Preliminary Investigation (PI-0403)

Caltrans Division of Research, Innovation and System Information

Charging Solutions for High-Speed Electric Buses

Requested by
Ryan Snyder, Feasibility Studies Manager, Caltrans District 7
Author
Mehdi Moeinaddini, Senior Transportation Planner, Office of Planning, Policy, and Program Development, Division of Research, Innovation, and System Information

July 25, 2025

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Executive Summary

Summary of Key Findings

This review involves selecting relevant studies, news articles, and reports, and synthesizing their key themes and findings to identify critical advancements and implementation considerations for enabling efficient, fast, and scalable charging infrastructure for high-speed electric buses. Key findings include:

- **Advanced Battery Technologies:** Solid-state batteries (SSBs) present significant potential, offering higher energy density and rapid charging. Commercialization expected around 2028–2030. Lithium-sulfur and graphene batteries have notable environmental benefits but face challenges in stability and scalability. Lithium titanate oxide (LTO) and silicon anode batteries exhibit strong performance, with companies actively addressing current technical limitations.
- **Battery Pack Swapping Systems:** Offer rapid vehicle turnaround times (1–5 minutes), extensively adopted in China but face hurdles in standardization, high infrastructure costs, and limited U.S. deployment. International pilots by companies like Ample indicate growing potential, with commercialization planned around 2025.
- **Overhead Catenary Charging:** Proven efficacy in continuous charging through trolleybus and eHighway systems. High infrastructure costs limit adoption, suggesting hybrid static charging approaches may be more feasible.
- **In-Road Wireless Charging:** Successfully demonstrated in pilot projects across Sweden, Israel, Italy, and the U.S. Challenges remain regarding cost, alignment efficiency, and power transfer capabilities at high speeds.
- **High-Power Charging Stations:** A viable near-term solution, facilitating rapid recharge during brief stops. Operational challenges include significant grid strain, infrastructure costs, and the necessity for robust scheduling integration.
- **Hydrogen Fuel Cell Buses:** Provide extended range (300–500 km) and fast refueling, ideal for intercity or high-speed transit routes. Current challenges involve high operational costs, infrastructure demands, and lower energy efficiency relative to battery-electric buses.
- **Grid and Infrastructure Implications:** Electric bus deployment demands significant but manageable grid upgrades. Managed charging, microgrids, renewable integration, and vehicle-to-grid (V2G) solutions are critical to mitigate infrastructure strain and support sustainable operations.

Research Needs for Caltrans

To enable successful integration and expansion of electric high-speed bus operations, Caltrans can prioritize research efforts addressing identified technological, operational, and economic gaps:

- **Battery Technology:** Accelerate studies in solid-state batteries (SSBs), lithium-sulfur, graphene, and silicon anode technologies focusing on performance, safety, scalability, and cost-efficiency.
- **Battery Swapping Standardization:** Investigate economic feasibility and technical requirements for standardizing battery designs across manufacturers, focusing on interoperability for broader adoption.

- **Charging Infrastructure:** Evaluate optimal infrastructure deployment models (battery swapping, in-road wireless, catenary) through rigorous economic analyses and comparative pilot studies to identify the most cost-effective and scalable solutions.
- **Grid Integration and Management:** Conduct comprehensive assessments of grid infrastructure demands, smart grid management technologies, renewable integration, and V2G opportunities to optimize energy usage and mitigate grid impact.
- **Hydrogen Fuel Cell Viability:** Explore cost reduction methods, green hydrogen production viability, and performance enhancements to ensure hydrogen technology's economic and operational feasibility in specific high-speed, long-distance applications.

Next Steps for Caltrans

To effectively advance high-speed electric bus charging technologies, Caltrans can undertake the following strategic steps:

- **Research & Development:** Fund and support targeted pilot projects and cross-sector collaborations aimed at validating emerging battery technologies, infrastructure standardization, and interoperability.
- **Infrastructure and Economic Analysis:** Coordinate detailed feasibility studies and economic evaluations for battery swapping, in-road wireless charging, overhead catenary systems, and high-power charging stations. Engage utilities early in infrastructure planning.
- **Standardization & Regulation:** Develop regulatory frameworks and standards in collaboration with industry stakeholders to facilitate technology adoption, ensure safety, and streamline infrastructure deployment.
- **Demonstration & Scaling:** Launch extensive demonstration projects across diverse geographic and operational contexts. Expand public-private partnerships to accelerate technology adoption and infrastructure development.
- **Implementation Mechanisms:** Establish collaborative multi-stakeholder frameworks to coordinate industry, government, utility, and academic efforts. Secure targeted funding, incentives, and supportive regulatory measures. Implement workforce development and knowledge-sharing initiatives to build organizational and operational capacity for managing new electric bus technologies.

Detailed Findings

Advanced Battery Technologies for Faster Charging and Longer Range

Recent advances in battery chemistry are poised to extend electric bus range and enable much faster charging. Currently, lithium-ion batteries dominate the EV landscape due to their high energy density, long lifespan, and lightweight design. They replaced older nickel-metal hydride (NiMH) batteries and have become standard in most EVs. Advancements like Tesla's 4680 cell design[1] are increasing energy density, reducing weight, and improving charging times and overall vehicle performance. However, lithium-ion batteries face limitations such as high production costs, overheating risks, and ethical concerns surrounding cobalt mining[2].

Emerging battery technologies aim to overcome lithium-ion's shortcomings. Solid-state batteries (SSBs)[3] can replace the flammable liquid electrolyte with a solid medium, promising higher energy density and improved safety. Prototype SSB cells have demonstrated energy densities around 350–400 Wh/kg – roughly 30–50% higher than today's lithium-ion cells – while supporting rapid charging (e.g. 15–90% charge in ~18 minutes at room temperature)[4] [5]. If commercialized by the late 2020s[6], SSB technology could roughly double the driving range of electric coaches or allow smaller battery packs for the same range, while also enabling 4C+ charge rates (charging a battery in 15 minutes or less) with improved safety[3] [7] [8]. Solid-state batteries have promising advantages over traditional Li-ion batteries but face technical, economic, and production challenges. Widespread commercial use—especially in EVs—will likely require 4+ years, with costs potentially competitive by 2028 under optimistic conditions[9]. Companies like Toyota, Samsung, and LG Chem are heavily investing in solid-state technology, with Toyota planning mass production around 2030[1].

Lithium-sulfur (Li-S) batteries[10] offer higher energy capacity and lower material costs by using sulfur instead of cobalt and they are lighter and more environmentally friendly[11]. However, current Li-S cells typically degrade after just 100–300 cycles—far short of Li-ion's 1,000+ cycles—mainly due to the polysulfide "shuttle" effect and cathode structural degradation[12]. They also suffer from poor conductivity, and structural issues[13], keeping them in the research and development phase for now[14].

Graphene batteries[15], utilizing a highly conductive and durable single layer of carbon atoms, offer potential improvements in energy capacity, charging speed, and heat management. Companies like Samsung and Huawei, along with research institutions, are actively developing graphene-enhanced batteries, with studies[16] showing significant gains in capacity, efficiency, and durability. These advancements could lead to better vehicle performance, quicker charging, and greater sustainability due

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[1] https://www.batterydesign.net/tesla-4680-cell/

[2] https://amprius.com/about/news-and-events/new-ev-battery-tech/

[3] https://www.mdpi.com/2079-4991/14/22/1773

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[10] https://pubs.acs.org/doi/abs/10.1021/ar300179v

[11] https://www.faraday.ac.uk/lis-advantages/

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[13] https://batteryswapstation.com/lithium-sulfur-battery/

[14] https://pubs.rsc.org/en/content/articlelanding/2024/cc/d4cc03085k

[15] https://www.sae.org/publications/technical-papers/content/2022-36-0100/

[16] https://www.sciencedirect.com/science/article/abs/pii/S1872580521600811

to reduced reliance on rare earth materials and longer battery life. However, high production costs and material instability limit current scalability[17].

A study evaluates lithium titanate oxide (LTO)-based lithium-ion battery cells[18] for high-power electric vehicle applications and compares them with conventional graphite-based cells. The results show that LTO cells offer excellent performance in low-temperature conditions, maintaining good charge acceptance even below 0 °C. They also demonstrate significantly better cycle stability and longer lifespan under high-current cycling, making them well-suited for applications that demand frequent fast charging and discharging. Thermal analysis indicated that LTO cells maintain stable temperatures during operation, contributing to improved safety and reliability. Incremental capacity analysis provided further insight into aging mechanisms, identifying different patterns of performance degradation over time. Although LTO cells have higher production costs than traditional graphite-based high-energy cells, their superior durability and performance—especially in extreme conditions—can justify the investment, particularly at higher production volumes.

Meanwhile, silicon anode batteries[19] are gaining traction by replacing graphite anodes with silicon, which can store up to ten times more lithium ions. This leads to longer battery life and increased range—up to 547 miles per charge in some tests. Despite challenges[20] like silicon expansion during charging, companies such as Amprius Technologies are making significant engineering progress to overcome these limitations. Silicon's abundance also makes it a more cost-effective alternative, offering strong potential for mass adoption[21].

In summary, emerging battery technologies – from solid-state electrolytes to high-silicon anodes – are expected to roughly double energy density and enable sub-15-minute fast charging in the coming decade. Indeed, Chinese manufacturer BYD announced a new EV battery capable of accepting 1 MW charging power – adding ~400 km of range in just 5 minutes – by using a low-resistance cell design that minimizes heat generation[22]. Such breakthroughs indicate that 5–10 minute charging for hundreds of kilometers of bus range may become feasible, drastically reducing vehicle downtime.

In conclusion, the race to develop next-generation EV batteries is well underway. While lithium-ion remains dominant, technologies such as solid-state, lithium-sulfur, graphene, and silicon-anode batteries offer exciting possibilities. Each brings its own set of benefits and hurdles, but with sustained innovation, investment, and regulatory alignment, these advancements could transform the future of electric transportation.

Battery Pack Swapping Systems Along Bus Routes

Battery swapping offers an alternative approach to keep electric buses and coaches moving with minimal delay: instead of recharging the onboard battery, the vehicle exchanges a depleted battery for a fully charged one at a swap station. This method can refuel an electric bus in as little as 1–5 minutes, comparable to a diesel stop and unlike conventional charging or refueling, battery swapping can be fully automated (drivers never need to exit their vehicles)[23]. The swapped batteries are then charged off-board, which decouples charging time from the vehicle's schedule. Swapping can be especially attractive for high-speed intercity routes or freight operations where long continuous range is needed and stops must be brief. In China, battery swapping has already seen significant adoption in the heavy-duty sector: by 2023,

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[17] https://www.azocleantech.com/article.aspx?ArticleID=1958

[18] https://www.sciencedirect.com/science/article/abs/pii/S2352152X20314936

[19] https://www.grepow.com/blog/what-is-a-silicon-anode-lithium-ion-battery.html

[20] https://pubs.acs.org/doi/10.1021/acsmaterialslett.3c00253

[21] https://amprius.com/about/news-and-events/new-ev-battery-tech/

[22] https://carboncredits.com/byds-five-minute-ev-battery-charging-a-new-era-for-electric-cars-or-just-hype/

[23] https://www.worktruckonline.com/10242042/international-consortium-rolls-out-ev-battery-swapping-initiative-in-tokyo

about 14% of new electric heavy-duty vehicles sold in China were swap-capable, including nearly half of electric tractor-trailer trucks[24] [25].

However, battery swapping faces significant challenges, primarily due to a lack of standardization across manufacturers, which limits interoperability and scalability. Without uniform battery sizes, voltages, and interface designs, a swap station might only serve a specific bus model or fleet. Even in China's mature swap market, truck drivers can only use stations compatible with their particular battery type. High infrastructure costs—largely driven by expensive maintaining an inventory of spare battery packs and automated handling equipment, making the initial investment substantial—further hinder widespread adoption, especially in markets like the U.S. where cost data and consumer familiarity are limited. Furthermore, swap stations require robust electrical infrastructure to charge multiple packs in parallel (often needing grid upgrades similar to large charging hubs). Additionally, the technology remains largely untested for medium and long distances, with most deployments so far limited to short-distance applications. While companies like Ample and Revoy are developing solutions to address these issues, battery swapping is still in its early stages of adoption, particularly outside of China[25] [26]. In the US, Ample has spent the past three years testing its electric vehicle battery swapping technology in San Francisco, Madrid, and Japan. Now, the company is getting ready to convert some of those pilot programs into commercial contracts starting in 2025[27].

International case studies underscore both the feasibility and challenges of swapping for buses and trucks. China has built hundreds of swapping stations, and companies like CATL and BAIC support standardized battery platforms for buses in some regions[28] [29]. In Japan, a consortium led by Mitsubishi Fuso, utility Yamato, and U.S. startup Ample is piloting modular battery swapping for delivery fleets – including light electric trucks and possibly buses – with 5-minute swap times and fully automated stations coming to Tokyo in 2025[23]. Ample's approach uses smaller battery modules that can adapt to different vehicle designs, aiming for cross-manufacturer interoperability[25]. Australia's Janus Electric has developed a swap system for heavy trucks (with ~400–600 km range per swap), retrofitting diesel rigs with swappable battery pods[25]. These pilots show that swapping can work for high-utilization routes, minimizing vehicle downtime and even enabling lower upfront costs by separating battery ownership from the vehicle[30] [31] [32] [33]. NIO's Battery-as-a-Service (BaaS) in China allows customers to purchase an EV without the battery. Instead, they subscribe to battery use. This greatly reduces the initial purchase price and enables quick battery capacity upgrades or downgrades. NIO now operates over 1,300 swapping stations supporting sub-five-minute swaps.

Overhead Catenary Charging (Trolleybus and eHighway Systems)

Overhead catenary systems[34] supply power to vehicles via overhead wires, a century-old technology now seeing renewed interest for high-speed electric transport. Traditional trolleybuses in cities use dual overhead wires and trolley poles to draw continuous current, allowing electric buses to run indefinitely without onboard charging so long as they stay on wired routes. Modern variants like "in-motion charging" trolleybuses can charge onboard batteries while on the wire, then disconnect to travel off-wire for portions

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[24] https://theicct.org/wp-content/uploads/2024/08/ID-191-%E2%80%93-EU-R2Z-Q1_final-1.pdf

[25] https://www.aceee.org/sites/default/files/pdfs/battery_swapping_for_truck_electrification_in_the_united_states.pdf

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[27] https://techcrunch.com/2024/11/19/mitsubishi-backs-amples-radical-approach-to-charging-ev-batteries/

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[30] https://evmagazine.com/top10/top-10-advantages-of-battery-swapping

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[32] https://cleantechnica.com/2024/06/03/ev-battery-swapping-means-less-downtime-for-fleets/

[33] https://arxiv.org/pdf/2503.08080

[34] https://www.macproducts.net/blog/what-is-a-catenary-system-and-what-are-its-benefits

of the route. This concept is now extending to highways with projects like Siemens' eHighway[35], which equips heavy-duty trucks (and potentially buses) with an automated pantograph on the roof. When the vehicle enters a catenary-equipped highway lane, the pantograph raises to contact the live wires and powers the electric motor directly from the grid (while also charging the battery)[36] [37]. This effectively turns key highway corridors into electrified "railway-like" routes, combining the efficiency of rail electrification with the route flexibility of rubber-tire vehicles[38]. Several pilot deployments have demonstrated the feasibility at highway speeds[37] [39] [40] [41].

Early results indicate that catenary electric trucks work well technically and can greatly cut fuel costs, though scaling up would require electrifying long stretches of road and a network of compatible vehicles[42]. Infrastructure cost is high – installing and maintaining miles of roadside masts and high-voltage wires is a major capital project. It may be justified on high-density corridors, but rural or less-traveled highways likely won't see such investment. Interoperability and standardization of the pantograph interface are also needed so that different makes of buses/trucks can use the same overhead lines (currently pilots use specific supplier systems). Acceptance of the technology is low in Germany. While manufacturers focus mainly on efficiency and cost, local residents are more concerned about traffic effects and safety[43]. Looking ahead, a hybrid approach might emerge: for example, buses or coaches could charge from overhead pantograph chargers at highway rest stops or terminals (discussed in the next section) – a simpler, more modular form of overhead infrastructure – if continuous wiring of the entire highway is impractical. Indeed, the line between "catenary" and "stationary" overhead charging blurs when considering high-power pantographs that connect only during brief stops. Each approach (dynamic catenary vs. static pantograph) can complement the other in enabling reliable long-range electric bus operations.

In-Road Wireless Charging Systems (Dynamic and Static)

Charging electric buses through the road surface – using electromagnetic fields – is another innovative solution being piloted for both urban transit and highway travel[44]. In-road wireless charging (also known as inductive charging)[45] works by embedding coils under the pavement that transmit power to a receiver coil mounted on the vehicle's underside. When the bus drives (or stops) over an energized section, the magnetic field induces current in the onboard coil, charging the battery without any plug or physical contact. This technology can be deployed in two modes: static wireless charging (charging vehicles while stopped at a station or stop light), or dynamic wireless charging (charging vehicles as they drive at highway speeds)[46].

Dynamic wireless charging has been demonstrated in a few high-profile trials. The Smartroad Gotland project[47] in Sweden retrofitted 1.6 km of a public road between Visby Airport and the town with inductive coils beneath the asphalt. An electric bus operating as an airport shuttle and a heavy truck were equipped with receivers to use this wireless road[48]. As they drove the route, they could pick up charge dynamically, extending their range without stopping.The system has been successfully charging an e-bus en route in

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[35] https://www.oemoffhighway.com/market-analysis/trends/press-release/21551491/siemens-industry-inc-siemens-begins-third-ehighway-trial-in-germany

[36] https://insideevs.com/news/546176/electric-truck-ehighway-overhead-cables/

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[38] https://www.mobility.siemens.com/us/en/portfolio/rail-infrastructure/electrification/ehighway.html

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[46] https://www.sandag.org/-/media/SANDAG/Documents/PDF/projects-and-programs/innovative-mobility/clean-transportation/wireless-electric-vehicle-charging/wireless-electric-vehicle-charging-white-paper-2022-08-01.pdf

[47] https://electreon.com/articles/worlds-first-public-wireless-electric-road

[48] https://smartcitysweden.com/best-practice/409/wireless-electric-road-charges-vehicles-as-they-drive/

real-world operation and demonstrated that even heavy vehicles can be charged on the move[49]. Similarly, Israel-based company Electreon has tested dynamic charging in Tel Aviv and elsewhere. In Tel Aviv, a section of road was equipped to wirelessly charge a bus on its regular route, and Electreon reported it could maintain the bus's battery state-of-charge while in service, proving the concept of charging as you drive[50] [51] [52]. Another notable trial is the Arena del Futuro project in Italy[53], where Stellantis and partners built a 1 km circular test track with inductive coils. Tests with a Fiat 500 and an Iveco E-Way bus showed that vehicles can maintain motorway speeds without draining their batteries, with charging efficiency similar to fast chargers and no safety risks from magnetic fields. The system uses DC power, enabling lighter, cheaper infrastructure and integration with renewable energy[54].

The first wireless electric road in the U.S. has been installed in Detroit, enabling electric vehicles (EVs) to charge while driving using inductive charging technology. A quarter-mile pilot section on 14th Street uses electromagnetic coils beneath the surface to wirelessly transfer power to EVs equipped with special receivers[55]. These trials underscore the appeal of dynamic charging: vehicles can have much smaller batteries (reducing cost and weight) since they periodically get energy en route, and they avoid the downtime of stopping to charge[56]. Though still in early testing phases with short pilot sections in places like Sweden, Michigan, and Indiana, these dynamic charging systems could one day power EVs on highways without the need to stop. Projects led by research institutions like Purdue and Utah State show promise, especially for heavy-duty trucks, potentially reducing battery size and increasing freight efficiency. While not expected to replace traditional charging stations, electric roads could complement them, enabling longer, uninterrupted travel[57]. If deployed on highways, this could allow seamless long-distance electric bus trips – the bus could recharge on electrified highway stretches, then exit with a full charge to cover off-network portions.

Despite its promise, dynamic wireless charging is still in an experimental stage, and there are significant limitations. One challenge is efficiency and alignment: the vehicle's receiver coil must be properly aligned over the road coil to achieve high power transfer. Lateral misalignment or excessive gap due to road clearance can reduce efficiency[58]. In practice, systems use segmented coils and smart inverters that activate only the segment under the vehicle to improve efficiency[59]. Oak Ridge National Laboratory demonstrated a 270 kW dynamic charging system in the lab with about 95% efficiency[60], but real- world efficiency can drop. The Fabric ICT platform[61] enables dynamic wireless charging for electric vehicles through a coordinated system of roadside infrastructure, vehicle communication, and cloud-based services. It integrates a Charging Station Control Unit for authentication and billing, a Power Electronics Controller for real-time coil activation, and a vision-based alignment system to help drivers stay centered over the charging coils. Tested over 120 driving hours in various conditions, the platform proved robust and efficient, activating coils only when needed and reliably managing charging sessions. While not yet tested with multiple vehicles simultaneously, the system sets a strong foundation for future scalable, in-motion EV charging solutions.

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[55] https://www.bbc.com/future/article/20240130-wireless-charging-the-roads-where-electric-vehicles-never-need-to-plug-in
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Another challenge is delivering sufficient power at highway speeds: At highway speeds, dynamic wireless power transfer is challenged by the very short time a vehicle spends over each coil—about 40 milliseconds at 55 mph—making high instantaneous power transfer impractical. Instead, longer powered segments are needed to gradually deliver energy. Thus, in practice, either the electrified road needs to be a substantial length or the system provides a moderate charge boost over long distances rather than a full recharge in a short segment. Power delivery varies as the vehicle moves between coils, requiring precise alignment, optimized coil design, and real-time synchronization. Managing power flow for multiple vehicles with different energy demands creates grid stability concerns, which may be addressed with local energy storage and smart control systems. Overall efficiency depends on coil geometry, alignment, magnetic gap, and frequency[62]. The paper "Engineering Challenges in High-Power Wireless Charging for Heavy-Duty Electric Vehicles[63]" examines the key technical barriers to implementing wireless charging for heavy-duty EVs like trucks and buses. These vehicles require high power levels, but wireless systems face challenges such as reduced efficiency due to large air gaps and coil misalignment, significant heat generation, electromagnetic interference (EMI), and system scalability. The paper highlights the need for advanced materials, smart control systems, and standardization to overcome these issues. It also discusses future trends and integration with renewable energy. The study calls for greater collaboration, policy support, and continued research to enable widespread adoption of wireless charging in the heavy-duty transport sector.

There are also cost considerations: installing coils, power electronics, and grid connections under the road is expensive, and maintenance can be complex if repairs under pavement are needed. Estimates vary, but dynamic Electric Road System (ERS) installations can cost several million dollars per kilometer in pilot projects, likely decreasing if mass-produced but still a heavy infrastructure investment. The Feasibility Study and Design of In-Road Electric Vehicle Charging Technologies[64] explores the potential for Dynamic Wireless Charging (DWC) in Indiana, focusing on enabling electric vehicles (especially heavy-duty trucks) to charge while driving. The study identifies high-traffic interstates like I-65 and I-70 as optimal locations and designs a test bed system to assess technical and economic feasibility. At medium to high EV adoption levels, DWC is financially viable, with estimated costs of $4.6–6.6 million per lane-mile and a payback period of 20–25 years. However, current substations may not meet future power demands, necessitating infrastructure upgrades. The report recommends integrating DWC deployment with pavement projects and incorporating renewable energy to reduce emissions and energy costs. A small-scale test bed is advised to validate system performance and guide large-scale implementation. A study evaluates the viability of Dynamic Wireless Power Transfer (DWPT)[65] for long-haul electric trucks from a fleet operator's perspective. It compares the total cost of ownership (TCO) of internal combustion engine vehicles (ICEVs), battery electric vehicles (BEVs), and DWPT-equipped BEVs using vehicle simulations and cost models. Results show ICEVs are currently the most cost-effective, but DWPT-BEVs could become competitive in future optimistic scenarios with high infrastructure utilization and reduced electricity and battery costs. DWPT reduces charging time and allows smaller batteries, but high upfront infrastructure costs limit feasibility. The study concludes that DWPT can support decarbonization if deployed along high-use freight corridors with supportive policies and cost reductions.

The Advances in EV Wireless Charging Technology – A Systematic Review and Future Trends[66] paper provides a comprehensive review of wireless power transfer (WPT) technologies for electric vehicle (EV) charging, highlighting recent advancements, technical designs, and future trends. It discusses various WPT methods (including inductive, capacitive, resonant inductive, microwave, laser-based, and magnetic gear

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[62] https://www.osti.gov/servlets/purl/1265561

[63] https://www.researchgate.net/publication/387069370_Engineering_Challenges_in_High-Power_Wireless_Charging_for_Heavy-Duty_Electric_Vehicles

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[65] https://www.sciencedirect.com/science/article/pii/S0306261924022220

[66] https://www.sciencedirect.com/science/article/pii/S2772671124003450?via%3Dihub

systems) evaluating their efficiency, complexity, and applicability. Key components like compensation topologies, power converters, and coil designs are analyzed for their role in improving power transfer and reducing electromagnetic interference. The study explores both static and dynamic wireless charging (DWPT). Despite the benefits (such as convenience, bidirectional power flow (V2G), integration with smart grids, and reduced wear and tear) the paper notes ongoing challenges, including high infrastructure costs, efficiency losses due to misalignment, lack of standardization, and safety concerns. It also outlines strong market growth, particularly in China and India, and calls for continued innovation, cost optimization, and global regulatory frameworks to support widespread adoption of WPT in EV ecosystems.

For urban transit, stationary wireless charging is another option that's closer to commercialization. Some transit agencies have installed inductive charging pads at bus terminals or bus stops. For example, Wenatchee, Washington (USA) uses a wireless charger at a bus terminus to quick-charge a battery bus on layover[67]. While slightly less efficient than plug-in charging, wireless pads avoid wear-and-tear on connectors and can be used opportunistically during dwell times. The Emerging Charging Technologies in Road Construction and Infrastructure[68] report forecasts the future of Electric Road Systems (ERS), comparing technologies like overhead and bottom-attached conductive charging and inductive charging through global case studies. Experts interviewed highlighted that while dynamic ERS can reduce battery size and enable continuous charging, the rapid advancement of battery technology may make static fast-charging solutions more practical, especially for urban and short-range applications. They emphasized that ERS investments must consider regional factors like grid capacity, vehicle types, and route characteristics. Experts also cautioned against premature standardization, urging flexible, scalable solutions and public-private collaboration to future-proof infrastructure as technologies evolve.

For high- speed buses, dynamic charging infrastructure would require broad coordination between road operators, utilities, and vehicle manufacturers – a long-term prospect. In the meantime, the lessons from the pilots will inform whether such systems can scale. One promising hybrid model could be charging lanes in select areas (e.g. dedicated busways) to assist vehicles where they need it most, combined with conventional charging elsewhere. In summary, in-road wireless charging canreduce reliance on huge onboard batteries and eliminate charging stops, but its deployment will likely be limited to specific high-utilization routes until the technology matures and costs come down.

High-Power Charging Stations and Dwell Time Considerations

While on-the-go charging solutions are emerging, the most immediate charging method for high-speed electric buses is still high-power DC fast charging[69] at depots or en route stops. Designing these charging stations for heavy-duty buses involves new standards and careful planning to minimize operational impacts. Modern electric buses support fast charging via a variety of interfaces: common approaches include roof-mounted pantograph chargers that connect to overhead conductive rails at bus stops, as well as high-power plug-in connectors for depot or en-route use[70]. The industry has coalesced around standards like SAE J3105 for overhead pantograph charging[71], which ensures automated connection and communication for different bus models. In practice, many transit agencies schedule 6–8 minute charging sessions at 450 kW for every hour of operation, often at route termini or key stops[72]. For example, a bus might reach the end of its route and automatically connect to a 450 kW overhead charger for 5–10 minutes while the driver takes a scheduled break. Such "opportunity charging" allows buses to carry smaller batteries than if they had to do the entire day on one charge, but it demands reliable station availability and careful timetable integration.

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[67] https://www.electrive.com/2022/06/23/wireless-chargers-help-to-halve-operating-costs-for-link-transit/

[68] https://upcommons.upc.edu/server/api/core/bitstreams/c47072fe-c6d9-46d5-afc4-bc5c977fb511/content

[69] https://evsafecharge.com/dc-fast-charging-explained/

[70] https://www.transportation.gov/rural/electric-vehicles/ev-toolkit/electric-bus-basics

[71] https://www.sae.org/standards/content/j3105/2_202001/

[72] https://www.nema.org/blog/view/2020/05/26/charging-infrastructure-for-battery-electric-buses

The good news is that several cities have proven this model: for instance, in OppCharge systems in Europe (used by Volvo, ABB, etc.), buses charge at 300–450 kW via overhead pantographs at end stops, keeping them in continuous service with minimal delay[73] [74]. The charging hardware is often robust enough to handle dozens of cycles per day and is designed for fast automated attachment to avoid wasting time.

For intercity coaches or highway buses, charging station design is evolving in parallel with electric truck infrastructure. The upcoming Megawatt Charging System (MCS)[75] is a new global standard for extreme fast charging for buses and trucks. Pilot projects in 2024 have already demonstrated MCS prototypes: for example, MAN Truck tested charging at 700 kW (1000 A)[76], and Mercedes eActros trucks have been charged at 1000 kW (1250 A at ~800 V) in trials[77]. This level of power could be transformative for electric coaches – it would allow a bus to recharge ~80% in under 30 minutes. A brief restroom or lunch stop could refuel the bus for another few hours of highway driving. MCS face challenges including strain on existing electrical grids, the need for major infrastructure upgrades, efficient power conversion at high loads, and the necessity for universal standards across diverse applications. Particularly in marine and industrial sectors, ports and facilities often lack the required infrastructure. Solutions such as battery-assisted charging, high-efficiency converters, smart grid integration, and vehicle-to-grid technology help mitigate grid stress and improve efficiency. Industry collaboration and standardization efforts, led by groups like CharIN, are crucial for widespread adoption. Overall, addressing these challenges with innovative technology and cooperation will enable MCS to support faster, cleaner electrification for heavy-duty and marine applications[78].

Even with ultra-fast chargers available, operational planning is critical to minimize the impact on routes. Unlike diesel refueling, electric buses may need charging during the service day. Scheduling software and smart charge management are employed by transit agencies to ensure buses charge without disrupting service[79] [80]. For high-speed intercity buses, operators might coordinate charging stops with mandated driver rest breaks. For instance, a coach could run 200–300 km (several hours) and then take a 30-minute break where it receives a charge – aligning with regulations that often require drivers to rest after ~4 hours. In many cases, thoughtful routing can integrate charging without large penalties (for instance, selecting a meal stop location that has a charger). The goal from an operations perspective is to maintain scheduling flexibility: as battery ranges improve and charge speeds increase, electric buses can increasingly match diesel timetables, needing only short infrequent stops that can be aligned with natural breaks in service. A key consideration is dwell time and charger throughput: a single high-power charger might serve multiple buses per hour, so station layouts often include several charging stalls to avoid queueing delays. Research suggests that beyond a certain fleet size, it's more cost-effective to oversize charging infrastructure to prevent buses from waiting for a plug[81] [82].

The Deploying Charging Infrastructure for Electric Transit Buses[83] report outlines best practices for deploying charging infrastructure for battery-electric transit buses, emphasizing the importance of comprehensive transition planning, early utility engagement, and careful facility design. Depot charging is generally preferred over on-route charging due to lower costs and higher reliability, though a mix of charging strategies may be needed for longer routes. Agencies are exploring dynamic solutions such as fast/slow

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[73] https://www.heliox-energy.com/us-press-releases/volvo-and-heliox-inaugurate-charging-station-for-electric-buses-based-on-oppcharge

[74] https://new.abb.com/low-voltage/news/abb-oppcharge-fast-charger

[75] https://v2charge.com/megawatt-charging-system-mcs-heavy-electric-vehicle-charging/

[76] https://new.abb.com/news/detail/113917/abb-e-mobility-and-man-demonstrate-megawatt-charging-on-the-etruck-for-the-first-time

[77] https://www.daimlertruck.com/en/newsroom/pressrelease/mercedes-benz-trucks-developers-successfully-test-electric-charging-at-1000-kilowatts-52680179

[78] https://advantics.fr/blog/mw-charging-powering-future-heavy-duty/

[79] https://www.ampcontrol.io/post/charge-scheduling-for-electric-buses-and-trucks-a-critical-tool-for-electric-fleet-optimization

[80] https://www.sciencedirect.com/science/article/pii/S221067072400324X

[81] https://arxiv.org/pdf/2408.05278

[82] https://www.sciencedirect.com/science/article/pii/S1361920920308300

[83] https://atlaspolicy.com/wp-content/uploads/2022/05/Deploying-Charging-Infrastructure-for-Electric-Transit-Buses.pdf

charger combinations, modular systems, and managed charging software to reduce costs, space needs, and labor. Inverted pantographs and wireless charging offer operational benefits but come with higher costs or technical challenges. Grid resilience is critical, with options like microgrids, generator ports, and redundant service. Agencies must plan for workforce training, reliable vendor contracts, and future-proofing infrastructure. High upfront costs and long timelines are major barriers, underscoring the need for strategic funding and phased implementation. Overall, early planning, scalable solutions, and stakeholder collaboration are key to successful electrification.

Grid and Infrastructure Implications (Renewables Integration and V2G)

Scaling up high-speed electric bus operations will require significant upgrades and smart management of the electricity grid infrastructure. A fleet of electric buses draws a substantial electrical load. Therefore, grid capacity at bus depots, terminals, and along highways must be assessed and likely expanded. Many bus depots have needed substation upgrades or new high-voltage grid connections when electrifying. The Multi-State Transportation Electrification Impact Study[84] estimates that accommodating the additional 3.9 million electric vehicles under the EPA's proposed emissions rules across five states (California, Illinois, New York, Oklahoma, and Pennsylvania) would require approximately $2.3 billion in incremental distribution grid upgrades from 2027 to 2032. This represents about 3% of current annual utility investment in distribution systems within those states. The grid upgrades would include 8 new substations, 125 feeders, and about 30,000 service transformers. However, if managed charging is adopted (where EVs charge during off-peak hours) the required grid investment could be reduced by 30%, saving nearly $700 million. Managed charging helps avoid overloading grid components and reduces peak demand, leading to fewer infrastructure upgrades. Overall, the analysis highlights that grid impacts are modest and manageable, especially when smart charging strategies are implemented.

The paper "Grid-Integration of High Power Charging Infrastructure[85]" introduces a smart and flexible system for adding fast electric vehicle (EV) chargers to the power grid without causing problems. Instead of upgrading the whole grid, which is expensive, the authors suggest using technologies from wind energy systems. These include advanced inverters that help keep the grid stable by adjusting voltage and frequency when needed. The proposed charging station can distribute power between different charging ports based on demand, which saves costs and avoids overbuilding. It also allows the use of battery storage at the site to reduce strain on the grid during busy times. The system can work with renewable energy sources and even support other uses, like producing hydrogen. This approach not only makes EV charging faster and more reliable but also helps make better use of the existing grid, supporting the broader shift to clean transportation.

The "Operational strategies for EV fast-charging and their impact on power grid and renewable integration[86]" study looks at how fast electric vehicle (EV) charging affects the power grid and how to manage it better. Fast chargers help drivers by charging quickly, but they can cause problems like voltage drops, overworked transformers, and high energy demand. To fix this, researchers suggest placing chargers in smart locations and using tools like solar panels and batteries to reduce strain on the grid. New technologies like smart charging and vehicle-to-grid (V2G) let EVs help balance the energy system. The study shows that better planning, renewable energy, and smart systems are key to making EV charging work smoothly and sustainably. Thus, agencies often coordinate closely with utility companies years in advance to ensure grid readiness by the time buses are delivered.

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[84] https://www.energy.gov/sites/default/files/2024-03/2024.03.18%20NREL%20LBNL%20Kevala%20DOE%20Multi-State%20Transportation%20Electrification%20Impact%20Study%20FINAL%20DOCKET.pdf

[85] https://mobilityintegrationsymposium.org/wp-content/uploads/sites/7/2017/11/3B_3_EMob17_036_paper_Johannes_Brombach.pdf

[86] https://journals.sagepub.com/doi/10.1177/01445987251352551

The "Future Ultrafast Charging Stations for Electric Vehicles in China: Charging Patterns, Grid Impacts and Solutions, and Upgrade Costs[87]" study looks at how ultrafast electric vehicle (EV) charging stations in China can grow without overloading the power grid. As charging power increases, the peak demand at stations doesn't rise as much as expected because charging is faster and sessions overlap less. Larger stations with more chargers handle this better. Two main solutions are suggested: briefly delaying charging sessions (dynamic waiting) or using batteries to store energy. The waiting strategy works well and keeps total charging time short. Battery storage also helps but costs much more than other options. A key finding is that upgrading transformers is a much cheaper way (about four times less expensive than battery storage) to support higher power demand, as long as the local grid can handle it. The study recommends building large stations with 350–550 kW chargers in busy areas and using smart strategies like waiting, storage, or transformer upgrades to manage electricity needs.

Integrating renewable energy and on-site generation is becoming a key strategy to both green the operations and reduce reliance on the grid during peak times. Many new bus charging depots are being built as microgrids with solar panels and battery energy storage. A notable example is Montgomery County, Maryland’s project for a large bus depot microgrid[88]. This setup can allow the depot to operate independently of the main grid or shave the peak load by using solar energy during the day and battery storage in the evening. By generating and storing energy locally, the transit agency improves resilience (critical services can continue during grid outages) and can cut electricity costs by avoiding demand charges at peak grid times. This kind of peak shaving can significantly reduce the required grid connection size. Additionally, timing bus charging to coincide with renewable generation can yield environmental and economic benefits.

Electric bus fleets also present an opportunity for vehicle-to-grid (V2G) services in the future. Buses have large battery packs that are often parked for extended periods (for transit buses, typically overnight; for coaches, maybe during off-peak seasons or midday lulls). With bi-directional charging capability, these parked buses could potentially feed energy back into the grid or provide ancillary services (voltage/ frequency regulation). For example, electric school bus (ESB) vehicle-to-grid (V2G) programs are growing across the U.S., with 26 utilities and 19 states now involved. These programs show that ESBs can support the power grid by delivering energy during peak demand, lowering school energy costs, and boosting community resilience. While real-world success is emerging, challenges remain, including battery wear concerns, high infrastructure costs, and inconsistent compensation. Successful pilots in places like California, Colorado, and the Northeast highlight the importance of strong utility partnerships, clear incentives, and standardized equipment. With continued collaboration, ESBs can become key tools for clean energy and grid reliability[89]. Transit buses could do similarly if equipped – for instance, a city bus parked all night could supply power back to the grid in the early evening when people are using electricity at home (if the bus had finished its runs and still had charge).

In summary, the transition to high-speed electric buses implicates not just vehicles and chargers but the electric infrastructure at large. It requires coordinated planning with utilities to ensure substations and distribution networks are ready for charging, as well as innovative solutions like on-site solar, energy storage, and V2G to optimize energy use. The literature and pilot experiences consistently highlight the importance of holistic energy management: the best outcomes arise when vehicle technology, charging strategies, and grid capacity upgrades are designed together as a unified ecosystem. This integration of transportation and power infrastructure will be crucial to successfully deploy high-speed electric buses on a large scale in the coming years.

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[87] https://www.sciencedirect.com/science/article/pii/S209580992500102X

[88] https://bus-news.com/us-construction-begins-on-nations-largest-renewable-energy-bus-depot/

[89] https://www.wri.org/update/electric-school-bus-v2g-lessons-examples

Hydrogen Fuel Cell Buses in Future High-Speed Transit Systems

Hydrogen fuel cell electric buses (FCEBs) are fundamentally electric buses that carry an on-board fuel cell system to generate electricity from hydrogen gas. A typical FCEB powertrain consists of three main components: (1) a fuel cell stack where hydrogen (from on-board high-pressure tanks) reacts with oxygen from the air to produce electricity, (2) an electric traction motor (and usually a battery) that drives the wheels, and (3) the hydrogen storage tanks (usually compressed gas cylinders) mounted on the bus[90]. In operation, hydrogen is fed into the fuel cell anode, where it is split into protons and electrons; the electrons flow through an external circuit (providing power) before recombining with protons and oxygen at the cathode to form water vapor[90] [91]. This electrochemical process emits only water and heat as byproducts (no tailpipe pollutants), making FCEBs a zero-emission technology.

Hydrogen has a much higher energy storage density than batteries – for a given weight, hydrogen contains far more usable energy. As a result, FCEBs can carry enough fuel for extended range without the massive battery packs that a battery-electric bus would require[92]. In terms of driving range, FCEBs are well suited to longer routes: they routinely achieve 300+ km per filling, and newer models approach 500 km range on a single tank of H2 (actual range depends on tank capacity, fuel cell efficiency, route terrain, and driving conditions)[90]. For comparison, this range is generally greater than what most battery- electric buses can do on a single charge, especially under heavy-duty cycle or cold weather conditions. The FCEB's ample range and quick refueling make it particularly attractive for routes where buses must travel long distances or operate for many hours per day. FCEBs can be refueled with hydrogen very quickly – typically on the order of 10 to 15 minutes for a full tank, similar to diesel bus refueling[93]. This fast refueling is a significant advantage over battery buses, which often require several hours to fully recharge unless expensive high-power charging infrastructure is used.

For regional, express, or highway coach services – where buses may need to travel hundreds of kilometers at high speeds (100 km/h) with minimal stops – batteries alone become a constraint due to range and the impracticality of long charging stops. Hydrogen buses, by carrying fuel for 300–400+ km and refueling in minutes, can seamlessly handle intercity distances and quick turnarounds. For example, in California, agencies running commuter express routes (with 200+ mile daily requirements and highway speeds) have embraced FCEBs so they don't need to add spare buses or mid-day charging – the hydrogen buses can cover a full day's work and refuel once, much like diesel coaches[94]. During high-speed operation, a challenge is ensuring the system can meet sustained power demand and fuel cell buses are designed with this in mind: the fuel cell provides the base load power, and the battery can assist when climbing grades or during passing acceleration[95].

Deploying fuel cell buses goes hand-in-hand with establishing a hydrogen supply and refueling infrastructure. There are several aspects to this: how the hydrogen fuel is produced (and whether it's low-carbon), how it's delivered or generated on-site, how it's stored and dispensed at the bus depot, and the technology of the refueling systems (pressures, nozzles, safety, etc.). To maximize the environmental benefit, the hydrogen fuel ideally should be produced from renewable energy (so-called green hydrogen, usually via water electrolysis using renewable electricity). Green hydrogen has near-zero greenhouse gas emissions in production[96]. Another pathway is blue hydrogen, where hydrogen is produced from natural gas but with carbon capture and storage to reduce CO_2 emissions[97]. In practice, many current hydrogen

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[90] https://www.karsan.com/en/blog/hydrogen-blog/what-is-hydrogen-fuel-cell-bus

[91] https://fchea.org/learning-center/fuel-cell-basics/

[92] https://www.transfinder.com/resources/battery-electric-vs-hydrogen-fuel-cell-buses

[93] https://www.samtrans.com/blog/2025/02/shift-hydrogen-powered-samtrans-buses-underway

[94] https://blog.ballard.com/bus/why-more-operators-choosing-fuel-cell-buses

[95] https://afdc.energy.gov/vehicles/how-do-fuel-cell-electric-cars-work

[96] https://www.iberdrola.com/sustainability/green-hydrogen

[97] https://www.gevernova.com/gas-power/resources/articles/2024/green-vs-blue-hydrogen_whats-the-difference

bus projects initially rely on gray hydrogen (produced from natural gas via steam reforming, without carbon capture), because it is currently the cheapest and most readily available[98]. This is a critical issue, because if the hydrogen comes from unabated fossil fuels, some of the upstream emissions benefits are negated (though tailpipe emissions are still zero, the overall lifecycle CO_2 might be significant). For example, South Korea's fast rollout of H_2 buses faces this dilemma – at present almost all hydrogen in Korea is gray, from fossil gas, and officials admit only a small fraction can be green by 2030[98]. One notable approach is on-site or local green hydrogen production for bus fleets. For example, Wuppertal is using local waste to produce green hydrogen to power the city's growing fuel cell bus fleet[99]. Some operators plan solar-powered[100] and wind-powered[101] electrolyzers at depots.

Overall, the technology marries the locally clean and efficient electric drive with an on-board fuel source (hydrogen) to avoid the range limitations of batteries. However, the battery-electric bus is more energy efficient than the hydrogen fuel cell bus. It uses electricity directly to power its motor with about 85-90% efficiency, whereas the hydrogen fuel cell bus uses hydrogen and oxygen to generate electricity with only 60-70% efficiency. This means battery-electric buses use more of the input energy to move the vehicle compared to hydrogen fuel cell buses[102].

The study titled "Techno-economic analysis of mixed battery and fuel cell electric bus fleets: A case study[103]" presents a comprehensive planning model for optimizing urban transit fleets composed of both battery electric buses (BEBs) and fuel cell electric buses (FCEBs). The authors develop an integrated model that incorporates both strategic and operational decision-making, accounting for real-world constraints such as non-linear energy consumption, partial recharging, bus compatibility with charging infrastructure, and energy costs. Applied to a real-world case study in Bozen and Meran, Italy, the model demonstrates that a heterogeneous BEB fleet using a combination of depot and pantograph opportunity charging achieves the lowest total cost. Under current cost conditions, FCEBs are not economically competitive due to higher vehicle and fuel costs and lower energy efficiency. Sensitivity analyses reveal that FCEBs become viable in the fleet mix only if their purchase cost falls below €625,000 or if hydrogen prices drop below €4.33/kg. Surprisingly, rising electricity prices do not favor FCEBs but instead shift the BEB fleet toward vehicles with larger battery capacities. The study concludes that BEBs are currently the most economical option for electric fleets, especially when a mixed charging strategy is employed. However, FCEBs could become competitive with technological advancements and cost reductions in hydrogen production and vehicle manufacturing.

Summary of Findings

This review explores a wide array of technologies and infrastructure strategies aimed at enabling fast, efficient, and scalable charging for high-speed electric buses. The key findings are organized under following categories:

Advanced Battery Technologies

- Solid-State Batteries (SSBs): Offer 30–50% higher energy density than lithium-ion, with sub-15-minute fast charging and improved safety. Commercial viability is expected around 2028–2030.
- Lithium-Sulfur and Graphene Batteries: Present high energy potential and environmental benefits, but still face stability and durability issues that limit near-term application.

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[98] https://www.fuelcellchina.com/Industry_information_details/4950.html

[99] https://blog.ballard.com/powergen/waste-to-wheels-wuppertal-hydrogen-fuel-cells

[100] https://pv-magazine-usa.com/2024/06/14/solar-powered-bus-depot-features-green-hydrogen-production/

[101] https://www.cummins.com/news/2021/05/03/green-hydrogen-power-wind

[102] https://www.transfinder.com/resources/battery-electric-vs-hydrogen-fuel-cell-buses

[103] https://www.sciencedirect.com/science/article/pii/S0306261924016684

- Lithium Titanate (LTO) and Silicon Anodes: Show strong potential for durability and high energy density, respectively, with rapid progress from companies like Amprius and BYD.

Battery Swapping

- Promising for minimizing downtime (1–5 minute swaps) and already adopted in parts of China.
- Hindered by lack of standardization, high capital costs, and limited U.S. deployment to date.
- Pilot programs by Ample (U.S., Japan, EU) and others are ongoing with commercial deployment expected around 2025.

Overhead Catenary Charging

- Proven through trolleybus and eHighway systems for continuous charging via pantograph.
- Effective on dense corridors but expensive to scale; hybrid models (e.g., rest stop pantograph charging) may be more feasible.

In-Road Wireless Charging

- Allows charging via embedded coils while driving (dynamic) or at stops (static).
- Demonstrated in Sweden, Italy, Israel, and Michigan with promising early results.
- Challenges include high cost, alignment efficiency, and grid integration.

High-Power Charging Stations

- Fast charging can be a viable near-term solution.
- Support rapid recharge during brief stops.
- Challenges include grid strain and costly infrastructure upgrades, space and scheduling constraints, cooling and safety requirements, lack of full standardization, and delays due to permitting and utility coordination.

Grid and Infrastructure Implications

- Electrification requires significant but manageable upgrades to substations and transformers.
- Smart charging, managed load, V2G integration, and microgrids reduce grid strain and enable renewables.

Hydrogen Fuel Cell Buses

- Offer longer range (300–500 km) and fast refueling (10–15 minutes), ideal for high-speed or intercity routes.
- Less energy efficient than battery-electric buses and currently more expensive.
- Infrastructure development and low-carbon hydrogen production are critical enablers for wider adoption.

Planning, Standards, and Operational Integration

- Successful deployment depends on early coordination with utilities, mixed charging strategies, standardized equipment, and robust scheduling software.
- Depot charging preferred for cost, but opportunity charging and hybrid models offer flexibility for different use cases.

Gaps in Findings

Despite significant advancements and ongoing innovation in electric bus battery and charging technologies, several key gaps and challenges remain:

Advanced Battery Technologies

- Solid-State Batteries (SSBs): Despite promising significantly higher energy density and rapid charging capabilities, SSB technology faces substantial technical, economic, and production barriers. Commercial viability and large-scale implementation remain uncertain and likely several years away.
- Lithium-Sulfur (Li-S) Batteries: Present notable limitations, including rapid degradation after relatively few cycles due to polysulfide "shuttle" effects and poor conductivity, indicating a need for extensive research into improved stability and lifespan.
- Graphene Batteries: High production costs and material instability limit scalability. Research into cost-effective manufacturing methods and stable graphene-based battery chemistries is needed.
- Lithium Titanate Oxide (LTO): While exhibiting strong performance in extreme conditions, the higher production costs compared to conventional cells suggest the need for research on reducing manufacturing costs to enable broader adoption.
- Silicon Anode Batteries: Significant engineering challenges, primarily related to silicon expansion during charging cycles, require further exploration to enhance durability and longevity in practical applications.

Battery Pack Swapping Systems

- Standardization and Interoperability: Lack of uniform battery designs across manufacturers severely restricts widespread adoption. Research into standardization frameworks and cross-manufacturer interoperability solutions is critically needed.
- Economic Viability and Scalability: High initial infrastructure costs and substantial inventory management pose economic challenges. Studies exploring economic models and reducing infrastructure costs could facilitate wider adoption.
- Medium and Long-Distance Applicability: Most existing deployments are limited to short-distance applications. Investigations into battery swapping viability for extended-distance bus operations are needed.

Overhead Catenary Charging

- Infrastructure Scalability and Cost: High capital expenditure to electrify extended highway segments limits adoption. Research on cost-effective infrastructure deployment strategies and hybrid approaches (dynamic vs. static charging) can address these gaps.
- Standardization: Further work is required to establish universal standards for pantograph interfaces and interoperability between different vehicle manufacturers.

In-Road Wireless Charging

- Efficiency and Alignment: Challenges related to coil alignment, maintaining efficiency at highway speeds, and real-world operational efficiency reductions need extensive research and optimization.

- High-Power Transfer Limitations: Delivering sufficient power during short periods vehicles spend over charging coils at highway speeds requires additional technological breakthroughs.
- Economic and Scalability Issues: The high cost of installing and maintaining infrastructure necessitates research on reducing costs and integrating wireless charging systems into existing road maintenance and construction programs.

High-Power Charging Stations

- Grid Infrastructure and Management: Charging stations impose significant strains on existing power grids. Further research into smart grid management, renewable integration, and energy storage solutions to alleviate these impacts is essential.
- Operational Integration: Strategies to optimize the scheduling of charging sessions, minimize dwell times, and prevent operational disruptions require continued exploration.

Hydrogen Fuel Cell Buses

- Hydrogen Production and Infrastructure: Development of economically viable green hydrogen production methods, reliable distribution systems, and standardized refueling infrastructure is necessary.
- Energy Efficiency: Current fuel cell buses are less energy-efficient compared to battery-electric buses. Research into enhancing fuel cell efficiency and overall system performance is critical.
- Cost Reduction: The high purchase and operational costs of hydrogen fuel cell buses limit widespread adoption. Economic analyses and technological improvements to lower costs are required for broader market viability.

Next Steps

To effectively address the identified gaps and accelerate advancements in electric bus technologies, the following next steps are recommended:

Research and Development

- Prioritize funding and support for pilot projects to test and validate emerging battery technologies under real-world conditions.
- Initiate cross-industry collaborations to develop standardized battery designs and charging interfaces to enhance interoperability and scalability.
- Invest in targeted research aimed at overcoming key technical barriers, especially in solid-state, lithium-sulfur, graphene, and silicon anode batteries.

Infrastructure and Economic Analysis

- Conduct detailed economic analyses and feasibility studies for battery swapping, in-road wireless charging, and overhead catenary systems to identify cost-effective deployment strategies.
- Engage utility companies early in infrastructure planning to prepare grid upgrades, smart grid integration, and renewable energy solutions tailored to regional needs.

Standardization and Regulation

- Work with regulatory bodies and industry groups to establish clear standards and protocols for charging technologies, interoperability, and safety.

- Develop policies to incentivize the adoption of standardized solutions and encourage private sector investments in infrastructure and technology development.

Demonstration and Scaling

- Implement comprehensive demonstration projects across diverse geographical areas to evaluate performance, operational impacts, and long-term sustainability.
- Expand public-private partnerships to leverage additional resources, expertise, and investment in infrastructure development.

Implementation Mechanisms

Successful implementation of the outlined steps will require structured mechanisms, including:

Collaborative Frameworks

- Establish multi-stakeholder working groups including government bodies, industry representatives, utilities, and academia to coordinate efforts and ensure alignment.
- Foster national and international collaboration to leverage global best practices, standards, and experiences.

Funding and Incentives

- Develop targeted financial incentives and funding programs to support early-stage research, technology demonstration, and infrastructure development.
- Secure government and private sector investments to accelerate scaling and commercialization of promising technologies.

Policy and Regulatory Support

- Enact supportive regulatory frameworks that streamline approval processes and remove barriers to innovative charging infrastructure deployments.
- Introduce performance standards and mandates for electric bus adoption and infrastructure expansion to drive market readiness and investment.

Capacity Building

- Implement training and workforce development programs focused on new technologies, infrastructure management, and operational best practices.
- Strengthen knowledge sharing platforms and dissemination activities to ensure rapid diffusion of innovation and lessons learned.