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Integration of Wireless Charging Systems into Urban Electric Buses: A Technical and Economic Feasibility Analysis for the City of Adana

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Abstract

Rising urbanization, air-quality concerns and the need for energy efficiency are accelerating the transition to electric buses in urban public transport. This study examines, from technical, design and economic perspectives, the integration of wireless power transfer (WPT) systems into urban electric buses. More than sixty sources were systematically reviewed, addressing receiver-coil placement and chassis interaction, battery optimization, thermal management, electromagnetic safety, urban integration and sustainability. A representative conversion scenario was then developed for bus line 114 in Adana, and a techno-economic feasibility analysis (CAPEX, OPEX and payback period) was conducted. When a 12 m electric bus equipped with a 200-kW static inductive charging system has its battery reduced from five to three packs (510 to 306 kWh), the kerb weight decreases by about 1170 kg, the consumption falls from 0.80 to 0.75 kWh/km, and the passenger capacity increases. Since the energy delivered during the 25-minute terminal layover is roughly twice that re-quired per round trip, operation is sustained without any dynamic charging infrastructure. The total investment for an eight-vehicle fleet is estimated at EUR 4.48 million. Feasibility is evaluated for both 2025 conditions and post-geopolitical May 2026 conditions. Under 2025 conditions the payback is about 5.1 years with a ten-year net profit of EUR 6.8 million; under May 2026 conditions, although the exchange rate and energy costs rose, the concurrent inflation-driven fare increase raises lira-denominated revenue, shortening the payback to 3.6 years and raising the net profit to EUR 13.1 million. The findings show that wireless charging is a strategic transformation tool for sustainable urban transport.

Keywords: Electric bus; Feasibility analysis; Inductive power transfer; Return on investment; Wireless charging

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1. Introduction

Accelerating urbanization, fossil-fuel-related emissions and the growing demand for energy efficiency are pushing urban transport toward more sustainable solutions. Electric vehicles lie at the center of this transition, while their charging infrastructures are being re-shaped in parallel with technological progress. The physical-connection, wear, operator-intervention and superstructure requirements of conventional conductive (plug- or pantograph-based) charging methods have created the ground for wireless power transfer (WPT) technologies to come to the fore [1-2].

Wireless charging offers a strong alternative for urban buses that regularly repeat fixed routes, in terms of both operational convenience and energy efficiency. The ability to charge vehicles while stationary or in motion can reduce battery size, ensure range continuity and lower the total cost of ownership (TCO) [3-4]. The route repetition of urban lines allows charging stations to be shared by many vehicles, enabling amortized use of the infrastructure investment [5].

This study addresses the integration of wireless charging into urban buses within an integrated technical, design and economic framework. Its original contribution is to move WPT technology, which is mostly examined in the literature with a component- or efficiency-oriented focus, into an application-oriented feasibility model that jointly considers the vehicle weight-consumption relationship, charging-scenario sizing and a ten-year return-on-investment (ROI) analysis on a real urban line (line 114, Adana).

The study also quantifies the relative advantages of the technology by comparing the wireless-charging scenario with an equivalent plug (conductive) charging scenario.

2. Theoretical Framework and Related Work

Although the roots of wireless power transfer go back to Nikola Tesla at the end of the 19th century, the technology became applicable to electric vehicles roughly a century later, with advances in electromagnetic induction and resonance principles, high-frequency semiconductor circuits and improved battery technologies [6-7]. WPT development accelerated from the mid-2000s, and standards such as SAE J2954 placed system safety and electromagnetic compatibility on a normative basis [8]. Ahmad et al. [1] classified wireless charging systems as inductive, resonant, capacitive and microwave-based, whereas Fisher et al. [9] focused on the structural and efficiency parameters of magnetically coupled systems, particularly the critical role of coil alignment.

In terms of vehicle chassis and design criteria, He et al. [10] emphasized that the placement of receiver coils under the vehicle is critical for both efficiency and structural integrity, and that airgap and alignment tolerances are decisive for system performance. Attaianese et al. [11] examined the mechanical effects of modular charging systems on the chassis and proposed structural-reinforcement strategies. On dynamic wireless charging (DWPT), Bi et al. [3] and Mahesh et al. [12] addressed the energy-transfer efficiency and infrastructure requirements of moving vehicles and revealed the potential to increase operational continuity by reducing battery capacity.

In recent literature, the integration of dynamic systems into public transport, high-power and alignment-tolerant designs, IPT-CPT hybrid solutions and electromagnetic-safety regulations are receiving increasing attention [13-16]. The bibliometric study by Gbey et al. [17] shows that publication and citation activity in the field has risen steadily over the past decade. For Turkey, Ozbas et al. [18] evaluated the operational efficiency of a wireless-charging application on the Istanbul Metrobus line, while Reyhan [19] examined the power-transfer methods used in wireless charging. Taken together, these studies show that wireless charging offers not merely energy-transfer technology but a holistic transformation in terms of vehicle design, infrastructure planning and urban sustainability.

2.1. Wireless power transfer methods

In inductive power transfer (IPT), following classical transformer logic, the alternating magnetic field produced by the transmitter (primary) coil is converted into alternating current in the receiver (secondary) coil across an air gap (Figure 1). In magnetic-resonant inductive transfer (MR-WPT), both transmitter and receiver operate at a specific resonance frequency; this method is more flexible in terms of airgap and alignment tolerance and is preferred particularly in dynamic applications (Figure 2). Capacitive power transfer (CPT) offers light weight and low cost but is not widespread in public transport because of efficiency and safety constraints (Figure 3). Microwave-based methods, despite their long-range advantage, remain limited in practice due to low efficiency and health concerns (Figure 4) [20-21]. In urban buses, the method that has become widespread is inductive transfer, owing to the constraints that speed bumps and inclined routes impose on under-vehicle placement. A comparison of the methods is given in Table 1.

Considering applicability to public transport in more detail, IPT and MR-WPT are the only methods presently mature enough for bus operation. Static IPT pads installed at terminals and major stops match the duty profile of urban lines, where vehicles dwell repeatedly at fixed points, and achieve 85–95% efficiency at air gaps of 5–20 cm; the principal design challenges are lateral/longitudinal misalignment tolerance and ground clearance over speed bumps. MR-WPT extends the tolerable air gap and misalignment and is therefore the basis of most dynamic (in-motion) charging demonstrations, at the cost of more complex resonant-network and electromagnetic-compatibility design. CPT and microwave transfer, by contrast, remain unsuitable for buses: the achievable power density of capacitive coupling is too low for heavy-duty traction, and microwave beaming raises efficiency and exposure-safety concerns that are incompatible with crowded urban environments. For these reasons the present study adopts static inductive (IPT) charging as the reference technology.

Hybrid solutions are also receiving growing attention. Inductive–capacitive (IPT–CPT) hybrid couplers seek to combine the high-power density of inductive coupling with the misalignment tolerance and reduced eddy-current loss of capacitive coupling, while hybrid energy-side architectures pair the wireless interface with on-board supercapacitors or with photovoltaic generation through shared compensation networks [16], [22]. For public-transport fleets, the most relevant hybrid concept is the combination of static terminal charging with limited dynamic charging on selected high-occupancy segments, which can further reduce the required on-board battery capacity; however, the additional infrastructure cost must be justified against the simpler static-only configuration adopted here.

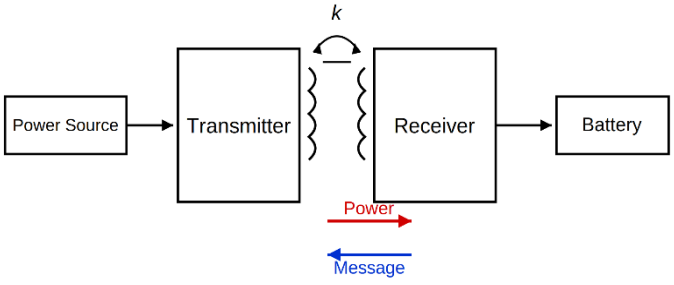


Figure 1. Working principle of inductive power transfer (IPT).

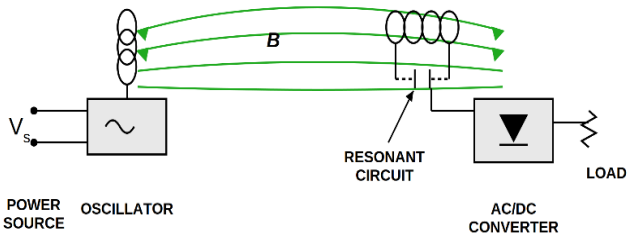


Figure 2. Working principle of magnetic-resonant inductive power transfer (MR-WPT)

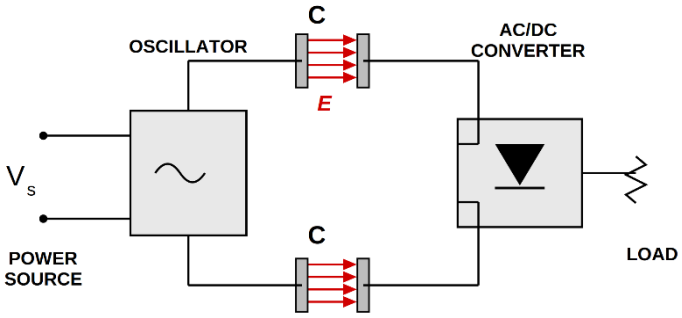


Figure 3. Working principle of capacitive power transfer (CPT).

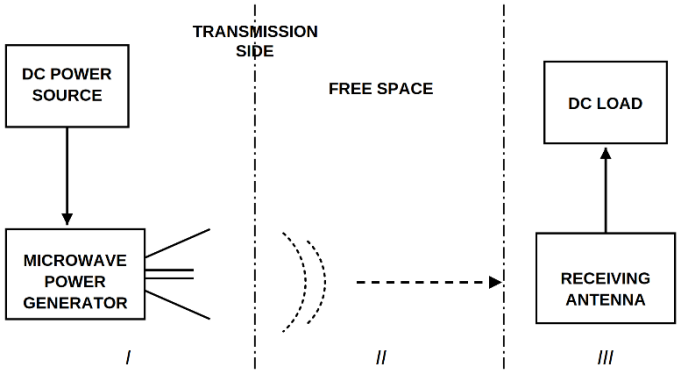


Figure 4. Working principle of microwave power transfer.

Table 1. Comparison of wireless power transfer methods [9,20].

Method	Frequency	Distance	Efficiency	Advantages	Disadvantages
Inductive	20-90 kHz	5-20 cm	85-95%	Safe, high efficiency	Short range, alignment
Resonant	6-13 MHz	30-200 cm	70-90%	Distance tolerance, flexibility	Complexity, EMC
Capacitive	MHz band	<10 cm	60-80%	Light weight, low cost	Safety, efficiency
Microwave	GHz band	>200 cm	<50%	Very long range	Low efficiency, safety
Hybrid	-	-	High	Flexibility	Complexity, cost

2.2. Static and dynamic wireless charging

WPT systems on buses can be implemented statically (while parked) or dynamically (while in motion). Static stations are generally used during dwell times at the route terminals or at stops in an "opportunity charging" scenario and, owing to high positioning accuracy, operate at 85-95% efficiency [3,7]. In dynamic systems the vehicle receives energy from coils embedded in the road while moving; although this approach has the potential to reduce battery size and ease range anxiety, its infrastructure cost is higher [3]. Because the amount of charge is proportional to the time the vehicle spends over the station, stops with long boarding-alighting times are the most suitable areas for dynamic charging. A comparison of the two approaches is summarized in Table 2.

Table 2. Comparison of static and dynamic wireless charging.

Feature	Static wireless charging	Dynamic wireless charging
Charging state	Vehicle parked	Vehicle in motion
Infrastructure cost	Low-medium	High
Efficiency	High (85-95%)	Medium-high
Battery size	Large	Can be smaller
Standards	Mature (SAE J2954, IEC 61980)	Emerging (SAE J2954/2 etc.)
Application area	Stops, depots, fleets	Highways, public transport

2.3. Worldwide applications of wireless bus charging

Wireless charging of urban buses has progressed from laboratory demonstrations to commercial and pilot deployments on several continents, providing real-world evidence for both static and dynamic concepts. Representative examples are summarized below.

Static (opportunity) charging is the more widely commercialized concept. In Wenatchee (Washington, USA), the transit authority operates BYD electric buses that are charged wirelessly at designated stops and layover areas, improving range and operational efficiency. In Utah (USA), a fleet project implemented with the WAVE inductive system demonstrated improved efficiency and battery life under real operating conditions and served as a reference for commercial-scale feasibility. In Changsha (China), a wireless system developed by ZTE and integrated with BYD buses has been used on commercial urban routes, illustrating the applicability and efficiency of static wireless charging in scheduled service.

Dynamic and mixed concepts have been explored mainly in Europe. In Braunschweig (Germany), Bombardier's PRIMOVE system provided both static and dynamic inductive charging for city buses, demonstrating the feasibility of in-motion charging at urban scale, while pilot studies in Berlin (Siemens–BMW) assessed inductive charging across multiple vehicle types. In the Netherlands, a small-bus wireless trial in Utrecht was completed successfully, and a longer-running project in 's-Hertogenbosch (Den Bosch) sustained inductive-charging operation with municipal and provincial support. Collectively, these projects show that wireless charging delivers tangible benefits in operational

efficiency, range management and fleet flexibility, while cost, energy efficiency, infrastructure standardization and safety remain the principal areas requiring further development.

2.4. Key physical parameters

The key parameters in vehicle integration of WPT systems are the air gap, operating frequency, power-transfer capacity and thermal management. The air gap and alignment tolerance between coils directly affect the coupling coefficient and efficiency; in dynamic applications the nominal gap is generally kept around 200-250 mm with a tolerance of about ±25 mm [10]. In high-power applications the operating frequency lies in the 20-85 kHz range; higher frequencies allow more power transfer but require compliance regarding electromagnetic interference (EMI) [1,19]. Power transfer of 50-300 kW is possible in static and dynamic applications; system efficiency varies in the 75-85% range depending on alignment, air gap, frequency and thermal management [5,15]. The heat loads generated in the coils and power electronics require effective (usually active/liquid) cooling for system life and safety.

2.5. International standards and regulations

The legal and technical framework of WPT systems is defined by the IEC 61980 series (general requirements, vehicle-infrastructure communication, magnetic field and dynamic applications), ISO 19363 (safety and interoperability in magnetic-field-based systems), the SAE J2954 series (performance, alignment tolerance, EMF limits) and UNECE regulations (No. 10 - electromagnetic compatibility; No. 100 - battery and powertrain safety; No. 107 - bus structural standards). International Commission on Non-Ionizing Radiation Protection (ICNIRP) limits for electromagnetic-field exposure are critically important for passengers and maintenance personnel. In integration into buses, it is essential that the system be designed so as not to compromise the basic safety standards of the vehicle.

2.6. Design effects

Receiver systems are placed in the mid-chassis region of the bus for air-gap optimization and weight distribution. This placement directly affects the approach-departure angles of the vehicle (typically 7-8°) and its clearance over speed bumps; since the opening required in the chassis for a centrally placed unit may create a disadvantage in terms of strength, precise design with computer-aided-engineering / finite-element-method (CAE/FEM) analyses is required. Adding an electromagnetic-field (EMF) source to the bus must be verified by the finite-element method (FEM) with copper or aluminum shielding to prevent noise in the vehicle communication lines and risk to passenger health [19]. Reducing the battery capacity lowers the kerb weight, thereby increasing passenger capacity and energy efficiency; in vehicles with roof-mounted batteries, lowering the center of gravity reduces suspension and braking loads [4,15]. The placement of the receiver coils under the vehicle floor and the general architecture of a bus suitable for wireless charging are shown in Figure 5.



Figure 5. Placement of wireless-charging receivers under the vehicle.

3. Materials and Method

The study follows a two-stage method. In the first stage, more than sixty sources accessed from the IEEE Xplore, ScienceDirect and Google Scholar databases were systematically reviewed, compiling the history of WPT technology, power-transfer methods, physical parameters, international standards and pilot applications worldwide. In the second stage, a representative conversion scenario was developed for bus line 114 in Adana; vehicle and charging-system selection, consumption modelling, charging sizing and a techno-economic feasibility analysis were carried out. Because accessible field data are limited and no application has yet been commissioned in Türkiye, all consumption and efficiency values are based on current literature averages, manufacturer catalogue/quotation data and theoretical assumptions. Items such as electricity tariffs, battery prices and infrastructure-installation costs are taken as fixed within the scenario.

In the economic analysis, foreign-currency-denominated (imported) investment items and lira-denominated operating and revenue items are treated separately: CAPEX items such as the wireless-charging equipment, vehicles and stations are defined in euro and are therefore independent of the exchange rate, whereas the euro equivalent of lira-denominated items such as energy, personnel, maintenance, insurance and fare revenue depends directly on the exchange rate. Feasibility was therefore calculated separately for two reference periods: (i) the 2025 reference conditions (EUR/TL parity 47.72; diesel 53.9 TL/L; industrial low-voltage electricity tariff 4.93 TL/kWh) and (ii) the May 2026 conditions after the rise in fuel and exchange rates following the US-Israel-Iran tension (EUR/TL parity 53.5; diesel 70 TL/L; industrial low-voltage electricity tariff 6.16 TL/kWh after a 25% increase in 2026). The electricity cost is taken over the industrial low-voltage tariff (including all taxes), since fleet charging is a high-consumption subscription. On the revenue side, an average fare of 22 TL is applied for the 2025 reference period, while for May 2026 the tariff that came into force in Adana on 26 April 2026 is used; in that tariff the card-based fare on private public buses is 39 TL for adults and 20 TL for students, so with an assumed mix of about 60% adult and 40% student an average fare of about 31 TL is taken. For both periods, an annual nominal increase of 10% is assumed for all lira-denominated cost and revenue items, and a ten-year projection is constructed. This 10% rate is adopted as a conservative planning figure that approximates the medium-term inflation

path targeted by the Central Bank of the Republic of Türkiye rather than the substantially higher short-term consumer-price inflation; it is applied uniformly to both costs and fare revenue so that the projection reflects the relative (real) balance between expenditure and income and is not distorted by the absolute inflation level [23]. The sensitivity of the results to this assumption is limited because the same escalation is applied to both sides of the cash-flow balance.

3.1. City and line selection

Adana has a population of 2,280,484 according to TURKSTAT 2024 records and is shaped by three main arteries on the east-west axis and five north-south arteries connecting them; buses are the dominant public-transport mode. As a preliminary examination, the private-car cost for the 19.8 km round trip between the Toros district and the historic Big Clock was estimated; with diesel consumption of 5.5 L/100 km and a 20% traffic tolerance, about 1.3 L of fuel is consumed. The fuel cost of this trip is about 70.4 TL at the 2025 reference diesel price (53.9 TL/L), rising to about 91.5 TL at the May 2026 price (70 TL/L) after the US-Israel-Iran tension. Adding an extra cost of 1.5 TL/km, the total private-car cost becomes about 100.4 TL for May 2025 and about 121.2 TL for May 2026. By contrast, the card-based fare of a two-person bus trip over the same distance (about 78 TL from the May 2026 adult fare of about 39 TL per person) is markedly lower than for the private car. The rapid rise in fuel prices pushes the private-car cost above that of public transport, increasingly shifting the balance in favor of public transport and increasing the need for charging technologies that lower operating costs and can suppress fares.

For the conversion scenario, the line was selected on the basis of the criteria that it (i) carries out intensive passenger boarding-alighting throughout the day, (ii) has the longest possible route, (iii) passes through the city's main arteries, and (iv) has a large parking area at the start/end stop where a static station can be installed. These criteria also represent the most unfavorable ("worst-case") scenario in terms of consumption. Line 114 on the M1 Real - Optimum AVM route, which meets these criteria, was selected (Figure 6). The line is about 23 km long with 64 stops; the vehicle completes one direction in 75 minutes, a service starts every 25 minutes, and eight vehicles operate simultaneously on the line. According to this schedule, each vehicle has a 25-minute dwell (static-charging) window at the M1 stop parking area, corresponding to the driver's rest. The number of stops was not used as an independent selection criterion because it is strongly correlated with the criteria already adopted: a long route passing through the city's main arteries inevitably has a high stop count and intensive boarding–alighting. Importantly, a high number of stops increases energy demand through frequent stop–start (acceleration) events and door-opening HVAC losses, so selecting such a line deliberately yields a conservative, worst-case consumption estimate; if the charging scenario is feasible on this demanding line, it is feasible a fortiori on lines with fewer stops. The frequent stop–start behavior is implicitly captured in the SORT 2 (mixed) consumption basis used here, which includes repeated acceleration and idle phases representative of urban duty.

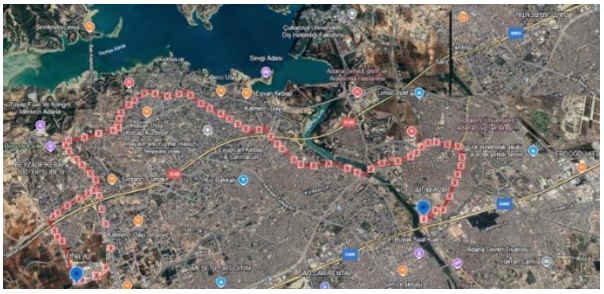


Figure 6. Route of bus line 114 in Adana (M1 Real - Optimum AVM, about 23 km).

3.2. Charging system and vehicle selection

The selection of the wireless-charging system was based on technical discussions with two suppliers (Electreon and ENRX) (Table 3). In terms of road integration, because the 100 m module length of the first supplier cannot be placed at every point and increases the installation cost, a solution offering a shorter (40 m) module, higher power per receiver (200 kW) and a lower unit cost (1.25 EUR/W static) was preferred. Delivery of the transmitter (primary coil) units pre-assembled in concrete provides significant ease and cost advantage in superstructure installation (Figure 7). The recommended road-side layout scenarios are shown in Figure 8. The vehicle-side receiver unit consists of the pick-up unit, the battery-charging interface and the user interface.

Table 3. Comparison of the two-candidate wireless-charging systems (manufacturer technical data).

Criterion	Supplier A	Supplier B (selected)
Charging power	30 kW/receiver	200 kW
Dynamic module length	100 m	40 m
Static cost/power	1.75 EUR/W	1.25 EUR/W
Dynamic cost/energy	2.00 EUR/Wh	1.95 EUR/Wh
System efficiency	85-92%	90%
Component mass (12 m bus)	300 kg	200 kg
Maximum air gap	150 mm	250 mm
Receiver modularity	Yes	No

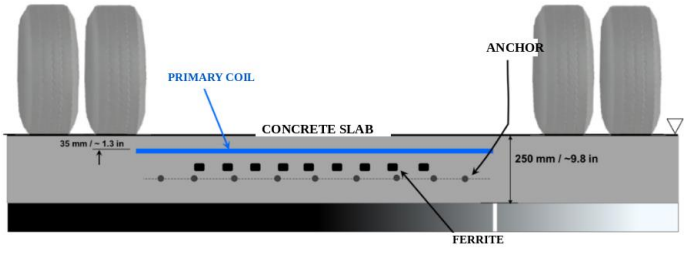


Figure 7. Installation cross-section of the road-side primary coil within the concrete slab and basic dimensions.

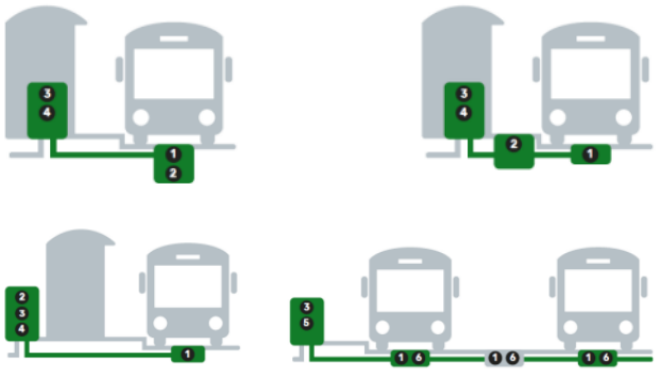


Figure 8. Recommended layout scenarios for the road-side components, where the numbered items denote: (1) primary coil (transmitters); (2) electronic components; (3) monitoring unit; (4) cooling system; (5) cooling system for multiple charging; and (6) electronic components for multiple charging.

As the reference vehicle, a 12 m bus with five battery packs (5×102 = 510 kWh) installed was selected. The vehicle's baseline consumption of 0.80 kWh/km was taken from its SORT2 test result. The Standardized On-Road Test cycles (SORT) constitute a reproducible test protocol developed by the International Association of Public Transport (UITP) to compare the energy consumption of buses; the methodology defines three driving cycles, SORT 1 (urban), SORT 2 (mixed) and SORT 3 (suburban), each with prescribed average speeds, acceleration phases and stop times, and the e-bus addendum (E-SORT, 2017) extends the protocol to measure the traction energy consumption and zero-emission range of electric buses [24,25]. The SORT 2 (mixed) cycle was adopted here because it best represents the stop-and-go duty of the selected urban line. Because all auxiliary climate-control devices are switched off during the SORT procedure, the SORT 2 value reflects traction energy only; to obtain a realistic operating figure, the nominal 7.2 kW (12 A, 600 V) power of the vehicle's heating, ventilation and air-conditioning (HVAC) unit was therefore added to the SORT 2 consumption. Each battery pack weighs 585 kg. An average mass of 68 kg per passenger was adopted in the capacity calculation, in line with the value widely used in battery-electric-bus energy and battery-sizing studies [26]; a half-load equivalent of 34 kg per passenger was used when expressing the loading difference. The relationship between vehicle mass and energy consumption was assumed to be linear (see Section 3.3).

3.3. Vehicle weight-consumption modelling

If, with wireless-charging integration, the number of batteries is reduced to three, the minimum that preserves the vehicle's range, the two removed packs provide a weight saving of about 1170 kg. The kerb weight of the reference vehicle is 12,815 kg, the passenger allowance for the 18-tonne limit in Türkiye is 5185 kg (about 76 passengers) and the test weight is 15,400 kg. After lightning, the kerb weight drops to 11,645 kg and, up to the same limit, the passenger allowance rises to 6355 kg (about 93 passengers). The first order (linear) dependence of energy consumption on vehicle mass was adopted to translate mass saving into a consumption reduction. This simplification is supported by the literature: the tractive energy demand of a road vehicle is, to first order, proportional to its mass through the rolling-resistance and inertial (acceleration) terms, and battery-electric buses in particular exhibit a markedly more linear consumption–mass relationship than diesel buses because of their simpler and more linear speed–torque characteristic [26,27]. Applying this proportionality to the ≈1170 kg mass saving, the consumption of the wireless-charged vehicle falls from 0.80 to 0.75 kWh/km (Table 4). It should be noted that this linear estimate is conservative for an urban duty cycle dominated by frequent stop–start events, in which the mass-dependent inertial term is more influential than at steady cruise.

Table 4. Comparison of the plug-charged and wireless-charged vehicle.

Item	Plug-charged	Wireless-charged
Number of batteries	5	3
Battery capacity	510 kWh	306 kWh
Kerb weight	12,815 kg	11,645 kg
Test weight	15,400 kg	14,807 kg
Consumption	0.80 kWh/km	0.75 kWh/km

4. Results and Discussion

4.1. Energy requirement and charging sizing

Taking a single round-trip distance of 46 km, the per-round energy consumption is 45.8 kWh for the plug-charged vehicle and 43.5 kWh for the wireless-charged vehicle (HVAC included). Over five rounds per day, the monthly total consumption is 6870 kWh and 6525 kWh, respectively (Table 5). Thanks to weight saving, the wireless-charged vehicle consumes about 5% less energy per month.

Table 5. Monthly consumption of plug-charged and wireless-charged vehicles.

Parameter	Plug-charged	Wireless-charged
Round-trip distance (km)	46	46
Traction consumption (kWh)	36.8	34.5
HVAC consumption (kWh)	9	9
Total per round (kWh)	45.8	43.5
Rounds per day	5	5
Daily consumption (kWh)	229	217.5
Monthly consumption (kWh)	6870	6525

The energy required before starting the next round is the sum of the per-round consumption (43.5 kWh) and the HVAC consumption during the 25-minute parking period (about 3 kWh),

i.e. about 46.5 kWh. The energy that can be transferred in 25 minutes at a 200-kW static station is about 83.5 kWh. This value is roughly twice the required energy and means that the consumption is only about 55% of the charging capacity. Therefore, the static charging at the line terminal meets the energy requirement on its own and leaves no need for dynamic-charging infrastructure. This both lowers the investment cost and provides a substantial safety margin and adaptability to different routes against external factors that increase consumption (heavy traffic, gradient, excessive air-conditioning). The retained 306 kWh (three-pack) capacity is therefore not dictated by the modest ≈46.5 kWh required between two charging events, but by three independent design constraints. First, range autonomy and operational resilience: the pack must allow the bus to complete several round trips and reach the depot safely in the event of a missed charging opportunity, a station outage or schedule disruption. Second, battery longevity: sizing the usable energy well above the per-cycle demand keeps the pack within a shallow, mid-range state-of-charge window (typically 10–90% SoC), which is the single most effective operational measure for limiting degradation and is the basis on which manufacturers grant their capacity warranties [28]. Third, derating margins: usable capacity must remain sufficient at end-of-warranty state-of-health (commonly ≈70–80% of nominal) and under cold-weather and high-HVAC conditions. Reducing the battery to the bare per-trip requirement would force deep, high-rate cycling that accelerates ageing and would leave no reserve for these contingencies; three packs represent the smallest standard configuration that satisfies all three constraints while still realizing the weight, cost and efficiency benefits of down-sizing from five packs.

Beyond sizing, the wireless opportunity-charging strategy itself is expected to be favorable for battery life. Terminal top-ups during the 25-minute layover allow the pack to operate within a narrow, mid-range state-of-charge band and avoid the deep full-depth discharges that characterize overnight depot charging of a single large pack. Because the accepted charge per event (≈46.5 kWh) is only about 55% of what the 200-kW station could deliver, the effective charging rate per cell remains moderate, limiting the lithium-plating and heat-generation mechanisms that drive capacity fade. Industry experience indicates that distributing energy throughput across frequent shallow cycles, rather than fewer deep ones, slows degradation and increases the likelihood of a single battery replacement over the vehicle life rather than two [28]. A detailed cycle-ageing analysis is beyond the present techno-economic scope and is identified as future work.

4.2. Investment costs (CAPEX)

The cost items for converting line 114 consist of the eight electric buses to operate on the line, a 1+1 (redundant) static station at the M1 stop and its electrical infrastructure, together with installation and commissioning costs. The unit price of a vehicle integrated with a wireless receiver is taken as EUR 500,000, the unit cost of a static station as EUR 200,000 and the total infrastructure-installation cost as EUR 75,000. Because the project area is surrounded by farmland and has no dense settlement, no large investment in energy infrastructure is required. The total investment budget is calculated as EUR 4,475,000 (Table 6).

Table 6. Total investment budget (CAPEX).

Cost item	Amount (EUR)
Vehicle investment (8 × 500,000)	4,000,000
Charging station (1+1 redundant)	400,000
Infrastructure, installation and commissioning	75,000
Total	4,475,000

4.3. Operating costs (OPEX)

Annual operating expenses consist of energy, service-maintenance, personnel and insurance-tax items. At a station efficiency of 80%, about 290.6 kWh is drawn from the grid per vehicle per day; for eight vehicles, about 848,625 kWh of energy is consumed annually. This energy is priced over the industrial low-voltage tariff at 4.93 TL/kWh in 2025 and 6.16 TL/kWh in May 2026 after the 25% increase. The other lira-denominated items are service-maintenance of 200,000 TL/year per vehicle, 20 personnel (24,000,000 TL/year in total) and insurance-tax of 82,000 TL per vehicle. The euro equivalent of these items is computed at the parity of the relevant period. The first-year total operating cost is about EUR 637,882 under 2025 conditions and about EUR 588,477 under May 2026 conditions, the latter being lower because the higher parity reduces the euro equivalent of the lira-denominated items (Table 7). Assuming a 10% annual nominal increase for all expense items, the ten-year total operating cost is about EUR 10.17 million for 2025 and about EUR 9.38 million for May 2026.

Table 7. First-year operating expenses (OPEX) under the two scenarios.

Expense item	May 2025 (EUR)	May 2026 (EUR)
Energy	87,672	97,711
Service-maintenance	33,529	29,907
Personnel	502,934	448,598
Insurance / tax	13,747	12,262
Total (first year)	637,882	588,477

4.4. Passenger capacity, revenue and fare

The reduction in kerb weight allows more passengers to be carried for the same consumption, meaning that about 25 more passengers can be added to the number the current bus carries. The increase in the average occupancy from 75 to 100 creates, in theory, a potential fare reduction of about 25%. In the revenue calculation, an average fare of 22 TL is used for the 2025 reference scenario; for the May 2026 scenario, the tariff that came into force in Adana on 26 April 2026 is used. According to that

tariff the card-based fare on private public buses is 39 TL for adults and 20 TL for students, giving an average of about 31 TL with a mix of about 60% adult and 40% student. Assuming an average of 200 passengers per round, 1000 per vehicle per day and 8000 across the fleet per day, the first-year revenue is about EUR 1.35 million under 2025 conditions and about EUR 1.69 million under May 2026 conditions. With a 10% annual nominal increase in revenue, the ten-year total revenue reaches about EUR 21.5 million for 2025 and about EUR 27.0 million for May 2026 (Table 8).

Table 8. Ten-year operating revenue under the two scenarios.

Parameter	May 2025 (EUR)	May 2026 (EUR)
First-year revenue	1,346,186	1,691,963
Fifth-year revenue	1,970,951	2,475,540
Tenth-year revenue	3,174,236	3,988,330
Ten-year total revenue	21,454,739	26,965,527

4.5. Return on investment (ROI) and comparison with the plug-charging scenario

When the CAPEX, ten-year OPEX and revenue projections are combined, the wireless-charging investment pays back in about 5.1 years under 2025 conditions and yields a net profit of about EUR 6.8 million at the end of ten years. Under May 2026 conditions, although the exchange rate (47.72 to 53.5 TL/EUR) and the energy cost (4.93 to 6.16 TL/kWh) have risen, the concurrent inflation-driven rise in fares (average 22 to 31 TL) markedly increases the lira-denominated revenue. Because the euro-denominated CAPEX remains fixed, the increased lira revenue amortizes the investment faster; the payback shortens to about 3.6 years and the ten-year net profit rises to about EUR 13.1 million. The cumulative net-cash-flow trajectories of both charging options under the two reference periods are shown in Figure 9, where the payback point corresponds to the year in which each curve crosses zero. This result shows that, in an inflationary environment, a foreign-currency-denominated infrastructure investment can become more attractive if revenues also rise in local currency. It should be emphasized, as the basis of Table 9, that the CAPEX items are euro-denominated (imported equipment) and hence independent of the exchange rate, whereas the OPEX, revenue and net-profit figures are obtained by converting the lira-denominated items to euro at the parity of the relevant period, with a uniform 10% annual nominal escalation applied to all lira-denominated items. A comparison of the two scenarios is summarized in Table 9. In addition, redundant installation of the station allows the line to be expanded to up to 16 vehicles, the stations can also serve wireless-equipped vehicles on other lines, no additional night charging is needed because the vehicles are charged during the day, and the stations can continue to be used at the end of ten years without re-investment.

In the equivalent plug (conductive) charging scenario constructed for the same number of vehicles and routes, because there is no vehicle-side receiver, the unit vehicle price is taken as EUR 400,000 and the unit station price as EUR 10,000, giving a total investment of EUR 3,280,000 (Table 10). In this scenario, owing to the lower CAPEX, the payback is shorter than for the wireless scenario in both periods (about 4.0 years and about EUR 8.0 million net profit in 2025; about 2.7 years and about EUR 14.3 million net profit in May 2026). However, despite the lower initial investment, the plug scenario has disadvantages such as occupation of the parking area, additional personnel for night charging, capacity loss due to the battery weight, and stations that are not suitable for shared use. The choice between the two options therefore depends not only on financial return but also on operational flexibility and long-term scalability.

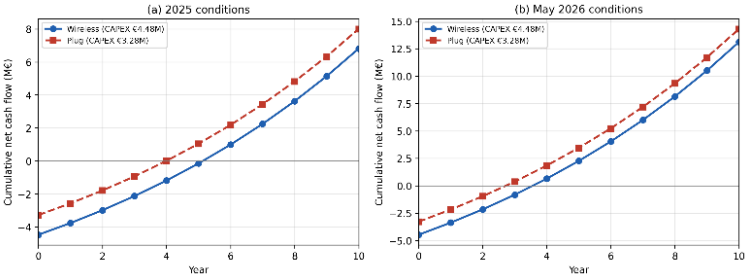


Figure 9. Cumulative net cash flow of the wireless and plug-charging scenarios over the ten-year horizon under (a) 2025 and (b) May 2026 conditions; the payback point corresponds to the zero-crossing.

Table 9. Comparison of economic-feasibility indicators under the 2025 and May 2026 conditions

Parameter	May 2025	May 2026
EUR/TL parity	47.72	53.50
Diesel (TL/L)	53.90	70.00
Industrial electricity (TL/kWh)	4.93	6.16
Average fare (TL)	22	~31
Total investment - CAPEX (EUR)	4,475,000	4,475,000
First-year OPEX (EUR)	637,882	588,477
First-year revenue (EUR)	1,346,186	1,691,963
Ten-year total revenue (EUR)	21,454,739	26,965,527
Payback period (years)	~5.1	~3.6
Ten-year net profit - wireless (EUR)	6,813,546	13,111,716
Ten-year net profit - plug (EUR)	8,008,546	14,306,716

Note: the CAPEX items are defined in euro (imported) and are therefore independent of the exchange rate; OPEX, revenue and net profit are obtained by converting the lira-denominated items to euro at the parity of the relevant period. A 10% annual nominal increase is assumed for all lira-denominated items.

Because most manufacturers warrant traction batteries for about eight years, at least one battery replacement is expected within the ten-year operating horizon [28]. Taking a conservative pack-level price of about EUR 130/kWh, a single fleet-wide replacement amounts to about EUR 318,000 for the wireless scenario (8 × 306 kWh) and about EUR 530,000 for the plug scenario (8 × 510 kWh). Incorporating this cost reduces the ten-

year net profit under the May 2026 conditions from about EUR 13.1 to about EUR 12.8 million for the wireless option and from about EUR 14.3 to about EUR 13.8 million for the plug option (and correspondingly from about EUR 6.8 to 6.5 million and from about EUR 8.0 to 7.5 million under the 2025 conditions). Notably, the smaller battery of the wireless configuration makes its replacement cost roughly 40% lower than that of the plug configuration, which partially offsets the higher initial CAPEX of the wireless system over the vehicle life. In all cases the investment remains clearly profitable over the ten-year horizon, confirming the robustness of the conclusions to the inclusion of mid-life battery replacement.

Table 10. Investment costs of the plug-charging scenario (comparison).

Cost item	Amount (EUR)
Vehicle investment (8 × 400,000)	3,200,000
Charging station	80,000
Total	3,280,000

5. Conclusions

In this study, the integration of wireless-charging systems into urban electric buses was examined multidimensionally in terms of vehicle design, operational efficiency, cost optimization and urban sustainability, using line 114 in Adana as a case. From a technical standpoint, because the receiver placement directly affects the chassis strength and the approach-departure angles, CAE/FEM-based chassis optimization is essential, and thermal management and electromagnetic shielding are critical design parameters. Optimizing the battery capacity from 510 kWh to 306 kWh reduces the vehicle weight by about 1170 kg, lowers consumption from 0.80 to 0.75 kWh/km and increases passenger capacity. The about 83.5 kWh of static charge delivered during the 25-minute terminal dwell is roughly twice the about 46.5 kWh required per round, so operation can be sustained without dynamic-charging infrastructure, which lowers the investment and increases feasibility.

Economically, the EUR 4.48 million investment pays back in about 5.1 years under 2025 conditions with a ten-year net profit of about EUR 6.8 million; under May 2026 conditions, in which fuel, exchange and fare prices have risen, the payback shortens to about 3.6 years and the net profit rises to about EUR 13.1 million thanks to the increased fare revenue. The investment is profitable over a ten-year horizon in both periods, which demonstrates the robustness of the model against macroeconomic fluctuations. Terminal/stop-based static charging emerged as the most efficient solution in the examined scenario, and supporting the stations with PV will strengthen sustainability.

It should be noted that, because no comparable application has yet been commissioned in Türkiye, all consumption, efficiency and cost values rest on theoretical assumptions, manufacturer quotations and literature averages, and the economic results are sensitive to the exchange-rate, tariff and inflation assumptions adopted. The principal practical risks of the conversion are the need to select forward-compatible systems in a still-maturing technology, the possibility of underbody/ground impact arising from the air gap, the requirement for spare-part supply and trained technical personnel, the high initial investment, and the need for carefully verified magnetic shielding. For these reasons a phased approach, collecting feedback through pilot applications before fleet-wide deployment, is advisable. Future work should refine the consumption model with on-road E-SORT measurements of the converted vehicle and incorporate a detailed battery cycle-ageing and degradation-cost analysis.

As a complementary measure, the favorable solar-irradiation conditions of Adana suggest that the charging stations could be supported by photovoltaic generation; a canopy carrying PV panels over the large car-park area at the M1 Real terminal could supply a significant share of the stations' energy demand; the literature has shown that wireless-charging systems can be efficiently combined with photovoltaic interfaces on a hybrid-compensation basis [22], further improving the environmental and economic balance of the system. The associated purchase, installation, operation and maintenance costs should be quantified in a dedicated follow-up study before implementation.

As recommendations, pilot applications should be initiated in Turkey through municipality-university-industry cooperation, compliance with the IEC 61980/ SAE J2954/ ISO 19363 standards should be ensured, the strategic positioning of charging stations and the strengthening of the energy infrastructure should be included in long-term urban-transport plans, and each city should develop differentiated charging strategies according to its own passenger density and grid capacity. In conclusion, wireless charging is not merely a technological innovation but a strategic component that jointly transforms vehicle design, economic efficiency, environmental sustainability and urban-transport planning.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Osman Baysal: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft.
Kadir Aydin: Conceptualization, Supervision, Validation, Writing - review & editing.

Declaration of Generative AI in the Writing Process

During the preparation of this manuscript, the authors used an AI-assisted language tool for language editing and formatting of the text. All AI-assisted output was subsequently reviewed and, where necessary, edited by the authors, who takes full responsibility for the final content of the manuscript.

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