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COMMUNICATION

Sustainable Management of Energy, Storage, and Wireless Transfer in Electric Vehicles Operating in an Ecological Environment

Adel Razek

Group of Electrical Engineering—Paris (GeePs), CNRS, University of Paris-Saclay and Sorbonne University, Gif-sur-Yvette F91190, France

ABSTRACT

Electric vehicles are progressively being employed for ecological transportation in green environments, thereby preserving eco-friendly biodiversity and ecosystems. The involved energy storage batteries are a crucial item of green mobility. The storage capacity state is intensely allied to the interconnection with energy supplies and charging methodologies, as well as the involved complexity. In an outstanding green urban background, charging schemes would operate wirelessly to transfer clean energy. However, the concerned wireless power transfer tools can implicate intricate settings and undesirable electromagnetic interferences. In this context, sustainable management of the condition of batteries and wireless chargers can improve their operation and reduce adverse effects. This includes the sustainable use of clean energy sources as well as the design and monitoring of complex interconnected systems. This contribution aims to highlight and analyse the role of a sustainable, clean, and efficient energy approach in the design and monitoring of energy storage and wireless transfer systems integrated into electric vehicles for environmentally friendly applications. The paper includes sections covering an introduction, electric mobility in a green urban context, energy storage and wireless power transfer, wireless electromagnetic interference and adverse effects, charging mode strategies, sustainable

*CORRESPONDING AUTHOR:
Adel Razek, Group of Electrical Engineering—Paris (GeePs), CNRS, University of Paris-Saclay and Sorbonne University, Gif-sur-Yvette F91190, France; Email: adel.razek@centralesupelec.fr

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energy management in electric mobility, discussion, and conclusions. The research presented in this communication is based on a narrative review of the literature.

Keywords: Electric Vehicles; Green Mobility; Storage State; Wireless Power Transfer; Sustainable Management; Adverse Effects; Biodiversity

1. Introduction

In recent decades, a significant shift has occurred in the association between humans and nature. There is a mounting awareness of the need to improve urban ecology by promoting biodiversity in order to foster more sustainable environmental well-being for city dwellers. Various proposed strategies emphasize specific areas, such as the protection of biodiversity, including human, through industrial innovations that reduce environmental threats [1]. A key modernization has been the decarbonization of daily life, particularly the replacement of internal combustion engine vehicles with battery-powered electric vehicles (EVs) [2]. This urban electric mobility primarily encompasses public transportation, but also private vehicles, taxis, and other forms of transportation. It is characterized by short journeys and frequent stops, unlike long journeys on roads and highways [3].

Regarding urban public transport, EVs can operate above ground (on the surface), underground, or in hybrid mode, connected to the electrical grid like trams or powered by batteries like buses. For example, a tram can operate in hybrid mode, both underground connected to the grid and above ground using energy storage batteries, thus avoiding the need for a complex surface infrastructure connected to the grid. Generally, surface urban transport systems, such as trams or buses, can use limited-capacity energy storage systems, reducing costs and space, by charging batteries at intermediate or terminal stops. Such charging requires automated and rapid wireless technologies such as inductive power transfer (IPT). This can be done at ground level or from the roof of the vehicle, depending on the situation. These wireless systems can produce electromagnetic radiation characterized by electromagnetic interference (EMI) that may be harmful to passengers, people around the vehicle, or the surrounding biodiversity [4,5].

Storage charging modes include direct sliding grid-connection, cable connection, and wireless charging systems. Wireless technologies are employed in different situations, mainly for static rapid charging stations or at home, running intermittent charging in stops or poses, and road driving in dynamic mode charging [6].

In general, for EVs, the state of the batteries and their charging systems (direct or wireless) can be monitored using sustainable management tools. This allows for optimized operation, reduced potential adverse effects, and improved integration into an environmentally friendly background through a clean and efficient energy approach. These objectives can be achieved in EVs through smart digital tools and their integration into the electrical grid of connected urban areas [7–10]. The involved complex procedure can be assisted by artificial intelligence (AI) algorithms [11–14] and monitored by digital twins (DT) [15–19].

Several literature reviews exist in this field, such as those cited in this article. These reviews are generally exhaustive and comprehensive; however, this communication aims to focus concisely on energy management for sustainable mobility in an ecological environment, highlighting the main characteristics of this strategy. The present communication objects to emphasize and examine the character of a sustainable, clean, and effective energy methodology, in the pattern, building, and supervision of energy storage and power transfer systems, incorporated into EVs, for environmentally responsive applications.

In reality, aspects such as electromagnetic safety, environmental impacts, and integrated monitoring systems are addressed in this article within a conceptual framework and a technological integration model (EV–battery–IPT–grid). Furthermore, the integrated approach to IPT, AI-assisted monitoring, and digital twin-based management systems constitute a key contribution of this study. Finally, the relevant environmental perspective, relating to ecological concerns such as the impacts of electromagnetic radiation on human health and biodiversity, distinguishes this study from purely technical analyses.

The paper's next sections cover electric mobility in a green urban context; energy storage, charging modes, and wireless power transfer; sustainable energy management; discussion, and conclusions.

2. Electric Mobility in Green Urban Context

Electric mobility in urban areas encompasses various types of EVs: public transport, professional transport, taxis, private cars, etc. An EV includes an electric motor, a grid connection device, and possibly an energy storage system. Energy transfer from the grid to the motor can occur directly when the EV is permanently connected to the grid via a catenary and a motor interface-converter, as is the case for trams. In this case, the vehicle does not require an energy storage system, but the necessary grid connection infrastructure is complex and expensive, especially for surface transport. Conversely, this infrastructure is simpler and better suited to underground transport. Other off-grid surface public transport EVs, such as buses, require energy storage systems. In this case, the batteries can be charged via a cable connection and a motor interface-converter. This connection cable is suitable for continuous and long-term charging operations, for example overnight, which corresponds to important storage capacities. High storage capacity allows for a long range for the EV; however, the resulting weight, size, and price become excessive, especially for short-distance urban transport, which does not require a long range. In this case, it is advantageous to use smaller storage capacities and charge more frequently, for example at bus stops, at the end of a journey, or after several journeys [3]. In such circumstances, wired connections become an obstacle, and only wireless technologies can be used. However, wireless charging requires specific precautions regarding exposure to electromagnetic fields (EMF). Handling such EMI problem can be achieved through shielding, depending on the situation.

The strategy described above can be applied to other types of EVs. For short urban trips, small storage capacities combined with fast wireless charging are sufficient. However, for long journeys, large storage capacities are necessary, as well as charging while driving (electric highways), where a dynamic wireless charging method can be used [6].

3. Energy Storage, Charging Modes, and Wireless Power Transfer

We saw in the previous section that the range of EVs is linked to energy storage capacity and charging time. We also observed that high storage capacity presents a challenge for EVs and can be overlooked in urban public transport, particularly due to the incidence of wireless charging. Indeed, the lower the storage capacity, which is economically advantageous, the shorter the charging time and the more frequent the charging needs. Therefore, it is essential to optimize storage capacity, charging frequency and time, as well as the complexity of the charging infrastructure and associated protection devices [20].

3.1. Charging Modes

Regarding EVs equipped with energy storage batteries, the main different types of charging modes are summarized as follows:

- Thanks to the sliding contacts (catenaries), at once with the direct power supply of the motor by the electrical network: trams or trains with direct grid-connection and simultaneous charging. The storage is used on sections of the route not connected to the grid;
- Through cables for parked EVs: overnight charging;
- In urban wireless rapid charging stations: EVs in urban or highway traffic;
- Via urban wireless charging systems during intermittent stops or at the end of a journey: urban buses or trams;
- By means of dynamic wireless road systems (electric roads): EVs traveling on roads or motorways.

In all these charging methods, EVs are equipped with converters connecting the supply to the electric motor, whose characteristics are adapted to the type of conversion.

3.2. Wireless EMI and Adverse Effects

Energy required for EV functioning is supplied by the public electrical grid, which can be converted to mechanical energy in the EV electric motor or accumulated in storage batteries. This energy transfer from the grid to the EV can be realized directly by cable in static EVs or sliding contacts in moving EVs. It can also be achieved indirectly by wireless power transfer (WPT), which can be fixed WPT in static EVs or dynamic WPT in moving EVs. There are different strategies of WPT devices depending on applications. Concerning the application in EV, the WPT device is commonly an IPT. The IPT device in an EV is placed between the grid and the EV storage batteries (see Subsection 5.1 for more details). It is constituted of a wireless inductive coupler transformer (ICT) connected to the energy grid and storage through adapting static converters. The ICT is shaped of two coupled coils, namely transmitter and receiver, which are separated by an airgap. The transmitter is fixed outside the EV (generally on the ground) while the receiver is fixed in the EV (in general on the EV bottom). Thus, the airgap normally exhibits a weak coil coupling due to their separating distance. In such conditions, the required active power transfer across the ICT occasions a high reactive power involvement corresponding to a trivial power factor. Therefore, the two coils of ICT are compensated by capacities permitting an effective power factor. Thus, the IPT can accomplish a galvanically detached power transfer involving a capacitive-compensated ICT allowing functioning at resonance, ensuring reliable efficiency.

In the operation of an IPT, the ICT airgap reflecting coils weak coupling can exhibit stray fields causing different unwanted side effects. These adverse effects can perturb near objects. Actually, in the ICT, besides the expected main field transmitted across its two coils, its unsolicited stray field radiations can induce fields in near objects depending on the stray field strength and frequency as well as the exposed object's physical and topological features. The ICT radiated objects include living tissues (human and biodiversity), possible medical wearable tools, and further electronic devices [21]. Relating to living tissues, the induced EMFs due to exposure yield biological effects (BEs) typified by the tissue-specific absorption rate (SAR) and the exposure frequency and duration. Such BEs commonly disclose thermal effects that can be hazardous in case of top-heavy SARs and exposure intervals [21,22]. The BEs control can be achieved by matching field results to thresholds established by safety standards [21]. For example, consider an ICT between the chassis of an EV and the ground, operating while the vehicle's battery is charging in an open space: this situation of "ground charging" poses a threat to surrounding populations and biodiversity. **Figure 1** illustrates an example of different cases corresponding to such risky situations.

Figure 1. Illustration of examples of typical threat situations that ICTs represent for surrounding populations as well as for domestic and wild biodiversity species.

Regarding medical tissue wearable supervision or assistance devices, they are expected to exhibit an invulnerability to EMI. Such EMI-immunity includes protection from exposure, exclusion of inside EMF-sensitive matters, or shielding. The EMI-immunity degree of a wearable tool determines its functional compatibility related to EMF radiation. This compatibility can be authorized by appropriate tool design or shielding strategy, both of which can be verified through electromagnetic compatibility (EMC) assessment routines involving experimental or computational techniques [23,24].

4. Sustainable Energy Management

Energy concerns in EVs related to its conversion origin, transmission, and storage, can be managed in a sustainable manner, permitting its integration into an ecological environment [25]. These concerns include clean energy conversion, the design of efficient and safe charging systems, and optimized storage state and capacity. As mentioned earlier, EV storage, power transfer (direct or wireless) and grid-connection can be supervised using sustainable management tools. Thus, a sustainable design added to sustainable monitoring in EVs allows for optimized operation, reduced possible adverse effects, and better adaptation to environmentally friendly backgrounds.

The sustainable monitoring can be achieved in EVs through smart digital tools and their possible integration into the electrical grid of connected urban areas. The involved complex procedure can be assisted by artificial intelligence (AI) algorithms and monitored by digital twins (DT).

4.1. Complex Connected Procedure

The abovementioned EV complex connected procedure includes EV–battery storage–IPT–grid. The energy management between EVs' storages and the grid can be achieved by control routines between the EV and the grid, grid-to-vehicle (G2V) or V2G [26,27], or between EVs (V2V) [28]. As well, guaranteeing the interoperability of two sides of the ICT [29] and the concern of a fitting charging framework [30]. Furthermore, connectivity and self-directed driving management [31,32], smart supervising in EV charging [33], accounting for energy storage [34] or control [35] would fashion EVs considerably more consistent. Thus, the involved complexity in EV connected procedure mentioned above can be handled for an EV combined with other EVs connected to the system.

4.2. AI-Assisted EV Connected Procedure

AI is basically a considerable assembly of tools that empower computers to perform smartly, mimicking human intelligence and working automatically, for instance, in EV charging [36–38]. It uses data to attain well-learned decisions and can become being more effective as it gathers further data. Machine learning (ML) is a dedicated branch within the widespread field of AI. Its central aim is to build and refine algorithms that become further dependable and competent as they perform jointly with data over time. It delivers computers to analyze information and shape informed decisions or forecasts, all without requesting particular programming for such tasks [39,40]. It objects to lessening human intervention as much as possible, standardizing the learning exercise through data. In various recent utilizations, AI and ML are practiced jointly to entirely power their individual capacities [41].

BI associated with big data, as mentioned before, permits the creation of real-time insights that enable effective decision-making in complex procedures [11,13]. Thus, associating great information debits with AI processes advances substantial capability for the extraction of utilizable data displaying outstanding swiftness and faithfulness.

In the present analysis, the procedure's intrinsic complexity outcomes from the interaction of its mutually dependent implicated occurrences. This involves the connected procedure including EV–battery storage–IPT–grid, accounting for EMI safety.

4.3. DT Monitoring of Connected EV in Ecological Environment

DT aids decrease uncertainties and peripheral hazards inside complex procedures [15]. A DT includes two matched constituents: a physical element and its virtual replica, together with near-immediate bidirectional data interchange among them. Such a matched twosome allows inherent self-adjustment; the physical element conveys processed measured data to the virtual element, while the latter transmits control commands to the physical element. This regulation support authorizes the abovementioned contractions in the complex procedure control. As regards the accurate matching running in the DT, the swapped information from the real procedure is corrected by means of external data, such as records from the Internet of Things (IoT), along with the system's acquired operational history. The fine-tuned outcome, next to training over data analysis, is subsequently spread to the virtual replica. The intrinsic intricacy of the communication between the parts of the real procedure is reproduced in its virtual model by a composite coupled model. As the matching within the DT is assumed to be instantaneous, this swiftness is discordant with the complex coupled model computation time. Consequently, such a complete model should be compressed to condense computation time while preserving a faithful picture of the real procedure. This decrease can be attained by model order reduction techniques, surrogate models, and ML substitution strategies [42–44].

In the present analysis, the complex connected procedure including EV–battery storage–IPT–grid, accounting for EMI safety and AI assistance, corresponds to the real element of the DT. Several applications of DT in monitoring of EV mobility are reported recently, related to storage state of charge and health [45,46] and charging management AI-assisted DT monitoring [47,48]. **Figure 2** illustrates the schematic of a DT monitoring of connected EVs in an ecological environment.

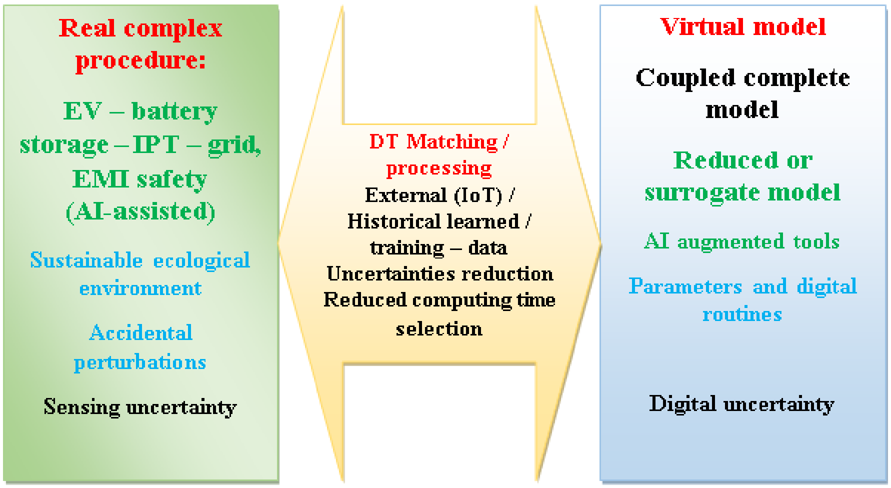

Figure 2. DT monitoring scheme of the complex controlled procedure including the connected EV–IPT–electric network, taking into account EMI safety and AI assistance, enabling EVs to operate in an ecological environment.

5. Discussion

In the studies developed in the preceding sections, a number of subjects deserve added discussion.

5.1. Sustainable Design and Function of IPT

As mentioned before, the sustainable management of EV energy concerns includes the construction and the operation of the charging IPT device [3]. The main component of this device is its ICT, which is characterized by the self and mutual inductances of the transmitter and receiver coils L_1, L_2 and M_{12}, as well as their compensation capacitances C_1 and C_2, as shown in **Figure 3a**. The other IPT components correspond to the conversion interfaces between the ICT and the AC grid and the energy storage. The interface with the grid side is composed of an AC/DC converter + a filter + a DC/AC adjusted frequency and voltage inverter, while this with the battery storage is composed of an AC/DC converter + a filter, as shown in **Figure 3b**. **Figure 3c** illustrates a schematic structure of the ICT and the EV chassis. The two ICT copper coils are externally-sided by ferrites, permitting the magnetic flux concentration, thus enhancing the coils coupling and reducing the stray fields. They are separated by a gap "d" and present axes shift "sh". The different IPT parameters involved in **Figure 3** are those implicated in its behavior and thus engaged in its design. Different published works on IPT design and optimization could be found in the literature [2,3,49–53]. As well, effective operation depends on the positioning of the two ICT coils [2,3,54–56].

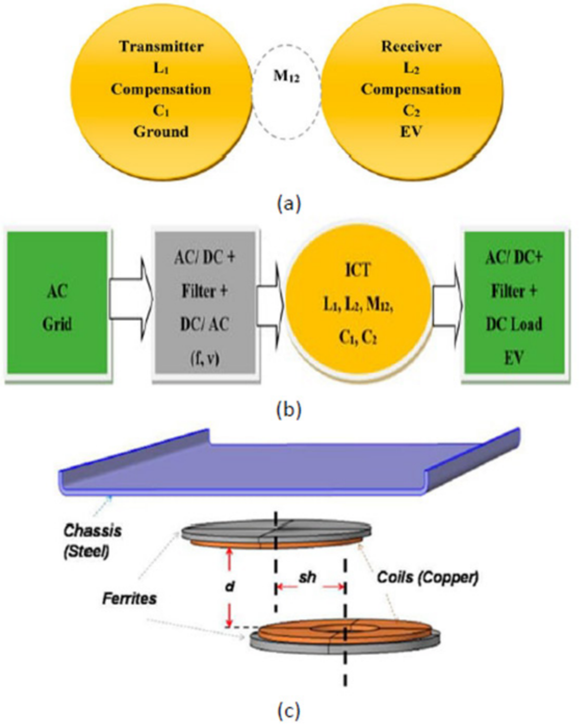

Figure 3. Schematic illustration of an IPT in an EV: (**a**) ICT inductances and compensation; (**b**) IPT conversion interfaces with the grid and battery storage; (**c**) Geometric representation of ICT coils between ground and the EV chassis [3].

5.2. ICT-EMI and Shielding

In the various mobility applications using EVs discussed in the previous sections, IPTs were used in specific situations. As mentioned earlier, the operation of the ICTs involved in these IPTs is associated with EMF radiation due to their air gap nature. These radiations can be reduced conceptually by sustainable design, however, in various operational conditions, they can prove harmful. Depending on the situation and charging mode, the protection of people inside or outside the EV must be ensured. In all situations where charging is carried out with passengers on board, such as ground-based charging of buses at stops or dynamic ground-based charging of EVs on electric highways, protective shielding must be installed between the ICT and the EV passenger compartment. Basic shielding is built of conductor materials, more sophisticated shields are built of multifunctional EMI shielding materials [57,58]. Similarly, in all situations where charging is carried out with empty EVs or EVs equipped with an internal protective shielding while stationary, people outside the EV must be protected. This is the case with static ground-based charging of EVs in open spaces for people or other biodiversity species nearby (see **Figure 1**), and with ground-based charging of buses at their stops for people on the platform or boarding. In such situations, the problem is that external shielding of the EV is practically impossible due to the nature and location of the ground-based charging device. Only solutions such as confining the EV or moving the charging device further away can be consistent. For example, the use of a charging device on the roof of buses during the break at the end of the journey without passengers (see **Figure 4**).

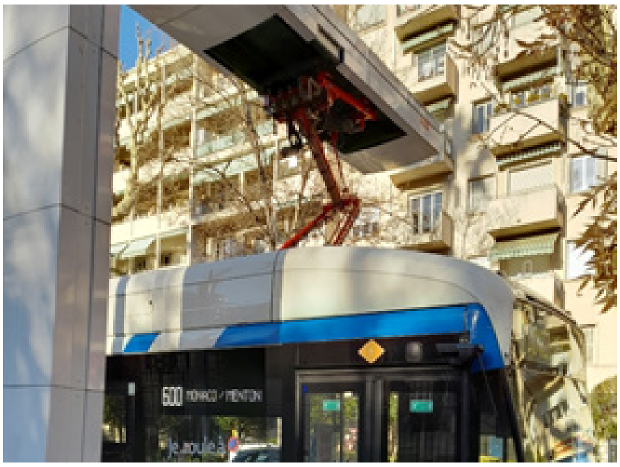

Figure 4. Bus using a rooftop charging device during the terminal break without passengers.

Relating to aspects such as EMI and safety considerations, typical EMF intensity levels generated by IPT systems matched with international safety standards, pedestrians, animals, or urban biodiversity near ground-based wireless charging stations (**Figure 1**), optimized coil design, and active control strategies to reduce electromagnetic leakage [2,3, 21–25].

5.3. Mixed Mobility and Charging Modes

As indicated in Sections 2 and 3.1, different types of mobility can utilize different charging methods. Recent planning for environmentally friendly and sustainable energy-conscious urban public transportation suggests using hybrid mobility technologies combined with various charging methods. A typical example involves EVs, such as trams, operating in different environments: underground, surface (simple environment), and/or surface (complex environment). The complexity involved is related to the urban environment of the route. In the case of underground and surface areas (simple environment), the EV can be directly and permanently connected to the grid via catenaries, using either a simple underground connection infrastructure or a relatively simple surface infrastructure. In the case of complex surfaces, the EV can utilize a battery storage system, which can be charged at the end of the journey, or on surface (simple environment) or underground sections of the route connected to the grid by catenaries. These different options are illustrated in **Figure 5**.

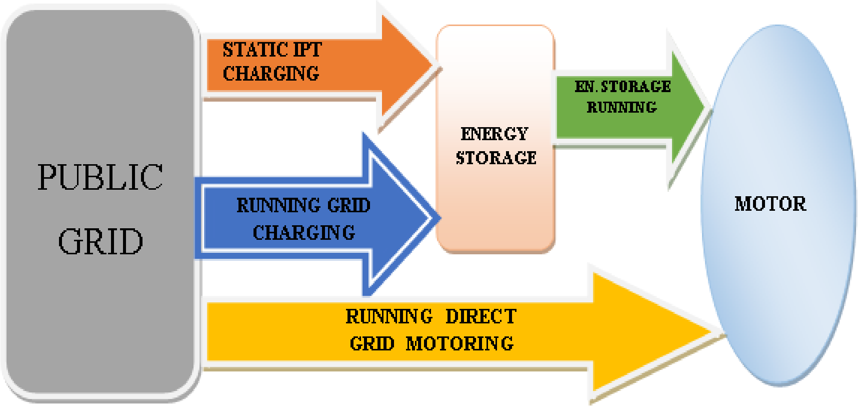

Figure 5. Mixed urban EV operations and corresponding battery storage charging modes [3].

Furthermore, various advanced smart charging technologies can be used, thereby improving efficiency and environmental benefits. For example, AI-driven fault management and diagnosis, maximum efficiency point tracking, scalable data-driven EV charging optimization, improving the absorption capacity of new energy sources and loads, and authentication techniques and driver identification systems [59–63].

Moreover, practical challenges such as infrastructure costs, system efficiency losses, safety regulations, and scalability in real urban environments have to be considered in the choice of different types of mobility as well as their charging methods.

6. Conclusions

This contribution reviewed and analyzed the role of a sustainable and efficient energy approach in planning and monitoring energy storage and IPT charging systems integrated into EVs for environmentally friendly urban applications. The main outcomes of this study can be summarized as follows:

- Energy storage capacity, EV range, IPT charging technology, connected EVs, and intelligent digital assistance and monitoring tools are essential and closely related topics in urban transportation;
- Urban public transportation can benefit from low-capacity storage systems, which offer low cost, reduced weight, and a minimal footprint. This is related to short start-up and stopping distances, enabling frequent battery charging;
- Advanced digital tools such as AI and DT hold promise for managing connected EVs in urban transport, for example, in connected smart cities;
- The IPT charging strategy in public transportation avoids the complexity of continuous infrastructure connected to the network thanks to its comparatively simpler configuration;
- Shielding the EV's passenger compartment is necessary for IPT charging, whether continuous or intermittent, while the vehicle is in operation;
- Precautions must be taken regarding static IPT charging in open spaces, relating to the location of the IPT in the EV and traffic restrictions nearby;
- The use of mixed transport technologies and charging methods enables reliable and sustainable urban mobility.
- Specific general recommendations for future studies

could be the optimization of wireless charging efficiency, the improvement of safety standards, and the discussion of AI-based energy management frameworks.

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Conflicts of Interest

The author declares no conflict of interest.

AI Use Statement

The author declares that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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