary wireless charging pad per vehicle was assumed.

Scenario 4: Dynamic Wireless Charging

To recharge the 150.4 kWh consumed per day, the pushback needs to move on a wireless charging segment for 1.29 hours that provides 120 kWh power with 97% efficiency. It was assumed that each of the three terminals has two dynamic wireless charging segment (one in each direction) of 0.32 miles, summing a total of 6 segments. Figure 5 shows a schematic illustration of this internal road. The pushback operation does not have a fixed routine, however, when not attached to an airplane, the vehicle follows the internal pre-fixed routes. In this scenario, each pushback serves 20 flights per day, moves aircraft between gates, and assists non-flying aircraft in the maintenance operation. The study assumes that each push back comes and goes from its base 30 times a day, covering all flights and services.

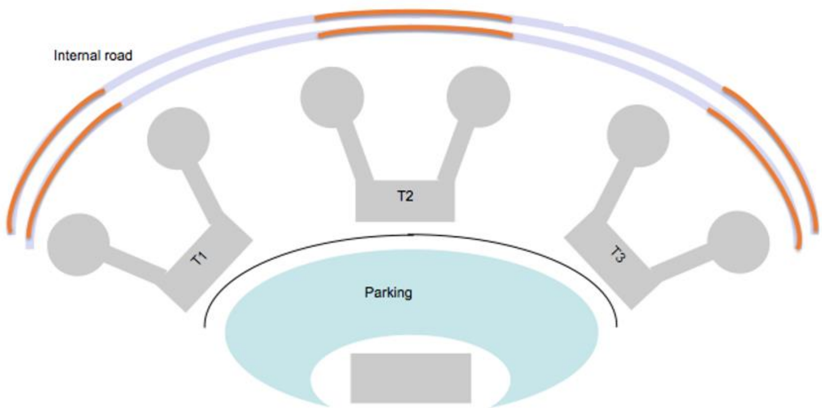


Figure 5 Schematic Illustration of Airport Layout and Pushback Route

The minimum service level must be met regardless of the charging/fueling method. Considering an initial scenario wherein 50 vehicles serve 1,000 flights a day, each vehicle serves 20 flights/day. It is worth noting that each vehicle may not necessarily push 20 aircraft per day. Pushbacks are used to move the aircraft from the gate to taxiway, to other gates, or to travel for maintenance. The number of aircrafts pushed per vehicle varies and depends on other factors in the field. For fleet efficiency calculation, it was assumed that the same daily number of flights was served by each pushback. This assumption represents average service level across vehicles as a good approximation for airport-level analysis. Considering the differences in fueling/charging time, the required pushback fleet size varies to reach the same service level. Table 5 summarizes the comparison of fleet size and service level using different fueling/charging methods.

Table 5 Fleet size and service level using different fueling/charging methods

Item	Conventional	Plug-in	Stationary Wireless	Dynamic Wireless
Fueling/Charging Time	6 minutes	39 minutes	156 minutes	N/A
Fueling/Charging Frequency	Every 48 hours	Every 48 hours	Every 48 hours	Charging while operates
Monthly Fueling/ Charging Time	90 minutes	585 minutes	2,340 minutes	N/A

Monthly Served Flights	600/vehicle 30,000/fleet	593/vehicle 29,650/fleet	568/vehicle 28,400/fleet	601/vehicle 30,050/fleet
% Served Aircraft	100%	98.9%	94.7%	100.2%
Number of vehicles added	0	1	3	0
New - Served Aircraft monthly	600/vehicle 30,000/fleet	593/vehicle 30,243/fleet	568/vehicle 30,104/fleet	601/vehicle 30,050/fleet
New - % Served Aircraft	100%	100.8%	100.3%	100.2%

As opposed to the plug-in charging and stationary wireless charging methods, dynamic wireless charging has the benefit of charging while operating. Charging while driving increases the productivity of the fleet and allows multiple vehicles to charge simultaneously. This method also reduces the marginal cost of adding a pushback to the fleet, since fleet size can be increased without purchasing more chargers or building more charging segments.

3.2.2 Cost Components

The general cost components used for LCCA are summarized in Table 6, including battery, electricity, diesel costs. The battery cost used in the analysis is $156/kWh; however, this value tends to decrease with time, increasing the feasibility of electric vehicles. Another important factor is the price of diesel, $2.659/gallon. Although this value is up to date, it is low compared to historical prices. If the price increases, the operational cost of fossil-fuel vehicles would also increase, thereby increasing the feasibility and attractiveness of electric options.

Table 6 General cost parameters for LCCA

Item	Value	Unit	References
Battery cost	156	$/kWh	(BNEF, 2019)
Energy cost– electricity	0.0837	$/kWh	(US EIA, 2020)
Energy cost – diesel	2.659	$/gallon	(NJ Turnpike Authority, 2020)
Energy efficiency - diesel	0.396	gallon/mile	Survey at EWR
Energy efficiency – electricity	3.76	kWh/mile	Calculated

Table 7 presented procurement costs, annual fuel costs, and maintenance costs of fueling/charging infrastructure. The conventional pushback value was obtained from the survey made at Newark Liberty International Airport. The price of the electric pushback was calculated using the proportional cost of an electric bus over a conventional (for which are values commercially available). The battery pack procurement and annual fuel cost were calculated assisted by values in Table 6. For all three electric options, besides the infrastructure and vehicle maintenance, it is assumed that the batteries are replaced every ten years. The annual energy consumption calculated based on the required daily energy is 5,840 gallons of diesel for conventional vehicles and 54,896 kWh for electric vehicles.

Table 7 Project cost parameters and intermediate calculated values

Item	Conventional (C)	Plug-in (P)	Stationary Wireless (SW)	Dynamic Wireless (DW)	Data Sources
Procurement cost - vehicle	$850,000	$1,040,000	$1,045,000	$1,045,000	C: Survey; P, SW, DW: Calculated
Procurement cost - battery pack	N/A	$56,160	$56,160	$56,160	Calculated
Procurement cost - charger	N/A	$9,500/each	$6,000 each + $5,000/vehicle	$377,264/mile + $5,000/vehicle	P: (Smith and Castellano, 2015) SW, DW: (Bi et al., 2017), (Gill et al., 2014)
Annual Energy Cost	$17,520	$4,595	$4,595	$4,595	Calculated
Vehicle Maintenance Cost	$0.726 /mile	$0.297/mile	$0.297/mile	$0.297/mile	C, P, SW, DW: (The U.S. Federal Transit Administration, 2018)
Infrastructure Maintenance Cost	N/A	$1,000 per 10 years	$1,000 per year	$3,773/mile	P: (Energetics Incorporated, 2017); SW: (Bi et al., 2017) DW: (Gill et al., 2014)

3.2.3 Analysis and Results

The results from LCCA are presented in the figures below. Figure 6 shows the initial investment of each fueling/charging method, which includes the procurement of vehicles, battery packs, and construction and installation of charger components. The conventional method has the lowest initial investment since it does not require any construction or procurement besides vehicles themselves. The highest initial cost is the stationary wireless charging, which requires on-board and off-board charger procurement and installation in addition to vehicle procurement. Furthermore, stationary wireless charging requires three more vehicles than the other electric options in order to maintain the same service-level as the conventional equipment.

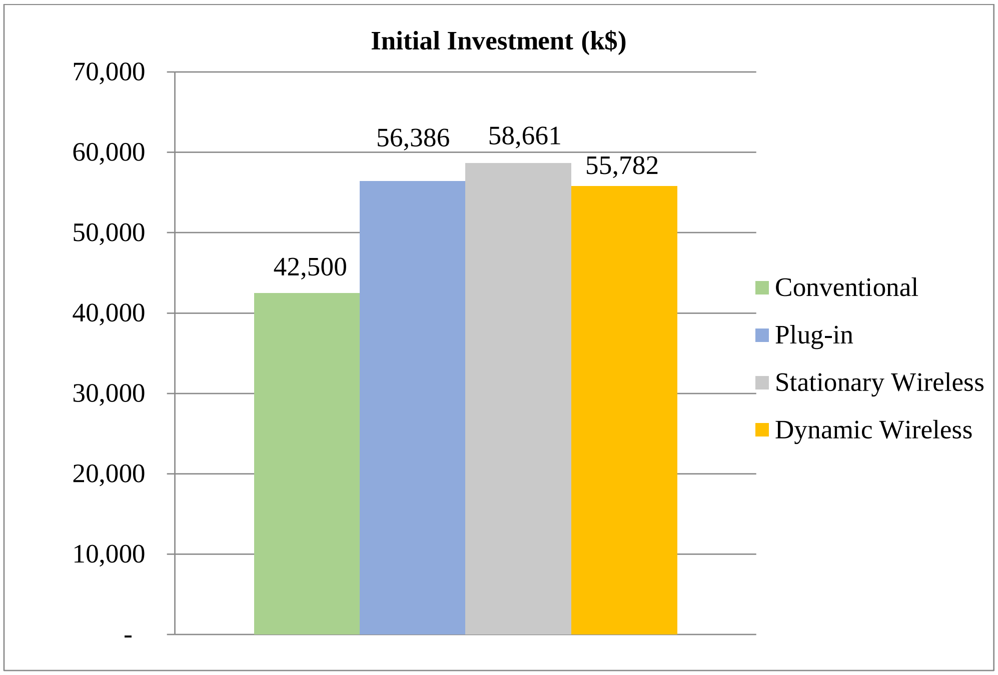


Figure 6 Initial Investments of Different Fueling/Charging Systems for Pushback

Figure 7 presents the Present Value of each year during the 30-year period. The operational cost of conventional vehicles increases significantly due to diesel cost and propulsion engine maintenance. Infrastructure maintenance costs were considered for the electric systems but not for the conventional fuel station. Even so, the lifetime cumulative cost for the conventional system is still greater than all three electric systems. In year 9 and 19, the electric vehicles have peak operational costs due to battery replacement. Although the depleted batteries could be resold and repurposed, this benefit was not considered in the analysis.

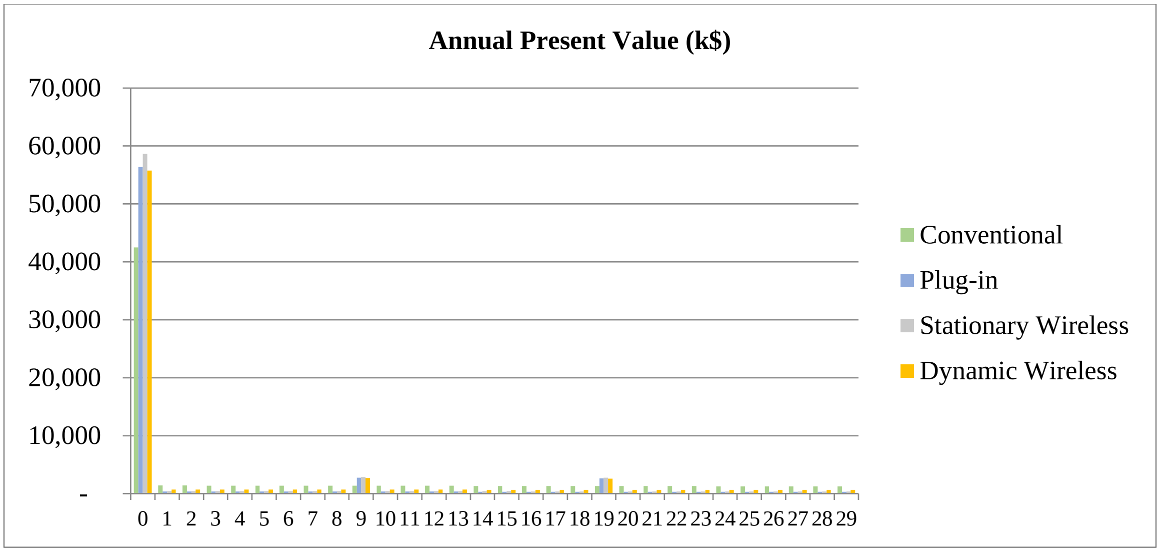


Figure 7 Annual Present Values of Different Fueling/Charging Systems for Pushback

The cumulative present value should be the cost with highest impact for decision-making purpose. This value represents the overall cost of the system's lifetime operation. Figure 8 summarizes the cumulative present value, in other words the amount of money invested over the studied period of 30 years. The conventional system is the most expensive option followed by dynamic wireless charging, stationary wireless charging, and lastly plug-in charging. Plug-in charging is the most economic option since it has the lower charger cost compared to the other electric options, additionally to the lower maintenance cost.

Stationary wireless charging system has the second lowest cumulative present value (17% lower than conventional, 9% lower than dynamic wireless charging). This method likewise has higher fleet efficiency. Dynamic wireless charging is the most expensive electric option although having the highest fleet efficiency, which allows increase in fleet size without cost increase in infrastructure. Furthermore, the possibility of electrifying other airport vehicles and equipment that will share the same charging infrastructure makes this an attractive option. Both are innovative methods and thereby create innovation value.

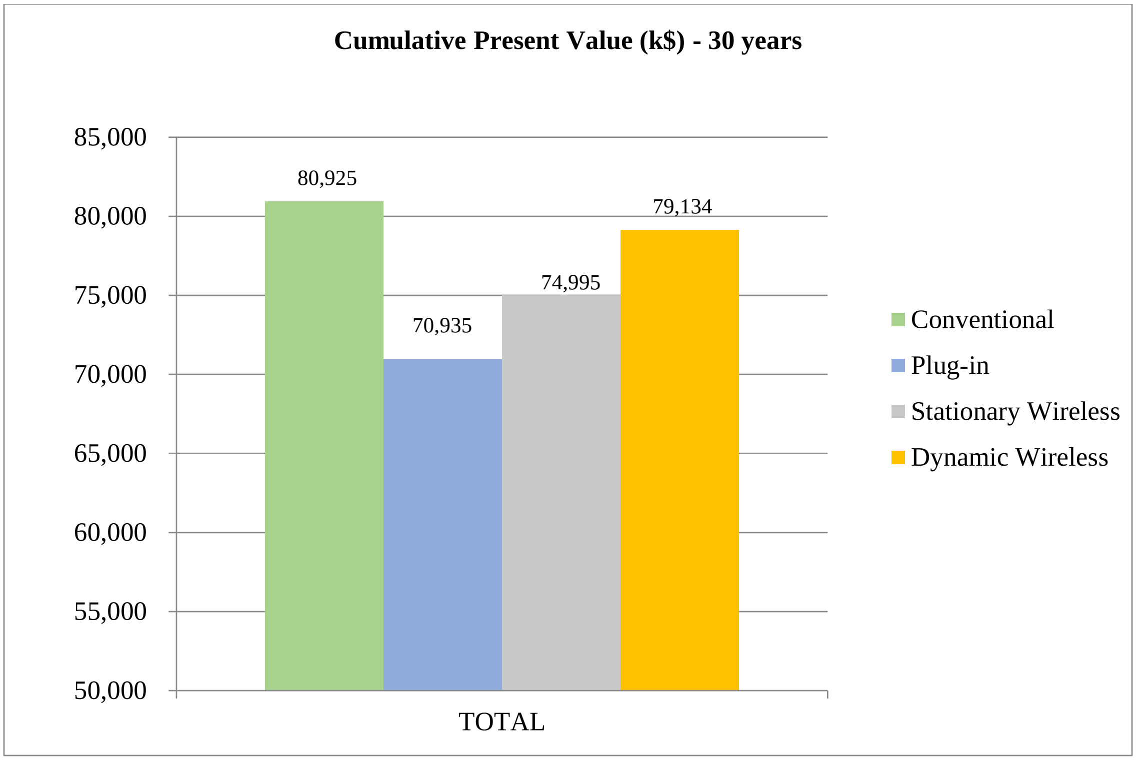


Figure 8 Cumulative Present Values of Different Fueling/Charging Systems for Pushback

3.3 Case Study for Inter-terminal Buses

3.3.1 Analysis Assumptions

The second case study was conducted for inter-terminal bus fleet, as shown in Figure 9. It is assumed that in the aforementioned hypothetical airport there is an inter-terminal network system with 16 buses, which provides one bus per minute during peak hours at each terminal. During less busy hours, the buses are refueled for internal combustion engine vehicles, and recharge for plug-in vehicles. Wireless charged electric vehicles are charged during its operation. On average, inter-terminal bus fleets do not operate with full capacity since passenger flights reduce in frequency during specific hours of the day. Each bus is assumed to perform 3 shifts of 6 hours each.

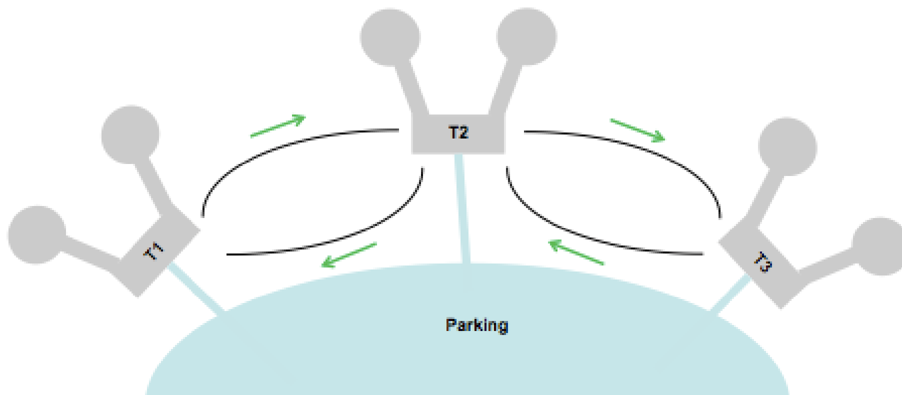


Figure 9 Schematic Illustration of Airport Layout and Inter-terminal Bus Route

It is assumed that each bus takes one minute to drop-off and board passengers, buses rides in an average speed of 20 mph, and it is one-mile-long between terminals. The total operation time for one loop (T1 – T2 – T3 – T2 – T1) lasts 16 minutes, 12 minutes in movement driving between terminals and 1 minute in each terminal for pick-up/drop-off operation. Each bus completes 66 loops per day divided in three 6-hours shift. To initiate a new shift the bus park in Terminal 2 for 8 minutes to switch drivers. In a one-day operation, each bus covers 264 miles, or 425 kilometers.

Scenario 1: Conventional Diesel Fuel

Considering fuel efficiency of 0.32 L/km, each bus consumes 136 liters of diesel per day. Assuming the fuel tank capacity of 450 liters, the bus needs to be refueled every 3 days. Diesel refueling operation is not critical since the fleet only operates at full efficiency during the peak hours of day.

Scenario 2: Plug-in Charging

The power efficiency of electric bus is 1.27 kWh/km (Potkany et al., 2018). The operation requires 540 kWh per day per bus to operate. Assuming using a 500-kW charging system, the bus needs 65 minutes to recharge. Since the fleet only operates 18 hours per day, it would be possible to have four plug-in chargers for 16 buses in an optimized charging operation. However, this economic analysis assumes the worst-case scenario, in which12 buses are charged at the same time using 16 plug-in chargers.

Scenario 3: Stationary Wireless Charging

The 120-kW charging system has 97% efficiency, which requires 4.6 hours to charge battery for one-day operation. For this charging system it is assumed that the wireless charging pads are installed where the bus stops for passengers boarding and drop-off, in all terminals. Since each bus stays in the stationary wireless charging zone for 4 minute per loop, and 8 minutes before each shift, the system provides 559 kWh per bus per day - higher energy than required. Theoretically, during peak hours there are always 1 bus on Terminal 1 and on Terminal 3, and 2 buses on Terminal 2. For the economic analysis, it is assumed the total of four wireless charging pads installed, one in each terminal except for Terminal 2, where two pads will be installed to guarantee normal operation even during shift changes which is not done during peak hours. The shift changes are assumed to be phased-out so they are not occurring simultaneously either.

Scenario 4: Dynamic Wireless Charging

With the same charging efficiency, the dynamic wireless charging requires the same charging time as the stationary charging system. However, dynamic system provides charging while the bus is in-motion. Considering average speed of 20 mph, the bus needs to ride over 92.8 miles on a wireless charging segment in order to provide the required energy. Since the operation occurs in a closed network, where buses rides 66 loops per day, an electric 1.4-mile segment is enough to provide the needed energy.

Table 8 Bus Fleet Characteristics per System

Item	Conventional	Plug-in	Stationary Wireless	Dynamic Wireless
Number of Buses	16	16	16	16
Number of Charging/Segment length	-	16	4	1.4 miles
Fuel efficiency	0.32 L/km	1.27 kWh/km	1.27 kWh/km	1.27 kWh/km
Total Energy per Day per Bus	136 L	540 kWh	540 kWh	540 kWh
Annual Consumption	794,240 L	3,153,600 kWh	3,153,600 kWh	3,153,600 kWh

3.3.2 Cost Components

The calculated costs were based on Table 6, and it is presented on Table 9

Table 9 Project cost parameters and intermediate calculated values

Item	Conventional (C)	Plug-in (P)	Stationary Wireless (SW)	Dynamic Wireless (DW)	Data Sources
Procurement - vehicle	$450,000	$550,000	$550,000	$550,000	C: (Aber, 2016) P, SW, DW: (Proterra, 2019)
Procurement – battery pack	-	$28,080	$28,080	$28,080	Calculated
Procurement – charger	-	$9,500/each	$6,000/each + $5,000/vehicle	$377,264/mile + $5,000/vehicle	P: (Smith and Castellano, 2015) SW, DW: (Bi et al., 2017), (Gill et al., 2014)
Annual Energy Cost - Vehicle	$131,993	$16,497	$16,497	$16,497	Calculated
Vehicle Maintenance Cost	$0.44/mile	$0.18/mile	$0.18/mile	$0.18/mile	C, P, SW, DW: (The U.S. Federal Transit Administration, 2018)
Infrastructure Maintenance Cost	-	$1,000 every 10 years	$1,000 per year	$3,773/mile	P: (Energetics Incorporated, 2017); SW: (Bi et al., 2017) DW: (Gill et al., 2014)

3.3.3 Analysis and Results

The LCCA was performed and the results are presented in the figures bellow. Figure 10 shows the initial investment of each method. The conventional method has the lowest initial investment; similar to the pushback tractor analysis, this occurs because conventional bus does not require any construction or other procurement components besides the vehicle itself. The initial investments for all three electric options have very similar costs with difference smaller than 5%, although their designs vary in the number and type of charger.

The annual cost of conventional vehicle is much higher than electric options, mostly driven by the fuel price. The cost per mile of an electric bus is extremely lower compared to the conventional vehicle, $0.1105 and $1.3566/mile, respectively. Due to the high mileage per day travelled by each bus, the fuel cost has great impact on the overall cost. Figure 11 presents the annual cost of different fueling/charging systems for 30 years. On year 9 and 19, there are another investment in all categories due to the procurement of new buses. Differently from pushback that has a lifetime of 30-years, buses usually have a lifetime between 10 to 12 years.

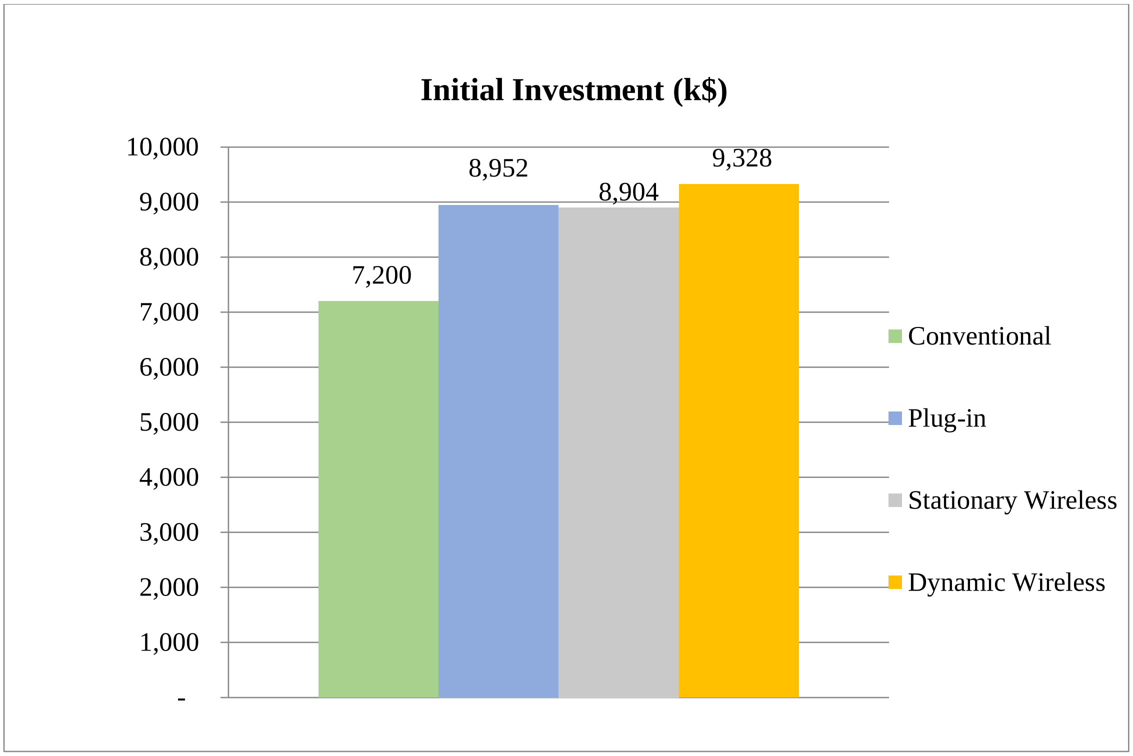


Figure 10 Initial Investments of Different Fueling/Charging Systems for Inter-terminal Bus

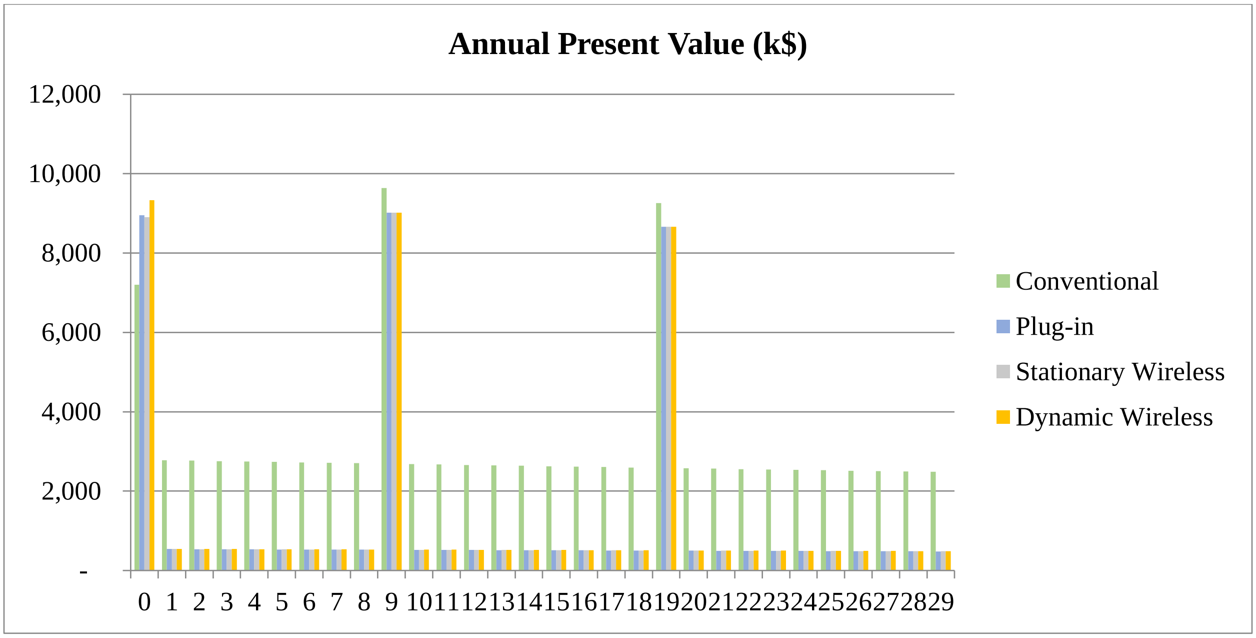


Figure 11 Annual Present Values of Different Fueling/Charging Systems for Inter-terminal Bus

Figure 12 presents the total investment over 30 years, including initial investment and operation, all calculated to the present value. Due to the high operation cost of conventional fleet, the cumulative value over 30 years is extremely high for conventional vehicle system. The electric options have very similar costs, with difference smaller than 1.5%. This result shows the impact of the operation cost on the cumulative present value, the electric options has almost the same operation price per year, deferring only by the infrastructure maintenance cost.

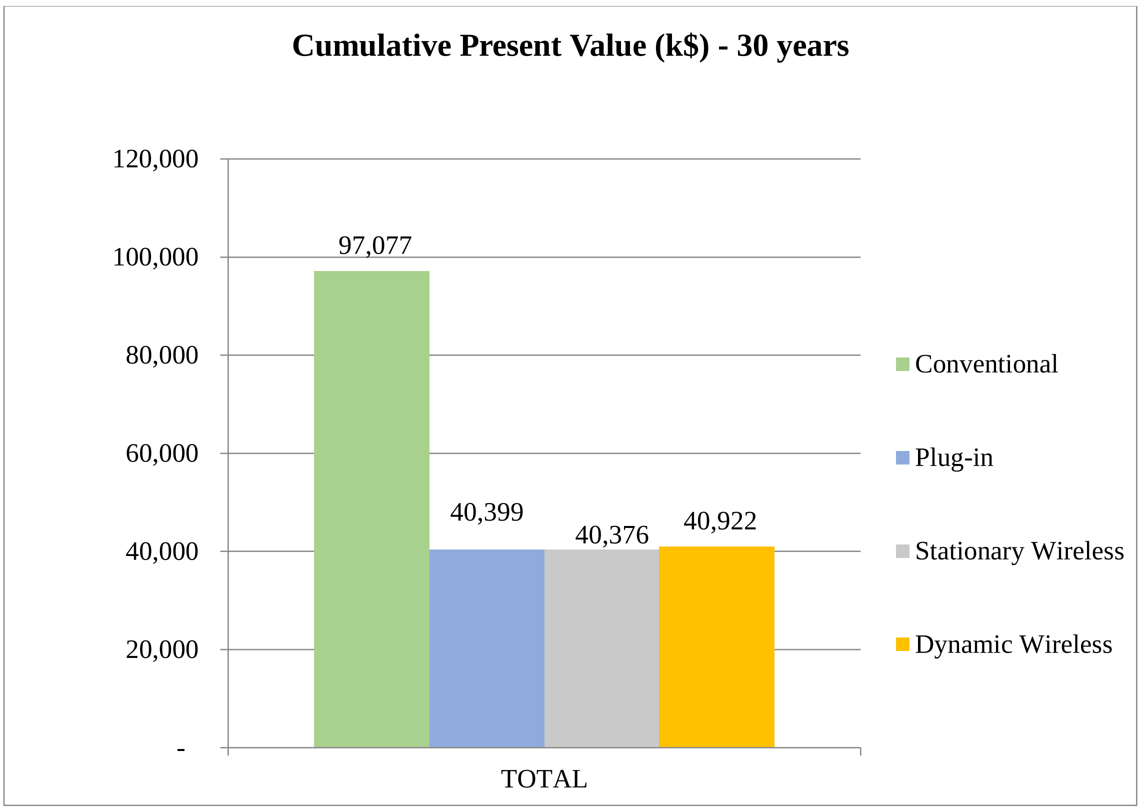


Figure 12 Cumulative Present Values of Different Fueling/Charging Systems for Inter-terminal Bus

3.4 Comparison Between Two Case Studies

This work presented two different LCCA analyses for distinguishes vehicles in an airport. The two case studies showed that conventional vehicle has the lowest initial cost but the highest cost in 30-year period, and plug-in charging system has the lowest cumulative cost.

The bus fleet travels a higher mileage than pushback tractors per day, and the cost per mile of conventional bus has great discrepancy compared to electric bus. Great portion of the operation cost is the relationship between travelled mileage and cost per mile. As a result, the cumulative cost of conventional bus fleet compared to the electric options is much higher than the same comparison for pushback tractors. The decision to migrate from conventional bus to electric is extremely clear, however the decision between different charging methods is very sensitive, since they have very similar cumulative costs.

Differently from the bus study, the decision to migrate from conventional pushback to electric is observable but not significant. Although the conventional pushback has greater cost over 30-year period, the difference between conventional and electric pushback is small, which could lead to other factor being considered, such as implementation of new process, investments in training, inconvenience of the implementation, and uncertainties caused by using new technology.

Electric options have very similar long-term investments. Since their economic differences are very small, the best benefit-cost may vary depending on the project. In this scenario, other non-economic criteria can play an important role in the decision between electric charging options. The plug-in charger for electric buses is a mature technology used worldwide, however the wireless technology can create other benefits not considered in this analysis such as labor optimization, and intangible innovation value for the airport. For pushbacks, wireless charging can also bring intangible labor wellness benefits. It has the advantage of avoiding human-wire interaction, which reduces shock risk especially on harsh weather conditions, since those vehicles are usually maneuvered in open space. In other words, the LCCA used in different situations showed that using electric charging method could be economic beneficial, however, the recommended method could vary when encountered different conditions.

Chapter 4 Life Cycle Assessment Analysis of Charging Techniques

4.1 LCA Methodology

4.1.1 Framework

The life cycle assessment (LCA) framework compiles the inputs and outputs of a product, process, material, or activity in order to evaluate its potential environmental impacts. While normally considered from cradle-to-grave, the LCA can also be applied to cradle-to-gate, gate-to-gate, and gate-to-grave. The approach in this study is a process-based, cradle-to-gate LCA. Furthermore, and in accordance with the ISO 14044:2006 guidelines, this study defines the goal and scope of the LCA and its constituent phases: the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, and the life cycle interpretation phase. The subsequent study provides a critical review of the LCA and discusses the relationship between the phases.

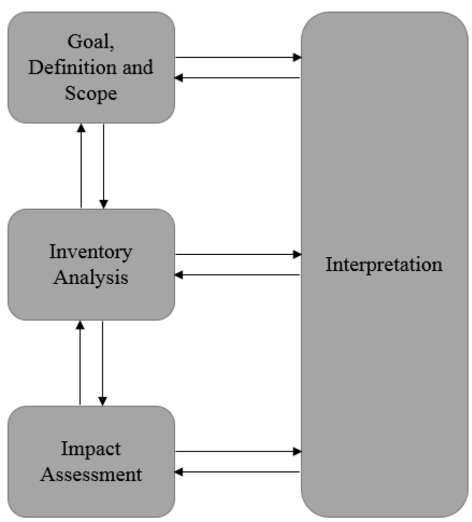


Figure 13 Life Cycle Assessment framework

4.1.2 Goal and Scope

This study conducted two separate LCA analyses (one on pushback tractors and one on inter-terminal buses) by comparing the environmental impacts of diesel-fueled versus electric-powered ground-vehicle fleets at airports. In addition, each LCA considered three charging scenarios for all-electric fleets: plug-in charging, stationary wireless charging, and dynamic wireless charging. The ensuing environmental impact assessment is expressed in the Cumulative Energy Demand (CED), which measures the total primary energy requirements of renewable and non-renewable sources, and the Global Warming (GW) Impact, which measures the warming effect on the Earth's surface from greenhouse gas (GHG) emissions.

Each LCA analyzes a hypothetical airport with an average of 1,000 flights per day, 2,000 acres in area, three terminals, and three runways, as presented in the previous chapter. Most assumptions used is based on interviews with the aeronautical operations managers, the ground fleet maintenance manager, and the ground fleet move team leader at Newark Liberty International Airport. The analyses make several further assumptions about the vehicle fleets, including vehicle uniformity within each fleet.

As presented in the LCCA section, this study presumes a pushback fleet size of 50. Each pushback travels 40 miles per day. For the conventional fleet, each vehicle has a 120-liter diesel capacity and a fuel consumption of 1.5 L/km (0.4 gallons/mile). For the electric fleet, the vehicle capacity is 2 batteries of 180 kWh each. The study assumes electric and conventional pushbacks require an equivalent amount of energy (Btu) to operate. Assuming an efficiency of 21% for combustion engines and 90% for batteries, the electric consumption rate is 3.76 kWh/mile.

The bus fleet is assumed to have 16 vehicles, with 600-liter capacity for the combustion engine vehicles and 180-kWh battery capacity for electric vehicles. Each vehicle travels 264 miles (425 km) per day with energy efficiency of 0.32 L/km and 1.27 kWh/km for conventional and electric bus, respectively.

The functional unit is an important element in the LCA, it is used to provide a reference to relate the input and output of the system. This LCA element defines de service that needs to be delivered by the system studied. The functional unit used in this study is GSE service required per flight, which is defined as the lifetime impact (over 30 years) of vehicle manufacturing, charger construction, and vehicle operation divided by the total number of flights over the same period.

4.1.3 System Boundary

Figure 14 illustrates the system boundary, which – in accordance with the process-based, cradle-to-gate approach – accounts for the burdens (including the material extraction, production, and manufacturing) of chargers, batteries, and fossil fuels in addition to the use-phase energy consumption, however does not include the end-of-life for the fleets. Neither the construction nor the assembly of pushbacks and buses bodies were considered in the project; moreover, the study assumes the impacts of these processes to be equal for electric and conventional vehicles. Likewise, vehicle end-of-life is considered equivalent regardless of power source. Usually used vehicles are sold to smaller carriers (Kerrigan, 2020) but this is not within the scope of this LCA analyses.

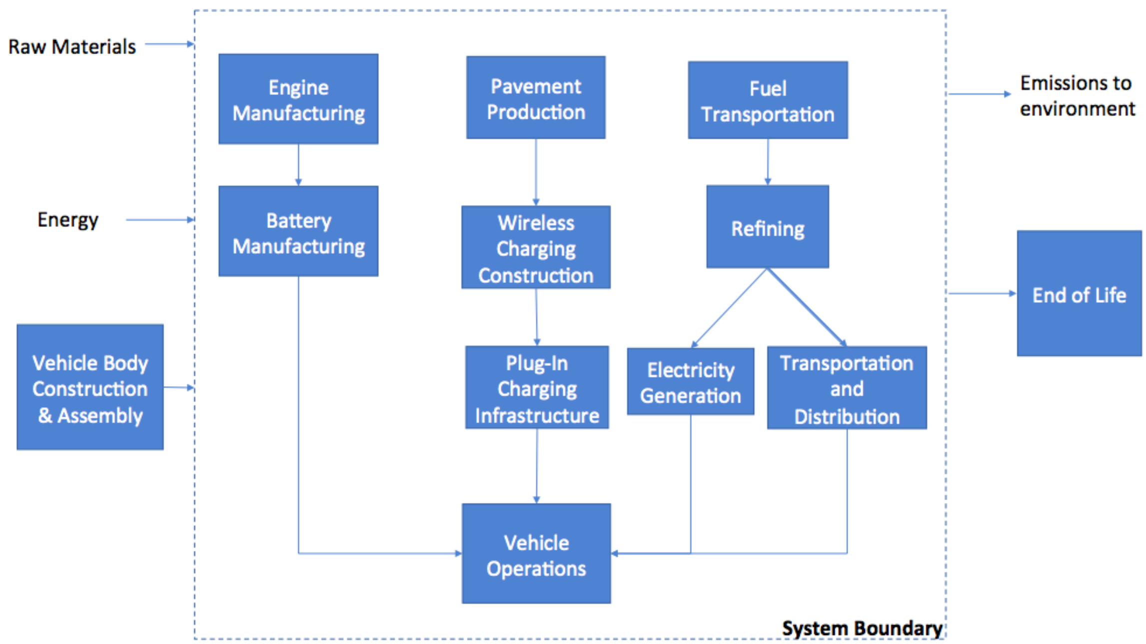


Figure 14 LCA System Boundary

4.2 Life-Cycle Inventory

The calculations for energy consumption and GHG emissions are based on various secondary data sources such as academic publications, online databases, and industry reports. There are three systems to consider for each LCA: vehicle equipment, charger construction, and operation. The vehicle chassis and frame serve the same purpose regardless of the energy used and thus are similar enough to be excluded from the comparison assessment. Similarly, the charging infrastructure for stationary wireless charging, plug-in charging and diesel as fuel include the existing pavement, while the dynamic wireless charging requires modifications in the pavement. Pavement maintenance is also excluded from the analysis since this procedure will occur regardless of the charging method. Finally, the study discusses the differences of energy demand and emission between electricity and diesel production in the operation section.

4.2.1 Vehicle Equipment

Each LCA considers one of two vehicle systems: the first is that of an electric vehicle, and the second that of a diesel vehicle with internal combustion engine (ICE). For both systems, the data has been scaled appropriately in terms of the engine power since data only for smaller vehicles was available. The study obtained the scaled values by multiplying the data for smaller engines, batteries, and inverter by the power ratio between the smaller vehicle and the pushback/bus. In cases where a range of values was available, the average was used. In each assessment there are three elements of the system inventory to consider: the manufacturing, the energy required for manufacturing, and the associated energy source.

The electric vehicle system inventory, shown in Tables 10 and 11, includes the energy demand used in obtaining and refining the raw materials, as well as the energy used to produce each component. Ranges of values are available for the manufacturing component because of factors including the manufacturing region/country, the use of recycled material, and the processes used to mine and refine raw material. For example, a study done by the World Steel Association (2015) emphasized the ability to reduce environmental impact by reusing, remanufacturing, or recycling steel; however, this LCA does not consider these methods. In another study Peiro and Mendez (2013) report there to be a lack of quantitative data regarding the material and energy requirements for extraction and refinement of rare earth materials because over 95% of the production is in China. Additionally, one of the primary processes in refining rare earth materials is separation from other minerals. These processes can vary dramatically in method and energy requirements depending on the other minerals (Peiro and Mendez, 2013). Silica, another raw material used to produce an engine, is similar: some primary factors that affect production emissions are the furnace operation and the properties of the raw materials (Kero et al., 2016).

The amount of energy required to manufacture an electric vehicle battery is high enough to render the energy to construct the engine and inverter negligible (Kurland, 2019). Kurland acknowledges that energy usage estimates for battery manufacturing also vary, largely because of manufacturing facility size and the estimation method itself. This study uses a CED of 1,126 MJ per 1KWh of battery (obtained using the Argonne National Laboratory Greenhouse Gases, Regulated Emissions and Energy Use in Transportation – GREET - Model) and encompasses energy consumed by the raw material production and transportation in addition to the battery manufacturing process (Dai et al., 2019).

Finally, the environmental impact is extremely sensitive to the source of energy generation (Kurland, 2019). Tables 10 and 11 show the global warming potential, in terms of equivalent carbon dioxide, for the production, refinement and manufacturing of the engine and battery. This study assumes that the batteries will be replaced twice during each vehicle's lifetime.

Table 10 Electric Pushback Tractor Vehicle System Life Cycle Inventory

Raw Materials - Engine and Inverter	**Amount**		**CED (MJ/kg)**	**GHG (kg CO2-eq/kg)**	**CED (MJ/vehicle)**	**GHG (kg CO2-eq/vehicle)**	**Reference**
Copper	16	kg	60-125	3.0-5.0	1480	64	Environmentally Benign Manufacturing, n.d; World Steel Association, 2015; Peiro and Menzed, 2013; Browning et al., 2016; Kero et al., 2016
Steel	130.7	kg	6-15	2-2.5	1372	294	
Rare Earth	4	kg	6-3	65.4	0.024	261.6	
Silica	1.3	kg	230-235	3.4	310	4.5	
Ferrite	13.3	kg	20-25	2-2.5	300	30	
Battery Manufacture	**Amount**		**CED (MJ/kWh)**	**GHG (kg CO2-eq/kWh)**	**CED (MJ/battery)**	**GHG (kg CO2-eq/battery)**	**Reference**
TOTAL ELECTRICITY AND MATERIALS	360	kWh	1126	72.9	405360	26244	Dai et al., 2019

Table 11 Electric Bus Vehicle System Life Cycle Inventory

Raw Materials - Engine and Inverter	**Amount**	**CED (MJ/kg)**	**GHG (kg CO2-eq/kg)**	**CED (MJ/vehicle)**	**GHG (kg CO2-eq/vehicle)**	**Reference**

Copper	12	kg	60-125	3.0-5.0	1110	48	Environmentally Benign Manufacturing, n.d; World Steel Association, 2015; Peiro and Menzed, 2013; Browning et al., 2016; Kero et al., 2016
Steel	98	kg	6-15	2-2.5	1029	220.5	
Rare Earth	3	kg	6-3	65.4	0.018	196.2	
Silica	1	kg	230-235	3.36	232.5	3.36	
Ferrite	10	kg	20-25	2-2.5	225	22.5	
Battery Manufacture	**Amount**		**CED (MJ/kWh)**	**GHG (kg CO2-eq/kWh)**	**CED (MJ/battery)**	**GHG (kg CO2-eq/battery)**	**Reference**
TOTAL ELECTRICITY AND MATERIALS	180 kWh		1126	72.9	202680	13122	Dai et al., 2019

The diesel engine is similarly evaluated and displayed in Tables 12 and 13, with the engine and transmission being the components assessed. The reference vehicle used in this report was a truck with 250 kW power (Shi, et al. 2015). The buses in this study assume the same values as this truck; however, pushback tractors require scaling the values by the power ratio 2:1. The material value ranges for energy demand and emissions in steel and iron production are from the same source as Tables 10 and 11. A report by the International Aluminum Institute (International Aluminum Institute, 2020) gives the aluminum and alloy values.

Table 12 Life Cycle Inventory for Pushback with Combustion Engine

Raw Materials (Engine and Transmission)	**Amount**		**CED (MJ/kg)**	**GHG (kg CO2-eq/kg)**	**CED (MJ/vehicle)**	**GHG (kg CO2-eq/kg)**	**Reference**
Steel	4	kg	6-15	2-2.5	60	9	World Steel Association, 2015; Aluminum Institute, 2020
Iron	68	kg	6-15	2-2.5	1020	153	
Cast Aluminum	160	kg	14.9	11.5	2384	1840	
Alloy	12	kg	14.9	11.5	178.8	138	
Cast Iron (Transmission)	140	kg	6-15	2-2.5	2086	315	
Cast Aluminum (Transmission)	20	kg	14.9	11.5	298	230	
Energy	**Amount**				**CED (MJ/Engine& Transmission)**	**GHG (kg CO2-eq/engine)**	**Reference**
Manufacturing of Diesel Engine and Transmission	16532	MJ			16532	965	Shi, et al., 2015; Hawkins et al., 2012

Table 13 Life Cycle Inventory for Buses with Combustion Engine

Raw Materials (Engine and Transmission)	Amount		CED (MJ/kg)	GHG (kg CO2-eq/kg)	CED (MJ/vehicle)	GHG (kg CO2-eq/kg)	Reference
Steel	2	kg	6-15	2-2.5	30	4.5	World Steel Association, 2015; Aluminum Institute, 2020
Iron	34	kg	6-15	2-2.5	510	76.5	
Cast Aluminum	80	kg	14.9	11.5	1192	920	
Alloy	6	kg	14.9	11.5	89.4	69	
Cast Iron (Transmission)	70	kg	6-15	2-2.5	1043	157.5	
Cast Aluminum (Transmission)	10	kg	14.9	11.5	149	115	
Energy	**Amount**				**CED (MJ/Engine& Transmission)**	**GHG (kg CO2-eq/engine)**	**Reference**
Manufacturing of Diesel Engine and Transmission	8266	MJ			8,266	483	Shi, et al., 2015; Hawkins et al., 2012

4.2.2 Charging Infrastructure

The infrastructure includes only the charging component, except in the case of dynamic wireless charging, which requires additional pavement installation. Regular pavement maintenance occurs regardless of the type of GSE and is therefore not considered. Tables 14 and 15 list the inventories of all GSE infrastructures.

The data for the dynamic wireless charging considers the demolishing of existing pavement, the installation of the wireless charging components, and a full-depth replacement of pavement (Marmioli et al., 2019). The life cycle inventory includes the production and transportation of the asphalt, bituminous emulsion and concrete, and the construction equipment used. The EcoInvent database was primarily used for the wireless charging components.

The data for stationary wireless charging and plug-in charging were obtained from the from an all-electric bus system study (Bi et al., 2015). The charges components were modeled based on a 60 kW wireless charger that was under development at University of Michigan-Dearborn. The plug-in charger was modeled based on a 2013 Chevrolet Volt charger, also 60 kW. For stationary wireless charger, the ratio used to scale it was based on its power. For plug-in charger, the ratio used was based on the charger dimension. The dimension data was obtained from the Proterra chargers' product (Vederek.com/Proterra), while a 60 kW charger has a power cabinet of 31 cubic feet, the 500 kW version has 129 cubic feet. The total value for CED and GHG is also based on the number for chargers. The pushback fleet needs 51 wireless charging (on-board and off board), and 51 plug-in chargers. The bus fleet needs 16 on-board wireless charging components, 4 off-board wireless chargers, and 16 plug-in chargers.

Table 14 Charging Infrastructure Inventory for Pushback Tractors

Wireless Charging	**Amount**		**CED (MJ/charger and MJ/km*)**	**GHG (kg CO2-eq/charger and kgCO2eq/km)**	**CED (MJ)**	**GHG (kg CO2-eq)**	**Reference**
Dynamic Wireless Charging (on-board)	50	units	36,000	2,060	1,800,000	103,000	Zicheng et al., 2015 calculated; and Marmioli et al., 2019
Dynamic Wireless Charging (off-board)	3.1	km	4,961,692*	168,316*	15,381,245	521,780	
Dynamic Wireless Charging Total					**17,181,245**	**624,780**	
StationaryWireless Charging (on-borad)	53	units	36,000	2,060	1,908,000	109,180	
Stationary Wireless Charging (off-borad)	53	units	152,000	9,060	8,056,000	480,180	
Stationary Wireless Charging Total					**9,964,000**	**589,360**	
Plug-In Chargers	**Amount**		**CED (MJ/charger)**	**GHG (kg CO2-eq/charger)**	**CED (MJ)**	**GHG (kg CO2-eq)**	**Reference**
Plug-in Charger	51	units	312,348.7	18,990.8	**15,929,782**	**968,531**	Zicheng et al., 2015 calculated

Table 15 Charging Infrastructure for Buses

Wireless Charging	**Amount**	**CED (MJ/charger and MJ/km*)**	**GHG (kg CO2-eq/charger and kgCO2eq/km)**	**CED (MJ)**	**GHG (kg CO2-eq)**	**Reference**

Dynamic Wireless Charging (on-board)	16	units	36,000	2,060	576,000	32,960	Zicheng et al., 2015 calculated; and Marmioli et al., 2019
Dynamic Wireless Charging (off-board)	2.25	km	4,961,692	168,316	11,176,707	379,149	
Dynamic Wireless Charging Total					**11,752,707**	**412,109**	
StationaryWireless Charging (on-board)	16	units	36,000	2,060	576,000	32,960	
Stationary Wireless Charging (off-board)	4	units	152,000	9,060	608,000	36,240	
Stationary Wireless Charging Total					**1,184,000**	**69,200**	
Plug-In Chargers	**Amount**		**CED (MJ/charger)**	**GHG (kg CO2-eq/charger)**	**CED (MJ)**	**GHG (kg CO2-eq)**	**Reference**
Plug-in Charger	16	units	312,348.7	18,990.8	**4,997,579**	**303,853**	Zicheng et al., 2015

4.2.3 Vehicle Operation

The vehicle operation accounts for the electricity used to charge the batteries and the diesel used in the conventional ICE. Natural gas is the assumed source of the electricity profile for this hypothetical airport region (U.S. Energy Information Association , 2019). A natural gas power plant typically operates at 42% efficiency; however, the closest power plant to the studied airport is a combined cycle plant, which operates at 60% efficiency. This is the value used in the analysis. The CED for electricity production includes the sum of the energy produced by the power plant, the energy loss from production, and the energy required to produce the natural gas itself. The CED and GW contribution from the production of natural gas are from the National Renewable Energy Laboratory (NREL) Life Cycle Inventory (LCI) database (Federal LCA Commons, 2020).

The diesel fuel system data, collected from the NREL LCI database, includes the energy and GHG emissions used in producing and transporting the diesel and the emissions from the pushbacks consuming diesel (Federal LCA Commons, 2020). Table 16 lists the CED and GW for the electric and diesel fuel sources.

Table 16 Total CED and GW for Operational Energy Demands

Energy Source	Phase	CED	unit	GHG	unit	Reference
Diesel	Diesel Production (Upstream)	46.44	MJ/L	7.4E-05	kgCO2/L	Federal LCA Commons, 2020
	Consumption (Combustion)	38.68	MJ/L	2.66	kgCO2/L	
Electricity	Natural Gas Production	0.83	MJ/kWh	0.16	kgCO2/kWh	
	Electricity Production	0.46	MJ/kWh	0.25	kgCO2/kWh	

4.3 Results and Discussion

The goal of life cycle impact assessment (LCIA) is to compare the environmental impacts of four charging/fueling methods, in terms of the functional unit. The impact categories considered in this analysis are cumulative energy demand (CED), and Global Warming (GW). The life-cycle phases analyzed included Vehicle Manufacturing, Charger Construction, and Operation.

4.3.1 Cumulative Energy Demand

Cumulative Energy Demand (CED) impact analysis calculates the total primary energy input for the generation of a product, material, system or process. Tables 17 and 18 summarize the CED value per phase and fueling/charging system for the pushback and bus fleets in terms of the LCA function unit, while Figures 15 and 16 show the values with the diesel fueled system as the normalized reference.

Table 17 CED (GJ) per phase and function unit – Pushback Tractor Fleet

	Equipment Manufacturing (GJ)	Charger Construction (GJ)	Operation (GJ)	Total (GJ)
Diesel Fueled	104	-	258,907	259,011
Plug-in Charger	1,915	1,463	13,749	17,127
Stationary Wireless Charging	1,999	919	14,354	17,273
Dynamic Wireless Charging	1,890	1,588	13,566	17,044

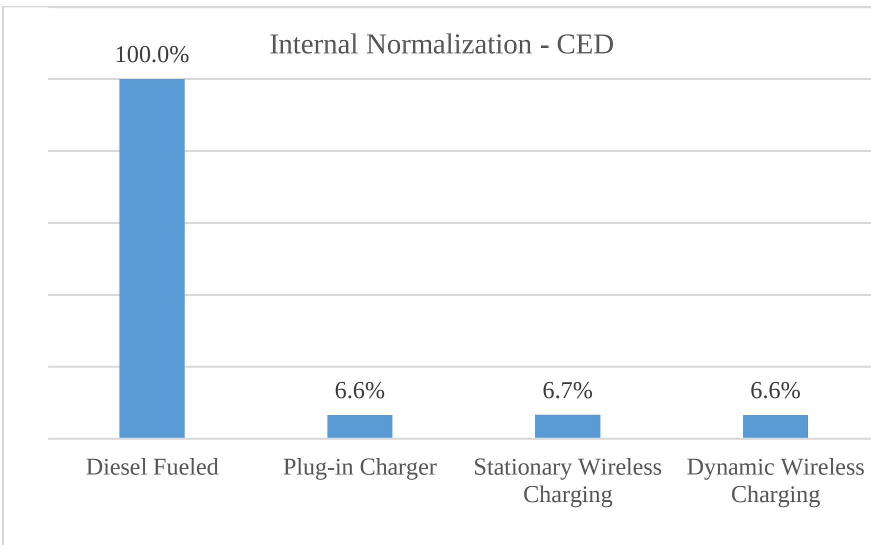


Figure 15 Cumulative Energy Demand of diesel fueled Pushback Tractor Fleet with Internal Normalization

Table 18 CED (GJ) per phase and functional unit – Bus Fleet

	Equipment Manufacturing (GJ)	Charger Construction (GJ)	Operation (GJ)	Total (GJ)
Diesel Fueled	50	-	187,794	187,844
Plug-in Charger	912	463	11,300	12,675
Stationary Wireless Charging	912	110	11,300	12,322
Dynamic Wireless Charging	912	1,088	11,300	13,301

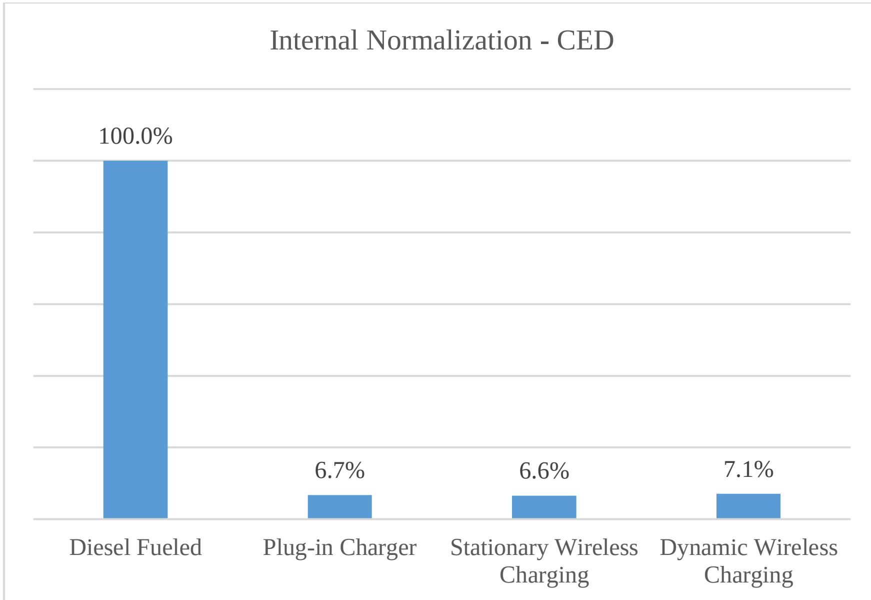


Figure 16 Cumulative Energy Demand Internal of diesel fueled Bus Fleet with Internal Normalization

For both fleets, the highest CED impact occurs in the operation phase because of the magnitude of energy required to operate over 30 years. Also, for both fleets, the system with higher CED is diesel-fueled vehicles. The energy used to produce diesel is extremely high, for all domestic and foreign crude production, transport, refining and diesel fuel transport, the used energy rate is 1.2MJ/MJ of final fuel. Resulting in 46.4 MJ per liter of diesel. On the other hand, to produce 1 kWh from natural gas, the energy require is 0.83 MJ.

Comparing the electric options, in the pushback tractor case, they all have very similar results, however differing in the charger construction stage. Although the stationary wireless charging has the most number of vehicles, and therefore battery replacement, compared to the other systems, the plug-in charger has a higher impact per charger due to its higher power and dimension, and dynamic wireless charging require high energy for its construction. The CED has its higher impact on stationary wireless charger, followed by plug-in charger, and lastly dynamic wireless charging. For the bus fleet the highest impact is associate to the dynamic wireless charging because of the charging lane construction, which requires more energy than manufacturing plug-in and stationary wireless charger. The second highest CED is due to plug-in charger, because of its high impact per charger and total number of chargers, 16. Stationary wireless charger has the lowest impact, also the lowest number of chargers requires, 16 on-board but only 4 off-board.

4.3.2 Global Warming

Global Warming impact compares GHG emissions using Global Warming Potential (GWP). GW has a strong relationship with overall environmental impacts and is therefore a primary factor in comparing the environmental load of different systems. Tables 19 and 20 summarize the GW value per phase and fueling/charging system in terms of the LCA function unit, while Figures 17 and 18 show the values with the diesel fueled system as the normalized reference.

Table 19 GW (10^3kgCO_2) per phase and function unit for pushback tractor fleet

	Equipment Manufacturing (10^3kgCO_2)	Charger Construction (10^3kgCO_2)	Operation (10^3kgCO_2)	Total (10^3kgCO_2)
Diesel Fueled	39	-	8,091	8,130
Plug-in Charger	126	89	3,446	3,661
Stationary Wireless Charging	132	54	3,598	3,783
Dynamic Wireless Charging	124	58	3,400	3,582

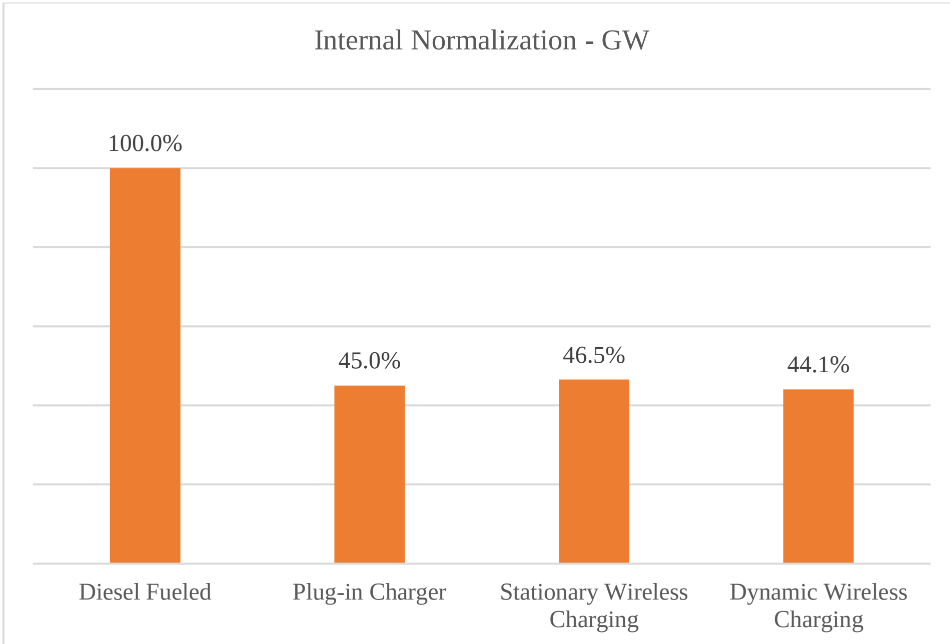


Figure 17 Global Warming Internal Normalization based on diesel fueled system for pushback tractor fleet

Table 20 GW ($10^3 kgCO_2$) per phase and function unit for bus fleet

	Equipment Manufacturing ($10^3 kgCO_2$)	**Charger Construction ($10^3 kgCO_2$)**	**Operation ($10^3 kgCO_2$)**	**Total ($10^3 kgCO_2$)**
Diesel Fueled	19	-	5,869	5,888
Plug-in Charger	61	28	3,634	3,722
Stationary Wireless Charging	61	6	3,634	3,701
Dynamic Wireless Charging	61	38	3,634	3,732

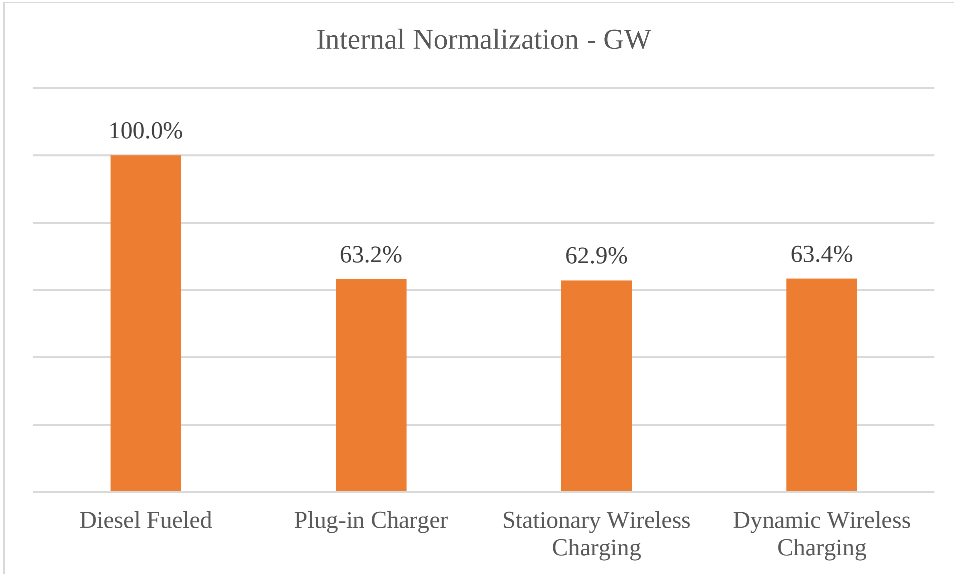


Figure 18 Global Warming Internal Normalization based on diesel fueled system for bus fleet

Like the CED, the highest impact occurs in the operation phase. For both fleets, the conventional diesel fueled vehicle has the highest GW impact, because of the emissions from fossil fuel burning. When comparing the electric options, the global warming impact are all very similar on both fleets. In the bus fleet is possible to observe the high impact of the dynamic charging lane construction compared to the other chargers, however pushback fleet has a different result.

For pushbacks, the chargers' construction impact has the opposite behavior because the number of plug-in chargers and stationary wireless chargers are very high, 51 and 53 respectively. This high numbers of chargers makes the impact of the dynamic wireless charging lane construction smaller. Since pushback vehicles are used 24/7, this study assumed the worse-case scenario where all pushbacks could charge at the same time, and so a charger for each vehicle was assumed. However, a charging operation optimization could change these results.

Chapter 5 Conclusions

5.1 Findings and Conclusions

The transportation sector contributes to a significant portion of greenhouse gas emission. Increasing the use of electric vehicles will mitigate the overall pollution of this sector, especially if supplied by electricity that comes from renewable source. To guarantee a large adaptation of electric vehicles, developing a charging infrastructure is crucial.

This study analyzed life-cycle costs of charging infrastructure for electric ground fleet in airports, as compared to the conventional fossil fuel option. The results show that the conventional fossil fuel option requires less investment initially, but it costs most over its lifetime. The LCCA results for the pushback tractors that plug-in charging has the lowest cumulative cost followed by stationary wireless charging, and then dynamic wireless charging., while for the inter-terminal bus fleet, three electric charging methods show negligible differences in cumulative costs. This indicates that the most cost-effective charging infrastructure may vary depending on driving mileage and system design.

The use of LCCA to analyze new systems and infrastructures for decision-making is highly recommended. The data provided by LCCA increase the level of information for a more informed decision. Knowing lifetime cost, instead of having only the initial investment, can change the course of a project, and decrease the payback time. Electric charging techniques are available in the market now but face several barriers for implementation. However, differently from the initial investment; the lifetime cost should not be one of those barriers. Decisions on implementation of electric vehicles should be based on long-term cost benefit.

Together with the LCCA, this study also studied the life cycle assessment of different charging technologies. Electric vehicles operate emitting less pollutants than conventional vehicles, however, to understand the real environmental benefit of this mobility method, it is necessary to account the impacts from material extraction until its disposal.

The results of the LCA showed the diesel production phase has the greatest CED impact on the conventional vehicle scenario; it accounts for 99.9% of conventional vehicle system CED for both fleets. The overall environmental impact has the same results in both electric ground fleets. Conventional combustion vehicles present a much higher CED and GW than the electric options for pushbacks and bus fleets. For pushback fleet, all the electric options have very similar results for both impact categories. However, when analyzing the vehicle manufacturing phase, and charger construction phase the impacts has more noticeable difference. Since to perform the same service level it was necessary to increase the number of vehicles in the plug-in and stationary wireless charging, the impact of the extra vehicles is representative for both technologies. Stationary wireless charging has the highest impact in the equipment manufacturing phase. In the charger construction phase, plug-in and dynamic wireless chargers have very similar results for CED, while for GW plug-in charger has the highest impact.

For the bus fleet, in which does not operate in full capacity and so there was no need to consider extra vehicles. The stationary wireless charging system has lowest impact for both categories. This result is due to the small number of stationary wireless chargers, only 4 off-board chargers, compared to 16 plug-in chargers and 1.4-mile dynamic wireless charging lane. Although the designs between electric systems differ, the difference between the impact categories are extremely small. On the other hand, conventional combustion bus fleet has much larger environmental impacts, due to the fuel combustion on the operation phase. The operation phase has the greatest impact, however, is important to emphasize that the impact on the equipment manufacturing and charger construction for the electric options are higher than for the conventional vehicle.

This simplified analysis represents a first step in the comparison of different charging methods for electric vehicle against conventional vehicles. The LCA did not consider maintenance of vehicles and charging infrastructure, and it assumed that vehicle construction and assembly, as well as end of life, are the same for all four scenarios. This study recommends further exploration of those assumptions as the next steps to support a better decision-making process.

5.2 Future Research Recommendations

Different charging infrastructures should be further studied, such as battery swapping station, stationary charging station, or in-motion charging. Each technology presents benefits and challenges, and the most adequate solution relies on the scale of the project, initial funds, government incentives, and benefit-cost ratio.

Several pilot projects have been built in the field, mostly using ICPT technology for the in-motion charging solution. Although those projects have relevant outputs that provide information for a decision-making process on this sector, there is lack of relevant real-life data. Further research that provides long-term field performance of electric roads need be performed for different traffic and climate conditions. Maintenance and operations data need to be monitored to supply more information about infrastructure performance.

This study showed that in an airport environment, where GSE uses close internal roads, electric vehicles (pushbacks and inter-terminal buses) have lower cumulative cost and lower environmental impacts when compared to its conventional ICE vehicles. The substitution of conventional buses for electric buses is recommended, however the type of charging technology should be analyzed for each project.

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