Advancing E-Buses:
A Guide to Batteries and Charging

ITDP

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Transformative Urban Mobility Initiative

Federal Ministry for Economic Cooperation and Development

Drive Electric CAMPAIGN

PUBLISHED FEBRUARY, 2025

COVER PHOTO: Jakarta Public Transportation Innovates by presenting environmentally friendly electric buses to realize the blue sky jakarta program with electric buses
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A Note from ITDP CEO Heather Thompson

We at ITDP know that investing in public transport systems centered on electric buses is essential to helping cities and governments achieve urgent climate, economic, and social equity goals. Existing efforts to electrify urban transport are already setting the stage for more livable cities with fewer carbon emissions, better air quality, cost savings for individuals, and improved accessibility. With more than 670,000 e-bus units already deployed around the world, there is no doubt that e-buses hold the key to tackling the transport-related challenges many cities face.

As the market share for e-buses continues to grow, the success of these fleets requires planners and decisionmakers to make more intentional decisions regarding battery and charging infrastructure as part of broader transport policies. Currently, many governments are focused primarily on the procurement and deployment of vehicles and fleets themselves. However, for the long-term success of these systems and their operations, an electric transition requires a much more comprehensive approach than just swapping out traditional bus fleets.

Governments must also place equal emphasis on assessing opportunities and challenges related to battery technologies, charging infrastructure, grid capacity, and operational planning to ensure e-bus fleets are made resilient and reliable in the long run. Otherwise, the lack of planning for a city's charging and grid capabilities can result in costly inefficiencies that hinder, rather than help, electric mobility.

This is why our team is excited to share the following Guide, which places a much-needed spotlight on the integration of vehicle electrification with well-planned charging strategies through five actionable steps. ITDP's leadership and expertise in public transport, and bus systems in particular, positions us well to build upon the emerging best practices and innovation in this sector. We hope that transport stakeholders will take advantage of this framework to make more informed decisions about the evolving landscape of e-bus systems, which will help ensure that the future of public transport benefits both people and the planet.

Best,
Heather Thompson
CEO of ITDP

CONTENTS

ADVANCING E-BUSES: A GUIDE TO BATTERIES AND CHARGING

LIST OF ACRONYMS

AC	Alternating current
BEB	Battery electric buses
CCS	Combined charging system
DC	Direct current
FAME	Faster adoption and manufacturing of electric vehicles
GCC	Gross cost contract
ICE	Internal combustion engine system
IMC	In motion charging
LFP	Lithium iron phosphate
NCM	Nickel cobalt manganese
NEMMP	National electric mobility mission plan
SoC	State of charge

Source: IndyGo

1 INTRODUCTION

Implementing battery electric buses (BEB) effectively requires a comprehensive plan for selecting batteries and charging technology that aligns with the unique needs of bus routes. To achieve this, decision-makers should follow these steps: 1) map the political framework, 2) prioritize e-bus routes and understand their charging needs, 3) assess the battery and charging market, 4) develop a charging strategy for the prioritized routes, and then 5) implement and monitor the strategy. This paper provides an overview of battery and charging technology options and the key considerations for each, serving as a practical guide for governments and planners.

Technological innovations in transportation—particularly electrification and battery technology—can significantly reduce global carbon emissions and air pollution, thereby improving public health and quality of life. Worldwide, the transport sector contributes to nearly one quarter of carbon dioxide emissions from end-use sectors (transportation, industry, residential, and commercial sectors). As of 2020, polluting vehicles from transportation[1] contribute up to 61% of particulate matter in cities around the world. Exposure to particulate matter is estimated to have been linked to 4.2 million premature deaths in 2019, with roughly 89% of these deaths occurring in low- and middle-income countries.[2] Shifting to clean technologies in transport is imperative to guarantee healthier lives and climate-friendly mobility, both locally and globally.

Within the transport sector, public transportation specifically has the capacity to create positive social, economic, and environmental impacts. E-buses present clear advantages over internal combustion engine (ICE) buses since address pressing urban issues. They offer clean and quiet alternatives that reduce overall emissions, even in cities with electricity grids that are not fully decarbonized. With the number of e-buses expected to reach 175 million by 2030, this technology is becoming more affordable and adaptable across various urban landscapes.[3] The transition also improves safety, through better driving control and reduced noise pollution, while offering opportunities to promote equity by ensuring access to clean, reliable transportation for underserved communities, making them a superior choice for sustainable urban transportation.

Many cities worldwide are committed to decarbonizing their fleets by acquiring e-buses. However, successful electrification requires more than just replacing vehicles; it demands a holistic approach that considers the broader implications of charging infrastructure on the urban environment and electrical grid. Strategic placement of charging infrastructure is crucial for achieving efficiency, enabling a closer one-to-one replacement of diesel buses with e-buses in terms of investment and performance.

OPPOSITE PAGE
India has grown its electric buses fleet with local companies enetring the EV bus market.
SOURCE: ITDP India

1 Heydari, S. et al. (2020). Estimating traffic contribution to particulate matter concentration in urban areas. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7273192/
2 WHO. (2022). Ambient (outdoor) air pollution. https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health
3 ITDP and UC Davis. (2021a). The Compact City Scenario—Electrified: The Only Way to 1.5°C. https://www.itdp.org/wp-content/uploads/2021/12/EN_Compact-Cities-REPORT_SINGLEPAGE-1.pdf

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The battery and charging technology selection is key for decision-makers and transport planners taking first steps toward electrification, often starting with a pilot project and then the transitioning of a fleet. This decision process will depend on many factors, such as local context, market availability, operational strategies, overall costs, and evidence-based studies and tests. Charging infrastructure can make a huge impact on reliability and comfort as well as on the neighborhoods surrounding where the infrastructure is placed.

Given the wide variety of battery and charging options available, this decision-making process should be informed by local context, market availability, and evidence-based studies. This paper aims to guide stakeholders in making informed choices that ensure cost-efficient electrification and seamless integration into the urban landscape.

ABOUT THE PAPER

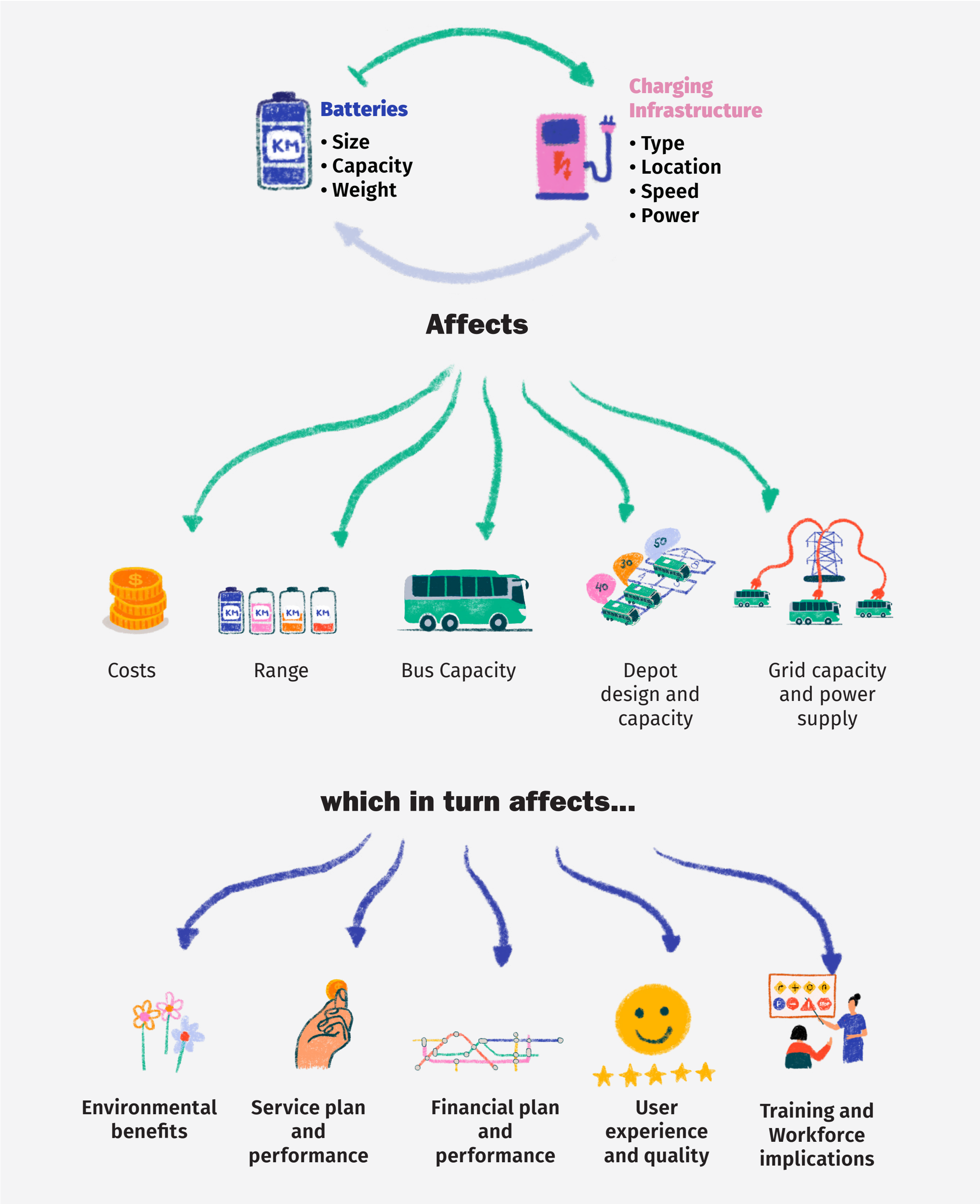
This Guide serves to support decision-makers and transport planners on the effective implementation of e-buses, emphasizing the importance of selecting appropriate battery and charging technologies tailored to specific urban contexts. It focuses specifically on battery and charging options for BEB, including e-buses that run partially on overhead electric power lines. A comprehensive understanding of these options is an important step for cities to take when determining what intervention is appropriate for them. The technology is ever evolving, so having a detailed guide to the latest cost estimates and technologies can aid in e-bus implementation.

Identifying the battery and charging options that are most appropriate for each context is a barrier that many cities face. A slew of economic, social, and operational factors go into ensuring a city can fully understand its best options for electrification. This guide provides a comprehensive outline with considerations and recommendations of the current methods and technologies surrounding e-bus batteries and charging. It also shares international best practices in planning, implementation, monitoring, and other considerations for e-bus charging infrastructure and strategies. Looking at these holistically will provide key stakeholders with a method to support their need to make an informed decision in their fleets' decarbonization.

Section 2 gives an overview of different battery types and materials as well as their health and life cycle, and it discusses the ways battery size relates to the different charging methods. Section 3 offers an overview and analysis of each charging type and the main options for charging planning strategy. This section also addresses the usual costs, the most appropriate scenarios for charging location, and the possible impacts on the energy grid. Finally, Section 4 provides a method to support decision-making, including the factors that need to be considered, such as quality, environment, social equity, efficiency, and economics. It is important to note that the deployment of e-buses continues to change rapidly. Therefore, while the numbers and figures provided are current at the time of this release, the primary focus of this publication is the broader framework in which decision-making should be applied in adopting e-buses.

ITDP examined and studied 60 documents, including reports, articles, educational materials, background resources, and relevant literature (academic, gray, or peer-reviewed) related to e-buses, fleet electrification, e-bus batteries, and charging technologies. E-bus technology is always evolving, and as such, best practices are constantly emerging. For each topic, ITDP reviewed the latest developments from the literature and input from key international experts. In addition, the paper draws on real information about pilots and fleets that include, but are not limited to, projects involving ITDP regional teams, where the research draws on direct expertise at various stages of e-bus charging infrastructure implementation.

Figure 1. The Interconnected Elements of E-Bus Planning: Batteries, Charging, and Their Impacts



2

BATTERY OPTIONS

Batteries are often the most expensive aspect of BEB, they are one of the heaviest components, and they have big repercussions on operations (along with charging type). This means that looking at battery characteristics, health, charging methods and the frequency of battery replacement will be key to selecting the most cost-effective and energy-efficient options. Some battery types may be used for multiple charging scenarios and their selection can be impacted whether the manufacturer has local supply available.

This section provides a comprehensive overview of the various considerations that go into e-bus battery selection, including cost, battery material, composition, size, health, life cycle, connectivity to charging methods, and charging infrastructure options.

2.1. BATTERY MATERIAL, COMPOSITION, AND SIZE

For e-bus batteries, the choice of the material has implications for the range, performance, cost, demand, and even end-of-life processes. Each composition has its advantages and disadvantages, and the selected chemistry may vary depending on the raw material supply, production, and battery pack requirements. Battery cells are made up of five subcomponents: anode, cathode, electrolyte, separator, and cell containment. The anode and cathode make up the electrodes of a battery—that is the conductive pole of electric current.

The most common batteries in the electric vehicle industry nowadays are lithium-ion, nickel-metal hydride, and lead-acid. Nickel-metal hydride and lead-acid batteries are less represented in the market because of limitations such as density of energy,[4] production costs, useful life, and amount of heat generated at high temperatures.[5] Lead-acid batteries are also characterized by their low cost, reliability, and well-established technology, but along with their very low energy density, they are heavy, have a short lifespan, can't be recycled, and require high maintenance.[6] Nickel-metal hydride and lead-acid batteries are mainly used in hybrid vehicles. Nickel-metal hydride batteries offer a good life cycle and are robust in varied temperatures, but they have lower energy density and are heavier than lithium-ion batteries.

OPPOSITE PAGE
Electric bus in charging depot in Bandung, Indonesia.
Source: Algi Febri Sugita via Shutterstock

4 Battery energy density refers to the amount of energy stored in a battery relative to its weight or volume. A higher energy density indicates that the battery can deliver more power for a longer duration in relation to its size. Therefore, batteries with high energy density are particularly advantageous when space is limited but a significant amount of energy is required.
5 Garche, et al. (2015). Lead-acid batteries for hybrid electric vehicles and battery electric vehicles. https://www.sciencedirect.com/science/article/abs/pii/B9781782423775000054
6 Garche, et al. (2015).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The battery used in e-buses is typically composed of lithium ions, a chemical element with high energy efficiency and voltage density that is becoming an increasingly popular form of battery for many types of technologies around the world. These batteries also have low self-rate discharge,[7] long service life, and high load capacity and discharge.[8,9] Lithium-ion batteries have several variations depending on the composition of the cathode material. In some cases, the cathode contributes up to 20% of the total battery mass, and most of them use cobalt.[10]

Lithium iron phosphate (LFP) batteries are by far the most dominant for use in e-buses, making up 98.9% of e-bus battery units sold worldwide.[11] LFP has a lot of benefits compared to nickel cobalt manganese (NCM) batteries: They offer a higher safety level and thermal stability; have a longer life cycle, which will lead to lower operational costs; and are more reliable in long-term projects. In terms of performance, NCM is more interesting, because of a slightly higher density power—however, the prices of nickel and cobalt are also high and extremely volatile, leading to much higher production costs for NCM batteries than for LFP batteries.

China, for example, as the global leader in the e-bus manufacturing landscape, uses LFP batteries because of their lower cost and the fact that they are produced domestically.[12] In the first six months of 2023, LFP batteries accounted for 66% of China's total battery output, while NCM batteries made up 33.91%.[13] However, because LFP batteries are not made with expensive materials like nickel, they tend to be less profitable to recycle.

North American and European markets use more NCM batteries, but they represent a significantly smaller percentage of the worldwide e-bus fleet.[14] The US market is focused on NCM batteries because of their higher capacity and better suitability to the needs of transit services operating in sparsely populated towns and cities. In the coming decades, existing patterns predict that emerging economies in Latin America, the Asia-Pacific region, and Africa will experience an influx of LFP batteries while North American and European markets will see more NCM.[15]

BATTERY LIFE CYCLE EMISSIONS

The different chemicals used in a battery contribute to its life cycle emissions. Lithium and cobalt are classified as critical minerals by several governments around the world, with many environmental and social sustainability and equity concerns. Because of the economic importance and supply risk of cobalt, manufacturers seek to reduce this metal's amount in lithium-ion batteries composition.

Although the vehicular technology used to power electric vehicles is emission-free, the production chain can be intensive in carbon emissions—especially in the production of batteries and in the energy sources used for electricity generation. The life cycle emissions from electric vehicles depend on the battery minerals and the energy mix used, but they can range from 18 to 30 tons of CO_2, while ICE emits approximately 45 tons.[16] In other words, with no careful and comprehensive planning, pollution that ceases to be emitted on the streets is transferred to power plants or mining and processing raw materials (such as lithium, nickel, and cobalt) to produce batteries. Besides being an environmental challenge, it has also proved to be a geopolitical issue involving extractive territorial disputes, child and slave labor complaints, and threats to the continuance of

7 Low self-discharge rate refers to a battery's ability to retain its charge over time when not in use. Batteries with a low self-discharge rate lose their stored energy very slowly, which means they can hold a charge for extended periods without significant power loss. This characteristic is particularly beneficial for applications where the battery might not be used frequently, ensuring that it remains ready for use when needed.

8 High load capacity and discharge refers to a battery's ability to deliver a large amount of current over a short period. Batteries with high load capacity and discharge can provide substantial power quickly, which is essential for applications requiring intense bursts of energy.

9 Bloomberg New Energy Finance. (2018). Electric buses in cities: Driving towards cleaner air and lower CO_2. https://www.c40knowledgehub.org/s/article/Electric-Buses-in-Cities-Driving-Toward-Cleaner-Air-and-Lower-CO2?language=en_US

10 Kara, O. N. (2019). Environmental and economic sustainability of zero-emission bus transport. http://essay.utwente.nl/78088

11 UC Davis. (2023). Electric Vehicle Lithium-Ion Batteries in Lower- and Middle-income Countries: Life Cycle Impacts and Issues. https://www.unep.org/resources/report/electric-vehicle-lithium-ion-batteries-lower-and-middle-income-countries

12 Nikkei Asia. (2023). BYD challenges CATL's EV battery crown in China. https://asia.nikkei.com/Spotlight/Electric-cars-in-China/BYD-challenges-CATL-s-EV-battery-crown-in-China

13 Fastmarkets. (2023). LFP batteries extend dominance over NCM batteries in China. https://www.fastmarkets.com/insights/lfp-batteries-extend-dominance-over-ncm-batteries-china/

14 Congressional Research Service. (2022). Critical Minerals in Electric Vehicle Batteries. https://crsreports.congress.gov/product/pdf/R/R47227

15 UC Davis. (2023).

16 IEA. (2021). Comparative life-cycle greenhouse gas emissions of a mid-size BEV and ICE vehicle. https://www.iea.org/data-and-statistics/charts/comparative-life-cycle-greenhouse-gas-emissions-of-a-mid-size-bev-and-ice-vehicle

Artisanal cobalt miners in the Democratic Republic of Congo. **SOURCE:** Wikimedia Commons.

Indigenous peoples[17]—where they live, their culture, and to their very lives. The sustainability of lithium-ion batteries is another environmental factor to be analyzed, since their production and recycling are more intensive in raw materials than the production of traditional combustion engines. By 2022, most lithium was extracted from hard rock mines or underground brine reservoirs, predominantly in the South American Lithium Triangle formed by Argentina, Chile, and Bolivia. Part of the energy used to extract and process lithium still comes from fossil fuels: For every ton of lithium extracted, 15 tons of CO_2 are emitted. For comparison, each ton of CO_2 represents the same as a gas-powered car would emit by running about 4,025 km. In addition, the production of lithium-ion batteries uses high volumes of water and risks contaminating and depleting natural reservoirs. Producing one ton of lithium requires approximately 2 million tons of water, making battery production very water-intensive.[18] The South American Lithium Triangle has experienced significant water depletion because of lithium extraction. Chile alone holds about 58% of the world's total lithium reserves.[19]

Many researchers, manufacturers, and other organizations have looked toward life cycle assessments to better monitor and understand the overall environmental impact of e-buses and their batteries. Life cycle assessments are a standardized method that can help quantify impact and include production, usage, and end-of-life. Manufacturers have partnered with global organizations to set standards for life cycle assessments that can be used globally in discussions with city authorities and operators.[20] While battery production can be a resource-intensive process, there are efforts and methods of evaluation that aim to decrease that environmental impact.

With the deployment of e-buses increasing worldwide, battery sizing has become a more critical factor for bus operators because an e-bus's battery pack size dictates its driving range (the distance a bus can travel before needing to refuel/recharge) and costs. The range for e-buses can vary based on the battery pack size and capacity, while the charging frequency will depend on the power of the charging infrastructure. The battery is the only power source on board, so it should be sized appropriately to ensure that it meets the e-bus's needs.

17 MIT CLIMATE PORTAL. (2022). How much CO_2 is emitted by manufacturing batteries? https://climate.mit.edu/ask-mit/how-much-co2-emitted-manufacturing-batteries#:~:text=CO2%20emissions%20for%20manufacturing,kg%20(16%20metric%20tons).&text=Just%20how%20much%20is%20one,as%20a%20great%20white%20shark!
18 Earth.org. (2023). The Environmental Impact of Battery Production for Electric Vehicles. https://earth.org/environmental-impact-of-battery-production/
19 United Nations. (2020). Commodities at glance. Special issue on strategic battery raw materials. https://unctad.org/system/files/official-document/ditccom2019d5_en.pdf
20 Volvo buses. (2023). How LCA helps to understand the true environmental impact of electric buses. https://www.volvobuses.com/en/news-stories/insights/lca-for-electric-buses.html

At present, multiple battery types exist, varying with regional market availability. They can be smaller or larger, depending on the frequency and methods by which energy is supplied to the batteries. Smaller battery packs have a usual range capacity of between 50 kWh and 250 kWh,[21] and a larger battery pack can typically run between 250 kWh and 500 kWh,[22] with buses reaching an optimal range when fully charged.[23]

Battery cost is one of the primary considerations for the transition to e-buses because it is approximately 40% of the vehicle procurement cost.[24] The battery is the component that can significantly reduce capital costs for e-buses, leading to scalability advantages. Typically, the larger the battery, the more expensive the overall project is. Both the initial battery cost and the cost of replacement are key expenses for a city to consider.

As e-bus demand and production increase, manufacturing greater quantities of e-bus batteries will lead to cost reduction. In 2016, a lithium-ion battery cost around US$150,000, but by 2021 the price was nearly half that.[25] In this context, it is predicted that the capital costs can become competitive with those of diesel buses between 2026 and 2030. Table 1 summarizes the different characteristics of battery types based on research from academic papers, reports from peer organizations, and others.

Table 1. Battery Types and characteristics

Characteristic	Lithium Iron Phosphate (LFP)	Lithium Nickel Cobalt Manganese (NCM)	Nickel-Metal Hydride (NiMH)	Lead Acid
Energy density (Wh/kg)	85–146	150–230	70	30–50
Capacity (kWh)	50–250 (small), 250–500 (large)	50–250 (small), 250–500 (large)	50-100	50–100
Maximum Manufacturer Range (km)	Up to 300	Up to 400	Up to 150	Up to 100
Costs ($/kWh)	100–300	150–500	200–400	100–200
Life cycle at 100% depth of discharge	3,000	1,000-5,000	500	200-300
Pros	▲ Lower cost, high safety, long cycle life, high thermal stability, stable chemistry, lower toxicity than NCM	▲ Higher energy density, longer range, suitable for high-performance needs, higher recycle value because of cobalt content	▲ Good cycle life, robust in varied temperatures	▲ Low cost, reliable, well-established technology
Cons	▼ Lower energy density compared to NCM, short life cycle, less profitable recyclability	▼ Higher cost, short cycle life, volatile prices of raw materials, safety concerns (risk of toxic and flammable leakage in accident)	▼ Lower energy density, higher weight, more expensive than lead-acid	▼ Very low energy density, heavy, short lifespan, high maintenance
Countries and regions	China, emerging markets in Latin America, Asia-Pacific region, and Africa	North America, Europe	Hybrid vehicles	Hybrid vehicles
Manufacturers	CATL, BYD, CALB, Nova Bus, Volvo	LG Chem, Samsung SDI, Panasonic, Proterra, New Flyer	Panasonic, Primearth EV Energy	Exide, Trojan, Enersys

Source: Developed by the authors.

21 Olsson, O., et al. (2016). Method to analyze cost effectiveness of different electric bus systems. http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1159796&dswid=6239
22 Olsson, O., et al. (2016).
23 Huang, D. (2023). A robust coordinated charging scheduling approach for hybrid electric bus charging systems. https://www.sciencedirect.com/science/article/abs/pii/S1361920923003528
24 UITP. (2019). The impact of electric buses in urban life. https://cms.uitp.org/wp/wp-content/uploads/2020/06/UITP-policybrief-June2019-V6-WEB-OK.pdf
25 Bloomberg New Energy Finance. (2021). Battery Pack Prices Fall to an Average of $132/kWh, But Rising Commodity Prices Start to Bite. https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/

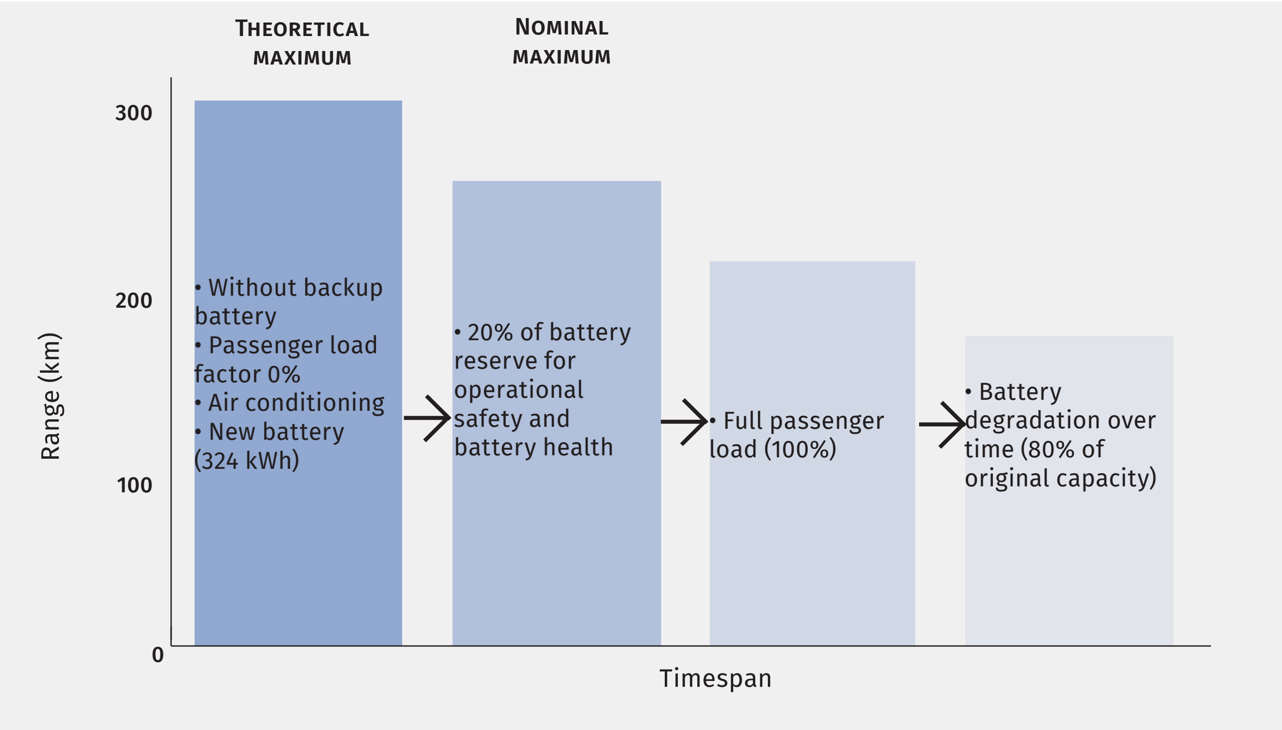
2.2. BATTERY LIFE AND RANGE

Battery life is usually measured by the number of years of durability. Their useful life is determined by the continuous chemical reactions that occur within their components. These reactions happen regardless of use but can intensify in unfavorable situations, such as when batteries are subjected to high temperatures. A typical battery life on e-buses should range from six to 12 years, with multiple manufacturers offering warranties for up to 12 years.[26] ITDP's China office has observed a trend in batteries lasting approximately four to five years as opposed to the generally accepted 8- to 10-year lifespan that e-bus and battery manufacturers project. This happened mainly due to the lack of maturity and experience about the real performance of the batteries when the first e-buses started to be implemented in China. Therefore, on average, the battery lifespan of e-buses in China is relatively shorter than anticipated. It is worth noting that few BEB have gone through a full life cycle yet, however, and as this technology continues to advance, battery life cycles will likely become longer.

While a diesel bus can have a range of 600 km to 900 km with a full tank, different factors will have an impact on e-bus ranges, and battery size is an important component of that as mentioned in the previous section.[27] Battery sizing can be a challenging task, since e-bus energy needs can vary: Different systems present a variety of conditions, including climate, topography, and necessary driving range. According to manufacturers, BEB have an average range of 250 km to 300 km on a complete charge.[28] However, many cities are reporting that the range can be significantly lower—from 200 km to 225 km.[29] The disparity between manufacturer-claimed ranges and real-world performance underscores how important it is for charging infrastructure to be planned and thought of in every step, considering local conditions when planning for e-bus deployments.

A variety of factors and local conditions can impact battery range and lifespan, including pavement quality, weather conditions, auxiliary systems (air-conditioning, ventilation, and heating), topography, inconsistent travel speeds, and passenger load.

FIGURE 2. Factors that can impact e-bus performance over time



Source: Adapted from ZEBRA, 2022a.

26 Johnson, et al. (2019). Financial Analysis of Battery Electric Transit Buses. https://www.worldtransitresearch.info/research/8100/
27 Thomas Built Buses. (2019). Determining fuel costs. https://thomasbuiltbuses.com/resources/articles/determining-fuel-costs/
28 WRI. (2023) Overcoming the operational challenges of electric buses: lessons learnt from China. https://transformative-mobility.org/wp-content/uploads/2023/06/TUMIVolt_Charging-Station_Webinar9_-Monitoring-EBus-Operations.pdf
29ZEBRA. (2022a). Análise da implantação de ônibus zero emissão na frota de um operador da cidade de São Paulo. https://theicct.org/publication/ze-hvs-sao-paulo-brazil-mar22/

The use of systems such as air-conditioning, ventilation, and heating impacts e-bus range. This impact is more significant in regions with extreme temperatures, such as harsh winters or very hot summers. To increase vehicle range, operators may choose to precondition (i.e., heat or cool) the buses in both summer and winter months while plugged in for charging.[30] The use of air-conditioning, heating, and ventilation can reduce an electric vehicle's range by 40% to 60%. A study based on operational tests found that 20% to 25% of the total energy consumption of an electric bus was attributed to the auxiliary heating system.[31] [32] [33]

Air conditioning enhance passengers comfort. **Source:** Erekutoo98 via Shutterstock

The varying thermal comfort conditions needed for a higher number of passengers can increase the energy consumption of an e-bus, as well as the additional weight.[34] As vehicle mass increases, energy consumption for both conventional diesel buses and e-buses increases proportionally.[35]

Topographic conditions are another important point to be considered. Routes with more hills and steeper slopes will drain the battery faster. Additionally, many manufacturers and pilot-testing in cities have reported that e-buses are not able to navigate slopes higher than 18%[36] [37] because of the amount of energy consumption needed to overcome vertical force.

The consistency of the speed of an e-bus can have huge impacts on its battery energy consumption, lifespan, and range. The amount of energy needed will increase with the amount of abrupt acceleration and deceleration. Therefore, more uniform speeds—achieved through reduced traffic and congestion, dedicated bus lanes, fewer incidents on the road, and smoother driver operations—result in longer vehicle ranges and enable greater battery efficiency. Leveraging the transition to e-buses as an opportunity to implement bus-only lanes can facilitate the creation of space for charging along the route without causing traffic congestion and ensure that bus services run quickly and efficiently, thereby enhancing battery efficiency and reliability.

30 Wu (APTA), n.d. (presentation). Lessons Learned From Operating Battery Electric Buses in the Real World. https://www.apta.com/wp-content/uploads/SMW10_Lessons-Learned-from-BEB_Tina_Wu.pdf
31 Suh, I-S., et al. (2015). Design and experimental analysis of an efficient HVAC (heating, ventilation, air-conditioning) system on an electric bus with dynamic on-road wireless charging. https://www.sciencedirect.com/science/article/abs/pii/S0360544214014054
32 Eudy, Jeffers. (2017). Foothill Transit Battery Electric Bus Demonstration Results: Second Report. https://www.nrel.gov/docs/fy17osti/67698.pdf
33 (APTA), n.d. (presentation). Lessons Learned From Operating Battery Electric Buses in the Real World. https://www.apta.com/wp-content/uploads/SMW10_Lessons-Learned-from-BEB_Tina_Wu.pdf
34 Basma, H. et al. (2022). Energy consumption and battery sizing for different types of electric bus service. https://www.sciencedirect.com/science/article/abs/pii/S0360544221027031
35 Liu, L., et al. (2019). Impact of Time-Varying Passenger Loading on Conventional and Electrified Transit Bus Energy Consumption. https://afdc.energy.gov/files/u/publication/time-varying_passenger_loading_impact.pdf
36 Build Your Dreams. (2024). 12m e-bus model. Available at: https://bydeurope.com/pdp-bus-model-12
37 ITDP Brasil and Logit. (2022a). Electric bus financing project for Belo Horizonte. https://www.gov.br/cidades/pt-br/central-de-conteudos/publicacoes/mobilidade-urbana/arquivos/projeto-de-financiamento-de-onibus-eletrico-em-belo-horizonte-ingles.pdf

The same goes for providing adequate training to drivers for optimal performance of e-buses to extend the daily range. Drivers should be educated on the benefits of gentle acceleration and braking, how an electric propulsion system functions, and efficient use of battery energy so they know how to optimize battery longevity.[38] Battery life is elongated when batteries are properly charged and maintained. The State of Charge (SoC) is a critical indicator of this, representing the percentage of energy stored in a battery relative to its full capacity. Operators should aim to keep the SoC between 20% and 80% while charging.[39] [40] [41] Going below or above this limit can negatively affect battery lifespan and health, as higher internal resistance to produce power will generate heat, accelerating degradation. Notably, charging from 80% to 100% takes as long as charging from 20% to 80%, offering diminishing returns and making it an inefficient use of charging resources.

In addition, it is possible to extend range through multiple alternatives. Proper driving techniques and regenerative braking systems can extend a battery's lifespan and lead to energy gains of up to 14%.[42] With smoother deceleration, the energy used in the regenerative braking process has greater potential to be reversed to charge the battery. Regenerative braking captures kinetic energy from braking and converts it into electricity that can charge the battery.[43]

Data collection and battery and vehicle monitoring is essential for evaluating performance in the local context, analyzing whether they meet the city's needs and expectations, and informing the planning for the acquisition of new vehicles and charging infrastructure. This information serves multiple purposes, including instructing drivers on range to ensure enough charge to return to the depot. The data collected can guide decisions related to bus and battery performance, fleet transition, route optimization, and the implementation of best practices for maintenance and operations, among other considerations. Since it is not possible to predict all the operating and local conditions, pilot projects are a good way to test different possibilities and to identify what is best for each reality. It is recommended that all data and information be gathered and monitored for both types of technology—the new electric technology and the standard technology, which will continue to operate in the remainder of the transportation system, usually diesel engine–based buses.

Mechanics need regular training for bus maintenance and battery swapping.
Source: Entre Acto

38 Li, J. (2016). Battery-Electric Bus Developments and Operations: A Review. https://doi.org/10.1080/15568318.2013.872737
39 Bloomberg New Energy Finance, 2018. Electric buses in cities—driving towards cleaner air and lower CO_2. Available at: https://www.c40knowledgehub.org/s/article/Electric-Buses-in-Cities-Driving-Toward-Cleaner-Air-and-Lower-CO2?language=en_US
40 Kostopoulos, E., et al. (2020). Real-world study for the optimal charging of electric vehicles. Available at: https://www.sciencedirect.com/science/article/pii/S2352484719310911
41 Charge Sim. (2024). What does the State of Charge really mean? Available at: https://www.chargesim.com/blog/what-does-the-state-of-charge-really-mean
42 Mueller, S., et al. (2017). Analysing the influence of driver behaviour and tuning measures on battery aging and residual value of electric vehicles. https://www.semanticscholar.org/paper/EVS-30-Symposium-Stuttgart-%2C-Germany-%2C-October-9-11-Mueller-Rohr/138122ab0db733c0fcc8a019988f42d486ed5350
43 Islameka, M., et al., 2019. Modelling of regenerative braking system for electric bus. Available at: https://iopscience.iop.org/article/10.1088/1742-6596/1402/4/044054

The uncertainties surrounding battery life cycle and performance make warranties a crucial aspect to be considered. However, warranties depend on the manufacturer and the terms of the contract and will be based on its time duration.[44] To account for this risk, it is essential to secure comprehensive warranty coverage that addresses both the unique operational demands of e-buses and the uncertainties associated with battery longevity. Warranties should cover the expected lifespan of the bus, typically eight to 12 years. With ongoing technological improvements and the continued collection of information about e-bus operations, we expect the length and structure of warranties to become more standardized, considering that the batteries will continue to become increasingly accessible and their performance more assertive.

Additionally, warranties should include provisions for capacity degradation, ensuring that the battery maintains a minimum level of performance. We also recommend that warranties incorporate clauses for regular performance checks and maintenance, as well as clear procedures for battery replacement or repair. By adopting these comprehensive warranty recommendations, transit agencies can mitigate the risks associated with battery performance and ensure the long-term viability and cost-effectiveness of their e-bus fleets.

2.3. BATTERY END-OF-LIFE

After the battery end-of-life for the e-bus, it is important to consider the next destination. There is currently no standardized policy for disposing of batteries, and the existing battery disposal policy was established before the rise of the electric vehicle market and does not adequately address e-bus batteries. Improper disposal increases overall emissions throughout the life cycle and can negatively impact the local environment through increased need for mining and refining processes, and increases the demand of GHG emissions.[45]

The sector must move to address this, particularly with governments outlining requirements for safe battery disposal. Such regulations can minimize project uncertainties and promote broader adoption of the technology, especially within the private sector. Thus, there are three possibilities on how to go forward when a battery achieves its end-of-life under e-bus operation—recycling, reuse, or disposal.

Battery recycling plant.
Source: Saubermacher

44 Bloomberg New Energy Finance. (2018).
45 Geuss. (2019). Electric Car Batteries Might Be Worth Recycling, but Bus Batteries Aren't Yet. https://arstechnica.com/science/2019/02/electric-car-batteries-might-be-worth-recycling-but-bus-batteries-arent-yet/

2.3.1. Recycling

When e-bus batteries are recycled, the materials recovered from the old batteries can be used to manufacture new ones, with some battery recycling processes claiming up to 95% recovery of critical minerals used in e-bus batteries.[46] Even so, this process needs to be formalized and standardized to ensure that the most environmentally sustainable methods are adopted. Around the world, some manufacturers are offering to recycle or dispose of the batteries after their end-of-life. As such, it is important to outline in procurement and/or contracts which stakeholder is responsible for end-of-life recycling or disposal, both financially and logistically.

2.3.2. Reuse

As the battery recycling industry and regulatory framework evolve to match market progress, the reuse of batteries for second- or third-life applications will become increasingly important and seen as a viable option in many countries. After a battery's initial useful life and prior to recycling there is potential for repurposing batteries for stationary power storage. Given that batteries retain approximately 80% of their storage capacity after their initial useful life, they can be repurposed for peak electrical energy management and energy storage.

Batteries can be used in a second life cycle, such as in solar or wind energy storage. In Brazil, for example, a manufacturer is already selling solar panels and closing sales packages for this purpose.[47] The use of batteries for energy storage can support the implementation of smart-grid concepts.

Many countries around the world, including China and countries in the European Union, have looked toward reuse as a viable solution for repurposing e-bus batteries.[48] In fact, China has historically prevented the export of used electrical vehicles to retain materials for recycling and recovering domestically. This has since changed, and countries worldwide are continuing to explore ways to develop primary and secondary battery uses. Europe and North America are working to develop their own form of recycling and reuse for both batteries and vehicles.

Second-life batteries offer multiple benefits. As the world's energy transition progresses, demand for storage solutions is constantly increasing. Because electricity generated from renewable sources like solar and wind is subject to fluctuation based on natural conditions, energy storage capable of balancing that fluctuation is key. Extending a battery's usage also helps to reduce CO_2 emissions.

After the second life cycle, which is estimated to be 30 years, batteries must be subjected to recycling, with lithium-ion components and other chemical components used to produce new units. Delaying the battery recycling process through reuse could be especially useful as there is no set standard yet—making use of the batteries as storage in the meantime can ensure that when they reach their second life, more environmentally and socially conscious recycling standards are available.

One key way of monitoring a battery's health and lifespan is by standardizing and sharing data on the battery's health. This can be collected while the battery is on board, and drivers can be trained on how to ensure that data is collected and saved (although this process is typically automated).

It is ultimately foreseeable that data has and will continue to play a major role in battery monitoring. The European Union is developing a digital battery passport, which would provide advanced information about the battery value chain and access to real-time battery health info. There is a lot of incentive to do this: Making e-bus batteries is extremely cost-intensive, so manufacturers, governments, and other stakeholders are motivated to look toward and fund recycling efforts.[49]

46 Argonne National Laboratory. (2021). Breakthrough research makes battery recycling more economical. https://www.anl.gov/article/breakthrough-research-makes-battery-recycling-more-economical
47 World Bank. (2019). Green Your Bus Ride: Clean Buses in Latin America. https://documents1.worldbank.org/curated/en/410331548180859451/pdf/133929-WP-PUBLIC-P-164403-Summary-Report-Green-Your-Bus-Ride.pdf
48 ICCT. (2023). Scaling up reuse and recycling of electric vehicle batteries: assessing challenges and policy approaches. https://theicct.org/wp-content/uploads/2023/02/recycling-electric-vehicle-batteries-feb-23.pdf
49 The Verge. (2022). Toyota will recycle electric vehicle batteries with Tesla co-founder's project. https://www.theverge.com/2022/6/21/23177039/toyota-redwood-materials-ev-battery-recycling-partnership-prius

3 CHARGING INFRASTRUCTURE OPTIONS

When electrifying fleets, cities are replacing bus systems that have historically used fuel stations in favor of new electrification infrastructure. This fundamental difference has many ramifications. Operations and maintenance planning will need to change with the transition. There will also be changes in route planning, infrastructure, refueling/charging schedule strategies, and maintenance practices. Because the battery range is less than that of diesel buses, the model of running the bus all day before refueling may not work for e-buses and that is the main reason for these changes, but also there are opportunities that come from this that will be shared in this section.

Designing the infrastructure and developing its operational recharging plan for running e-buses is the key to improving efficiency, supporting battery health, and creating a bigger positive impact on people's lives and on the corridor's efficiency. Planners need to evaluate the types of charging infrastructure, quantity of chargers and stations for each type, available space for charging stations, and grid capacity for a successful pilot and scale-up. In terms of spaces for the infrastructure, the designated charging location should include maintenance facilities and electrical systems, with transformers to match voltage levels between the power grid and charging stations. Charging infrastructure may require more space at the depot than diesel refueling stations and may necessitate a rethinking of depot design.

This section addresses the main charging strategies and their components, strengths, and potential challenges. Additionally, for each charging strategy, there is an overview of the foundational considerations needed to set up the strategy and the most appropriate scenarios, given the local environment and project needs. Finally, power grid capacity and the main considerations to be taken in the decision will be addressed.

3.1. CHARGING INFRASTRUCTURE LOCATIONS AND TYPES

The first step in developing a charging plan is to understand two facets of this plan—the types of charging infrastructure and where they can be deployed. Charging locations and types, including the speed of charging for each, will have major ramifications on a given bus system's operation. Establishing a charging strategy that suits the local context is crucial for the project's success.

Charging location designation can require a substantial amount of space depending on the number of e-buses, and the placement of the charging infrastructure may impact the surrounding community. If ICE depots are to be retrofitted, planners should consider the distance between depots and the beginning of the routes when thinking about e-bus range or battery needs for the distance covered. It is important to think about existing or future depot locations and consider ways to maximize access across a city. Cities should put care into assessing the social impact of a project like this and explore how the transition could be harnessed into a tool for social change.[50]

OPPOSITE PAGE Passengers entering a bus from the Santiago Red metropolitana de movilidad **Source:** Claudio Olivares

50 López, C., et al. (2019). On the Environmental and Social Sustainability of Technological Innovations in Urban Bus Transport: The EU Case. https://www.mdpi.com/2071-1050/11/5/1413


Red Metropolitana de Movilidad
1391
Red
BYD
Chile
GC·BD·46
TRANSANTIAGO

Charging infrastructure is often located either at the depots, where the buses can charge overnight, or along the route, where buses can get a recharge while in service. Each option delivers certain benefits and has specific challenges when thinking about the charging plan and how it intersects with the operational plan. Locating charging infrastructure in low-income neighborhoods can potentially offer significant benefits, such as improved air quality and reduced noise pollution, contributing to better public health and overall quality of life. However, it's essential to consider the potential for environmental injustice. The placement of charging infrastructure should not impose additional burdens on these communities, such as increased traffic or noise during installation and maintenance. To ensure equitable outcomes, cities should engage with residents, assess the social impact comprehensively, and explore how this transition to e-buses can be harnessed as a tool for social change, enhancing the well-being and resilience of all urban communities. Below is an overview of the possible placements for the charging infrastructure.

EN-ROUTE. Some forms of charging infrastructure, such as pantograph, in-motion charging, and wireless, can be located along the routes and will depend on the infrastructure of the power grid. Often this will be at bus stations, bus route endpoints, or stations or stops where multiple bus routes intersect. A key issue for deciding where these should be is whether there is adequate land available for charging infrastructure. Depending on the charging strategy plan, passengers can be on board when charging is taking place.

DEPOTS. Regardless of charging type, bus depots will need to be retrofitted or constructed for e-bus infrastructure. Bus depots should accommodate and provide convenient access to charging infrastructure, which will likely demand 15% to 30% more floor space than an average depot.[51] (How much storage room a given system requires depends on the charging strategy, which will be addressed in the next section.) Because batteries may degrade more quickly in high temperatures or perform worse in colder weather (and buses will use more energy to heat or cool a bus), planners should ensure that battery charging is in an adequately covered and ventilated place and that there are sufficient facilities for heating or cooling electric hardware, taking into account sensitivity to local weather and seasonal fluctuations.

LEFT:
Electric buses charging at Zajezdnia autobusowa Wola Duchacka in Krakow Poland.
SOURCE: Longfin Media via Shutterstock

RIGHT:
Depot for electric buses in Glasgow.
SOURCE: richardjohnsonvia Shutterstock

Planning and modeling the service will depend on the kind of charger a transit agency decides to utilize and what is feasible given geographic constraints and availability in the local market. The chargers may require different kinds of infrastructure and land area.

There are five main BEB charging types: traditional plug-in, pantograph charging, flash charging, in-motion charging, and wireless charging. Some types may be combined depending on the charging strategy plan developed.

51 UITP. (2019a). The impact of electric buses in urban life. https://cms.uitp.org/wp/wp-content/uploads/2020/06/UITP-policybrief-June2019-V6-WEB-OK.pdf

REVIVING TROLLEYBUSES WITH IN-MOTION CHARGING: A MODERN TWIST ON A CLASSIC SOLUTION

Reintroducing trolleybuses using the traditional overhead lines with batteries offers a strategic advantage by leveraging existing infrastructure that many cities established during the energy crises of the 1970s with the flexibility that batteries can provide. In-motion charging (IMC) is a form of e-bus charging that combines a standard BEB with the traditional overhead lines of a standard trolleybus system. In traditional trolleybuses systems, the buses were powered by the overhead lines and had no battery, so they could not leave the corridor where the overhead lines were located. With in-motion charging, the bus can run free from the wire using its on-board battery and, when needed, use the overhead lines to charge the on-board battery while driving, decreasing the need for overhead lines along the entire route.[52]

In-motion charging offers the flexibility of an e-bus with the energy supply of overhead lines. The most recent research indicates that as little as 20% to 30% of a given route would need to be wired, depending on the battery.[53] With a system that employs IMC, overhead lines can be strategically placed on long, straight stretches of a route. Historically, the most expensive areas of overhead lines to maintain are those on complicated turns or intersections. Avoiding those switches can help make IMC e-bus operation more efficient and cost-effective. E-buses that run on overhead lines also are ideal for climbing hills, because of the constant supply of energy. Many cities that had trolleybuses in the past have reintroduced IMC systems in recent years:

- In Tallinn, a city in Estonia, investments are underway for 40 battery-powered trolleybuses and to upgrade the contact network;[54]

- In San Francisco, there is a process under development for implementing a major battery upgrade for enhanced IMC capability on electric trolleybuses;[55]

- In Jinan, China, the double-source electric trolleybuses are contributing to operation flexibility. Leveraging real-time charging, these buses can operate offline for more than 20 km with the air-conditioner on;[56]

- In Mexico City, until 2019 the city operated a nine-line trolleybus network with low frequency, using old units dating back to 1975. Starting in September 2019, the city began renewing its entire trolleybus fleet with new BEB, which allowed for the extension of routes to areas without overhead lines. By May 2023, the total fleet was of 310 new trolleybuses, including articulated ones;[57] [58] [59]

- Prague closed its last trolleybus line in 1972 but has since incorporated a system that combines both IMC and opportunity charging.[60] In 2017, the city implemented a pilot with two sections of overhead lines that cover 15% of the 5 km route. These routes were chosen for a variety of factors: Sloped hill terrain, the proximity of the existing depot, and the possibility of using the tramway energy supply network allowed the project to potentially scale and take advantage of existing substations used for tramlines.[61]

52 Bartłomiejczyk, M., & Połom, M. (2021). Sustainable Use of the Catenary by Trolleybuses with Auxiliary Power Sources on the Example of Gdynia. https://www.mdpi.com/2412-3811/6/4/61
53 UITP. (2019b). In motion charging. Innovative Trolleybus. https://cms.uitp.org/wp/wp-content/uploads/2021/01/Knowledge-Brief-Infrastructure-May-2019-FINAL.pdf
54 EU Urban Mobility Observatory. (2024). Tallinn investing in electrifying its trolleybus network as part of its SUMP. https://urban-mobility-observatory.transport.ec.europa.eu/news-events/news/tallinn-investing-electrifying-its-trolleybus-network-part-its-sump-2024-03-01_en
55 Kiepe Electric. (2023). San Francisco to prototype a major battery upgrade for enhanced in motion charging capability on electric trolley buses. https://kiepe.knorr-bremse.com/en/us/company/media/press-releases/san-francisco-to-prototype-a-major-battery-upgrade-for-enhanced-in-motion-charging-capability-on-electric-trolley-buses.json
56 China Buses. (2015). Zhongtong double-source electric trolley bus highly welcomed in Jinan. https://m.chinabuses.org/news/7841.html
57 Vorágine. (2019). Gobierno capitalino anuncia compra de 63 trolebuses eficientes de energía con inversión de 453 mdp. https://voragine.com.mx/2019/09/13/gobierno-capitalino-anuncia-compra-de-63-trolebuses-eficientes-de-energia-con-inversion-de-453-mdp/
58 Jefatura de Gobierno de la Ciudad de México. (2020). Encabeza Jefa de Gobierno salida de pruebas preoperativas de 80 nuevos trolebuses. https://jefaturadegobierno.cdmx.gob.mx/comunicacion/nota/encabeza-jefa-de-gobierno-salida-de-pruebas-preoperativas-de-80-nuevos-trolebuses
59 Gobierno de la Ciudad de México. (2022). Nuevas unidades de Trolebús y RTP. https://gobierno.cdmx.gob.mx/noticias/nuevos-trolebuses-y-rtp/
60 UITP. (2019b). In motion charging. Innovative Trolleybus. https://cms.uitp.org/wp/wp-content/uploads/2021/01/Knowledge-Brief-Infrastructure-May-2019-FINAL.pdf
61 Sustainable Bus. (2019). Trolleybuses return to Prague 47 years later. Available at: https://www.sustainable-bus.com/trolleybus-tramway/trolleybuses-return-to-prague-47-years-later/

By revitalizing these dormant networks, cities can significantly reduce the costs associated with the transition to electric public transportation. Although this approach has the challenge of needing access to an appropriate energy supply, the use of trolleybuses not only capitalizes on previously invested resources but also aligns with modern sustainability goals. Trolleybuses, with their continuous connection to overhead power lines, provide a reliable and efficient mode of transport that can seamlessly integrate with current urban mobility plans. Utilizing this infrastructure can expedite the shift toward greener public transit while minimizing financial and logistical challenges.

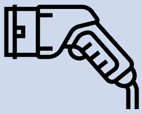
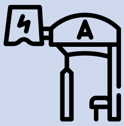
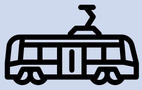
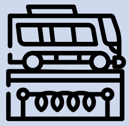
ABOVE:
Trolebús system in Mexico City expanded up to 12 lines in 2024.
Source: Bruno_Doinel via Shuttestock

BELOW:
Trolleybus on Prague's line 58.
Source: Martyn Jandula via Shutterstock.

Each charging type requires specific infrastructure and has different space requirements, time to reach full charge (also known as fast versus slow charge), charger power needs, and costs. Table 2 summarizes different aspects of these charging infrastructure types, based research from academic papers, reports from peer organizations, and others.

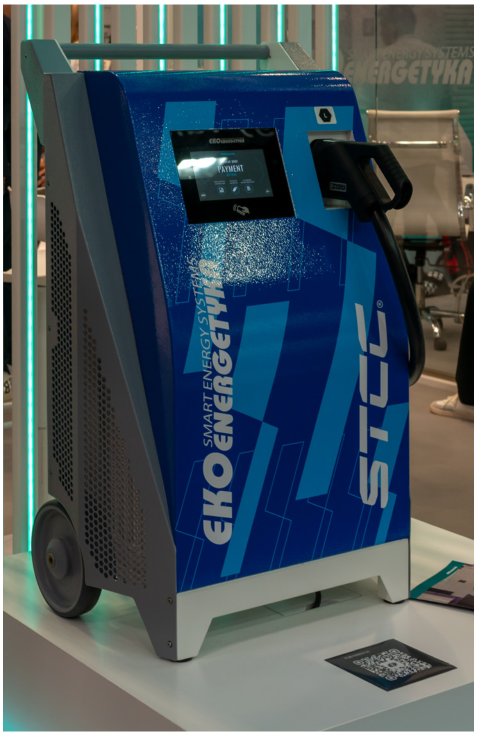
62 Based on information from Canada, Switzerland, and United States.

TABLE 2. CHARGING INFRASTRUCTURE TYPES AND CHARACTERISTICS

	Plug-In	Pantograph	Flash	In-Motion	Wireless
Description	 Also known as overnight charging. Requires someone to plug the bus from its port to a charging facility usually by a long coil/cord. It is the most common and accessible method.	 Requires contact between a pantograph charger and rods installed in the vehicle roof, usually through maneuvering the vehicle.	 Requires contact between an overhead pantograph charger and a small transmission mechanism mounted on a movable arm.	 Mounted poles atop the e-bus connect to overhead lines.	 Inductive charging uses an electromagnetic field to transfer electricity.
Charging speed	Slow: 5 to 8 hours.	Fast: From 5 to 20 minutes to reach full charge	Fast: 15 to 20 seconds	Fast: Approximately 9 minutes	Fast and dynamic: From 20 minutes to 1 hour to reach full charge
Charging location	At the end/ beginning of routes, in closed public areas, or in depots.	At the end/ beginning of routes; in depots or in the stations; can recharge along route (in the case of trolleybus).	Can be placed anywhere, typically along a route.	Along a route, while e-bus is driving, on long and straight stretches of road.	At the end/beginning of routes, along the routes, or in depots.
Space requirements	Enough space in a depot for the bus to park as well as space for the charger.	Typically requires both space in the depot and potentially along the route.	Space needed for infrastructure near the road to charge along route.	Overhead space as well as infrastructure at points on the side of the road.	Space needed under the road and transformer box next to charging pad.
Cost (per charger)[62]	Approximately 230,000 USD	Approximately 1,120,000 USD	Approximately 1,230,000 USD	Approximately 750,000 USD per km	Approximately 570,000 USD
Charger power requirements (kW)	40–125	125–500 (on-route)	Up to 600	Up to 500	200 to 300
Battery size suggested to use (kWh)	300–450+ (some models up to 660)	60–250+ (can use larger if desired)	50–250+	100–200+	60–125
Countries and regions	China, Latin America, Europe, U.S., New Zealand	China (although less common), South Korea, Europe, U.S., Canada	Europe, China, India	United States, Brazil, Mexico, China, Europe	Europe, South Korea, US
Manufacturers	ABB, BYD, ChargePoint, Proterra, Siemens	ABB, Alstom, Heliox, Schunk Carbon Technology, Siemens	ABB, ElectReon, Heliox, Siemens	Alstom, Kiepe Electric, Schunk Carbon Technology, Siemens	Bombardier Primove, ElectReon, Proterra, Momentum Dynamics, WiTricity

SOURCE: Developed by the authors

Charging types must also be evaluated in the context of the service plan, which delineates how many buses are needed, over what routes and with what types of services to meet passenger demand. This evaluation also must consider projections of growth in demand and route extension, as most infrastructure generally has a planning horizon of 10 to 20 years at a minimum. Planners must understand what future ridership demand will be to adequately plan for the long-term installation of an electric system.



ABOVE LEFT:
Pantograph charger at Sunset Transit Center in Portland, United States.
SOURCE: Steve Morgan via Wikimedia Commons

ABOVE:
Mobile electric bus charger displayed at IAA Summit 2023 in Munich, Germany.
SOURCE: Matti Blume via Wikimedia Commons

LEFT:
Plug-in charging.
SOURCE: Ruslan Sitarchuk via Shutterstock

When planning for capital costs of charging infrastructure, operators and related planning stakeholders should consider: charging station hardware; charging station construction and implementation; available space and grid connections, including land acquisition costs; labor costs for construction and implementation (including preconstruction costs, such as personnel for on-site consultations); and municipal permitting costs.

3.2. CHARGING PLANNING STRATEGIES

Implementing charging infrastructure intelligently is imperative to the success of the system. This will affect service planning, since it will directly impact how much time buses are out of service for recharging and how long they can run before they need to be recharged, and consequently, impact the number of buses needed. This is critical for cities that want to achieve as close as possible to a 1:1 replacement of electric to diesel buses.

This section will look at three main charging strategy options for e-buses: depot charging, opportunity charging, and combined/mixed charging. An overview and analysis around strengths, potential challenges, scenarios, and considerations are discussed for each charging strategy plan.

3.2.1. Depot Charging

Depot charging is the name of the most common way of charging for e-buses, and it is usually done during the night, so it is also known as overnight charging or slow charging. It can also be done during prolonged shifts throughout the day when out of service. The name "slow charging" can sometimes be deceitful, since this way of charging can be done using different types of chargers, including faster ones. The name came from the plug-in, the most common charger used for this charging method.[63] Charging times will depend on the charger used, and they have continued to decrease as technology improves and this is expected to continue.[64]

Transantiago electric buses.
SOURCE: Cristian Silva Villalobos via Shutterstock

In terms of service planning, with depot charging, there is a need for a more consistent time schedule because of the battery's driving range to ensure the bus can return to the depot before running out of power. To ensure that the routes will be covered during service, the buses may need to return to the depot for intermittent charging during service. For that, it's often necessary to have more buses than with ICE buses to maintain reliability and ensure that there are consistently charged buses that can accommodate the routes.[65] Buses can be strategically charged and deployed to accommodate the increase in demand during peak hours. Overall travel time, compared to charging along the route, could decrease, because the bus doesn't need to stop to charge.

Most appropriate locations to place it

The chargers are typically positioned at the ends of routes and/or in bus depots, partly because of the space needed for this type of charging infrastructure. Depending on the scale, resources available, and budget of the project, these could be new facilities or existing locations retrofitted as depots. This method is more appropriate for long-range e-bus deployment.

Placement is also a key factor, especially considering that land is scarce in most cities. The most important things to evaluate are proximity to the selected routes to guarantee a more efficient service use, proximity to existing electrical infrastructure to mitigate potential challenges and costs, space available, and potential impacts to the neighborhood.

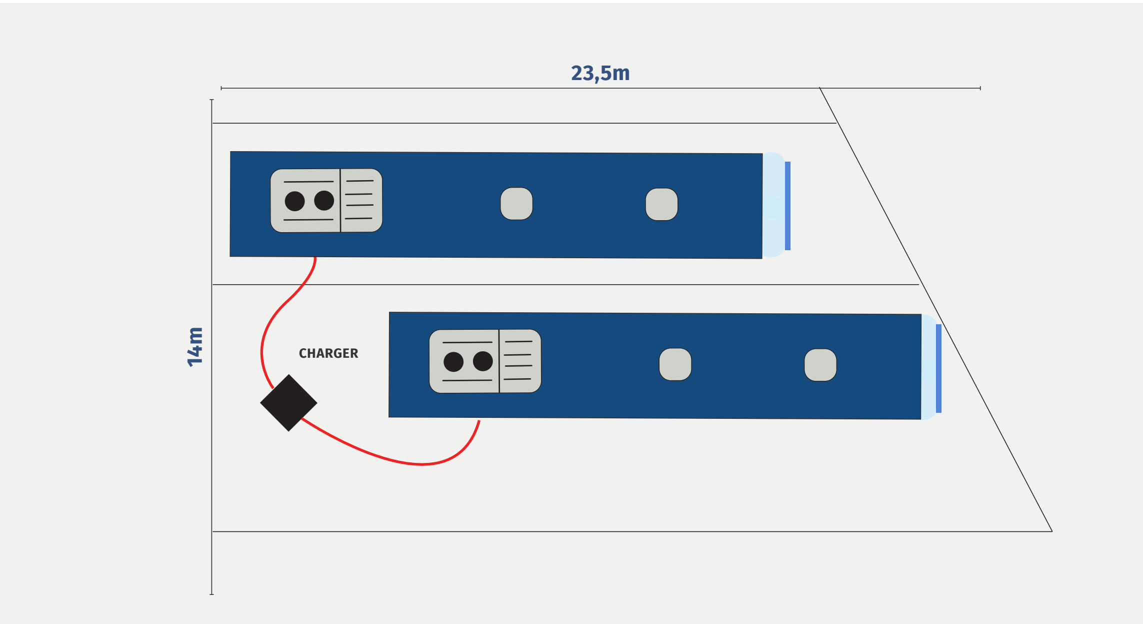
63 ITDP. (2021b). From Santiago to Shenzhen: How Electric Buses Are Moving Cities. https://www.itdp.org/publication/from-santiago-to-shenzhen--how-electric-buses-are-moving-cities/
64 ZeEUS. (2017). ZeEUS eBus Report #2: An Updated Overview of Electric Buses in Europe. https://zeeus.eu/uploads/publications/documents/zeeus-report2017-2018-final.pdf
65 Urban Transport Magazine. (2021). Bus Electrification: A comparison of capital costs. https://www.urban-transport-magazine.com/en/bus-electrification-a-comparison-of-capital-costs/

Infrastructure needs and costs

The infrastructure of depot charging typically involves the addition of charging enclosures and plug-in chargers within bus storage depots, terminals, or other designated charging areas. The additional infrastructure may require larger spaces than ICE buses, which usually had a refueling station for all buses and then the rest of the space (outside of maintenance areas) was for bus parking. The additional infrastructure requirements needed for an electrified depot—including chargers, cables, and transformers—can reduce the amount of space available for operations. This can be mitigated through planning and selecting infrastructure that takes up minimal space. In depots that already are constrained in space, fleet size may need to be reduced. Various other depot setup factors must be considered in the equation, such as staff spaces, inspection areas, and maintenance and cleaning areas.

The most appropriate size for the depot or charging facility will depend mainly on the number of buses the fleet has, the number of chargers, and the layout chosen. The recommended layout is parking a bus in a manner that it can move without impacting others. For that, a parking space with a 45-degree angle with a 10m turning space plus 2m for the charging infrastructure would allow for ease of parking and turning for 12m medium-size buses, as can be seen in Figure 2.[66] Since the most common setup is two buses using a single charging unit, the width will need to take this into consideration. Usually, for each e-bus without blocking parks, the space required will be 90m²; for an e-bus with blocking parks, 64m² will be enough.[67] It is worth noting that considering the electric vehicle as an emerging technology, various layouts for depots have been evaluated by experts for the design of the necessary facilities.

FIGURE 3. Space requirements for a 12m bus parking space



Source: Adapted from CFF, 2022.

To provide a few examples of costs: In Jinan, China, the cost for electrification, charging infrastructure, and other items such as construction and land acquisition for a depot for 100 e-buses totals around $58.9 million USD. In San Francisco, the cost for these components for a fleet of 38 e-buses and expansion of the depot yard amounted to approximately $54.3 million USD.

Energy consumption and costs

The number of buses charging simultaneously, charging technology, and grid capacity all have an impact on local energy consumption and supply.[68] A depot charging strategy plan requires charging capacities ranging from about 25 kW to 150 kW per charger, with most cases falling between 50 kW and 100 kW. This

66 CFF. (2022). Depot electrification for zero-emission bus systems. https://cff-prod.s3.amazonaws.com/storage/files/ntxVux2cwtL1ktfVHHhAa3fR4GMmg627CiWJtM2O.pdf
67 ITDP India. (2023). E-Bus Basics. A Guide for Cities to Transition to Electric Buses. https://www.itdp.in/wp-content/uploads/2023/07/E-Bus-Basics.pdf
68 Spirii. (2024). Electric bus charging: Understanding sustainable public transport. https://www.spirii.com/en/resources/blog/electric-bus-charging

typically results in charging times of three to six hours, depending on the charger power and battery storage capacity.[69 70 71] In some cases, charging times may extend up to eight hours, depending on the charger's power output. This strategy is usually done during the nighttime, when buses can sit out of service for the required time to fully charge.

Comparatively, a depot charging strategy is one of the least expensive options, because off-peak charging has reduced electricity rates and the costs of the actual infrastructure. A study in Canada showed the cost of depot charging to be approximately $37 million less than opportunity charging.[72] Because they charge overnight, there is more sustained energy consumption during nonpeak hours, putting less strain on the grid than some other charging methods.

The number of chargers needed for a fleet will depend on the average daily operating mileage of buses, the charger, and the battery size of the buses. Generally, one charger per one to two vehicles is needed for depot charging.[73] With new technological innovations in charging, it's possible that this ratio will become even smaller.

Implementing this infrastructure offers benefits. By allowing for a longer charging period, the necessary power for chargers can be lower, reducing the strain on the electrical grid and the electricity costs. However, depending on fleet size, many vehicles charging simultaneously could still strain the grid.[74] To minimize this, smart charging systems should be implemented to assess each vehicle's charge state and allocate power as needed.

A CASE STUDY ON DEPOT CHARGING STRATEGY IN JAKARTA, INDONESIA

To reduce carbon emissions and improve air quality, Jakarta has committed to electrifying 50% of Transjakarta's fleet by 2027 and achieving full electrification by 2030, as outlined in a governor decree.[75] This ambitious goal reflects Jakarta's dedication to sustainable urban mobility and its role in combating climate change.

To meet these targets, Transjakarta initiated a pilot project in 2022, deploying 30 units of 12m electric low-entry buses equipped with 324 kWh LFP batteries on three non-BRT routes. This pilot project aimed to gather valuable data on the operational efficiency and range capabilities of e-buses in Jakarta's unique urban environment. A depot charging strategy was chosen for this pilot phase because each bus traveled an average of 230 km daily, consuming approximately 70% of its battery capacity.[76] Charging stations were located at a privately owned bus depot, in line with the current business model that requires the e-bus operator to provide the necessary charging infrastructure. These facilities were exclusive to Transjakarta's e-buses and were not accessible to the public or other bus operators.

Transjakarta installed fast chargers to meet its operational needs. Each charging station was equipped with double-gun 100 kW CCS2 plug-in chargers capable of fully charging a bus battery in 90 minutes. Charging typically occurred between 10 p.m. and 4 a.m., allowing each station to charge three buses per night. The use of fast chargers for depot charging proved effective, ensuring that buses were ready for daily operations.[77]

69 ZEBRA. (2020). From pilots to scale—lessons from electric bus deployments in Santiago de Chile. https://iea.blob.core.windows.net/assets/db408b53-276c-47d6-8b05-52e53b1208e1/e-buscase-study-Santiago-From-pilots-to-scale-Zebra-paper.pdf
70 Randhahn, A., & Knote, T. (2020). Deployment of charging infrastructure for battery electric buses. https://link.springer.com/chapter/10.1007/978-3-030-38028-1_12
71 ZeEUS. (2017). ZeEUS eBus Report #2: An Updated Overview of Electric Buses in Europe. https://zeeus.eu/uploads/publications/documents/zeeus-report2017-2018-final.pdf
72 Urban Transport Magazine. (2021). Bus electrification: A comparison of capital costs. https://www.urban-transport-magazine.com/en/bus-electrification-a-comparison-of-capital-costs/
73 Guschinsky, N., et al. (2023). Cost-minimizing decisions on equipment and charging schedule for electric buses in a single depot. https://www.sciencedirect.com/science/article/abs/pii/S1366554523003253
74 Bloomberg New Energy Finance. (2018). Electric buses in cities—driving towards cleaner air and lower CO2. Available at: https://www.c40knowledgehub.org/s/article/Electric-Buses-in-Cities-Driving-Toward-Cleaner-Air-and-Lower-CO2?language=en_US
75 DKI Jakarta Province Legal Documentation and Information Network. (2022). Governor's Decree Number 1053 of 2022. https://jdih-jakarta-go-id.translate.goog/dokumen/detail/5368?_x_tr_sl=id&_x_tr_tl=en&_x_tr_hl=en&_x_tr_pto=sc
76 ITDP Indonesia & TUMI. (2023). TUMI E-Bus Mission: Supporting and Building the Capacity in Monitoring and Evaluating Pilot E-Bus Implementations. https://itdp-indonesia.org/wp-content/uploads/2023/07/Final_TUMI-E-bus-Mission-Jakarta-by-ITDP.pdf
77 ITDP Indonesia & TUMI. (2023). TUMI E-bus Mission: Supporting and Building the Capacity in Monitoring and Evaluating Pilot E-Bus Implementations. https://itdp-indonesia.org/wp-content/uploads/2023/07/Final_TUMI-E-bus-Mission-Jakarta-by-ITDP.pdf

However, pilot results indicated that the dead kilometers were higher than estimated, significantly impacting the range and charging patterns for the e-buses. Jakarta's pilot project demonstrates the viability of depot charging for e-buses, highlighting the importance of fast-charging infrastructure to meet daily operational demands. Key lessons include the importance of strategic placement of depots or charging stations to minimize dead kilometers. When the depot is far away from the service route, it is important to evaluate a combination of overnight and opportunity charging to enhance overall efficiency and flexibility, considering terminal space availability and grid accessibility.[78]

Transjakarta bus recharging in Mayasari Bhakti.
Source: Toto Santiko Budi via Shutterstock.

3.2.2. Opportunity Charging

Opportunity charging refers to the process of charging a vehicle while it is still in service, typically at predetermined locations along the route, such as terminals or bus stops. This strategy, also known as en route or fast charging, may rely on fast-charging technology due to the limited time available for charging during operation. With opportunity charging, an e-bus's range can be extended based on the availability of charging infrastructure along the route, reducing the need to return to the depot. This expanded range enables longer routes and the potential to serve more passengers without compromising operational efficiency.

Pantograph, plug-in, flash, in-motion, and wireless are options that can be used for opportunity charging. However, the most common approach is the use of pantographs.

ABOVE:
Pantograph charger console.
Source: Open Charge Alliance

LEFT:
En-route pantograph charger in Shanghai.
Source: helloabc via Shutterstock

78 UK Pact. (2023). Building a Regulatory and Financial Basis for Transjakarta First Phase E-Bus Deployment. https://itdp-indonesia.org/wp-content/uploads/2023/05/4.7.-Transjakarta-First-Phase-E-Bus-Deployment-Business-Case.pdf

Most appropriate locations to place charging

Opportunity charging infrastructure is typically dotted along routes. Strategically placing charging stations on stretches of route that have multiple bus lines running through it can make the most of the charging infrastructure available.

Fast-charging requires more intricate planning. This will include an assessment of the land available: where it is in proximity to the route, whether there is space available to accommodate fast chargers along a route, and if that land is adequate for charging infrastructure. Placement of chargers will be city-specific. Assessing a city's needs for a route is the first step to figuring out the placement of these charging stations to maximize the range of a bus. A bus bay, turnout, or designated area separate from traffic would allow the bus to charge, typically in a few minutes.[79] Bus layover areas, where buses are parked between trips along a route, can be good places to locate fast chargers, depending on the location. Usually, it is recommended to have one opportunity charging station for each 10 km of bus route.[80] Passengers can safely board and wait in the bus while it is charging.

A passenger pays for the bus with a transport card. It is part of the city government's program of Surakarta, Indonesia, to modernize the city's bus service..
SOURCE: wina soe via Shutterstock

Infrastructure needs and costs

The size of opportunity chargers can vary from method to manufacturer, and it will be important to look at the space constraints of methods. For example, some opportunity chargers extend overhead above the road, while others charge and connect from the side of the bus. Charger manufacturers often have resources available that outline the specifications and dimensions of opportunity charging systems.

Charging equipment for opportunity charging can cost more than other methods. The primary costs will come from the charging equipment and land acquisition depending on the chargers' location. Balancing the strategic placement of these charging stations against the cost of land will be necessary to implement this technology in an efficient and cost-effective manner. Thinking about pull-outs, bus bays, and other ways of separating the bus for charge can help alleviate these issues, but there can be obstacles to doing so if these locations are on privately owned land.

Energy consumption and costs

Opportunity charging usually requires a high-powered (150 kW to 450 kW) charger at regular intervals along the route.[81] Charging times vary depending on the power of the technology used, but they are generally shorter than depot charging, ranging from a few seconds to a few minutes for a partial charge.[82]

79 Rogge, M., Wollny, S., & Sauer D. U. (2015). Fast Charging Battery Buses for the Electrification of Urban Public Transport—A Feasibility Study Focusing on Charging Infrastructure and Energy Storage Requirements. https://www.mdpi.com/1996-1073/8/5/4587
80 Lajunen, A. (2018). Lifecycle costs and charging requirements of electric buses with different charging methods. https://www.sciencedirect.com/science/article/pii/S0959652617323594#tbl5a
81 ViriCiti. (2021). Opportunity charging for e-buses insights and tips for optimizing charging behavior. https://www.sustainable-bus.com/wp-content/uploads/2021/06/Opportunity-charging-report.pdfort.pdf
82 ITDP. (2021b). From Santiago to Shenzhen: How Electric Buses Are Moving Cities. https://www.itdp.org/publication/from-santiago-to-shenzhen--how-electric-buses-are-moving-cities/

Opportunity chargers can place higher demand on the electricity grid during peak hours of transport service because of the need to quickly charge the batteries during service—consequently, that can happen during peak hours for energy consumption.

Opportunity charging works best when a high-capacity grid connection is available because of the power needed to produce the wattage for opportunity charging.[83] Cities should therefore factor in the cost of electricity to be higher for this method, and plan to coordinate with utility companies in the early planning stages of a project. To address that, communication between project leaders and utility companies early in the process is essential. As an example, in Canada, the cost of 100 direct current fast chargers—each with 500 kva transformers—for a fleet of 280 e-buses was approximately $112 million USD.

A CASE STUDY ON FAST CHARGING STRATEGY IN CHENGDU, CHINA

In response to the growing need for efficient and flexible e-bus charging solutions, several cities in China have piloted the use of pantograph chargers. Shanghai and Chengdu have adopted this advanced charging technology to enhance the operational efficiency of their e-bus fleets. Pantograph chargers, known for their high power and rapid charging capabilities, are strategically installed at bus hub stations or at the starting and ending points of routes. This method supports the continuous and seamless operation of e-buses, reducing downtime and maximizing route coverage.

At the Chengdu Jinniu Hub Station, an innovative approach has been implemented, utilizing both mount-down pantographs and plug-in charging stations. The station boasts 32 sets of mount-down pantographs, each capable of delivering up to 720 kW of power. This high-power supply enables the full charging of an e-bus in just 10 to 20 minutes. Such efficiency is crucial for maintaining the frequent departures required by urban bus services. Each pantograph set at the hub can serve between 10 and 20 e-buses per day, effectively addressing challenges related to limited space and high operational demands faced by bus companies.[84]

The deployment of pantograph chargers in Chengdu and other cities has yielded several notable benefits. The rapid charging times significantly reduce the downtime of e-buses, allowing them to spend more time in operation, increasing the overall efficiency. Also, high-power chargers at strategic locations like hub stations optimize the use of available space, as fewer charging stations are needed to serve many buses. However, the high initial investment cost and the need for careful integration with the existing electrical grid are significant considerations. To maximize the benefits and address these challenges, it is recommended that cities conduct thorough feasibility studies, engage in careful planning, and ensure close collaboration with grid operators.

Battery charging stations for electric buses on a road in Chengdu, Sichuan. **Source:** B. Zhou via Shutterstock

83 ITDP India. (2023). E-Bus Basics. A Guide for Cities to Transition to Electric Buses. https://www.itdp.in/wp-content/uploads/2023/07/E-Bus-Basics.pdf
84 All the information listed in the box was provided by Chengdu Bus Group during a meeting with ITDP China team.

3.2.3. Combined / Mixed Charging

Implementing mixed or combined charging strategies for e-buses involves strategically integrating various charging methods to optimize the efficiency and effectiveness of the overall charging infrastructure. By combining different charging approaches, service planning operations can mitigate the limitations of individual methods and ensure continuous operation of their e-bus fleets. Many cities have opted for a combination of charging modes because of the benefits of flexibility, operational efficiencies, and increased scalability of the fleet.

By combining different charging technologies, transit agencies can tailor their charging approach to specific route requirements, operational needs, and infrastructure constraints, enhancing flexibility. This flexibility allows for optimized charging schedules and ensures that buses remain operational throughout the day without significant downtime.

Electric bus of the public transport system on a street in Paris, France. **Source:** JeanLuclchard via Shutterstock

This method can enable higher operational efficiency by strategically locating fast-charging stations at key points along routes or in transit hubs. Agencies can minimize downtime, extend vehicle range, and minimize operational disruptions, ultimately contributing to the successful deployment and operation of e-buses. This results in more efficient use of fleet resources, reduced route deviations for charging, and improved overall service reliability.

Implementing this method can also contribute to scalability and futureproofing for e-bus operations. Transit agencies can adapt their charging infrastructure over time to accommodate changes in fleet size, route expansions, and advancements in charging technology. This scalability ensures that charging infrastructure investments remains relevant and effective as e-bus fleets grow and evolve.

Despite its benefits, this method also comes with a few challenges because of the increased operational complexity associated with managing multiple charging methods and schedules. Operators must carefully balance the need for fast charging with the availability of charging infrastructure and the practicalities of bus schedules, which can be a logistical challenge.

Although the adoption of mixed/combined charging strategies can help transit agencies optimize costs associated with e-bus deployment and charging infrastructure by leveraging a combination of en route and depot charging, this method can entail higher upfront costs compared to a single charging approach. This includes investments in diverse charging infrastructure, equipment, and management systems. There may be ongoing operational costs associated with maintaining and managing multiple charging stations, as well as potential expenses related to training staff and upgrading existing infrastructure.

One of the other challenges is related to ensuring compatibility between different charging technologies and infrastructure. This includes interoperability among various charging standards and protocols and the integration of different charging speeds and power levels. Without proper compatibility, it can be difficult to efficiently manage charging operations and optimize the use of charging infrastructure. This topic will be addressed in Section 3.4.

A CASE STUDY ON COMBINED CHARGING STRATEGY IN MÉRIDA'S E-BUS FLEET, MEXICO

In early 2023, the Yucatán state government launched the IE-Tram system, a fully electric light BRT network in Mérida. This system features three corridors with 30 e-buses from Irizar, connecting the city center with the northern, southeastern, and southwestern parts of the metropolitan area, along with an extension to nearby stations of the "Mayan Train," Teya, and Umán.[85] This initiative represented a significant step toward sustainable urban transportation, aiming to reduce emissions and improve air quality in the region.

For the charging infrastructure, Mérida adopted a mixed charging strategy combining depot and opportunity charging options. At the central station and bus depot in "La Plancha" park, where all routes begin, they installed 16 depot charging stations (ABB Terra 184 CC). Additionally, three five more placed along the longer routes.[86] This strategic mix allows for overnight charging of buses and opportunity charging during the day at terminals when buses complete their routes.

The ownership of the charging infrastructure is from the state government, which provides greater control and flexibility, supporting the IE-Tram e-buses and allowing energy supply to other vehicles operated by different entities. Currently, Mérida is testing various types and sizes of e-buses, with the support of the ITDP Mexico team, to evaluate their suitability for different routes, highlighting the importance of adaptable and well-planned charging infrastructure in the successful deployment of e-bus fleets.

The mixed charging strategy approach offers the benefit of doing overnight charging to ensure that the buses are fully charged and ready for service each day, while fast charging during the day maximizes operational efficiency by minimizing downtime. This flexibility ensures that buses can maintain their schedules without long interruptions for recharging, thereby improving the reliability and service levels of the IE-Tram system.

Bus of the Va y Ven Metropolitan Mobility Sysetem in Yucatán.
SOURCE: Arlette López via Shutterstock

3.3. BEST BATTERY SIZE FOR EACH CHARGING STRATEGY PLAN

Battery size is an important factor to consider, as it can impact a vehicle's internal space and layout, energy consumption, and the battery cost. E-buses equipped with large batteries benefit from prolonged driving range but have high battery costs. It is important to highlight that the battery size options will depend on the local context and supply availability.

Depot charging strategy planning must ensure that the bus can run for a long time. To meet operational requirements, this approach requires larger battery packs

85 ATY. (2024). Agencia de Transporte de Yucatán. https://transporteyucatan.org.mx/ietram
86 ATY. (2024). IE-Tram Carga De Las Unidades. https://transporteyucatan.org.mx/ietram/carga-unidades

(250 kWh to 500 kWh) to provide the necessary range for the vehicle. As mentioned earlier, larger batteries increase vehicle weight and battery acquisition costs, and they may decrease energy efficiency.

E-buses that employ opportunity charging can use smaller batteries.[87] The storage capacity of the batteries may vary from 30 kWh to 90 kWh, which lowers the purchase cost.[88] For in-motion charging, battery replacement occurs less frequently, because the bus is both being supplied with energy and charging while on the wire, which puts less strain on the battery.[89]

Mixed/combined charging strategies offer a promising approach to addressing the diverse possibilities and batteries available. Combining different charging methods can optimize the use of charging infrastructure, balance energy consumption, and minimize operational disruptions. Despite the challenges associated with mixed charging strategies, the potential benefits in terms of increased flexibility, efficiency, and cost-effectiveness make them a compelling option for electrifying bus fleets.

IS BATTERY SWAPPING A REALISTIC STRATEGY FOR E-BUS CHARGING AND OPERATION?

Battery swapping is a method where a depleted battery is removed and replaced with a fully charged one rather than charging the battery while it is still on the bus. This system requires specialized battery-swapping stations equipped with automated arms (because the battery is very heavy) to complete the swap, making the technology expensive to implement and maintain.[90] While it offers the advantage of significantly reducing downtime compared to traditional charging, implementation is expensive because multiple batteries are needed and each can cost the same as a diesel bus. There is also complex automated technology. Additionally, the infrastructure for battery-swapping stations requires considerable space and investment.

The main benefits of battery swapping include minimizing bus downtime and potentially extending battery life by avoiding the potential stress of fast charging.[91] Operationally, it offers flexibility, as batteries can be charged during off-peak hours, reducing electricity costs and without significant impacts on the power grid. However, it also includes operational challenges for maintaining a reliable schedule for battery swapping and ensuring the availability of charged batteries, which requires careful planning and coordination.

This approach has been explored in cities in China such as Beijing, Tianjin, and Qingdao, but it has not been used on a large scale.[92]

Electric bus revision and maintenance by a mechanic in Bogotá.
Source:
Entre Acto

87 Lajunen, A. (2018). Lifecycle costs and charging requirements of electric buses with different charging methods. https://www.sciencedirect.com/science/article/pii/S0959652617323594#tbl5a
88 Klein, E. & Lantz, M. (2019). Evaluation of electric bus adoption in Sweden. Chalmers University of Technology. https://odr.chalmers.se/server/api/core/bitstreams/e826ef31-d5da-4f10-9d35-f43c95bc3b15/content
89 Pedestrian Observations. (2018). In-Motion Charging. https://pedestrianobservations.com/2018/12/09/in-motion-charging/
90 An, K., Jing, W., & Kim, I. (2020). Battery-swapping facility planning for electric buses with local charging systems. https://doi.org/10.1080/15568318.2019.1573939
91 Zhang, L., Wang, S., & Qu X. (2021). Optimal electric bus fleet scheduling considering battery degradation and non-linear charging profile. https://www.sciencedirect.com/science/article/pii/S136655452100209X#b0220
92 Solution 1. (2023). Battery-swapping technology: A comparison of different approaches and applications. https://solution1.com.tw/battery-swapping-technology-a-comparison-of-different-approaches-and-applications/

3.4. CHARGER STANDARDS AND INTEROPERABILITY

The physical charging connections, software, and charging speeds are important components of the charging system. They are key elements since they can directly impact service operation. Charging speeds are associated with the type of current—alternating current (AC) or direct current (DC). While all e-buses will store electricity in the form of DC power, the electric grid transmits and provides electricity through AC power. With AC, the flow of electrical charge alternates direction, and it is the most common form in which electrical power is delivered.[93] DC power is a current that constantly runs in one direction and is most found in fuel cells, solar cells, and batteries.[94] Employing AC current in e-bus charging typically results in slower charging rates, necessitating onboard equipment for conversion to DC. Conversely, DC charging is known for its rapid charging speeds.[95]

The technology of the bus, whether AC or DC, will determine the technology of the charging infrastructure. The physical charging connections are heavily dependent on the manufacturer and can create a real challenge if not aligned, since interoperability is a key requirement. The table in Appendix 1 provides an overview of models, features, and regions of predominant use for the main plug-in charger models. To mitigate the standardization challenge, the Combined Charging System (CCS) was created based on universal standards for electric vehicles to ensure interoperability between vehicles and components from different manufacturers.[96] In Europe, a regulation was created mandating that all new public charging stations should be equipped with CCS connectors to ensure compatibility across different EV brands. This regulation supports the widespread adoption of CCS as the standard. Most of the public charging networks across Europe, such as Ionity and Fastned, are equipped with CCS connectors.[97]

Another possibility that has emerged to support the connection between different standards is the use of software protocols, such as the Open Charge Point Protocol. This is a standard communication protocol that facilitates the exchange of information between electric vehicle charging stations and charging management systems, allowing different chargers to operate seamlessly between different standards. Cities should require interoperable charging plugs and standards when purchasing buses, batteries and charging equipment so they avoid locking themselves into using a single manufacturer.

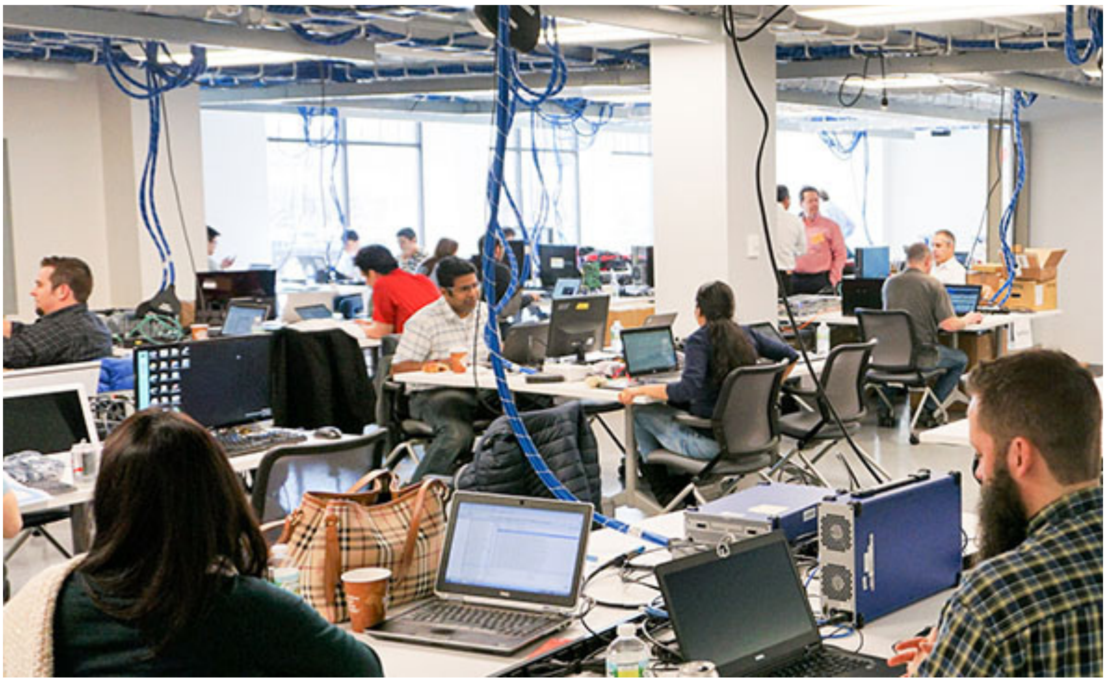


Image from a Plugfest organized by the Open the InterOperability LAboratory from the University of New Hampshire where developers test their Charging Station Management Systems with other implementations. **Source:** University of New Hampshire

93 Anker. (2023). AC vs DC Power: The Ultimate Guide to Electrical Currents. https://www.anker.com/blogs/ac-power/ac-vs-dc-power-the-ultimate-guide-to-electrical-currents
94 Anker. (2023).
95 World Bank. (2020). Latin America Clean Bus in LAC: Lessons from Chile's Experience with E-Mobility. https://openknowledge.worldbank.org/handle/10986/34435?show=full
96 ITDP Brasil and Logit. (2022b). Technical Reference Manual for Electromobility in Brazilian Cities. https://www.gov.br/cidades/pt-br/central-de-conteudos/publicacoes/mobilidade-urbana/arquivos/caderno-tecnico-de-referencia-para-eletromobilidade-nas-cidades-brasileiras-2013-volume-i-ingles.pdf
97 European Union. (2014). Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels infrastructure. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32014L0094

Even with advances in standardization on the horizon, it is recommended that cities seek continuous training to deal with new technologies and to prioritize battery and charging technology that uses universal standards. This can be done by considering standardization as a requirement in tenders or using it as a criterion to evaluate them. This reduces the dependence on certain manufacturers and suppliers, while investing in continuous capacity building and personnel training can help them operate equipment of different sizes and specificities.

3.5. POTENTIAL ENERGY NETWORK IMPACT

For the implementation of pilot projects and large-scale transitions, it is necessary to evaluate the energy sources that feed the process, the necessary electrical infrastructure, and the capacity of the local electricity grid. This can be an environmental conundrum in many countries because of their dependence on fossil fuels for power generation, but it can also have a substantial impact on the local power grid. Therefore, it is crucial to assess the grid's ability to handle this new demand while continuing to supply energy to other users.

The opportunity charging strategy method could be considered the most likely method to overwhelm the grid, as the minimum power required from each charger is significantly higher compared to depot charging to deliver the necessary energy in a short period. Therefore, it's essential to assess whether the local electrical grid can supply this power without causing instability for other users.

On the other hand, because opportunity charging can usually be spread out across bus stops or terminals and the vehicles aren't all charged simultaneously (as may occur with depot charging), the overall power demand tends to be lower. To that end, using lower-power charging over longer periods of time, such as the depot charging strategy method, is a way to reduce impact on the grid and lower costs at the same time. The same applies to the distribution of any charging infrastructure to more than one location.

Other strategies are being applied by many cities around the world to reduce charging costs, especially in the case of systems that have restricted access to the electricity grid. Charging vehicles during off-peak hours and making agreements with electric power companies to access differentiated rates can help.

When planning infrastructure, it is also crucial to consider how to maintain a reliable power source and implement resiliency measures in case of grid disruptions. In urban areas with more advanced energy infrastructure, the impact of higher levels of distribution and transmission may be less significant. The dependability of the power grid becomes even more vital when the entire transit system relies on electricity for operation. Gradual implementation of e-bus fleets could accompany incremental changes to the power grid, allowing necessary adjustments to the grid to be made over time.

HOW TO AVOID ENERGY SHORTAGE IN E-BUS DEPLOYMENT DURING AN EXTREME CLIMATIC EVENT

E-bus fleets are heavily reliant on a stable electricity supply, and any disruption can significantly impact public transportation services. To continue supporting the public during crises or natural disasters, operators need to have a robust backup electric system in place. To mitigate these risks, operators should consider additional optimization strategies for energy storage. One approach is to implement decentralized storage systems, which involve storing energy outside the main electric grid. This can include separate, smaller solar-powered grids or backup generators, ensuring that e-buses can remain operational even if the central grid fails. For example, during natural disasters like typhoons or earthquakes, having decentralized energy sources can be crucial for maintaining transit services.

Constructing depots as smart buildings equipped with their own means of capturing and storing electricity, such as solar panels, is another effective strategy. These depots can generate and store energy independently, providing a reliable power source during emergencies. In China, several cities have adopted this approach, integrating solar panels and battery storage systems into their e-bus depots.[98] This not only enhances resilience but also reduces the overall demand on the main grid.

Maintaining a digitalized energy management system is also essential for optimizing energy use and ensuring reliability during crises. Such systems can provide real-time data on energy demand, pricing, and weather conditions, enabling operators to make informed decisions about when to charge their e-buses. This approach can help avoid peak demand times and reduce costs, while also ensuring that buses are charged and ready for service when needed most. For example, in Shanghai, an advanced energy management system has been implemented to optimize the charging schedules of its e-bus fleet, considering factors like electricity prices and weather forecasts.[99]

Regular drills and simulations of potential crisis scenarios can also prepare operators and ensure that backup systems function as intended. They can also test the resilience of their e-bus infrastructure. These proactive measures, combined with strategic investments in technology and infrastructure, can significantly enhance the reliability and safety of e-bus services in the face of natural disasters and other crises. By learning from these examples and continuously improving their systems, cities can ensure that their public transportation remains resilient and dependable under all circumstances.

Additionally, addressing potential fire risks is critical for the safe deployment of e-buses. Lithium-ion batteries, commonly used in e-buses, can pose fire hazards if damaged or improperly managed. To mitigate these risks, it is crucial to implement stringent safety protocols and regular maintenance checks. Installing advanced fire detection and suppression systems in e-bus depots and on the buses themselves can help prevent and manage fire incidents. For instance, e-bus depots can be equipped with state-of-the-art fire-suppression systems specifically designed for battery-related fires. Moreover, training personnel in fire safety and emergency response procedures is essential to ensure quick and effective action in a fire. By adopting these safety measures, cities can minimize the risks associated with battery fires and enhance the overall safety of their e-bus fleets.

An electric bus continues its route despite flooded streets in Gdansk, Poland. **Source:** Michal Bednarek via Shutterstock.

98 Times of India. (2020). Kolkata: Solar panels on depot roofs to charge e-buses. https://timesofindia.indiatimes.com/city/kolkata/solar-panels-on-depotroofs-to-charge-e-buses/articleshow/74016804.cms

99 Qiang, L., et al. (2008). Advanced EMS and its trial operation in Shanghai power system. https://link.springer.com/article/10.1007/s11431-008-0010-3

As a strategy to both improve resilience of the system and increase environmental benefits, planners should explore incorporating renewable energy sources into the transit system infrastructure. By utilizing sustainable energy options, transit agencies can decrease the risk of power outages and improve system reliability. Having local renewable electricity sources can also guard against potential shocks as a result of sudden peaks in energy prices because of external factors. Approaches that can be employed for resilience include:

- **On-site solar panels:** Installing solar panels at bus depots or along transit routes can provide a source of clean energy and reduce reliance on the grid;
- **Energy storage systems:** Utilizing battery storage or other energy storage technologies can help maintain power supply during outages and peak demand times;
- **Wind turbines:** Using this approach can reduce dependency on the main grid and provide a consistent energy supply, especially in areas with strong, steady winds. Wind energy can also supplement other renewable sources, such as solar power, to create a diversified and robust energy system;
- **Microgrids:** Creating localized energy grids can offer greater control over energy distribution and enhance resilience by isolating parts of the system from the main grid during disruptions;
- **Smart grid technologies:** Implementing advanced grid management tools can help optimize energy use, balance loads, and improve overall efficiency;
- **Hybrid charging solutions:** Combining various charging methods such as on-site solar and grid-powered charging can provide flexibility and increase system resiliency.

By integrating these tactics, transit agencies can create a more resilient and sustainable e-bus system.

Salvador, Brazil.
Source: Diogo Pires Ferreira

4

DECISION-MAKING PROCESS

Decarbonizing bus fleets through the adoption of e-buses is a pivotal step toward sustainable urban mobility. However, this transition involves more than merely replacing traditional vehicles with electric ones. Cities worldwide are discovering that successful e-bus implementation requires comprehensive planning that encompasses charging infrastructure, route optimization, and stakeholder engagement. In short, implementing e-buses entails planning a new service for the public transport system. A holistic approach is essential, taking into account battery management, charging strategies, and their impact on both the urban environment and electrical grids. Thoughtful planning not only ensures a smoother transition but also helps avoid costly delays, ensuring the efficient and sustainable deployment of e-buses.

This section provides a structured guide for decision-makers to develop effective e-bus charging strategies. By following the five steps below, decision-makers will be equipped with the knowledge and tools necessary to make informed, strategic decisions that support the successful decarbonization of their bus fleets.

OPPOSITE PAGE
Electric bus from the SunuBRT system in Dakar, Senegal.
Source: Pierre Laborde via Shutterstock


SUNUBRT
180
AA·345·QY
ANGLES MORTS

Five Essential Steps
for E-Bus Deployment Planning

Step 1 — Map the political context and key stakeholders

1. Map policy goals
2. Map key stakeholders
   - Identify relevant policies and institutions
   - Assess institutional responsibility

Step 2 — Understand route charging needs and prioritize routes

1. Establish goals for decarbonization
2. Conduct preliminary analysis to identify the most interesting routes to prioritize
   - Well-connected routes
   - Routes that cross congested areas
   - Routes with bus lane priority
   - Routes within battery range
   - Routes that operators would like most
   - Flatter routes
   - Routes with consistent ridership
   - Routes along high-density areas
   - Number of vehicles per route
3. Conduct data analysis and pilot testing to prioritize routes
4. Estimate energy consumption for the prioritized routes
5. Identify the charging needs for each route

Step 3 — Assess battery and charging market

1. Identify options that meet charging needs
   - Evaluate battery and charger pros and cons
   - Select the battery and charger specifications
   - Assess grid capacity and compatibility
   - Ensure scalability
   - Check for potential environmental impact
2. Evaluate local availability and costs for the selected options
   - Consider regional production capabilities
   - Document the process of information collection
   - Assess potential life cycle costs

Step 4 — Evaluate charging scenarios and select the best strategy for the case at hand

1. Identify most appropriate charging locations considering
   - Terrain availability, space, and ownership
   - Zoning and regulatory constraints
   - Grid power and proximity to the electrical infrastructure
   - Proximity to the prioritized routes
   - Available area for infrastructure placement
   - Possibility of closing off the areas
2. Conduct grid assessments at selected sites
   - Analyze the existing distribution capacity
   - Check the need for potential upgrades or expansion
   - Ensure energy supply stability
   - Identify renewable energy integration opportunities
   - Engage with the local power company
   - Evaluate costs of grid connection and upgrades
3. Analyze and compare charging strategies
   - Assess pros and cons using comparison indicators
   - Evaluate the best use case
   - Check the potential scalability of the charging strategy
   - Define the best charging strategy

Step 5 — Implement and monitor

1. Elaborate service planning and time schedule
2. Develop design for infrastructure development
3. Identify and monitor data indicators
4. Implement technical training
5. Develop external communication strategy
6. Plan for battery reuse or recycling

4.1. MAP POLITICAL FRAMEWORK AND KEY STAKEHOLDERS

Implementing and operating an e-bus system requires the strategic involvement of multiple actors. For that, there are two fundamental aspects to be considered: (1) the mapping of policy goals and the different levels of involvement for each stakeholder identified; (2) the mapping of potential stakeholders who should be involved in the process of implementing and operating the infrastructure needed, at the technical and political level.

To engage each stakeholder politically and ensure their higher involvement, it is key to identify decarbonization incentive mechanisms within the political framework at the national, regional, and local levels. This process helps understand the potential responsibilities or duties of each stakeholder. Plans, laws, decrees, policies, tax incentives, goals, and guidelines are a few examples of that. When mapping these incentives, it is important to consider all the potential sectors that can be impacted by or benefit from electrification, such as the economy, health, and environment.

The regulatory framework of the transit and energy sector assessment is also critical. Understanding and evaluating the existing contracts is key to laying the ground for incentivizing fleet decarbonization, since they can determine technical and operational questions about how the fleet will be made available and how the service will be provided. In this sense, reviewing the conditions of compensation and the penalties if the obligations are not fulfilled may speed up the shift to e-buses. Some transition incentives include fines for fleet renewal that do not meet environmental quality standards and the adoption of compensation criteria for operators that meet quantifiable environmental targets.

Stakeholders' involvement can differ depending on the local context, but it will usually include:

- **Government:** Provide regulatory oversight, set policies, allocate resources necessary for the deployment and operation of e-bus infrastructure, and for the decision-making and implementation related to transport and the energy sectors;

- **Transit operators:** Responsible for the day-to-day management of the e-bus system, including scheduling, maintenance, and ensuring efficient operations. Their practical experience and insights are invaluable for identifying operational challenges and opportunities for improvement. Transit operators also need to ensure that the e-buses are effectively integrated into the existing public transport network and provide reliable and efficient service to passengers. Their involvement also includes training drivers and maintenance staff on the specific requirements of e-buses, which is crucial for optimizing vehicle performance and safety;

- **Manufacturers:** Play a vital role in supplying the necessary e-buses, batteries, charging infrastructure, and technological solutions required for the system's functioning, contributing to its reliability, performance, and sustainability. Manufacturers bring expertise in the design, production, and maintenance of e-buses, ensuring that the vehicles meet the specific needs and standards of the city. They play a pivotal role in providing technical support and training for local operators, helping to maximize the efficiency and lifespan of the e-bus fleet;

- **Electricity suppliers and concessionaires responsible for its distribution and/or commercialization:** Analyze the need to extend the grid (if necessary), ensure stable charging that does not overuse the grid, and identify ways to reduce charging costs. This articulation should be established as early as possible, since it can predict potential impacts and costs. New business arrangements can be negotiated to enable a more efficient and economical e-bus operation, such as the free energy market. It is a business environment where participants can freely agree on all commercial conditions, such as supplier, price, amount of energy contracted, supply period, and payment method. In this environment, for example, the price for the electricity needed to charge the batteries can be negotiated directly with the concessionaires and in a personalized way, according to service demands, which mitigates the risk of rate variations;

- **Financing institutions:** Financial stakeholders, banks, and potential investors can expand the source of resources to be incorporated into the project at this stage. These institutions provide the necessary instruments to enable cities to undertake the significant capital investments required and can help to mitigate the high upfront costs of purchasing e-buses and installing charging stations;

- **International organizations:** Bring a wealth of expertise, resources, and global best practices; facilitate knowledge sharing and capacity building, helping local stakeholders to stay informed about the latest technological advancements and innovative solutions. By leveraging the experience and support of these international bodies, cities can develop more robust and sustainable e-bus systems that align with global standards and contribute to broader environmental and climate goals;

- **Civil society organizations:** Expand the articulation between cities and civil society to promote the exchange of knowledge and professional training—it is an opportunity for different segments of society to participate in the transition. They play a crucial role in advocating for sustainable and equitable transport solutions, ensuring that the voices and needs of diverse community groups are heard. They can mobilize public support, raise awareness about the benefits of e-buses, foster community engagement, and provide valuable feedback on the social impacts of the system;

- **Other cities' officials and technicians:** Exchange experiences with e-bus pilots to help optimize resources and explore paths to full fleet scale-up. These stakeholders bring practical insights, technical challenges, and lessons learned from their own experiences with e-bus implementation. This cooperation can lead to the development of standardized solutions and innovative approaches tailored to different urban contexts.

During collaboration with key stakeholders, it is important to identify and assign the main responsibilities, competencies, time frames, and periods of involvement to the project. To this end, cities must ensure that they have qualified human capital with the expertise, knowledge, and skills necessary to conduct the activities. While the entry of new stakeholders can increase the level of complexity in decision-making processes related to the management, operation, and maintenance of the fleet, it also allows cities to dilute the responsibilities and potential expenses. Each stakeholder can be engaged at different phases and/or areas of the project, and their involvement can be limited to a period of time or to the long term.

ACCELERATING E-BUS ADOPTION WITH INDIA'S HOLISTIC APPROACH FOR FINANCIAL SUPPORT

A holistic approach that includes both vehicle procurement and infrastructure development is essential for the successful integration of e-buses into public transport systems. Government financial support and subsidies are crucial to initially offset the higher upfront costs associated with e-buses and their infrastructure. India's experience with supportive policies provides several key lessons. India's supportive initiatives were incentivized by the broader National Electric Mobility Mission Plan (NEMMP) of 2020, which set ambitious targets for electric vehicle sales by 2030 to curb vehicular emissions, including 40% of all bus sales.[100]

In 2015, the government of India introduced the Faster Adoption and Manufacturing of Electric Vehicles (FAME) scheme to provide subsidies to state transport corporations to support the procurement of e-buses and the development of supporting charging infrastructure. The initial phase, FAME I, aimed to boost consumer demand and industry development, though it did not include an incentive structure for fully electric buses until mid-2017. Despite the challenges, FAME I supported the purchase of 425 e-buses in 10 cities across India.[101]

The implementation of FAME II marked a shift in focus toward the electrification of public and shared transportation. Unlike its predecessor, FAME II provided incentives for e-bus procurement on a gross cost contract (GCC) basis, reducing the financial burden on transit agencies and facilitating the adoption of e-buses without substantial capital expenditure. Adopting flexible procurement models, such as the GCC model, can alleviate financial pressures on transit agencies, making it easier to transition to electric fleets. This phase also emphasized the importance of a supportive charging infrastructure, recognizing that a holistic approach to fleet electrification must include both vehicle and infrastructure investments. The success of these schemes underscored the necessity of government support in reducing upfront costs and fostering the adoption of e-buses. Over 5,595 e-buses have been sanctioned under FAME II, with more than 1,000 already operational.[102]

In addition to the FAME schemes, the Indian government launched the PM e-bus Sewa Scheme (Prime Minister Service E-bus Scheme), further reinforcing its commitment to e-bus deployment. This program allocates $2.4 billion to deploy and operate 10,000 e-buses across up to 169 cities through Public-Private Partnerships.[103] Crucially, this initiative also includes support for depot development and power infrastructure, addressing critical infrastructure needs alongside vehicle procurement. These efforts highlight the importance of comprehensive planning and financial support from the government, not only for the purchase of e-buses but also for the necessary infrastructure to ensure their effective and sustainable operation.

Electric buses at Cochin International Airport, India.
SOURCE: Sebastian Castelier via Shutterstock

100 Government of India. (2020). National Electric Mobility Mission Plan. Press Information Bureau. Ministry of Heavy Industries & Public Enterprises. https://pib.gov.in/newsite/printrelease.aspx?relid=116719#:~:text=Government%20of%20India%20launched%20the,on%20year%20from%202020%20onwards
101 ITDP India. (2022). Status of Electric Buses in India. https://www.itdp.in/wp-content/uploads/2022/10/Status-of-E-buses-in-India.pdf
102 ITDP India. (2022). Status of Electric Buses in India. https://www.itdp.in/wp-content/uploads/2022/10/Status-of-E-buses-in-India.pdf
103 Government of India. (2023). Guidelines for PM-eBus Sewa Part I. Ministry of Housing and Urban Affairs. https://mohua.gov.in/upload/uploadfiles/files/PM-eBus-Sewa-Guidelines-Part-I.pdf

Governance for implementing e-buses guides cities on how to delegate and assign responsibilities among the parties involved. On that note, after the initial mapping of the main stakeholders, cities can assess the institutional responsibility models for the implementation of the charging infrastructure. That helps define the decision-making processes and determine how capital should be invested. New business arrangements can be negotiated to enable more efficient operation. In general, there are a few models for charging infrastructure, in which different actors act as the instigator for bus electrification.

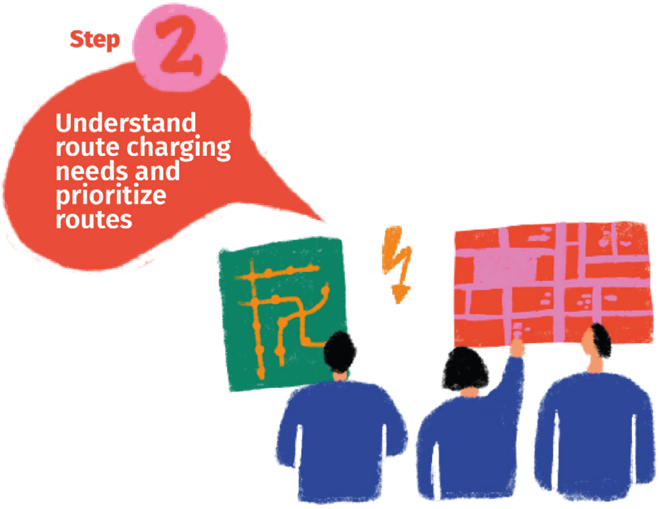
TABLE 3. Institutional responsibility models for charging infrastructure

Model	Advantages	Disadvantages
Government driven (i.e. public) The government is the main investor for charging infra-structure and is responsible for its construction and operation	▲Conducive to wellorganized and intensive development (assuming efficient government capacity and management) ▲May allow for overcoming barriers in beginning until costs lower due to scale ▲May relieve some stress on the financial model	▼Depending on government funding, is less sustainable over the long term (if the initial investment is from govern-ment, this model can enable scaling over time until the private sector can catch up and/ or costs reduce) ▼Low negotiating power of the public entity in infrastructure acquisition processes ▼Limited technical capacity and ad-ministrative structure for contracting of goods and services, preparation and monitoring
Enterprise driven (i.e., private) Enterprise (i.e., manufacturers and others) is the main investor for charging infrastructure and is responsible for its construction and operation	▲More financing available ▲Higher-quality operations and manage-ment ▲Private sector expertise and investment can accelerate deployment ▲Encourages innovation and efficiency as a result of competitive market forces	▼May not prioritize public interest or long-term sustainability ▼Risk of monopolistic practices if not properly regulated
Mixed model Enterprise plays an important role under government supervision and support	▲Combines public oversight with private sector efficiency and investment ▲Balances risk and funding between pub-lic and private sectors ▲High efficiency for operations ▲Avoids unsustainable development and/ or operations that are in conflict with government's interest for the public	▼Requires strong coordination and collaboration between government and private entities ▼Potential for conflicting interests and priorities ▼Complex governance structures may slow decision-making

Source: Updated from ITDP (2021) based on inputs from ITDP's regional offices

Each of these models offers distinct advantages and unique challenges. After evaluating each model, select the one that meets the specific context, including the local regulatory environment, market maturity, and available resources.

4.2. SELECT ROUTES AND UNDERSTAND ROUTE CHARGING NEEDS



When selecting routes, it is important to understand the city's goals and local context as well as the city's characteristics and the current fleets' performance. It is key to establish the city's main objectives for the implementation of e-buses and the justifications behind them.

Traditionally, routes are developed based on a few factors: trip origin and destination need of the public, ridership, urban expansion, and future demand. There are various strategies for e-bus route selection. Given the complexity in planning the energy transition and the volume of investment required, these are some key criteria to prioritize when selecting routes for electrification:

- **Well-connected routes:** To enable vehicle sharing between services and concentrated deployment of charging infrastructure;
- **Routes that cross congested areas of the city:** To generate the greatest short-term decarbonization benefits on busy roads; information such as vehicle speed profiles should be considered;
- **Routes that already have public transport priority lanes planned to be implemented:** As long-term circulation in priority lanes enhances energy consumption efficiency and operational dynamics of services;
- **Routes within the range of the battery:** Ensuring that all buses have sufficient charge to complete route services and return to charging stations. With the more limited battery performance of e-buses compared to diesel buses, operators may need to adjust system routes or fleets because of battery performance;
- **Routes with greater interest and openness from operators:** As operator engagement is crucial to ensuring realistic regulatory arrangements among various stakeholders;
- **Flatter routes:** Considering the impact of topographic conditions on vehicle performance;
- **Routes with consistent and predictable ridership** to make the most efficient use of the battery and to ensure that the benefits of e-buses are enjoyed by a maximum number of commuters;
- **Routes along high-density areas, higher number of potential vulnerable beneficiaries, major employment hubs**, and routes connected to other transit modes;
- **Number of vehicles per route:** To ensure a greater benefit in terms of electrifiable fleet, while always considering the most feasible number within the city's defined objective.

To start, the area in a city to be chosen for e-bus deployment should consider a balance between the optimal place to implement it in terms of visibility for the initiative—usually in the central areas—and the places that will have the greatest impact for the most vulnerable and marginalized beneficiaries,[104] such as low-income individuals who typically live in the outskirts of a city. Whatever the choice, it's important to select routes that benefit a city's population equitably. In this sense, prioritizing the electrification of the most demanded routes by this public can be an alternative and can provide an equivalent benefit to investing in expanding access to opportunities with relevant social and economic returns.

The routes should then be analyzed considering a fleet's characteristics and performance. The technical information—such as distances traveled per route, topography, and the city's geospatial socioeconomic characteristics—needs to be evaluated to measure the social impact that the introduction of an electric fleet can provide. It is also important to collect data and information for the fleet specification for each route as well: bus size, technology, and age.

When analyzing routes, it is suggested that planners consider the most realistic scenarios, using operating conditions of a typical day and the most rigorous operation performance in terms of passenger load, use of auxiliary systems (such as air-conditioning), weather conditions, and maximum slopes. Since it is not possible to predict all the operating conditions buses might encounter, pilot projects are a good way to assess the feasibility of introducing an e-buses, identifying challenges early on, minimizing risks and adjusting operational strategies. From this, an understanding of the routine behavior of e-buses on test routes or pilots can inform the next steps in planning and scaling up a project.

TESTING PILOTS IS A WAY TO PREPARE FOR THE TRANSITION

Pilot planning should be integrated with the charging infrastructures placement and guided by equality and inclusion criteria. Ensuring accessibility for low-income people, especially women, since the beginning of the pilot planning is crucial to balancing the distribution of benefits with a focus on who most depends on public transport. Another criterion is the prioritization of more polluting routes. Prioritizing the most critical routes based on these criteria is a strategy to maximize the benefits of the transition until the service is scalable.

The second phase is to plan the performance evaluation of drivers and technicians to deal with vehicles and infrastructure properly. In this sense, the initial phase should not predict the presence of passengers and must occur under the supervision of trained personnel. Forming partnerships with manufacturers is an alternative for training and basic assistance during the pilot and the first year of operation of the vehicles. In addition, this phase should provide for charging experimentation with vehicles, paying close attention to real-time charging of the battery corresponding to the availability and capacity of electricity and the location of garages and terminals.

The third phase should monitor vehicle behavior when driving on an experimental route. This behavior depends on topographic or road conditions, specific temperature conditions, and other weather events. When contemplating the passengers' transportation, it is also possible to assess the brake and the gear of the engines in the pickup and drop-off stops and to check to what extent the battery autonomy is preserved (or not) throughout the service. Although pilot projects have a specific operational role, they allow managers to identify necessary actions at tactical planning levels. The tactical level is responsible for any corrections necessary for failures verified during the operational test. From the performance results, identify the stakeholders needed for e-bus operation, define responsibilities, and plan management for a permanent fleet.

104 Groups that depend most on public transport: low-income population, black people, women, people with disabilities, the elderly, and children.

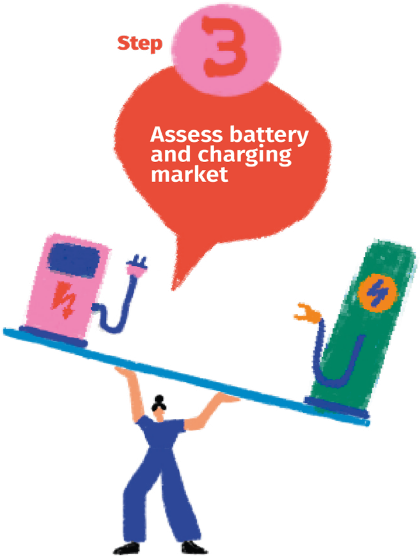
Finally, one last aspect is to ensure the population's involvement, especially in planning routes. Quality public transport needs to focus on user satisfaction. This factor is crucial to retain and attract people, especially those who use other modes of transport that need to be discouraged, such as cars. Although electric fleets require an optimized route to meet their operational needs, cities must reconcile that with users' technical demands and demands.

Route viability is dependent of population's needs for transportation. **Source:** NG-SPACETIME via Shutterstock

These pieces of information will help cities define criteria for prioritizing routes that would benefit most from electrification. After the evaluation of viability and the identification of the best places to implement the charging infrastructure, select the priority routes for bus electrification.

After gathering all the data to be analyzed, it is important to estimate the energy consumption efficiency, which measures the amount of energy used per kilometer traveled, as well as the estimated autonomy for a vehicle operating on the route. The latter is determined by the energy consumption required to operate the service during a typical workday, considering the vehicle's battery capacity. For energy consumption, it is important to take into account battery degradation and operational impacts on its range, as mentioned in Section 2.2. The energy consumption will be key to understanding the charging characteristics and needs for each route prioritized and will support the charger infrastructure assessment.

4.3. ASSESS BATTERY AND CHARGING MARKET



Understanding the availability and technical specifications of the different batteries and chargers is important for mapping the possibilities and the potential impacts of each choice. Each model will have, as mentioned previously, different requirements and operational standards, such as range and efficiency. The information gathered about the power needed to charge the prioritized routes' fleets and its characteristics will be key in evaluating the potential energy cost for each of the prioritized routes. At the same time, it will also support the assessment of the batteries and chargers that match the charging characteristics needs. The main characteristics of the batteries are available in Section 2.1, Table 1. The characteristics of each charger option are available in Section 3.1, Table 2, and their main pros and cons can be seen in Table 4 below. This information will be key for the assessment and determining the possibilities that are viable for the prioritized routes selected.

TABLE 4. CHARGERS PROS AND CONS

	Traditional Plug-In	Pantograph	Flash	In-Motion	Wireless
Pros	▲Lower infrastructure and electricity costs, therefore lower initial investment ▲Flexible layout ▲Fewer requirements for the power grid ▲Slow charging has least impact on battery life	▲Enables longer operation ▲Short charging time ▲Less area required	▲ Enables longer operation ▲Short charging time ▲Less area required	▲ Enables longer operation ▲Lower electricity costs ▲More constant flow of electricity/ less strain on grid	▲Enables longer operation ▲Seamless charging ▲Flexible layout
Cons	▼Longer time charging ▼Lower charging efficiency ▼Scattered infrastructure layout ▼Fast charging can reduce battery life and require more capacity from the power grid ▼More area required for infrastructure	▼More expensive infrastructure and electricity costs ▼Fast charging can reduce battery life and require more capacity from the power grid	▼High infrastructure costs ▼Demand of high power in a short amount of time can put strain on the grid ▼Less data available for this mode	▼High infrastructure costs ▼Must maintain overhead lines	▼Requires significant construction, both in terms of area used (all of the route designated for charging) and timing (longest installation timeline) ▼Less data available for this mode

SOURCE: Developed by the authors

The selection of battery size for e-buses should be informed by several factors, primarily the daily distance covered by the buses and the availability of charging infrastructure. Accurately estimating the required battery size is crucial for ensuring efficient and uninterrupted operation.

Estimating energy consumption is critical to determining the optimal battery size. A simple calculation can be made: Assuming only depot charging, the daily distance traveled by the bus (km) should be multiplied by the energy efficiency of the bus (kWh/km). The energy efficiency will vary depending on the size of the bus (e.g. 0.8 kWh/km for a 9m bus and 1.2 kWh/km for a 12m bus).[105] In addition, a 20% state of charge (SoC) buffer should be considered to maintain battery health and provide a more realistic and sustainable estimate of operational requirements. If opportunity charging is also considered, the battery capacity and size can be further reduced, which would also reduce the overall cost of the bus.

After assessing the most viable options for the batteries and chargers, a market study is recommended to assess whether the local supply meets the city's demand and goals. Although this analysis can be carried out via official websites, technical datasheets, and publications, it is suggested that this analysis be done by direct contact with manufacturers through official channels so it can be used later in a bidding process if necessary. Table 5 shows the main specifications and characteristics suggested for those analyses.

Table 5. Battery and charger especifications

Scope	Specifications to Consider in the Market Assessment
Battery 	• Minimum range with a full charge (km) • Minimum battery capacity (kWh) • Maximum efficiency loss over the life cycle • Battery management and monitoring system • Cost per unit • Warranty time frame • Detailed description of warranties and services included in the cost • Deadline and maximum delivery time for the battery
Charger 	• System type (plug-in, pantograph, etc.) and connector type (GBT, CCS2, etc.) • Maximum time for a full charge; • Charging power (kW) • Voltage (V) • Charging current (A) • Number of connectors • Charger dimensions • Charging management system • Cost per unit • Warranty time frame • Detailed description of warranties and services included in the cost • Deadline and maximum delivery time for the chargers

Source: Developed by the authors

4.4. SELECT THE CHARGING STRATEGY FOR THE PRIORITIZED ROUTES

After analyzing the charging infrastructure and battery options available in the market using the information gathered in the steps above, it is imperative to select what charging strategy will be used based on the different potential scenarios of charging strategy implementation. For each of the three charging strategies presented in Section 3.2, it is important to evaluate different scenarios considering the following steps:

105 UITP. (2022). Electric Bus Performance evaluation. Lessons from Six Indian Cities. Available at: https://cms.uitp.org/wp/wp-content/uploads/2022/11/Action-Points-Electric-Bus-Performance-Evaluation-OK.pdf

4.4.1. Potential Charging Infrastructure Placement

The first point is to make a preliminary list of potential areas where the infrastructure could be implemented considering the routes selected previously. With a list at hand, it is possible to prioritize the locations for infrastructure implementation taking into consideration:

- **Terrain availability, space, and ownership:** E-buses do require additional infrastructure for charging, which can become a problem because land use restrictions in urban areas might block the placement of new depots or the current depot's owner might object to the reduced amount of space that would then be available for typical bus operations. While this challenge can be addressed through meticulous space planning and the selection of infrastructure with minimal spatial footprint, it may still necessitate a reduction in fleet size in extremely space-constrained depots;

- **Environmental license:** The installation of charging infrastructure may require environmental licensing because of government regulations, depending on the country—this would assess and mitigate potential environmental impacts.;

- **Grid power and proximity to the electrical infrastructure:** Conduct an evaluation of current infrastructure at depot and terminal locations. Some setups may only need slight upgrades, others may require subtransmission lines and substations. Selecting a location physically close to existing substations can help reduce the cost of new infrastructure;

- **Proximity to the prioritized routes** for decarbonizing the system to minimize idle kilometers as much as possible and to ensure operation throughout the day;

- **Available area for infrastructure placement:** Making room for e-buses at existing depots is a concern because of limited space for parking and maneuvering, development of grid infrastructure, and setting up battery charging/swapping stations;

- **The possibility of closing off the areas** to ensure their security and enable greater surveillance of the equipment.

The relative positioning of the areas should be evaluated based on the prioritized routes to receive electric fleets, estimating the average travel time between each of the routes and each of the potential charger installations. This helps quantify any inherent inefficiencies in the system as a result of the need for out-of-service travel.

Specifics related to the charging infrastructure and charging placement layouts should be evaluated to make sure there is available space for the number of buses involved. For the charging types, there are different sizes depending on the choice, as seen in Section 3.1.

4.4.2. Evaluate the Grid Assessment for Each Charger Placement

After selecting the potential chargers' placement, it is imperative to assess the capacity of the grid by analyzing the local distribution network. The introduction of e-buses may result in a significant increase in energy demand in areas of the city where charging infrastructure is implemented, as seen in Section 3.5. The determination of electricity demand is one of the main factors to be considered, and it will depend on the charging strategy selected. This is because the bigger the volume of energy demand required in a short time, the greater the possibility of impact if the grid is not prepared.

The combined chargers' power requirement in a designated area will influence the adjustments and investments needed to make sure the energy supply can meet the demand of the fleet. This factor will directly impact the choice of charging method, and the number of chargers required. The overall network load of each designated charging area should be calculated based on safety standards, the number of chargers, maximum charging power per charger, and other elements, such as the charging strategy, fleet size, and route characteristics.

Therefore, it is crucial to assess the energy requirements of the specified routes in the project to ensure efficient implementation. Engagement with the local power company is recommended to support evaluations of the charging infrastructure implementation and the electrical grid, as it possesses specific knowledge to verify the information.

INVOLVING UTILITY COMPANIES IN E-BUS CHARGING PLANNING

Engaging utility companies in the planning of e-buses and charging infrastructure from the outset is crucial for the success of these projects. Establishing direct communication and fostering a partnership with electric companies can yield significant benefits for both public transportation and the utility sector. Early involvement allows planners to assess the existing electrical service at depots and other key locations, ensuring that the infrastructure can support the increased demand from e-buses. Utility companies can provide critical insights and resources to help estimate the adequacy of current electrical services and identify necessary upgrades.

This collaboration can lead to financing and infrastructure schemes that reduce financial burdens and potentially lower electric fare costs. Agreements on infrastructure implementation responsibilities and safety precautions are essential to prevent strains on the energy grid. Utility companies can offer expertise in designing charging solutions that are both cost-effective and efficient. Additionally, they can assist in implementing safety measures to ensure the reliability and stability of the power supply, which is vital for the continuous operation of e-buses.

Price fluctuations in electricity throughout the year can significantly impact on the total cost of operating an e-bus fleet. Utility companies can provide valuable insights into these variations and recommend feasible financing schemes tailored to the specific needs of the project locale. To maximize efficiency and cost-effectiveness, it is also essential to integrate e-bus charging strategies with broader demand-side management policies in the electricity sector. Aligning e-bus operations with grid capacity planning and demand response programs can help balance energy loads, prevent grid congestion, and optimize electricity distribution. By actively coordinating with utilities to incorporate dynamic pricing, peak load management, and renewable energy integration, cities can enhance the resilience and sustainability of their e-bus systems. By working closely with utility companies, planners can develop strategies that optimize energy use, manage costs effectively, and ensure that the necessary electrical infrastructure is in place to support the long-term sustainability and scalability of e-bus programs.

TABLE 6. Charging strategies pros, cons, and best-use case

	Depot Charging	Opportunity Charging	Combined/Mixed Charging
Pros	▲ Requires minimal changes to operational schedules, reducing disruptions ▲ Allows for consistent charging overnight, ensuring buses are fully charged and ready for service the next day ▲ Lower costs compared to opportunity charging due to reduced infrastructure needs ▲ Lower overall energy consumption compared to fast charging methods ▲ Potential for cost savings with off peak electricity demand rates and reduced strain on the grid due to overnight charging during off-peak hours ▲ Potential cost savings with lower power chargers ▲ Aligning charging schedules with peak traffic periods optimizes battery life and efficiency	▲ Extends the bus range significantly, allowing for continuous service without the need for buses to return to the depot for charging ▲ Reduces downtime and allows for modifications to bus routes, expanding service coverage and accommodating passenger demand ▲ Offers flexibility in charger placement, accommodating various road configurations, city-specific needs, and operational requirements ▲ Strategically placed charging stations along routes maximize the charging infrastructure's utility ▲ Charging stations can be placed along the route at strategic intervals to optimize bus range and service coverage ▲ Charging times range from seconds to minutes, depending on the power output, ensuring efficient battery replenishment during service	▲ Enables rapid charging at key points along routes or in transit hubs, minimizing downtime and extending vehicle range ▲ Enhances operational efficiency by reducing route deviations for charging and improving overall service reliability ▲ Enhances flexibility by integrating various charging technologies tailored to specific route requirements and operational needs ▲ Supports scalability and futureproofing of charging infrastructure to accommodate changes in fleet size and advances in technology ▲ Optimizes fleet resources and reduces route deviations for charging, leading to more efficient use of electricity and minimized grid strain ▲ Cost-effective electrification by leveraging existing electrical grid infrastructure and minimizing capital investments
Cons	▼ Limited bus range may require more buses compared to ICE vehicles. Intermittent charging might be necessary for longer routes ▼ Longer charging times may necessitate larger batteries, potentially increasing upfront costs and bus weight ▼ Land scarcity in urban areas can be a challenge. May require retrofitting existing depots or building new facilities ▼ Additional space requirements for charging infrastructure within depots may reduce operational space and require adjustments ▼ High initial costs for infrastructure setup, potential need for depot modernization, investment for chargers, cables, and transformers ▼ Charging times may be longer, potentially impacting bus availability during peak operational hours ▼ May require additional planning to optimize charging schedules and energy usage	▼ Requires intricate planning for charger placement and infrastructure development, leading to higher costs and potential land acquisition challenges. ▼ Higher power demand during peak hours may strain the electricity grid ▼ Chargers can have higher costs compared to other methods, requiring significant investment in charging equipment and potentially land acquisition ▼ Higher power demand during peak hours can strain the electricity grid, potentially leading to increased energy costs	▼ Increased operational complexity associated with managing multiple charging methods and schedules ▼ Logistical challenges in balancing rapid charging needs with practical bus schedules and availability of charging infrastructure ▼ Higher upfront costs compared to single charging approaches because of investments in diverse infrastructure and equipment ▼ Ongoing operational expenses associated with maintaining and managing multiple charging stations ▼ May have challenges in compatibility between different charging technologies and infrastructure ▼ Potential expenses related to training staff and upgrading existing infrastructure to ensure compatibility

Best use case	• This is most appropriate for routes where buses can operate most of the day on a single slow charge. That means, usually routes that are 180 km to 230 km long.[106] This most likely includes shorter routes on flat terrain. For routes longer than 200 km, either ensure intermittent charging at depots or consider other charging strategy • Routes with moderate distances and predictable schedules, allowing buses to charge overnight or during off-peak hours without disrupting service operations • Depots with sufficient space for charging infrastructure and minimal impact on operational areas, allowing for efficient overnight charging and minimal disruption to service operations • Routes with predictable service hours and moderate to low grid demand, allowing for overnight charging with minimal impact on energy consumption and costs	• This is most appropriate for longer routes (> 200 km) • Routes with high-frequency service, high passenger demand, longer operating hours, and/or overlapping routes where buses can charge when they may not have sufficient time for full depot charging between trips • Routes with dedicated bus bays, turnouts, or designated areas separate from traffic that allow charger placement • Urban areas with high grid capacity and sufficient electricity supply, allowing for rapid charging intervals and minimizing grid strain during peak hours	• The mixed charging strategy aims precisely to minimize the constraints and impact of each of the other strategies. This is most appropriate for longer routes (> 200 km) • Routes with high demand and frequent stops, where rapid charging at transit hubs or key points along the route can minimize downtime and ensure continuous service reliability • Transit systems with plans for future expansion and advancements in technology, where flexible and scalable infrastructure designs can accommodate evolving fleet needs and support interoperable charging standards • Urban areas with diverse charging needs and existing electrical grid infrastructure, where fast charging can maximize fleet efficiency and minimize capital investments in charging infrastructure

Source: Developed by the authors

4.4.3. Analyze the Charging Strategy Options Considerations and Best-Case Use

When deciding on a charging strategy, it is imperative for planners to analyze the economic, operational, and social factors involved. The charging strategy directly impacts the procurement of electricity, requiring alignment between the determined tariffs, operational planning, and fleet allocation. This alignment is crucial for ensuring service operation and reliability for users. The strategy to be used needs to consider the prior analyses of the local electrical grid and planning for the charger installation, which is crucial to increasing system efficiency, mitigating risks and costs, and optimizing the necessary infrastructure, as mentioned above in Section 3.5 and Section 4.4.

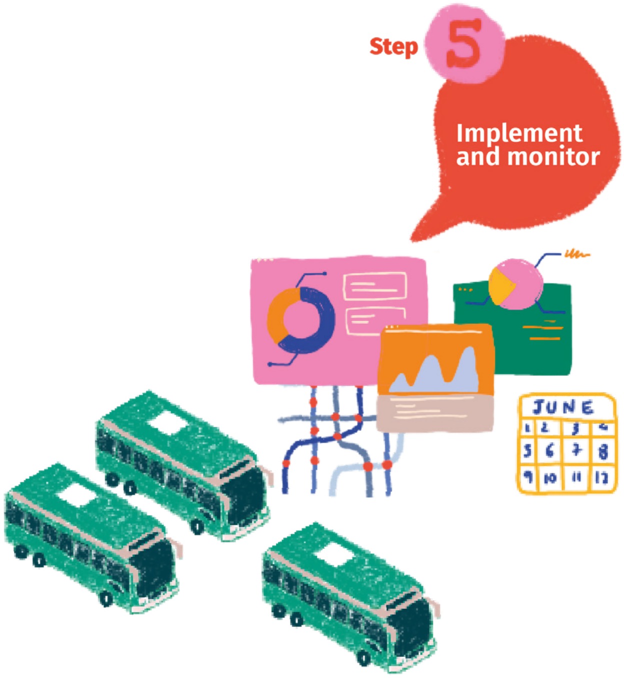
The main considerations and the best-use cases suggested for each of the charging strategies evaluated are summarized in Table 6.

The cost efficiency of e-buses is dependent on achieving as close as possible to a 1:1 replacement of fuel-based buses with e-buses, given the very high capital costs of buses and batteries and the lower operational costs. Adequate route planning can ensure that the system is financially viable for planning and funding stakeholders while remaining reliable for passengers. This is directly tied to an optimized charging strategy and efficient route operation.

To estimate the cost of electricity that these chargers would use and compare it with the fuel cost of the current fleet in the system, it is necessary to consider the different project decisions regarding the charging strategy, fleet operational planning, and installed power in the areas designated for charging. The time window during which energy will be required for charging will influence the electric tariff. Additionally, the operational cost structure of the system relates to the total installed power in the areas designated for charging, as this characteristic influences the voltage of the distribution network connected to the chargers. Therefore, it is important to note that the higher the installed power, the higher the electrical voltage required for energy consumption, which may eventually require investments and adaptations to the electrical network. It is emphasized, therefore, that the design of charging facilities should be conducted in conjunction with the energy distribution company.

After weighing all factors to determine the most effective approach for their specific context, planners must make the final decision about the charging strategy to be used.

4.5. IMPLEMENT AND MONITOR THE STRATEGY



Once the charging infrastructure and strategy plan are selected, the following next steps would be considered:

- **Elaborate service planning and time schedule:** Proper planning and scheduling are crucial to ensure that the e-bus system operates efficiently and meets the needs of the community. This step involves optimizing routes and aligning operational aspects to maximize system performance.
    - Optimizing routes to ensure buses have sufficient charge for services and return to depots or charging stations;
    - Planning route impacts on operational aspects like charging and service schedules, the number of buses required, and financial models;
    - Aligning charging schedules with peak traffic periods and locating stations close to route start and ends to optimize battery life and overall efficiency.

- **Develop the engineering design for charging areas:** This step ensures that all infrastructure meets the system's requirements and includes necessary adjustments and preparations.
    - Validate that on-site infrastructure meets system needs;
    - Anticipate infrastructure and garage requirements in contracts, including ownership responsibility for modernizing bus garages;
    - Ensure efficient water drainage systems to prevent water logging and safeguard charging equipment and bus electrical components.

- **Identify and monitor data indicators**: Collecting and analyzing data is vital for optimizing the e-bus system and making informed decisions. This step focuses on setting up a robust monitoring framework to track key performance indicators and operational metrics.
    - Collect and monitor data on route characteristics, vehicle and equipment performance, service planning adjustments, users and drives perspective, battery and chargers performance, costs, and others;
    - Monitor during pilot phases to optimize route schedules and operational costs, including drivers, construction, maintenance, and electricity;
    - Gather data on both electric and diesel bus technologies to enable a comparison evaluation between them and support optimization;
    - Use the quantitative and qualitative data collected to develop a comprehensive communication strategy.

- **Implement technical training:** Technical training is essential to ensure that all stakeholders, including planners, operators, drivers, and mechanics, are well-prepared to manage and operate the e-bus system efficiently. This step involves planning and conducting regular training sessions.
    - Plan regular and mandatory technical training for planners, operators, drivers, and mechanics;
    - Focus on the impact of charging strategy and driving behavior on vehicle efficiency and battery life;
    - Ensure managers and operators are trained to use, monitor, and oversee the system efficiently, managing new equipment and specific technologies;
    - Train drivers on extending battery life through proper driving methods, such as regenerative braking.

- **Developing external communication strategy:** An effective communication strategy is crucial for engaging stakeholders, raising awareness, and garnering support for the e-bus project. This step involves planning and executing communication efforts to highlight the benefits and progress of the project.
    - Use all the data and information collected to communicate the project to drive the decarbonization agenda, raise awareness, and mobilize specific target audiences;
    - Ensure greater local receptivity and demonstrate the city's commitment to improving public transportation quality, air quality, and reducing greenhouse gas emissions.

- **Planning for battery reuse or recycling:** Planning for the end-of-life phase of e-bus batteries is essential to minimize environmental and financial impacts. This step involves developing strategies for battery reuse or recycling to ensure sustainable practices.
    - Properly plan for battery reuse or recycling after the e-bus lifespan to minimize environmental and financial impacts.

- **Promoting a more equitable network:** Implementing e-buses offers a unique opportunity to rethink urban mobility, reduce stigmas associated with bus transport, and promote environmental justice and equity. This step focuses on integrating these considerations into the electrification project to maximize social benefits.
    - Prioritize electrification projects on the most demanded routes to benefit marginalized populations;
    - Engage in participatory planning to ensure that changes align with user needs and garner community support;
    - Promote a more equitable and integrated road space, addressing environmental justice and equity.

Successful e-bus deployment requires new thinking, commitment and a shared vision among stakeholders. By following these steps, planners can effectively implement charging strategies that contribute to the success and long-term sustainability of e-bus implementation. This holistic approach ensures that cities not only meet transportation needs, but also improve overall quality of life, supporting a future where public transport is a key driver of sustainable and equitable cities.

OPPOSITE PAGE
Passengers waiting for a public transport e-bus in the city of Salvador, Brazil.
SOURCE: Joa Souza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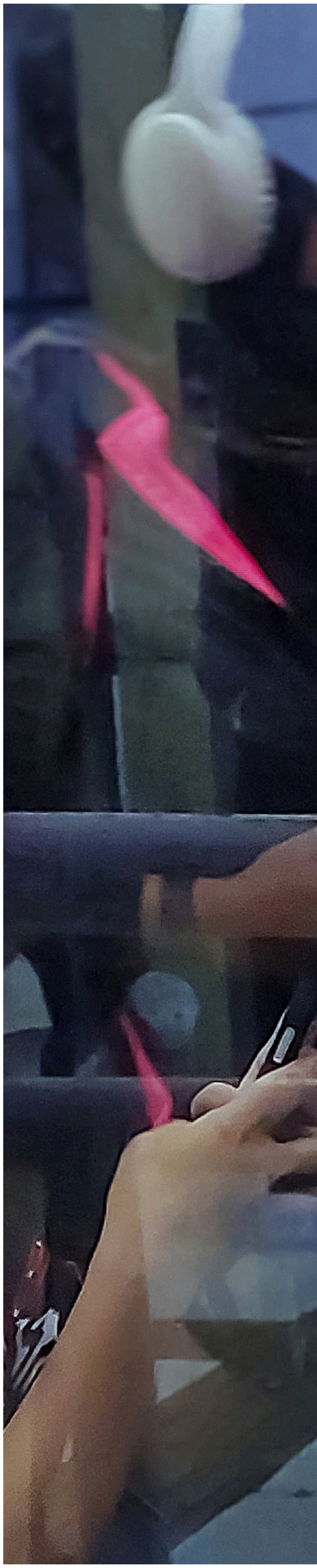

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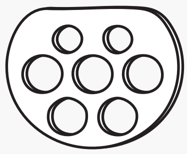
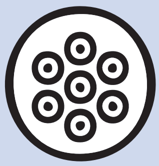
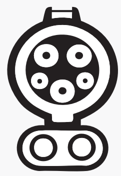
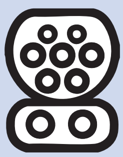
APPENDIX

Electric bus in Mexico City from the Metrobús BRT system. **Source:** Azul Carazo

TABLE 7. Plug-in Charger Models

Plug models		Charging speed	Countries and regions
Type 1 (J1772)		Slow-speed, alternating current (AC)	Japan, North America, and South Korea
Type 2 (Mennekes)		Slow-speed, alternating current (AC)	Europe, New Zealand, Latin America and Indonesia
CHAdeMO		Fast-speed, direct current (DC)	Japan, Europe, Indonesia, North America, and South Korea
Tesla supercharger		Fast-speed, direct current (DC)	Japan, North America, and South Korea
GB/T		Depend on the model, can be low-speed, alternating current (AC) or fast-speed, direct current (DC)	China
Combo CCS Type 1		Fast-speed, direct current (DC)	South America, Europe, South Africa, India, Indonesia, and Australia
Combo CCS Type 2		Fast-speed, direct current (DC)	South America, North America, South Korea, Taiwan and China

Source: BID and MDR, 2022; CFF, 2022; complemented by information from ITDP's regional offices.

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FEBRUARY 2025