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Technical Overview of Inductive Charging for Electric Buses in Europe

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Abstract

Within in the last 15 years, many cities and authorities have decided to test and implement electric buses into their public transit networks. Besides using conductive plugs to charge the buses overnight at the depot, they also can be wirelessly charged with inductive energy transfer technology. When implementing wireless charging pads into the streets and considering charging time in operation planning, a bus with a small battery (e.g. 60 kWh) can complete a whole day of driving. Both study cases Mannheim and Madrid have proven that this technology is applicable for everyday service. Within Europe, 17 cities are currently or going to use wireless charged electric buses. Opportunity Charging with inductive charging pads means that fixed points in the network are created that must be stopped at regularly. It is also costly and hard to license their implementation within public space. Therefore, the authorities in Madrid and Mannheim both decided to use conductive overnight charged buses in the future. The City of Brunswick remarks that no bus manufacturer is currently willing to equip new buses with wireless charging technology. A representative of inductive charging developing company IPT-Technology GmbH states that new bus manufacturers are in the early stages of developing new vehicles.

Introduction

Modern municipalities must manage local air pollution which is caused by individual automobiles and heavy road traffic. One attempt is to electrify the local bus fleet. Around the world, pilot projects are running and testing different alternatives of electric bus systems and none are perfect equals in terms of vehicle components used and operational integration. So far, there is no technological standard that has proven to be the best solution to fit in all cases. All electric buses have a common attribute: their engines run on electricity. The drive train and other electric components of buses receive their power from a battery or from overhead catenary lines. If a combustion engine retrofitted the onboard power supply chain to connect to an electrical system, it becomes a hybrid bus. One option to recharge the onboard batteries of electric buses is to use wireless inductive charging technology. This paper provides a review of this technology, identifying trends in its development.

Project Scope

This paper only considers electric vehicles which can be recharged with inductive technology. This includes derivatives which have secondary power sources besides the battery. First, the alternatives of inductive charging technology that are available and currently in use are explained and their specifications presented. This includes the necessary infrastructure for a potential implementation of this technology. Thereafter, case studies will provide an overview where and in which context such buses are in use. This paper takes a deeper look into every public use of inductively-charged electric buses within Europe which are currently in use (late 2018). The scope focuses on Europe because, in most cases, necessary data is available. City structures, housing, national regulations, and modal shifts in Europe are based on comparable situations and the resulting needs and impacts of public transit networks are similar. By sticking to cases within Europe, a certain comparability can be ensured. This will be important in the third part where cases will be compared in terms of basic specifications. This will identify trends in the development of this technology. The last chapter summarizes the application of inductive charging for electric buses and states the conclusions that can be drawn from secondary sources and field experts.

Basic technological knowledge

Technological Background

The basic technology for electrical buses was developed in 1882 by Werner von Siemens in Berlin. The “Elektromote” received power from an overhead contact wire (Vuchic, 2007, p. 29). Buses running with catenary systems are called trolley buses and have been running on electricity ever since. The number of trolley bus networks is diminishing all over the world. Buses with internal combustion engines outdid trolley buses in terms of construction costs for new lines and flexibility. Over time, some pilot projects of battery electric vehicles were pursued. Two examples: because of the oil crises in the 1970’s MAN and Bosch developed the first battery powered bus. The battery was in a trailer that was tugged by the bus. It was also equipped with a pantograph to recharge the battery at the termini of the bus line (Rheinbahn, n.d.). Zermatt, the city in Switzerland, which does not allow combustion vehicles in town, has run electric buses since 1988. The battery changes of the electric buses currently in use at the termini require only one minute. (Einwohnergemeinde Zermatt, n.d.)

Wireless transfer of electrical energy

When current is applied to an electric coil, a magnetic field will be created. A second coil that is placed along the lines of force of the magnetic field create a transformer-type coupling. The electric circuit is closed, and power is induced in the second coil. The better the coils are congruent with each other, the more efficient the power transfer compared to a wired connection. The figure to the left below shows the transformation from a closed electric circuit; on the right, the transfer via a ground-based copper coil is shown.

On electric buses, the coils are set up in a “pick-up module” underneath the chassis. The mechanical components of the bus and the surface of the “transfer module” in the ground lead to a minimum vertical distance between the coils. The lateral positioning of the vehicle must be precise to ensure efficient power transfer. The maximum efficiency of the power transfer differs for each setup and varies between approximately 80 % and 93 %.

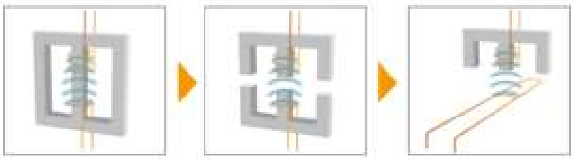


Fig. 1. Conversion from a closed conductive electric circuit to an inductive transfer of electricity (PRIMOVE I, n.d.)

Recharging Strategies

Electric buses can be recharged in three different operational scenarios which are presented in this chapter: Overnight Charging, Opportunity Charging and In-Motion Charging.

Overnight Charging

A usual day operation of a bus consists of phases in which it runs on the lines and on which it is at the depot. For example, the bus leaves at 4 a.m. in the morning and returns at 8 p.m. The time at the depot is used for maintenance, cleaning, and preparation for the upcoming tour. An electric bus can use this period the recharge the batteries. The time to fully recharge depends on the battery capacity and the power output of the transformer. Overnight Charging is the strategy in which the time in the depot is the only chance to recharge the bus for the following operating day. It means that these vehicles need large batteries. For example, the 2018 EVOBUS eCitaro is a 12 m long Battery Electric Vehicle (BEV) that has lithium-ion batteries with a capacity of 243 kWh that lasts in a worst-case summer scenario for 150 km. This was tested on a “SORT2” standardized on-road test cycle. This bus recharges via a Combo-2-plug or a pantograph (Mink, 07.03.18). For the time being, there is no known case in which inductive recharging is used for overnight charging only.

Opportunity Charging

Opportunity charging describes operational cases in which buses are not only recharged at the depot but also at designated charging stations throughout the network. Buses do not have to drive back to the depot to recharge. Time and energy can potentially be saved. As a result, smaller batteries are needed onboard the buses. Accurate planning is necessary to ensure that no vehicle runs out of energy. Backup solutions for different scenarios must ensure stable operation in case of incidents, construction works, or detours. Nowadays, the minimum turning time at terminal stations is optimized to compensate for route delays. If delays occur, recharging time adds more waiting time as an additional constraint and modifications to bus tours may be necessary. To save time, recharging stations can be equipped with inductive charging pads. As soon as the bus occupies the station, it is detected and the process of recharging is initiated.

In-Motion Charging

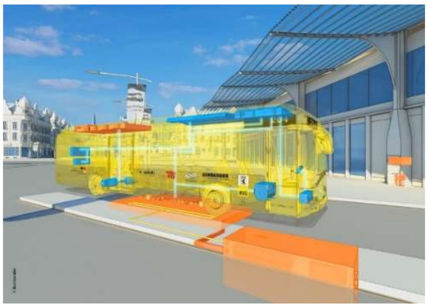
In-Motion Charging enables electric buses to recharge while moving. This has the advantage that no extra time for recharging must be considered during an operating day. When set up smart, On-Line Electric Vehicles (OLEV) that have access to In-Motion Charging can run perpetually. As with opportunity charging, the flexibility is restricted due to the fixed lines that must be called at regularly to make sure that the state of charge (SOC) is always high enough to reach the next power lane. Testing sites have shown that as few as 17 % of the network length equipped with shaped magnetic field in resonance (SMFIR) technology is enough for sufficient power transfer (Suh, 2011, p. 229). It is highly probable that setting up a redundant network of lanes for a reliable bus network will require more infrastructure. While this strategy is only being used in combination with overhead catenary power supply for the time being, there have been test projects around the globe to equip roads with copper coils to wirelessly charge the batteries on the go (i.e. KAIST OLEV, South Korea, see chapter 3: Excursion).

Contemporary alternatives of components

There is a wide range of electric buses on the (European) market, but none of them are available off-the-shelf with inductive power components to enable wireless charging. Two companies can deliver the necessary equipment at the moment: BOMBARDIER and IPT-TECHNOLOGY GmbH.

BOMBARDIER PRIMOVE

Bombardier Primove covers the three components: charging station, battery, and electric drive train to offer turnkey systems. The charging station includes multiple components. The loading pad contains coils to generate the electric field which is picked up by the onboard unit, which lowers mechanically as soon as the vehicle covers the charging pad completely. The smaller air gap ensures a transfer efficiency of 89.99 % (Mannheim) of the 200 kW input (Menges, 2015, p. 10). The electronics must be connected to the wayside electronics. Additionally, a cooling unit must be placed on ground nearby. TÜV Süd validated that the PRIMOVE recharging setup complies with the electromagnetic standards and meets the requirements for electromagnetic fields in public space (PRIMOVE, 2013, p. 7).



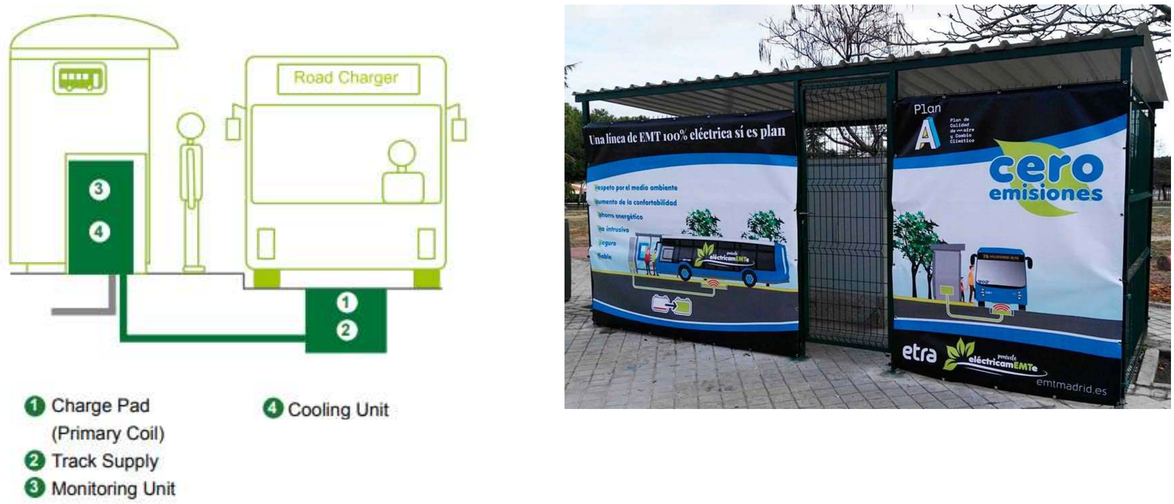
(a)

(b)

Fig. 2. (a) Animation of the road side and vehicle side components (orange parts) of PRIMOVE (PRIMOVE II, n.d.); (b) Picture of a PRIMOVE equipped bus stop in Mannheim

IPT-TECHNOLOGY GmbH IPT-CHARGE

The strategy of IPT is similar to Bombardier Primove. Wireless charging stations along the route top the SOC throughout a day of operation. At night the battery is fully recharged for the next day. IPT has also proven usability in many cases [see chapter 3.4.]. An advantage of IPT is that the modular integration of components allows the installation of 50 kW modules up to 300 kW. The positioning of the elements of the charging station is also variable. A typical setup is shown in the picture below. Charge Pad (1) and Track Supply (2) are installed directly underneath the road surface. Monitoring and cooling units are placed in a case next to the bus stop. Depending on the setup the gap between the road side and vehicle side copper coils can vary (IPT-Technology GmbH, n.d.). In Madrid, the gap measures 130 mm and leads to a 10 % loss of power while transferring (Bueno et al., 2018). Fig. 3. (b) gives an idea of show much space is needed for the off-road unit in Madrid.



(a) (b)

Fig. 3. (a) Drawing of the infrastructure elements at an IPT bus station (IPT-Technology GmbH, n.d.); (b) Picture of the sidewalk installation at an IPT bus station in Madrid (Bisio, 2018)

Excursion to South Korea: KAIST OLEV

The first case of In-Motion Inductive Charging was initaited in 2009 by the Korean Advanced Institute of Science and Technology (KAIST). The gap between the power line and the pick-up plates on the bottom side of the bus ranges from 17 cm to 20 cm. Their 4th generation of OLEVs reached 83 % efficiency in power transmission (Jun Huh and Chun-Taek Rim, 2011). The City of Gumi upgraded an inner-city route with a length of 24 km for testing purposes. The latest generation of buses from 2013 is promoted to transfer 85 % of 100 kW on the go (Rovito, 2014). There have been no information updates for this technology over the past three years and no cases of its application within Europe.

Case Studies

Mannheim

With 300.000 inhabitants, Mannheim is the biggest city in the Rhein-Neckar-Region in southwest Germany, which holds a total of 2.3 million inhabitants (Metropolregion Rhein-Neckar GmbH, 2015). The City Center is located at the merging of the rivers Rhine and Neckar and expands to the north, the east, and the south. On the western side of the Rhine River is the City of Ludwigshafen am Rhein. Public Transit is managed by the RNV GmbH. The bus route 63 begins at the main station, which is at the edge of the City Center. It then expands along one of the main radial streets without a streetcar line towards the southeast, as it is shown in Fig. 4. (a). It then turns to the right and functions as tangential line to Lindenhof Pfalzplatz. The total length is 9 kilometers (see Fig. 4. (b)).

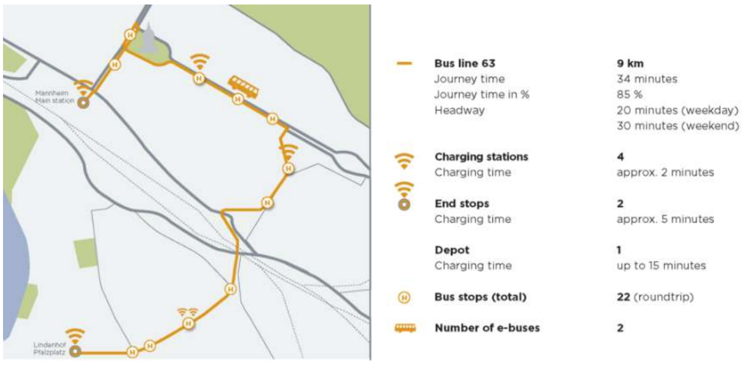
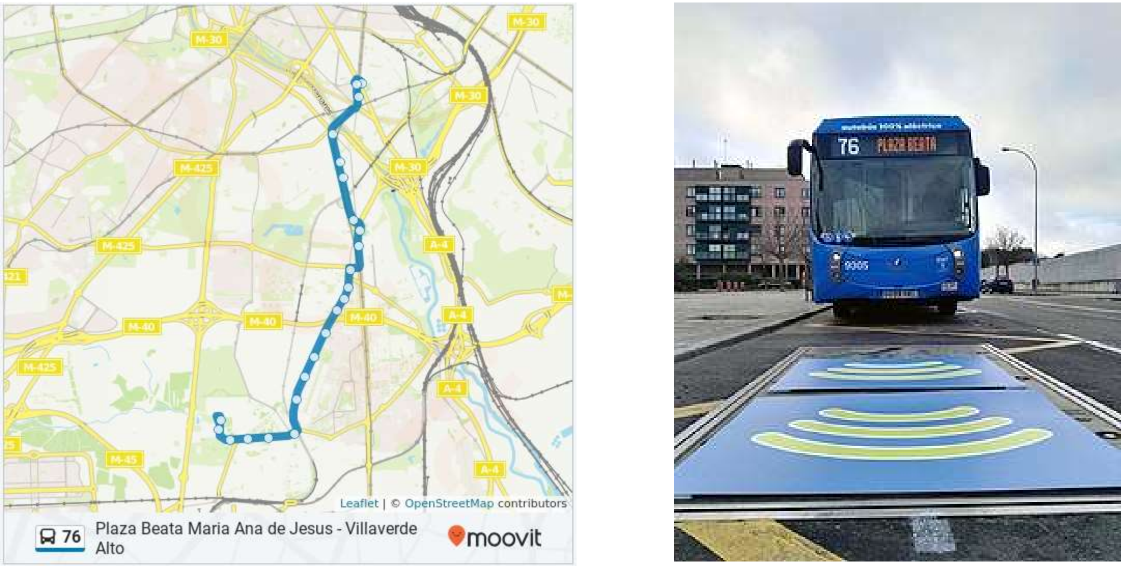


Fig. 4. Map and fact sheet of the Mannheim PRIMOVE project. The Mannheim city center is adjacent to the line in the northwest corner (PRIMOVE, 2015)

The batteries of the two buses have a capacity of 60 kWh each and were introduced in 2015. The charging pads have a power of 200 kW and energy is transferred with an efficiency of 90 % (Menges, 2015). At 90 %, it would theoretically take 20 minutes to recharge the battery if it is empty. To complete the route, a bus needs 21 minutes according to the timetable (Rhein-Neckar Verkehr GmbH, 2018). Every round trip includes a recovery time of 7 minutes, which can potentially be used as charging time (Berthold, 2018).

Madrid

Madrid, the capital of Spain has a population of 3.2 million inhabitants (Instituto Nacional de Estandisticá, 2018). It is located in the middle of the Country with a dedicated City Center and surroundings that expand radially. The responsible authority for public bus transit is Empresa Municipal de Transportes de Madrid, S. A. (EMT). In 2016, bus line 76 was equipped with wireless charging equipment. Its average route length is 7 km, connecting the edge of the City Center with an outskirt. This makes it comparable to the pilot project in Mannheim. The map in Fig. 5. (a) shows the geographic location of the route relative to the City Center. Its southern half is the northern part of the map. The charging stations are located at both termini of the route. The horizontal gap between the bottom and the top coils varies between 130 mm and 150 mm and is the result of different vehicle configurations (load, tires, etc.) and uneven surfaces. The vertical tolerance for the vehicle positioning is 100 mm and must be ensured by the driver. Fig. 5. (b) shows a bus approaching one of the charging pads in Madrid.



(a) (b)

Fig. 5. (a) Map of the bus route 76 in Madrid. The city center is adjacent to the bus route in the north (MOOVIT, n.d.); (b) Picture of a route 76 bus maneuvering towards a charging station (S., 2017).

The power of each charging station is 100 kW, which is half the power of the ones in Mannheim. The lithium battery of the bus has a capacity of 124 kWh, which equals 154 Ah at ~ 650 V. They are configured to operate at a state of charge between 23 % and 100 % (Diaz, 2015). Effectively, 95.48 kWh are used in operation. Considering the efficiency of 93 % of IPT it takes theoretically 62 minutes for a full recharge. The minimum headway on the line is 10 minutes (MOOVIT, n.d.). During operation, an average of 6.95 minutes of recharging time at each terminus (Diaz, 2015) resulted in a minimum SOC of 55 Ah (~ 36 %) as shown in the figure below. This value can be interpreted as stable enough in case a charging period has to be skipped, to reach the depot and to compensate the aging of the battery.

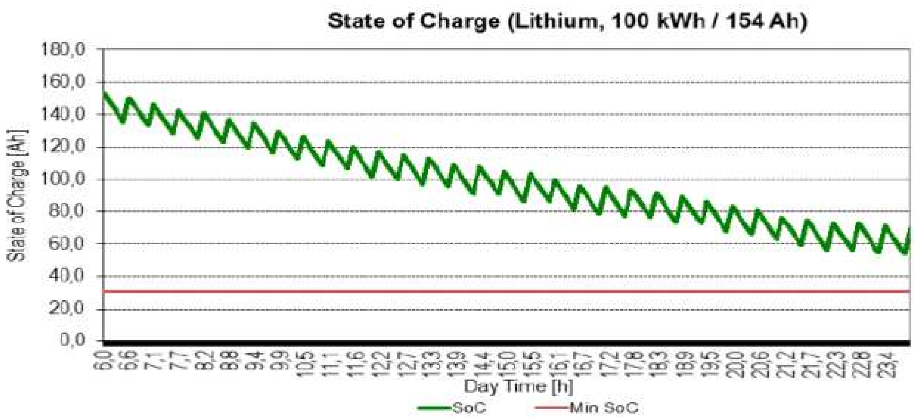


Fig. 6. Proposed SOC for bus line 76 in Madrid during a day of operation (Diaz, 2015)

Comparison

Although the charging technology is similar, the operation strategies differ in multiple ways. The smaller battery in Mannheim causes the need to recharge not only at the terminals but also at the intermediate stops. To ensure a reasonable power transfer within a stopping time, the power of a charging station must be higher than in Madrid. Madrid's charging pads only transfer half the energy within the same time but the battery capacity is doubled. As a result they can operate the whole route but need longer recovery time. This reduces the number of charging pads needed but may increase the number of buses. Both settings have advantages and disadvantages. Future implementations of wireless charged electric buses will need evaluating analysis to properly weigh up all the significant configuration options.

Quantitative Research

The following tables are giving an overview of cities in Europe which are using inductive charging bus systems. Table 1 shows the transportation companies and which, of the two producers ("Bombardier" and "IPT"), established this technology. Furthermore, it presents the area of operation and the number of buses. Finally, it shows the different charging and battery capacities for each city. The company IPT founded this technology in Italy, Genoa (2002) and Turin (2003). Bombardier, IPT´s only competition, applied their technology in Braunschweig (2014). The total number of buses which operate with wireless charging batteries is 69. IPT has more buses in use (55) than Bombardier. The reason for this may be the accrued experience over the years and customer acceptance. Italy, with the two cities Genoa and Turin, have used this technology the longest. Additionally, these cities have the most buses (31) on their routes. Furthermore, IPT is more variable in charging and battery capacity. Bombardier offers only one charging configuration (200 kW). In contrast, IPT is more flexible in their loading performance. Both companies have offer alternatives for battery capacity.

Table 1. Stats of wireless charged electric buses within Europe. References in A**ppendix D.**

City	Transportation company	Producer	Startup	Area of operation	Number of busses	Charging capacity	Battery capacity
Berlin	BVG	Bombardier	2015	Line 204	4	200 kW	90 kWh
Braunschweig	VRB	Bombardier	2014	Line M19	5	200 kW	60 kWh
Bristol	GBBN	IPT	2015	Citycentre	2	n.a.	n.a.
Bruges	De Lijn	Bombardier	2015	Citycentre	3	200 kW	36 kWh
Genoa	AMT	IPT	2002	Citycentre	8	4x60 kW	63 kWh
London	TL	IPT	2015	Line 69	5	2x100 kW	61 kWh
Madrid	EMT	IPT	2017	Line 76	5	100 kW	124 kWh
Mannheim	RNV	Bombardier	2015	Line 63	2	200 kW	60 kWh
Milton Keynes	Arriva	IPT	2014	Citycentre	8	2x120 kW	150 kWh
S`Hertogenbosch	GVU	IPT	2012	Citycentre	1	60 kW	129 kWh
Turin	GTT	IPT	2003	Line 1/2	23	4x60 kW	63 kWh
Utrecht	Qbuzz	IPT	2014	Line 2	3	60 kW	86 kWh

Table 2 presents the number of stations and travel time for each route. Moreover, it shows the different wireless charging options. The companies often use two wireless charging points for recharging the battery. All the use cases mentioned are also geographically located in the map in Appendix E. This map also includes future applications.

Table 2. Stats of wireless charged electric buses within Europe. References in Appendix D.

City	Use	Number of stations	Journey Time (min.)	Depot charging	Terminal Stop charging	Station charging
Berlin	Line 204	18	24	yes	yes	
Braunschweig	Line M19	26	39	yes	yes	yes
Bristol	City	n.a.	n.a.	yes		yes
Brügge	City	8	27	yes		
Genoa	City	n.a.	n.a.	yes		yes
London	Line 69	37	53		yes	yes
Madrid	Line 76	23	37		yes	
Mannheim	Line 63	22	34	yes	yes	yes
Milton Keynes	City	n.a.	n.a.	yes	yes	yes
S´Hertogenbosch	City	n.a.	n.a.			yes
Turin	Line 1	17	34	yes	yes	yes
Turin	Line 2	18	28	yes	yes	yes
Utrecht	Line 2	11	24			yes

Statements and Conclusions

Problem of the City of Brunswick, Germany: Project EMIL

Similar to Mannheim, Verkehrs-GmbH, the public transit authority Brunswick, Germany, began using wirelessly-charged electric buses in 2014. The newspaper "Zeitung für kommunale Wirtschaft" (ZfK) published a related article on December 3rd, 2018. It quotes Jörg Reincke, CEO of the Verkehrs-GmbH, who considers the project EMIL a true success. The lifespan of the battery exceeded prior expectations. The insurmountable obstacle is that none of the bus manufacturers are willing to equip their existing vehicles with fast and wireless charging equipment any longer.

Statements received per E-Mail

Mr. Bittler from IPT expects that more manufacturers, especially those entering the market, will soon produce buses using induced power supply technology such as the "Vero" from the company TAM Europe. Ongoing standardization and reduction of costs, especially for high-power charging stations, will increase the economic efficiency and therefore the adoption of wireless charging. He states that market leaders in bus manufacturing fail to integrate new technologies in their existing products. IPT received positive feedback from the IPT networks in Turin, Milton Keynes, London, and Madrid.

Mr. Orihuela from the EMT (Madrid transit authority) states that bus route 76, with wirelessly charged buses, will remain an exclusive project. Major issues include installing the charging stations within the city environment and the reduction of flexibility because of fixed charging points that must be integrated with the network. Therefore, EMT's future strategy is to use overnight charged buses instead.

Mr. Hertweck from the RNV GmbH in Mannheim states that the PRIMOVE project is a success. Employees who had the chance to gain experience working with electric buses were particularly advantaged. Still, as in Madrid, the project in Mannheim will remain a pilot. The company has begun setting up charging stations for overnight charged electric buses. The reasons are similar to those in Madrid: implementation of the charging pads is difficult and the reduction of the flexibility cannot be scaled to the whole network.

As of this writing, a statement from BOMBARDIER is still pending.

Conclusion

Wireless charging is a cutting-edge technology that many transit authorities consider worth adopting. Although the basic strategy is the same in all cases - using inductive pads for opportunity charged electric buses - the specific configurations of batteries and charging power differ. A standard has not yet evolved. There are more projects coming up in the future within Europe. The main issues are the reduction of flexible operation and the integration of high-voltage equipment within the public space. Therefore, Mannheim and Madrid both have decided to follow alternative means of integrating electric buses into their respective fleets. As new players join the market and battery technologies continue to develop, popular wireless charging use may come to fruition.

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