Emergent Trolleybuses:
The Potential for Trolleybus Technology in Low- and Middle-Income Countries

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1 Introduction

As urban areas in low- and middle-income cities (LMIC) continue to grow at an unprecedented rate, the challenges associated with urban mobility become increasingly complex and pressing. The surge in urban population has not only strained the existing public transportation systems but has also exacerbated environmental concerns such as air pollution and carbon emissions. In this context, electrification of public transport emerges as a critical strategy for sustainable urban development. Two main electric bus technologies spearhead this transformation: battery electric buses (BEBs), which rely entirely on onboard batteries and trolleybuses, which draw power from overhead wires often supplemented with batteries.

As the electrification of public transportation systems gains global attention, the focus is predominantly on BEBs. While BEBs are a relatively novel technology, they received a lot of attention over the past decade, with China leading the market. In 2024, about 75,000 electric buses were added to the global fleet, with two-thirds being registered in China. On the other side, trolleybuses have been in use over the past 100 years, with the majority of systems being deployed in Eastern Europe.

Cities across Africa, Asia, and Latin America are investing in high-capacity public transport networks that will operate for decades, making it crucial that these systems adopt electric solutions. Electrifying urban transport not only reduces greenhouse gas emissions and air pollution, but also lowers energy costs and decreases reliance on imported petroleum by shifting toward locally generated electricity.

This report explores the opportunities and challenges associated with trolleybus systems in comparison to BEBs, particularly for use in low- and middle-income countries (LMICs). It investigates, whether investing in the infrastructure for trolleybus systems can provide a cost-effective alternative to BEBs which still face high upfront cost.

1.1 Historical Context and Technological Evolution

The concept of trolleybuses dates to the late 19th and early 20th centuries, with their initial adoption motivated by the need for quieter and cleaner alternatives to the steam-powered and horse-drawn trams of the era. Over time, trolleybus technology has evolved significantly, adapting to the changing demands of urban mobility and advancements in electrical engineering. Today's trolleybuses incorporate sophisticated technologies such as regenerative braking, automated control systems, and advanced battery storage solutions, allowing them to operate efficiently and reliably in diverse urban environments with the possibility to operate without connection to overhead catenary for extended distances.

Despite their many benefits, the deployment of trolleybus systems in LMIC has been at a slow pace facing several challenges. These include the initial cost of infrastructure development, the need for continuous maintenance of overhead electrical systems, and the integration with existing urban transport networks. However, recent innovations in trolleybus technology, particularly the development of battery-equipped models capable of off-wire operation, present new opportunities to overcome these barriers.

Last but not least, there seems to be a generally negative perception of trolleybuses, which often relates to experience with poorly maintained and under-invested legacy systems. Similarly, the existence of overhead catenary lines is often perceived to disturb the optical appearance of city centers. While this might be the case for some historical city centers, those considerations might be of lower priority when implementing high capacity bus trunk lines in rapidly growing metropoles of the global south. Modern trolleybuses can have multiple economic and environmental benefits over battery electric buses (BEBs), which is what this technical paper aims to explore.

1.2 Environmental and Socio-Economic Benefits

From an environmental perspective, both trolleybuses and BEBs offer clear advantages over conventional diesel buses, which remain the benchmark technology (e.g. Euro V). By running on electricity, they eliminate tailpipe emissions, reduce reliance on imported petroleum fuels, and create opportunities to shift toward renewable power generation, thereby improving energy security and reducing air pollutant and GHG emissions.

The revival and modernization of trolleybus systems can play a pivotal role in the sustainable transformation of urban transport in LMICs as trolleybuses provide solutions to some of the challenges associated with BEBs:

- Due to the large battery (250–500 kWh, depending on the size and range requirements of the bus) and associated battery costs of around US$130–150 per kWh, BEBs are expensive.
- BEB batteries will need to be changed at least once during the bus lifetime.
- Many bus systems in LMICs are in hot and humid climate regions and air conditioning greatly improves service quality. However, air conditioning systems significantly reduce BEB range or increase the BEB price since larger batteries are needed.
- Many LMICs have a large solar energy potential. Since in LMICs BEB charging will mostly take place at night, integrating solar energy requires additional energy storage capacity.
- Charging BEBs also requires upgrading power supplies at depots for overnight charging or for super- fast charging along bus routes.
- Trolleybuses can be much more energy efficient, as there is no need to carry large batteries, which often makes the difference between an empty bus and a fully charged one.

From an economic standpoint, the comparison between trolleybuses and BEBs is critical. While trolleybus systems require significant upfront investment in infrastructure, they often achieve lower operating and maintenance costs, along with longer vehicle lifespans, resulting in competitive life-cycle costs. BEBs, on the other hand, may reduce the need for fixed infrastructure but carry higher costs linked to battery production and replacement. Assessing these trade-offs through a cost-benefit analysis is essential to guide cities in selecting the most suitable technology for their long-term public transport needs. In both cases, transitioning away from diesel buses can also generate co-benefits by stimulating local economies, creating jobs, and attracting investment in sustainable urban development. By leveraging technological innovations and addressing socio-economic factors, stakeholders can improve the viability and attractiveness of trolleybuses as a cornerstone of green urban mobility.

2 Overview of Trolleybus Development in Different Regions

Trolleybuses, iconic for drawing electrical power from Overhead Contact Systems (OCS) as they navigate city streets, represent a significant and sustainable mode of urban transportation. Globally, since the beginning of the 20th century trolleybuses have been a significant element of city public transport networks. They continue to be relevant, especially in cities that already have the necessary trolleybus infrastructure. With the advent of BEBs, many cities find themselves evaluating between the use of pure battery electric buses and a new generation of trolleybuses. This is particularly true for many cities in LMICs which are planning for the introduction of bus rapid transit (BRT) systems. BRT systems are usually used for high-capacity trunk-line services with large 12m, 18m or even longer buses operating in short time intervals on routes, which are often completely disconnected from the rest of the road traffic. Such BRT systems, which often span limited distances and networks are ideal for the deployment of large trolleybuses.

2.1 Development of Trolleybuses in Different Regions

Trolleybuses have existed in over 70 countries worldwide' and they continue to represent a significant mode of transit. In this analysis, the focus is on trolleybus systems in 23 LMICs identified in Eastern Europe, Central & Western Asia and Latin America. The maximum number of trolleybus systems recorded was in these 23 countries was 260, reaching its peak in 1997. As of 2023, there are 183 operational in 47 city networks.

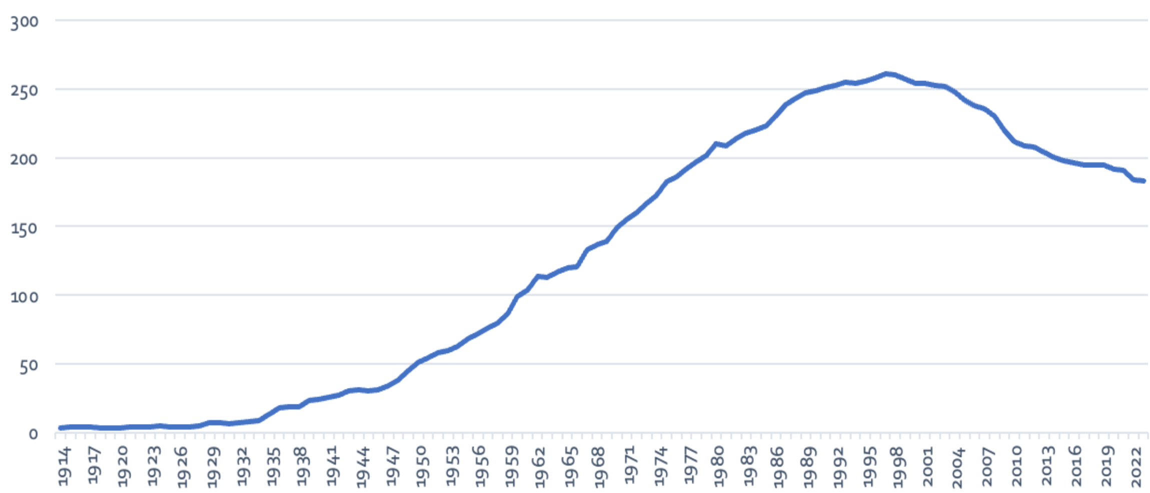

Figure 1 Number of active trolleybus systems per year (own data).

Of the 183 operational networks today, the highest concentration is found in Eastern Europe, Central & Western Asia, accounting for 78% of all trolleybus systems worldwide. Latin America, as well as the North Africa regions also have trolleybus systems; however they jointly account for less than 5% of the total trolleybus systems.

In Europe, adoption rates vary widely and countries such as Switzerland and Germany lead the prevalence of trolleybus systems in Western Europe. Trolleybus systems have been widely used in the former Soviet Union including Ukraine, Belarus, Moldova, Kazakhstan, Georgia and the Baltic countries, where together a fleet of approximately 11,200 trolleybuses is still in operation. Other Eastern European nations such as Czech Republic and Poland operate around 2,800 vehicles. This data underscores the substantial role that trolleybus systems play in the public transportation infrastructure of these regions.

In Latin America, cities such as Mexico City, Guadalajara, Rosario, São Paulo and Quito have adopted trolleybus systems as efficient public transport solutions aligned with contemporary technological standards. In contrast, Asia and particularly China, has emerged as a pioneer in trolleybus implementation in urban centers such as Beijing and Shanghai. In Africa, trolleybus use has remained limited but nascent initiatives in cities such as Marrakech, Morocco, indicate an emerging interest in trolleybus systems.

The substantial role that trolleybus systems play in public transportation infrastructure, particularly in regions like Eastern Europe, Eurasia, and parts of Western Europe, is rooted in several key factors

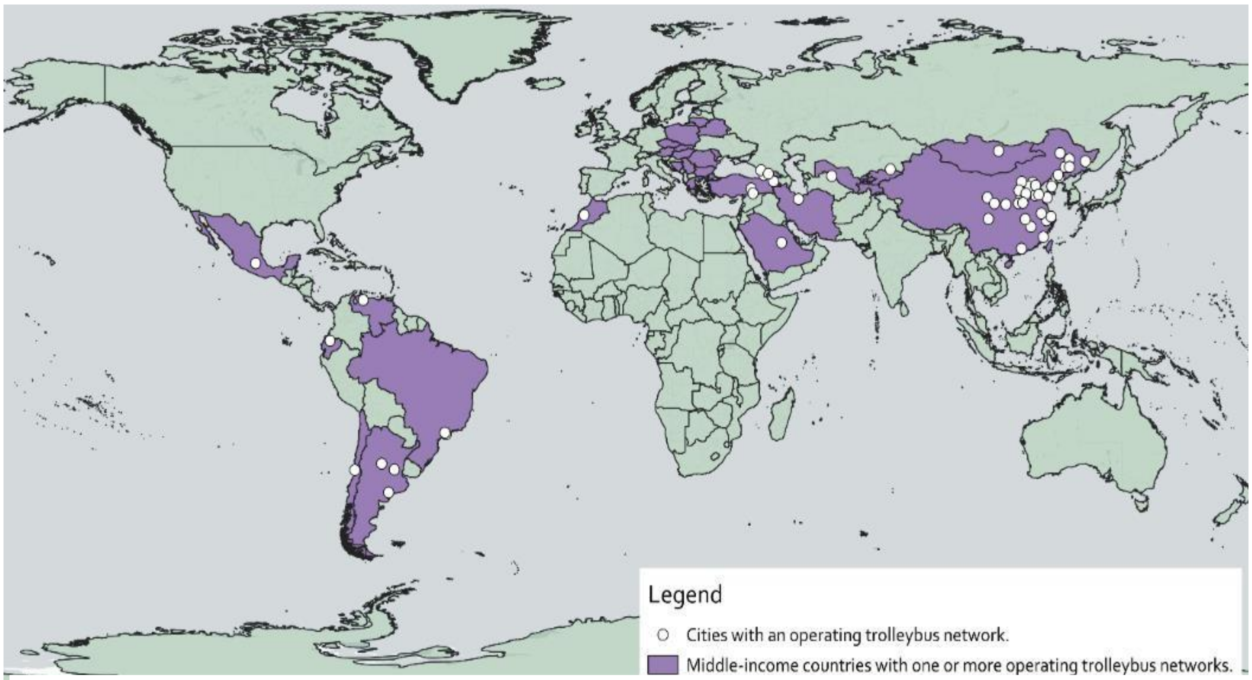

Figure 2 Active Trolleybus Networks in low and middle-income countries. Source: Own elaboration with data from Map of the World (trolleybuses)

that contribute to their importance in both current and future urban mobility. Here's an explanation backed by data and operational insights from the document:

Significant Passenger Volumes

Moscow Example: The trolleybus system in Moscow is a prime example of a high-capacity public transport mode. With 1,242 operating vehicles across 85 routes covering 918 kilometers, this system transports approximately 975 million passengers per year, accounting for 23.1% of the city's total passenger transport. This indicates that trolleybuses are a critical component of the public transport mix in large urban areas, capable of handling substantial passenger volumes.

Extensive Coverage and Accessibility

Regional Reach: In regions like Eastern Europe and Eurasia, trolleybuses provide essential connectivity, particularly in cities where other forms of electric transport (such as trams or metro systems) may not be as feasible due to higher costs or geographic limitations. For example, the large number of trolleybuses in operation in these regions—26,666 in Eurasia alone—demonstrates their extensive reach and the vital role they play in urban mobility.

In some cities, the trolleybus subsystem is treated on par with the tram subsystem, with similar numbers of vehicles and passengers. The trolleybus is also noted for its efficient operation and ability to cover significant urban areas with relatively low investment compared to other electric transport systems. Italy and Switzerland lead in trolleybus technological innovation; there are 15 OEMs that build new generation trolleybuses, while many other countries are reintroducing or planning to implement this “vintage” mode of transportation[1].

2.2 Comparative analysis of trolleybus adoption rates and success factors across regions

Almost all well-functioning and user-friendly public transport systems are dependent on government subsidies and are not economically self-sufficient. Against this background, trolleybus systems have often been in disuse in the past due to market liberalization and the withdrawal of the government's steering role from public transport and not due to causes specific to trolleybus technology itself.

In the context of analyzing the construction, operation, and potential reasons for the discontinuation of trolleybus systems globally, four distinct typologies of countries have been delineated by Pavel Stepanov[2]. These criteria include:

- *Opening Period of Systems:* This metric evaluates the timeframe during which trolleybus systems were inaugurated within a given country, providing insight into historical and developmental contexts.
- *Closing Period of Systems:* Where relevant, this metric scrutinizes the timeframe in which trolleybus systems ceased operations, offering perspectives on the lifespan and termination phases.
- *Motivations for System Inception:* This aspect delves into the underlying reasons for establishing trolleybus systems, considering economic incentives, societal behavioral trends, or international support, among other factors.
- *Rationale Behind System Closure:* For cases where systems were discontinued, this examines the contributing factors, such as financial constraints or shifts in socio-economic or political landscapes.
- *Fleet Renewal Practices:* This evaluates the strategies employed for fleet renewal within trolleybus systems, focusing on the timing (specific intervals or ongoing), as well as the models and production years of replacement vehicles.

Using a set of defined criteria, Pavel Stepanov has developed a classification system for trolleybus systems worldwide grouping them into four distinct categories: "Market Type," "Planned Type," "Introductory Type," and "Exceptions." This taxonomy offers insights into the diverse management approaches and evolutionary trajectories of trolleybus systems across various countries:

- *Market Type:* This category encompasses nations with established market economies, including the United States, Western Europe, Japan, Canada, and Australia. In these regions, the lifecycle of trolleybus systems has historically aligned with market economy dynamics, experiencing both growth and contraction based on economic factors. For instance, Canada once hosted trolleybus systems in 15 cities, the majority of which were decommissioned prior to the 1973 oil crisis, illustrating the market-driven decisions

[1] Tica, S., Filipović, S., Živanović, P., & Bajčetić, S. (2011). Development of Trolleybus Passenger Transport Subsystems in Terms of Sustainable Development and Quality of Life in Cities. International Journal for Traffic and Transport Engineering (IJTTE).

[2] Stepanov, P. (2019). Characteristics of construction and operation of trolleybus systems in the world. Prace Komisji Geografii Komunikacji PTG, 22(3), 64–72. https://doi.org/10.4467/2543859xpkg.19.018.11284

impacting public transportation infrastructure.

- *Planned Type:* Countries such as Russia, Ukraine, Belarus, China, North Korea, the Czech Republic, and Slovakia fall under this classification. Characterized by their strategic development of trolleybus systems from the 1950s through the 1980s, these nations have maintained many of these systems to the present day. Belarus, for example, continues to operate seven trolleybus systems established during this period, showcasing the sustained investment in public transit infrastructure within planned economies.
- *Introductory Type:* This group includes countries that were part of the Soviet Union, located mainly in Western Asia, Central Asia, and Eastern Europe regions. The establishment of trolleybus systems in these regions was initially facilitated by colonial or Soviet authorities. Post- independence, however, many of these countries faced challenges in maintaining and operating their trolleybus systems, leading to widespread closures. Uzbekistan serves as a poignant case, where most of its trolleybus systems were shut down between 2002 and 2010, a few decades after achieving sovereignty, highlighting the difficulties in sustaining such infrastructure.
- *Exceptions:* This classification is reserved for countries where the development and decline of trolleybus systems are not easily attributed to straightforward economic or political factors, often due to volatile conditions. Nations such as Bosnia and Herzegovina, Iran, India, and Vietnam fall into this category, reflecting the complex interplay of diverse influences on public transportation systems.

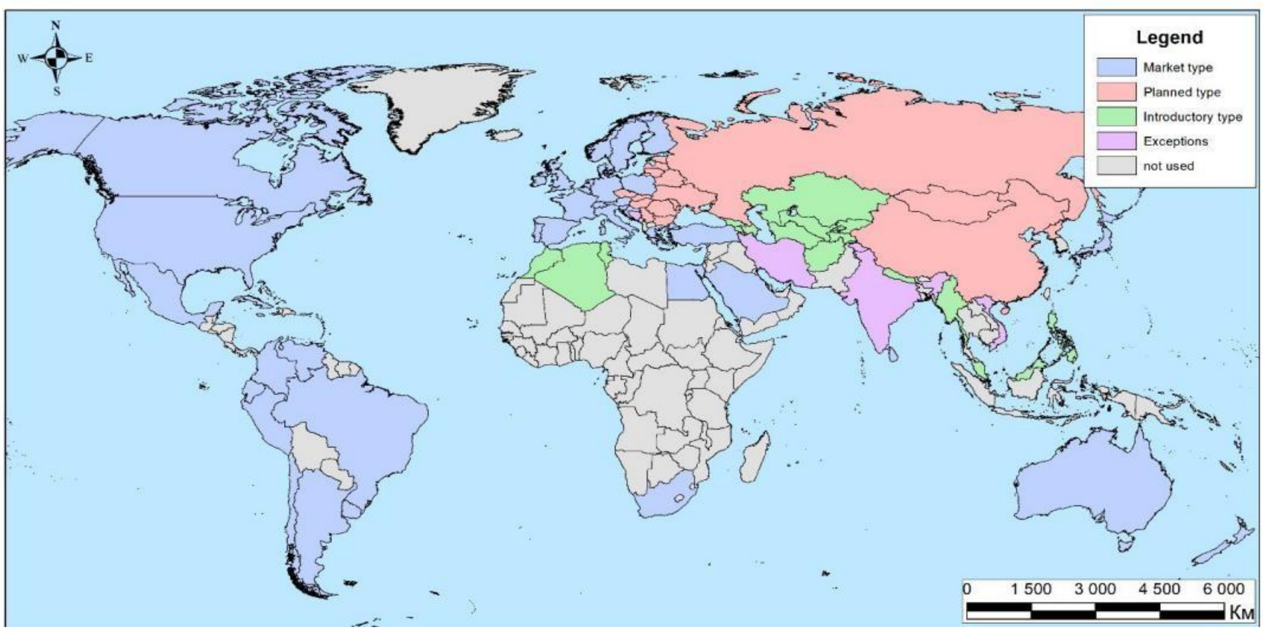

Figure 3 Classification of trolleybus system development Source: Stepanov, P. (2019)

Stepanov P.'s categorization provides a framework for analyzing the multifaceted drivers behind the establishment, operation, and discontinuation of trolleybus systems globally and the intricate relationships between economic models, governance structures, and the evolution of urban mobility solutions[3].

[3] Stepanov, P. (2019). Characteristics of construction and operation of trolleybus systems in the world. Prace Komisji

The development and operation of trolleybus systems worldwide has been influenced by a variety of economic, political, and cultural factors, resulting in significant differences in infrastructure development, operation, vehicle typology as well as technical characteristics. These differences have seen substantial growth over the last decade due to the inclusion of batteries, providing additional autonomy and flexibility to these vehicles.

Regarding the current state of technology, infrastructure, and trolleybus operations, there is a consistent trend in the implementation of more efficient and sustainable trolleybus systems. The electric traction technology used today has evolved to offer higher levels of autonomy, allowing these vehicles to operate for extended distances without needing to be connected to the overhead wires. This has enabled trolleybuses to become a viable alternative in cities where the installation of catenary is not possible along the entire route.

Geografii Komunikacji PTG, 22(3), 64–72. https://doi.org/10.4467/2543859xpkg.19.018.11284, 64-72.

3 Trolleybus Technology, Infrastructure and Operations

3.1 Trolleybus technology

To integrate trolleybus systems into urban public transportation networks, it is imperative to secure a consistent and economical electricity supply. This is foundational to the operation of trolleybus services as power blackouts bring the whole trolleybus system to a stop (rather than for example individual buses in the case of BEB failure). Therefore, the technical specifications for the installation of the overhead contact system, traction substations, and the provision of high voltage contact lines necessitates meticulous planning and execution.

Distinct from trams and metros, which utilize steel rails and wheels for operation and grounding, trolleybuses are equipped with rubber tires and traverse predefined routes. Due to the insulating nature of rubber tires, the electrical circuit of a trolleybus cannot be completed via its wheels, necessitating a dual-conductor setup (positive and negative) for the contact cable to facilitate the electrical current flow.

To safeguard passenger safety and mitigate the risk of electric shocks, it is crucial to implement enhanced insulation measures for the electrical equipment, particularly in areas accessible to passengers. This is of high importance considering that certain components of the electrical system operate at high voltages, typically ranging between 600V to 750V. Such high-voltage operation not only increases the vehicle's weight but also increases the cost of the system[4].

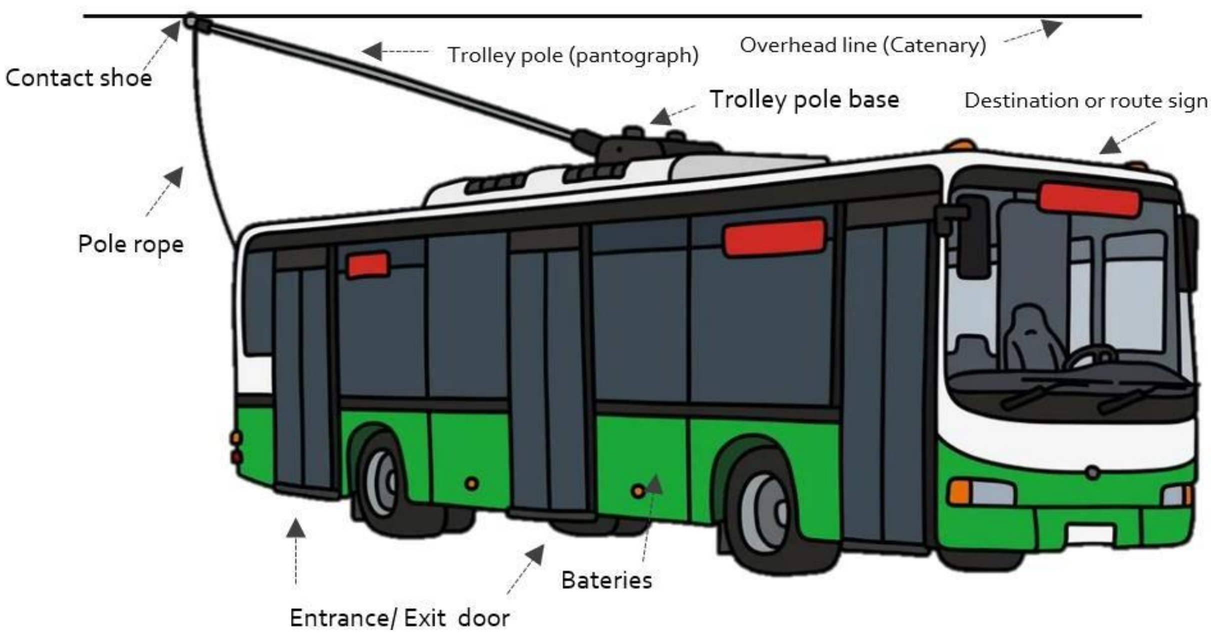

Figure 4 Scheme of a trolleybus (own elaboration)

Key Elements of a Trolleybus

A trolleybus is propelled by an electric motor drawing power from overhead wires, known as catenaries. Key elements include the electric traction motor, the catenary system, and the trolley

[4] Zavada, J., Zavada, J. B., & Miloš, K. (2012). Conditions for implementing trolleybuses in public urban transport. Promet, 22(6), 467–474. https://doi.org/10.7307/ptt.v22i6.212

poles that maintain contact with the wires. Modern trolleybuses with In-Motion Charging (IMC) technology also incorporate advanced batteries, allowing them to operate autonomously in areas where there is no overhead wiring.

Trolleybuses are known for their high energy efficiency, typically consuming around 1.2 to 2.5 kWh per kilometer, depending on the specific model and operating conditions. The introduction of semiconductor elements in the 1980s marked a significant leap forward in energy efficiency allowing for improved vehicle speed regulation and enabling energy recovery techniques, cutting energy consumption by up to 40%.

The introduction of battery storage and In-Motion Charging (IMC) technology has marked a significant evolution in trolleybus technology. This enables trolleybuses to operate without continuous overhead wires for portions of their routes, extending their operational range and reducing the need for extensive charging infrastructure. When IMC trolleybuses are connected to the cable, they benefit from direct energy transfer to the motor, minimizing energy losses. When operating without catenary connection, the batteries are discharged similar to BEBs. The batteries are then recharged in motion when connection to the catenary is re-established. This technology leverages existing wiring for conventional trolleybuses without IMC, ensuring full compatibility with current infrastructure and significantly lowering implementation costs. The integration of IMC technology has profoundly augmented the useability of trolleybuses, offering increased route versatility and operational optimization, thereby bolstering the efficacy of trolleybuses as a public transportation solution[5].

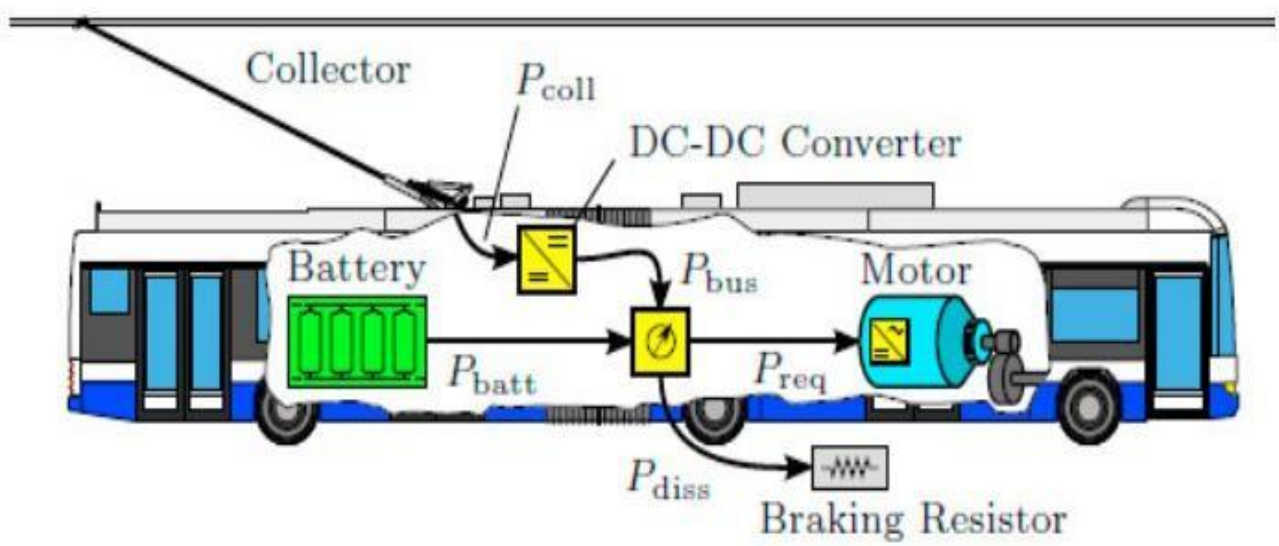

Figure 5 Illustration of key components of battery-assisted trolleybus (Ritter et.al. (2016)

IMC trolleybuses do not necessitate complex catenary systems but can utilize the same wiring infrastructure already installed for conventional trolleybuses. This compatibility significantly reduces the financial and logistical barriers to implementation. Furthermore, on-board IMC chargers only require a basic electrical substation for power supply, obviating the need for complex charging protocols. This standardization makes IMC technology a robust, flexible solution for urban

[5] In motion charging: Innovative trolleybus | UITP. (n.d.). UITP. https://www.uitp.org/publications/in-motion-charging-innovative-trolleybus/ [Access: 08/02/2024].

transportation networks, facilitating the rapid electrification of diesel bus systems.

Trolleybuses have been equipped with control guidance devices to assist drivers in navigating routes more safely and efficiently. Future advancements are expected to include autonomous operation facilitated by Advanced Driver Assistance Systems (ADAS). These systems could be mechanical, using small wheels to follow guides on the route, or electronic, employing sensors and cameras to track road markings and the surrounding environment.

3.2 Trolleybus Infrastructure

The trolleybus infrastructure is comprised of the following components:

- *Overhead Line:* The catenary system is the central element of the trolleybus system. It consists of suspended steel cables along the route through which electrical energy is transmitted to the trolleybuses. The catenary can be single or double, depending on the type of trolleybus and energy demand. In more complex systems, such as those integrating emerging technologies like in- motion charging (IMC), it is crucial that the catenary maintains a constant voltage within an operational range of 500 V to 1000 V, with a nominal voltage of 750 V DC. This infrastructure not only facilitates the continuous power supply to vehicles but can also serve as a backbone for integrating renewable energy sources and stationary energy storage systems, transforming the network into an intelligent and adaptable trolleybus system.
- *Electrical Substations:* Electrical substations are critical facilities that transform electrical energy from the distribution network to the voltage and current levels required by the trolleybuses. These substations are strategically located along the route to ensure a constant power supply. Typically, these substations operate with 12-pulse diode-based rectification units, which convert the alternating current (AC) from the medium voltage grid into direct current (DC) suitable for trolleybus operation. Additionally, the substations are equipped with voltage stabilizers that help mitigate voltage drops along the catenary, especially in sections far from the substation. This design ensures that the system can support the operation of both conventional and IMC trolleybuses, which require higher energy demand due to the charging of their batteries while in motion.
- *Poles and Connectors:* Poles and connectors are components that enable the trolleybus to connect to the overhead network. The poles are articulated devices that slide along the catenary cables, while the connectors ensure safe and efficient contact for energy transfer. Reconnection funnels and overhead contact lines are components that allow trolleybuses to reconnect to the electrical infrastructure after passing through sections without contact lines. This reconnection is automatic during passenger boarding at the bus stop and takes between 3 and 15 seconds, ensuring a quick and uninterrupted transition in power supply[6].
- *On-board chargers*: In the case of IMC trolleybuses, on-board chargers are essential for IMC operation, as they allow trolleybuses to charge energy from the electrical infrastructure without the need for specific charging protocols. This ensures system flexibility and robustness, avoiding technological lock-ins and enabling multiple trolleybuses to independently charge

[6] Day, John M. et al. "In Motion Charging Infrastructure: Interface to The Trolleybus." Knowledge Brief. UITP, 2021.

simultaneously.

Table 2. Comparison of classic trolleybuses vs IMC trolleybuses vs battery electric buses (BEBs).

Aspect	Classic Trolleybuses	IMC Trolleybuses	Battery Electric Buses (BEBs)
Technology	Relies entirely on overhead wires (catenary) for power, limited autonomy without wires.	Combines overhead wires with in-motion charging (IMC) for increased flexibility and autonomy.	Powered entirely by onboard batteries, no need for overhead wires.
Power (12m / 18m buses)	Typically, around 150-200 kW for 12m buses; 240-300 kW for 18m buses.	Similar power range as classic trolleybuses but equipped with additional battery packs for off-wire operation.	Power ranges from 150-350 kW depending on battery size and bus model.
Energy Consumption (kWh/km)	Approximately 2.25 kWh/km.	Slightly higher due to the combined use of batteries and overhead power, approximately 2.5-3.0 kWh/km.	Lower overall, typically around 1.2-1.5 kWh/km depending on the route and driving conditions.
Cost per Bus	US$ 200,000 - US$ 500,000 depending on size and specifications.	US$ 250,000 - US$ 600,000, potentially higher in case of additional battery capacity.	US$ 250,000 - US$ 600,000, with significant variations depending on battery capacity.
Infrastructure Costs	High due to the need for continuous overhead wires and substations; approximately US$1-3 million per km of catenary; substation costs vary from US$1-3 million depending on size and location.	Like classic trolleybuses but with reduced need for continuous overhead wires; lower overall infrastructure costs due to IMC.	Lower infrastructure costs but requires investment in charging stations and potential grid upgrades US$ 50,000 – US$ 500,000 per charging station, $500,000 EUR each, depending on charging speed and technology.
Operational Flexibility	Limited to routes with overhead wiring.	Greater flexibility; can operate off-wire for up to 20-80 km, depending on battery size.	Highly flexible, can operate on any route within battery range, typically 250-400 km per charge.
Maintenance Costs	Lower due to fewer moving parts and the absence of batteries; simpler maintenance.	Moderate; similar to classic trolleybuses but with additional battery maintenance.	Higher, primarily due to battery degradation and the need for battery replacements every 5-8 years.
Environmental Impact	Zero tailpipe emissions; depends on the carbon footprint of the electricity used.	Like classic trolleybuses, but with potential benefits from more efficient grid use and reduced infrastructure needs.	Zero tailpipe emissions; overall impact depends on the source of electricity and battery production lifecycle.
Route Flexibility	Low; dependent on the presence of overhead wires.	Moderate; can adapt to various routes with partial catenary	High; can operate on any route within battery range.

		coverage.	
Lifecycle Costs	Lower lifecycle costs due to durability and lower energy costs; typically, cost-effective over 25 years.	Like classic trolleybuses but with higher upfront costs for IMC technology.	Higher overall due to battery costs and replacements but improving with advances in battery technology.
Voltage and Power Supply	Operates at 600V to 750V DC; requires multiple substations along routes.	Similar voltage requirements: fewer substations needed due to IMC capabilities.	Operates typically at 400-750V depending on battery systems; relies on depot charging infrastructure.

4 Comparative Analysis of Trolleybus and Battery Electric Bus Total Cost of Ownership

This section presents a detailed Total Cost of Ownership (TCO) comparison of the two leading electric bus transport technologies: trolleybuses and battery electric buses. The analysis is grounded in data research on critical parameters—including vehicle cost, charger and wiring infrastructure, fuel efficiency, and maintenance costs—and is validated by a comprehensive 40-year lifecycle cost model for a typical fleet size and service scenario.

4.1 Key Parameters and Methodology

This TCO analysis covers what could be considered typical LMIC BRT operation with 150 buses serving a 25 km trunk line corridor, similar for example to the currently developed operations in Abidjan (Cote d'Ivoire). The parameters evaluated include:

- Bus capital cost: Purchase price of trolleybuses and BEBs, considering market price differences influenced by scale and product tailoring.
- Infrastructure cost: Includes catenary wiring for trolleybuses (lifetime of 40 years) and depot charging infrastructure for BEBs (chargers with 20-year lifetime).
- Fuel efficiency: Electrical energy consumption per kilometre for both bus types.
- Maintenance costs: Routine and overhaul expenses, including periodic battery replacements for BEBs.
- Fleet size adjustment: Approximately 20% more BEBs are needed compared to trolleybus fleets to provide the same service reliability due to BEBs' charging and operational constraints.

The analysis includes capital expenditures (CAPEX) and operational expenditures (OPEX) over a 40-year horizon, integrating vehicle replacement every 10 years and infrastructure renewals as applicable.

4.2 Results of the TCO analysis

Capital cost:

- Fleet Size and Cost Premium: BEBs require about 20% more buses to maintain service equivalence due to charging time and range limitations, increasing total fleet cost beyond just individual vehicle pricing.
- Vehicle Capital Cost: Despite trolleybus technology being more mature with longer production history at scale, they are currently about 15% more expensive largely due to smaller market size and specialized production for trolley systems.
- Infrastructure Investment: Trolleybus wiring demands significant upfront investment but benefits from a longer lifetime (40 years) compared to BEB chargers (20 years), which require at least one replacement over the same period.

Operating costs:

- Trolleybuses have no major periodic battery replacement costs, reducing lifecycle maintenance expenses. BEBs face recurring battery change and higher charger maintenance costs.

- Trolleybuses exhibit higher energy efficiency owing to continuous power supply without carrying heavy batteries.
- Fuel and Energy Costs: Both run on electricity, but trolleybuses can integrate renewable energy during the day more seamlessly due to continuous grid connection, potentially reducing carbon footprint and energy storage needs.

Table 1 Results Summary (40-Year Horizon)

Metric	Trolleybus	Battery Electric Bus	ICE Bus (Reference)
Total Cost of Vehicles (CAPEX)	Significant, slightly higher per unit	Slightly lower per unit, but larger fleet size	Lowest initial but higher fuel and maintenance
Total Infrastructure Cost (CAPEX)	High upfront wiring with 40-year lifespan	Significant depot and charger replacement costs	Minimal infrastructure investment
Total Operating Cost (OPEX)	Lower maintenance; no battery replacement	Higher maintenance; battery replacements required	Highest fuel and maintenance costs
Fleet Size Needed	Baseline (150 buses)	20% larger fleet (~180 buses)	Baseline (150 buses)
Overall TCO	About 18% lower than BEB	Higher than trolleybus	Highest cost overall

The conservative estimates show that for this example trolleybus systems are approximately 18% cheaper than battery electric buses and about 30% cheaper than diesel-powered buses over a 40-year operational cycle. The key financial advantage for trolleybuses lies in lower operating costs and the prolonged lifespan of infrastructure relative to charger replacements for BEBs.

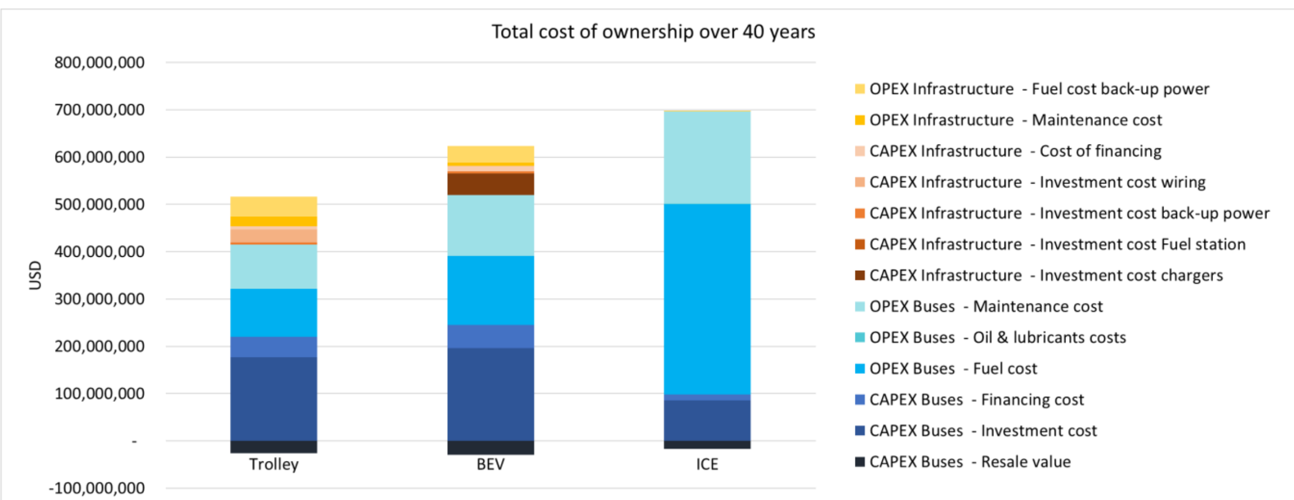

Figure 6 Comparative total cost of ownership.

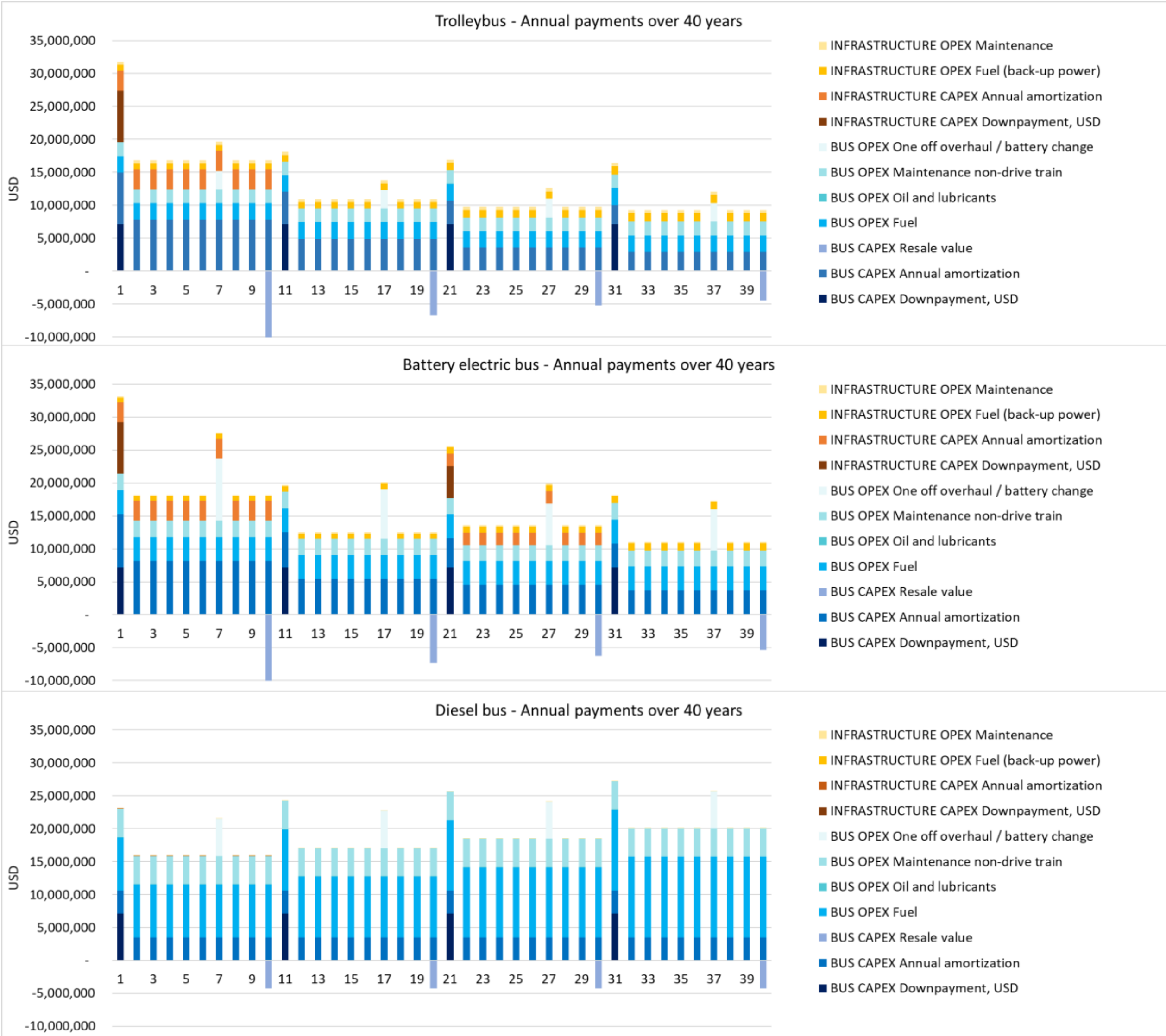

Figure 7 Comparison of annual payments over 40 years.

While BEBs benefit from flexibility and rapidly growing market scale, the TCO analysis indicates that trolleybus systems currently offer significant cost benefits and operational advantages in contexts like LMIC cities with suitable urban context. The higher upfront costs for trolleybuses are offset by lower operating expenses and infrastructure longevity, with the added benefit of superior system integration with renewable energy and improved service quality for example through the provision of air conditioned buses.

Decision-makers aiming for sustainable urban mobility should weigh these comprehensive cost and operational factors, positioning trolleybuses as a competitive, and at times preferable, alternative to battery electric buses for high-capacity bus rapid transit (BRT) corridors.

5 Opportunities for Trolleybus Systems in LMICs

5.1 Trolleybuses in bus rapid transit systems

Trolleybus systems offer significant opportunities for sustainable urban transport in LMIC cities. They can contribute to sustainable development by reducing greenhouse gas emissions, improving air quality and reducing fuel demand therefore reducing the need to import costly petroleum fuels. By providing a reliable, efficient, and environmentally friendly mode of transport, trolleybuses can enhance the quality of life in urban areas, particularly by reducing traffic congestion and noise pollution[7].

Figure 8 Trolleybus BRT Line 10 in Mexico City (SEMOVI 2023).

Many LMIC cities are currently planning and implementing BRT systems. Since these high-capacity bus systems will be shaping the urban transport landscape for the next decades, it is imperative to ensure that these system become electric. Trolleybus systems should be considered a serious alternative to BEB systems for the reason lined out in previous chapters. However, the political and institutional structure distinctive to these cities makes it challenging to implement effective public transport projects, such as Bus Rapid Transit (BRT) systems (Wijaya & Imran, 2019).

A Bus Rapid Transit (BRT) system is a high-quality public transportation system that uses buses to deliver fast, efficient, and reliable services like metro systems. BRTs operate in dedicated lanes, which helps avoid traffic delays, and they feature stations with elevated platforms for easy boarding, as well as off-board fare collection to speed up the process. These systems are cost-effective and can be implemented quickly, making them popular in cities looking to improve public transit without the high costs of rail systems.

BRT systems have been widely adopted in many LMIC cities, offering a practical solution for renewing and upgrading public transport infrastructure. By prioritizing bus services at intersections and using dedicated lanes, BRT systems provide a significant improvement over traditional bus services, helping cities meet the growing demand for efficient and reliable public transportation.

[7] Tica, S., Filipović, S., Živanović, P., & Bajčetić, S. (2011). Development of trolleybus passenger transport subsystems in terms of sustainable development and quality of life in cities. International Journal for Traffic and Transport Engineering, 1(4), 196-205. https://doi.org/10.7708/ijtte.2011.1(4).04

Figure 9 shows the rapid advancement of BRT in the last 25 years across the global south[8].

Public transport continues to be one of the aspects with the greatest lag in LMICs , as they present delays in terms of regulatory frameworks, the formalization of the sector, capacity building, access to financing and credit worthiness. However, in those cities where these factors have been addressed, a transition from informal of transports systems to transport systems with a governance that allows the provision of a better service to the population was possible. In many cases such transition was spearheaded through the implementation of BRT systems, since these allow a transformation of transport at relatively lower costs compared to, for example, commuter rail, light rail or metro systems.

Spotlight – E-Buses in Africa

Nairobi, Kenya - the city is implementing a BRT project and is increasingly interested to integrate e-buses. Nairobi's metropolitan transport authority (NaMATA) is bringing in some electric busses to pilot them. The government has expressed interest in the electrification of transport. Kenya's power grid is ready for electrification as there is surplus energy generated and the grid is 90% renewable.

Kisumu, Kenya – Kisumu is Kenya's third populous city and has traditionally been leading in Kenya on cleaner mobility. For example, Kisumu is now targeting electric motorcycle taxis. The city of Kisumu has expressed interest in bringing e-buses.

Kigali, Rwanda - Rwanda has some of the most comprehensive e-mobility policies and targets in Africa, with a target to electrify 20% of public transport by 2030 (and 100% electric motorcycles). National policies and incentive packages including import taxes and VAT waivers and preferential tariffs for charging exist.

Seychelles - Seychelles is keen to completely switch to electric buses of the Seychelles Public Transport Corporation (SPTC). They are currently implementing an electric bus pilot and developing a programme to switch to e-buses. SPTC is keen to electrify its entire fleet of about 250 public buses.

Accra, Ghana - a technical feasibility study on 75 intra and inter-city e-buses including options for greening charging systems and financing needs was developed by UNEP. The Ministry of Transport has developed a concept note focusing on e-buses.

Kampala, Uganda - Kampala plans to formalize its public transport systems. Ongoing electric mobility initiatives include a demonstration on EV charging for 2-wheelers and local assembly of e-buses by Kiira Motors.

Abidjan, Cote d'Ivoire – Abidjan is currently implementing a World Bank financed e-BRT project. The BRT line will connect the east with the west of Abidjan, covering about 25km of completely separated road infrastructure.

LMIC cities that have already these BRT systems in place should use the opportunity to advance towards electric BRT fleets, for example as part of the renewal of their rolling stock. Given the potential long-term cost savings, trolleybus systems should be considered as a electric drive option.

[8] Global BRTData. (n.d.). https://brtdata.org/?lang=en

31,596,612 PASSENGERS PER DAY

191 CITIES

5,842 km TOTAL LENGTH

› KEY INDICATORS per Region

Filter

Regions	Passengers per Day	Number of Cities	Length (km)
Africa	491,578 (1.55%)	6 (3.14%)	152 (2.59%)
Asia	7,987,756 (25.28%)	46 (24.08%)	1,772 (30.33%)
Europe	3,169,846 (10.03%)	47 (24.6%)	950 (16.25%)
Latin America	18,505,436 (58.56%)	64 (33.5%)	2,044 (34.98%)
Northern America	1,005,796 (3.18%)	23 (12.04%)	815 (13.95%)
Oceania	436,200 (1.38%)	5 (2.61%)	109 (1.86%)

Figure 10 BRT Data across the world (Source: Global BRT Data 2024)

5.2 Key Success Factors for Trolleybuses in LMICs

The successful implementation of trolleybus systems in Low- and Middle-Income Countries (LMICs) hinges on a multifaceted approach that addresses key areas essential for long-term viability and effectiveness. These areas encompass political and institutional support, financial planning, infrastructure readiness, technological adaptation, and public and stakeholder engagement. Each of these components plays a critical role in ensuring that trolleybus projects are not only feasible but also sustainable and well- integrated into the broader urban transport network.

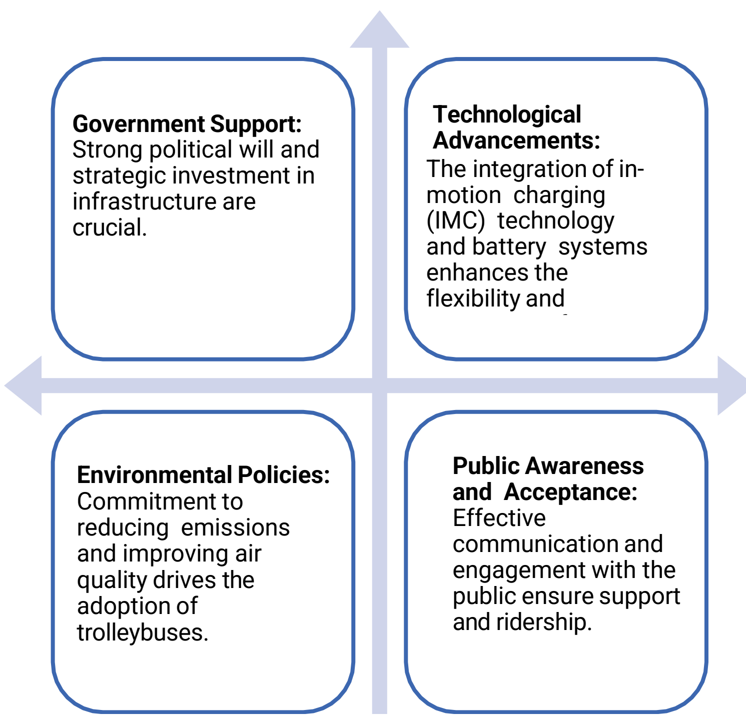

Figure 11 Key success factors for trolleybus systems in LMICs

The importance of each of these factors and how they contribute to the successful deployment of trolleybus systems in LMICs is as following:

- *Political and Institutional Support:* Securing strong political will and institutional backing is essential for the successful implementation of trolleybus systems. This includes integrating trolleybus development into national and municipal transportation policies, ensuring long-term commitments from governments, and fostering collaboration between different levels of government and international stakeholders.
- *Financial Planning and Investment:* Establishing a comprehensive financial plan is critical. This should involve assessing the total cost of ownership (TCO) of trolleybus systems, including upfront infrastructure investments, operational expenses, and long-term maintenance costs. Exploring diverse financing mechanisms, such as public-private partnerships (PPPs), international development funding, green bonds and government guarantees can provide the necessary financial support.
- *Infrastructure Readiness:* The existing urban infrastructure must be evaluated to determine its suitability for trolleybus deployment. This includes assessing the capacity of the electrical grid, the availability of space for overhead contact systems (OCS), and the condition of existing roads. Infrastructure improvements or new developments should be planned in phases to minimize disruption and optimize resource use.
- *Technological Adaptation:* Leveraging advanced technologies, such as In-Motion Charging (IMC) and energy storage systems enhance the flexibility and efficiency of trolleybus systems. These technologies enable trolleybuses to operate in areas without continuous overhead wiring and reduce reliance on large batteries (as in BEBs), lowering overall system costs and improving energy efficiency.
- *Public and Stakeholder Engagement:* Engaging the public and key stakeholders early in the planning process is vital to ensure broad support for the trolleybus system. This includes transparent communication about the benefits of trolleybuses, such as reduced emissions and improved air quality, and addressing concerns related to potential disruptions during construction or operation.

5.3 Policy Support Frameworks for Trolleybus Systems in LMICs

Implementing trolleybuses in LMIC can offer several benefits but requires careful consideration of various factors, including policy implications and support mechanisms.

The success of trolleybus implementation depends heavily on supportive policies and strategic planning. strong supportive policies and other incentives are needed to make electric high-capacity bus systems and in particular trolley bus systems a reality in LMIC cities.

- *Urban Planning Integration:* Integrating trolleybus systems into urban planning processes requires long-term city development strategies such as sustainable urban mobility plans. This includes, for example, zoning policies that prioritize the development of trolleybus corridors in densely populated or high traffic areas. Exclusive rights for high-capacity bus operations which prevent direct competition with informal transport on the same corridor have been implemented in many of the pilot cities to improve profitability of the trunk-line operations. The combination of various public transport operations – including for example large 18m+ trolleybuses for high capacity trunkline operations, smaller 12m or 8m BEBs for feeder services, and paratransit based on electric mini-buses and electric 2&3 wheelers can offer low cost, low carbon integrated mobility systems for metropolitan areas in the global south.

- *Regulatory Frameworks:* Establishing clear regulatory frameworks that mandate or encourage the use of electric and low-emission vehicles in public transport can drive the adoption of trolleybus systems. These frameworks can include emission reduction targets, low-emission zones, and requirements for public transport operators to transition to electric fleets.
- *Subsidies and Incentives:* Governments can implement subsidies and incentives for the adoption of trolleybus systems, reducing initial capital expenditure. This includes direct financial support for infrastructure development and vehicle procurement, operational guarantees (for example minimum fare income based on ridership thresholds) as well as tax incentives to encourage private sector investment.
- *Capacitating and Funding of Metropolitan Transport Authorities:* The continuity in budgets in for the operation of metropolitan transport authorities is key to the establishment of formalized transport systems and the introduction of complex operations such as BRTs and trolleybus systems. Long-term funding commitments enable the building-up of the necessary human resources and operational routines and enable maintenance of infrastructure and rolling stock.
- *Socially acceptable fares:* The introduction of pricing schemes which reflect the purchase power of the target use group is pivotal for the successful of any formalized high-capacity bus system, including trolley bus systems. Fares need to be competitive to ensure sufficient ridership. Special tariffs providing lower cost transport for certain vulnerable target groups might be considered.
- *Incentivizing of local production and assembly of electric buses, including trolleybuses:* The localization of part of the value chain, for example through local assembly of electric buses and trolleybuses can unlock scaling potential through competitively priced equipment and the continued exemption from import taxes and excises while creating jobs at the same time.
- *Just transition and gender equity:* System transitions such as shifting to high-capacity transport systems deploying novel technology provide the opportunity to improve gender equality and inclusion both for transport users (e.g. through improved bus design providing and connectivity) and transport professionals and decision makers (e.g. through the incentivizing of female professionals along the transport value chain).

5.4 Financing Models and International Funding Opportunities for Trolleybus Systems in LMICs

Financing the development and expansion of trolleybus systems requires diverse and innovative financing approaches. Various models, including government funding, public-private partnerships (PPPs), and international grants offer advantages and challenges. The following table outlines key financing models, their descriptions, case studies, advantages, and considerations, highlighting the multifaceted strategies employed to support trolleybus projects globally.

Financing Model	Description	Example / Case Study	Key Advantages	Challenges or Considerations
Government Funding	Direct investment by local or national governments. Can include subsidies or grants or government guarantees.	Mexico City trolleybus fleet	Reliable source of funding; promotes public accountability.	Depending on government budget and priorities; may be limited in scope.
Public-Private Partnerships (PPPs)	Collaboration between government and private entities, where the private sector may handle operations, maintenance, or partial financing. Private sector partner collects revenues for an agreed period.	Shenzhen International Low Carbon City, China [(Zhan & Jong, 2018)	Can leverage private investment and expertise reduces direct government expenditure.	Requires careful management to balance public and private interests.
Multilateral Development Finance	Funding support from international institutions such as development banks and regional funds to design, build and operate infrastructure projects	Expansion of Trolleybus network in Balti, Moldova by EBRD	Access to substantial finance, MDFI's provide technical assistance and advisory services. Long term development mandate	Includes complex approval process, lengthy project preparations, strict compliance requirements
Green Bonds	Raising capital from investors through the issuance of bonds specifically earmarked for environmentally beneficial projects.	Shandong Spring City Green Modern Trolley Bus Project	Attract dedicated sustainable investors, attract long term investors so stable financing can achieve lower interest rate compared to conventional bonds	Lack of well-established debt capital market can limit the accessibility and competitiveness of green bond, additional cost of issuance of green certificate
Grants	Funding from grant programs, often targeting sustainable transport and urban development. Enables project development through technical assistance.	UNEP Global Electric Mobility Programme Expansion project in Gdynia funded by the EU (Wyszomirski, 2010)	Access to substantial funding for eligible projects; fosters sustainable practices.	Strict eligibility criteria; mostly applicable to European cities.
Innovative Financing Mechanisms	Includes mechanisms like green bonds, climate funds, or other innovative financial instruments dedicated to sustainable transport initiatives.	N/A	Potentially large source of funding; aligned with sustainable development goals.	Requires a developed financial market and investor interest in sustainability.

Spotlight – Innovative Financing and Operation– Dakar SunuBRT

Picture: https://www.meridiam.com/news/meridiams-podcast-series-beyond-second-episode-the-bus-rapid-transport-brt-project-in-dakar-senegal/

Dakar's BRT system is designed to carry 300,000 passengers daily, cutting travel time from 95 to 45 minutes. It will operate 144 electric articulated buses, promoting zero-emission transport.

Dakar is among the first cities in Sub-Saharan Africa to formalize its informal bus system and engage the private sector in modernizing its public transport fleet. Like many African cities, Dakar has long relied on informal transport. To improve service quality, the city's transport authority, CETUD, launched a fleet renewal and service upgrade initiative in 2005.

The project formalizes informal transport by requiring operators to form cooperatives responsible for loan repayments, backed by government and World Bank credit. Services are regulated through concession agreements.

Funded by the World Bank and European Investment Bank, the BRT is operated by Dakar Mobilité (Meridiam and FONSIS) under a 15-year concession. The private sector invested USD $144 million, with an additional USD $22 million from MIGA.

Risks are mitigated through minimum revenue and passenger guarantees (100,000 passengers/day). The operator collects fares and maintains infrastructure, while the government supports feeder services.

Fares are zone-based and include a 50% discount for low-income riders (17% of users), with the government compensating USD $17 million over 15 years. The concessionaire also pays a fee to the government.

Source: https://itdp.org/2024/03/22/dakar-senegals-electric-brt-leads-the-way-for-african-cities/

6 Guidelines for Implementing Trolleybus Projects in LMICs

Conduct Feasibility Studies:

Undertake comprehensive feasibility studies to assess the viability of trolleybus systems in the target city or region. These studies should evaluate demand, route selection, cost-benefit analysis, environmental impact, and potential challenges. Include pilot projects in the feasibility phase to test trolleybus operations in specific corridors and gather data on performance, public acceptance, and operational efficiency.

Develop a Phased Implementation Plan

Implement trolleybus systems in phases, starting with key transit corridors that have high passenger demand and significant traffic congestion. This phased approach allows for gradual integration of the system, minimizing risk and ensuring that lessons learned in initial phases can be applied to subsequent expansions. Incorporate flexibility in the design to allow for future scalability and technological upgrades.

Strengthening Regulatory and Institutional Frameworks

Establish a robust regulatory framework that defines the roles and responsibilities of all stakeholders, including government agencies, private operators, and financiers. This framework should include clear guidelines on safety standards, operational procedures, and environmental compliance. Create or reinforce institutional bodies responsible for overseeing the planning, construction, and operation of trolleybus systems. These bodies should be empowered to coordinate between different sectors and ensure the alignment of trolleybus development with broader urban mobility goals.

Focus on Capacity Building and Knowledge Transfer

Invest in capacity building for local authorities, transit operators, and technical staff. Training programs should focus on the design, operation, and maintenance of trolleybus systems, as well as the managementof electric transportation networks. Facilitate knowledge transfer from cities or countries with established trolleybus systems through partnerships, workshops, and technical exchanges. This can help LMIC cities avoid common pitfalls and accelerate the learning curve.

Optimize System Design for Local Conditions

Design trolleybus routes and infrastructure that consider the specific geographical, climatic, and socio- economic conditions of the LMIC city. For example, in regions with challenging topography, trolleybuses with enhanced traction and braking systems may be necessary. Tailor the trolleybus fleet to local needs, including considerations for vehicle size, capacity, and energy efficiency. Ensure that vehicles are equipped to handle local weather conditions, such as high temperatures or heavy rainfall.

Seek Integration with Existing Public Transport

Ensure that trolleybus systems are seamlessly integrated with existing public transport networks, including bus, metro, and rail systems. This integration can be facilitated through common ticketing systems, coordinated schedules, and well-designed interchange stations. Consider the potential for trolleybus systems to complement or replace less efficient modes of transport, such as aging diesel bus fleets, to enhance overall urban mobility.

Monitor and Evaluate Performance

Establish a comprehensive monitoring and evaluation framework to track the performance of the trolleybus system over time. Key performance indicators (KPIs) should include ridership levels, operational reliability, energy consumption, and environmental impact. Use data-driven insights to make continuous improvements to the system, addressing any operational challenges and optimizing service delivery.

Plan for Long-Term Sustainability

Ensure that trolleybus systems are designed with long-term sustainability in mind. This includes planning for future expansions, incorporating renewable energy sources, and implementing measures to extend the lifespan of infrastructure and vehicles. Explore opportunities for local manufacturing and assembly of trolleybus components to reduce costs and build local capacity.

By following these general guidelines, LMIC cities can successfully develop and implement trolleybus systems that contribute to sustainable urban mobility, reduce environmental impact, and enhance the quality of life for their residents.

6.1 Challenges for Trolleybus systems in LMICs and Case Studies for Solutions

Technical Challenges and Solution Case Studies

Developing and operating trolleybus systems in LMICs involves confronting several technical challenges. These challenges are intricately tied to the urban infrastructure, technological advancements, and financial constraints faced by these cities.
One of the critical technical challenges is related to the development of efficient and reliable power systems. Trolleybuses require a continuous supply of electricity, often provided through overhead lines. However, in LMICs, where electrical infrastructure may be underdeveloped or unstable, ensuring a consistent and robust power supply can be difficult. Nevolin et al. (2023) highlighted the potential methods for organizing trolleybus routes using autonomous running to minimize the costs of establishing a contact network, indicating the need for innovative approaches to address power supply issues in these cities.

Key Challenge	Description	City Example	Reference
Infrastructure Development	Establishing infrastructure like overhead electric lines and substations is technically demanding.	Riyadh, Saudi Arabia	Khan, K. A., Quamar, M. M., Al-Qahtani, F. H., Asif, M., Alqahtani, M., & Khalid, M. (2023). Smart grid infrastructure and renewable energy deployment: A conceptual review of Saudi Arabia. Energy Strategy Reviews, 50, 101247. https://doi.org/10.1016/j.esr.2023.101247

Vehicle Procurement and Maintenance	Despite the higher initial costs, trolleybuses compensate with improved operational performance and longer lifespan. Electric propulsion systems typically have lower levels of wear. trolleybuses in Valparaiso have been operational for over 70 years, showcasing their longevity.	Valparais, Chile	Scherf, C., & Wolter, F. (2016). Electromobility. Overview, Examples, Approaches. ResearchGate. https://doi.org/10.13140/RG.2.2.207 57.73 447
Integration with Existing Systems	The first metropolitan corridor for trolleybuses will help improve connections between the eastern part of Mexico City with its metropolitan area, to the benefit of approximately 120,000 people, which includes the integration with an existing Trolleybus line.	Mexico City, Mexico	Sener. (2023, July 3). Sener plans the first trolleybus to connect Mexico City and the State. https://www.group.sener/en/noticia s/sen er-plans-the-first-trolleybus-to-connect- mexico-city-and-the-state/
Energy Supply and Stability	Nine substations of the first stage are powered at 6 kV from Empresa Eléctrica Quito S.A. were implemented for Ecovia, a short Trolleybus Route.	Quito, Ecuador	Taco, J. P. A., & Ibarra, A. (2020). Trolebus eléctrico, una primera solución a la movilidad en el Distrito Metropolitano de Quito-Ecuador. Tordesillas, Revista De InvestigacióN Multidisciplinar, 17, 81–92. https://doi.org/10.24197/trim.17.20 19.81- 92
Training and Skills Development	Investment in training and knowledge transfer is necessary to develop technical skills for operating and maintaining trolleybus systems.	Mexico City, MX	It was important for the Staff and the Secretariat of Mobility to learn about IMC Trolleybuses and their benefit for the network.
Adapting to Urban Conditions	Specialized urban planning and technical design skills are needed to design trolleybus routes adaptable to specific traffic conditions and urban densities.	Şanlıurfa, Turkiye	Trambüs Şanlıurfa'da test sürüşüne başladı. (n.d.). Şanlıurfa Büyükşehir Belediyesi. https://www.sanliurfa.bel.tr/icerik/1 3473/ 21/trambus-sanliurfada-test-surusune- basladi
Environmental Considerations	Addressing environmental concerns like minimizing the ecological footprint of construction and operation.	Almaty, Kazakhstan	GRCF2 Almaty Trolleybus Project - Feasibility and Due diligence study. (n.d.). https://www.ebrd.com/sites/Satellit e?c= Content&cid=1395289648643&d=To uch &pagename=EBRD%2FContent%2FC ont entLayout&rendermode=live%3Fsrch -pg

Safety and Reliability	Power shortages during peak winter periods could lead to trolleybuses being stranded, as the buses rely on a constant electricity supply. Trolleybuses use electricity continuously, including during peak demand periods, which can strain the power system.	Bishkek, Kyrgyzstan	Bank, A. D. (2023, October 12). Electric buses to reduce air pollution in Bishkek. Asian Development Bank. https://www.adb.org/news/videos/electri c-buses-reduce-air-pollution-bishkek

Operational Challenges and Solution Case Studies

Operational challenges encompass the everyday functioning of trolleybus systems. These challenges include route planning, fleet management, and service regularity, all of which are crucial for the efficient operation of a public transport system.

Key Challenge	Description	City Example	Reference
Infrastructure Maintenance	Regular maintenance of overhead wires, substations, and charging infrastructure, Quito known for its well-maintained trolleybus system despite resource constraints.	Quito, Ecuador -	Yáñez-Pagans, P., Martínez, D., Mitnik, O. A., Scholl, L., & Vázquez, A. (2018). Urban Transport Systems in Latin America and the Caribbean: Challenges and Lessons Learned - See more at: https://publications.iadb.org/handle/113 19/9179#sthash.fkZq3bBz.dpuf. https://doi.org/10.18235/0001346
Technical Expertise	Technical expertise is utilized to assess the safety features, performance metrics, and overall quality of electric buses to ensure their suitability for operating in the challenging urban environment of Bishkek	Bishkek, Kyrgyzstan	Bank, A. D. (2023, October 12). Electric buses to reduce air pollution in Bishkek. Asian Development Bank. https://www.adb.org/news/videos/elect ric-buses-reduce-air-pollution-bishkek
Traffic Management	Implemented strategies to manage trolleybuses in highly congested areas.	Mexico City, Mexico	Editorial, UTM. (2024, January 1). Trolleybus, light rail and cableway in Mexico City: The transformation of the STE - Urban Transport Magazine. Urban Transport Magazine. https://www.urban-transport-magazine.com/en/trolleybus-light-rail-and-cableway-in-mexico-city-the-new-ste/
Traffic Congestion	Presence of traffic congestion affecting trolleybus schedules.	Istanbul, Turkey -	Akyüz, E. (2015). İSTANBULDA TRAFİK SORUNUNA ÇÖZÜMLER. Asosjournal, 16(16), 442. https://doi.org/10.16992/asos.792
Public Perception and Acceptance	Gaining public support for trolleybuses can be challenging.	Shanghai, China	You, X. (2023, December 8). How China's buses shaped the world's EV revolution. https://www.bbc.com/future/article/202 31206-climate-change-how-chinas-electric-vehicle-revolution-began-with-buses

Passenger Safety and Security	Existing practices, resources, and tools will be assessed, and measures will be recommended to ensure the successful introduction of the new trolleybus fleet onto all company trolleybus lines, with a focus on passenger safety and security.	Almaty, Kazakhstan	GRCF2 Almaty Trolleybus Project - Feasibility and Due diligence study. (n.d.). https://www.ebrd.com/sites/Satellite?c =Content&cid=1395289648643&d=Touch&pagename=EBRD%2FContent%2FContentLayout&rendermode=live%3Fsrch-pg
Integration with Other Modes of Transport	Shanghai, along with Beijing, has been advancing the integration of trolleybuses into their BRT systems. This includes the adoption of battery-backed trolleybuses	Shanghai, China	Díez, A. E., & Restrepo, M. (2021). A Planning Method for Partially Grid-Connected Bus Rapid Transit Systems Operating with In-Motion Charging Batteries. Energies, 14(9), 2550. https://doi.org/10.3390/en14092550
Capacity and Demand Management	The project involved various stakeholders including the Municipality of Marrakech, TLDC, SIE, and RADEEMA.	Marrakech, Morocco	Renewable energy for the city of Marrakech's bus rapid transit system. Terminal Evaluation report. (n.d.). https://erc.undp.org/evaluation/evaluati ons/detail/9001

Financial Challenges and Solution Case Studies

The financial feasibility of such systems is further complicated by the need for technological adaptation to suit local conditions. Trolleybus systems need to be resilient to the specific environmental and urban challenges of LMIC, requiring customized solutions which can increase costs (Sindi et al., 2018; Zhang et al., 2016). Another critical factor is the revenue generation from the trolleybus system, which is often uncertain and may not cover the operating and maintenance costs, let alone the initial investment (Nevolin et al., 2023).

Key Challenge	Description	City Example	Reference
Initial Capital Investment	The funding for the Bus Rapid Transit (BRT) project in Marrakech involved various sources, including the Global Environment Facility (GEF) co-financing, which was a long process to get funds approved.	Marrakech, Morocco	Renewable energy for the city of Marrakech's bus rapid transit system. Terminal Evaluation report. (n.d.). https://erc.undp.org/evaluation/ev aluations/detail/9001
Operational Costs	The main operational expenses for the trolleybus company in Bishkek primarily consist of labor costs, energy costs for trolleybuses, and maintenance and repair expenses.	Bishkek, Kyrgyzstan	Bank, A. D. (2023, October 12). Electric buses to reduce air pollution in Bishkek. Asian Development Bank. https://www.adb.org/news/videos/electric-buses-reduce-air-pollution-bishkek

Revenue Generation	The economic model of the Marrakech BRT system already demonstrates that it is sustainable. It is expected to be even more so with the connection of the plant to the electric bus station. However, this was not so apparent from the outset.	Marrakech, Morocco	Renewable energy for the city of Marrakech's bus rapid transit system. Terminal Evaluation report. (n.d.). https://erc.undp.org/evaluation/ev aluations/detail/9001
Funding Sources	European Bank for Reconstruction and Development (EBRD) Loan: The EBRD loan would be provided for the benefit of *Almatyelectrotrans LLP* to finance the renewal of the trolleybus fleet through the purchase of new hybrid trolleybuses and associated depot equipment.	Almaty, Kazakhstan	GRCF2 Almaty Trolleybus Project - Feasibility and Due diligence study. (n.d.). https://www.ebrd.com/sites/Satel lite?c=Content&cid=13952896486 43&d=Touch&pagename=EBRD%2FContent%2FContentLayout&rendermode=live%3Fsrch-pg
Sustainability of Funding	Retrofitting trolleybuses in their line	Tehran, Iran	https://plus.google.com/11340375 6129291503583. (2014, September 29). Electric Buses to be Back Soon. Financial Tribune. https://financialtribune.com/articl es/people/1479/electric-buses-to- be-back-soon
Cost-Benefit Analysis	This analysis includes capital expenditures (CAPEX), operational costs, maintenance expenses, and potential savings compared to alternative bus technologies	Bishkek, Kyrgyzstan	Bank, A. D. (2023, October 12). Electric buses to reduce air pollution in Bishkek. Asian Development Bank. https://www.adb.org/news/videos/electric-buses-reduce-air-pollution-bishkek

Social Challenges and Solution Case Studies

The success of trolleybus systems also hinges on social acceptability, which encompasses public perception and the willingness of the community to adapt to new transportation modes. The implementation of trolleybus systems is significantly influenced by social challenges, primarily related to public perception and community adaptation.

Key Challenge	Description	City Example	Reference
Communication and Engagement	Special attention is given to vulnerable groups, ensuring their concerns are understood and addressed. The engagement process aims to be inclusive, considering gender, age, ethnicity, and other social characteristics.	Almaty, Kazakhstan	GRCF2 Almaty Trolleybus Project - Feasibility and Due diligence study. (n.d.).https://www.ebrd.com/sites/Satellit e?c=Content&cid=1395289648643 & d=Touch&pagename=EBRD%2FCo ntent%2FContentLayout&renderm ode=live%3Fsrch-pg
Community Adaptation to Trolleybuses	Successful adaptation to trolleybuses depends on how well they meet community transportation needs.	Urgench, Uzbekistan	Budach, D. (2023, February 21). Surrounded by the desert: Uzbekistan's last trolley bus service - Urban Transport Magazine. Urban Transport Magazine. https://www.urban-transport-magazine.com/en/surrounded-by-the-desert-uzbekistans-last-trolley-bus-service/

Supply-Chain Challenges and Solution Case Studies

The development of trolleybus systems in low- and middle-income (LMIC) cities encounters several supply-chain barriers. While the specific research on this topic is limited, we can infer challenges based on similar infrastructure projects in LMIC and general supply chain management issues.

Key Challenge	Description	City Example	Reference
Availability of Trolleybuses and Parts	Developing sourcing strategies for trolleybus parts involves identifying reliable suppliers, negotiating favorable contracts, and establishing contingency plans for emergency part requirements.	Bishkek, Kyrgyzstan	Bank, A. D. (2023, October 12). Electric buses to reduce air pollution in Bishkek. Asian Development Bank. https://www.adb.org/news/videos/el e ctric-buses-reduce-air-pollution-bishkek
Maintenance and Technical Support	For options like trolleybuses, there's a focus on the maintenance of additional infrastructure, such as overhead lines.	Bishkek, Kyrgyzstan	
Financial Constraints	The revival of the emission-free trolleybus corridors in Mexico City	Mexico City, Mexico	Editorial, UTM. (2024, January 1). Trolleybus, light rail and cableway in Mexico City: The transformation of the STE - Urban Transport Magazine.

Regulatory and Policy Barriers	Regulatory barriers related to infrastructure development, including zoning regulations and permitting processes, can hinder the expansion of trolleybus routes and the modernization of existing infrastructure	Bishkek, Kyrgyzstan	Bank, A. D. (2023, October 12). Electric buses to reduce air pollution in Bishkek. Asian Development Bank. https://www.adb.org/news/videos/ele ctric-buses-reduce-air-pollution-bishkek
Market Dynamics and Demand Uncertainty	Efforts to improve trolleybuses include modernizing the existing infrastructure and rolling stock.	Russia	Grigorieva, O., & Nikulshin, A. (2023). Trolleybuses and trams in the urban public transport network of Russian regions: problems and prospects. E3S Web of Conferences, 371, 04019. https://doi.org/10.1051/e3sconf/202337104019

7 Existing LMIC Trolleybus City Case Studies

7.1 Mexico City, Mexico[9]

Mexico City is the capital of Mexico. It is situated at the center of the country. Mexico City is the second most populated metropolitan area in Latin America. Mexico City: 9.2 million inhabitants (2020). The Metropolitan Area of the Valley of Mexico: 22 million inhabitants (2020). Mexico City is divided into 16 municipalities.

Figure 12 Figure 10 Yutong articulated trolleybus (12 meters) in Mexico (Alejandro Palmerín (2022))

Trolleybus network development

The Mexico City trolleybus system serves Mexico City and is operated by Servicio de Transportes Eléctricos (STE). The system opened on 9 March 1951. The trolleybus network in the best moment had 30 lines and over 1,100 vehicles. However, due to neglect and aging infrastructure, only 130 trolleybuses are operational on 8 lines, often running irregularly up t0 2019. By 2019, the lines were identified with the eight following letters: A, CP, D, G, I, K, LL and S. As of 2024, the fare is MXN $4.00 (€ 0.18, or US$ 0.21).

Transformation and Improvements

In Mexico City, the trolleybus network has seen significant improvements in recent years. As of 2023, the average daily ridership on the STE trolleybus lines has more than doubled compared to 2019. Daily ridership was around 120,000 passengers in 2019. After a change in city government in 2019, the new administration under Mayor Claudia Sheinbaum prioritized public transport. Since then, they have purchased a total of 425 new trolleybuses from the Chinese manufacturer Yutong, including articulated vehicles. Mexico City is also introducing an elevated Bus Rapid Transit (BRT) trolleybus line, which offers the advantages of a crossing-free guided rapid transit system. Trolleybus passenger numbers have significantly increased, with an average of 315,000 passengers per day in 2023.

Upcoming Developments

Two new trolleybus lines (Line 11 and 12) are currently under construction and are expected to open soon, by the end of 2024. Initially, these new Trolleybus lines will serve 120,000 passengers per day, and when fully operational, they will accommodate 230,000 passengers daily.

[9] Source: Trolleybus, light rail and cableway in Mexico City: The transformation of the STE. Urban Transport Magazine. Available in: https://www.urban-transport-magazine.com/en/trolleybus-light-rail-and-cableway-in-mexico-city-the-new-ste/ (24 april,2024).

7.2 Marrakech, Morocco[10]

Figure 13 Yangtsebus in Marrakesh, Morocco (Transitphoto.org https://transphoto.org/photo/1715524/)

Marrakech, also known as Marrakesh, is a major city in the kingdom of Morocco. It is in the center of the fertile, irrigated Haouz Plain, south of the Tennsift River. The city lies west of the foothills of the Atlas Mountains. Marrakech is a significant urban agglomeration with a growing population. As of 2020, the city had an estimated population of approximately 966,990. By 2024, the population is projected to reach 1,067,172. The city is divided into several districts, with the most notable divisions being the Medina, the Kasbah, and the Mellah within the old city walls. Outside the walls lies the new city.

Trolleybus Network Development

The network is operating15 high-capacity electric trolley buses, each 18 meters in length. Initially, 10 buses were from Yangtze Motors. It includes a 7 km route from Bab Doukkala to Al Massira, with 3 km equipped for trolleybus operation and in-motion charging. Buses owned by Société de Développement Local (SDL) and operated by ALSA Marrakesh.

Transformation and Improvements

750 kW solar park developed through a GEF-funded project, partly powering the system. Insufficient ridership due to mismatched route planning and travel demand distribution. Limited monitoring and evaluation of fleet operations, highlighting the need for better technical support. Proof of concept for integrating renewable energy with public transport. The initial phase reduced 952 tons of CO_2 compared to conventional diesel buses.

Upcoming Developments

Purchase of additional electric buses and expanded solar power integration recommended. Investment Required for financing for 48 electric buses and a 5.7 MWp solar installation estimated at 82 million USD.

[10] Source: Islamic Development Bank (IsDB) and Centre for Environment and Development for the Arab Region and Europe (CEDARE), 2024. Case Studies of Egypt, Jordan, and Morocco: Situation Analysis and Preliminary Market Study for Advancing E- Bus Systems. Resilience and Climate Action Department, Economic and Social Infrastructure Department.

7.3 Almaty, Kazakhstan[11]

Figure 14 Yutong bus in Almaty Kazahstan (Source: Transitphoto.org https://transphoto.org/photo/1911721/)

Almaty, formerly known as Alma-Ata, is the largest city in Kazakhstan. It is in the southeastern part of the country, near the border with Kyrgyzstan, at the foothills of the Trans-Ili Alatau mountains. Almaty is a major cultural and economic center in Kazakhstan. It has a population of more than 2 million people, making it the most populous city in the country.

Trolleybus Network Development

Almaty's public transport system carries over 375 million passengers per year.
The bulk of passenger traffic (circa 86%) is carried out by buses and minibuses operated by private and municipal companies. Electric public transport, including trolleybuses, accounts for approximately 10% of the total traffic, with the trolleybus network comprising 9 routes managed by Almatyelectrotrans LLP.

Transformation and Improvements

The European Bank for Reconstruction and Development (EBRD) is financing the upgrade of Almaty's trolleybus fleet and infrastructure under the Green Cities Framework 2 Window II ("GrCF2 W2"). The project involves acquiring 190 modern, energy- efficient trolleybuses, rehabilitating trolleybus depots, and modernizing trolleybus infrastructure. This investment is expected to reduce greenhouse gas emissions, improve public transport services, and support a shift to electric mobility.

Upcoming Developments

The project will serve as Almaty's 'trigger investment' under GrCF2 W2 and formally initiate Almaty's participation in EBRD Green Cities.
It aims to develop a Green City Action Plan (GCAP) for Almaty, focusing on environmental challenges and promoting inclusive and sustainable urban development.

Gender and Inclusion Initiatives

The project includes initiatives to improve women's access to employment as trolleybus drivers and increase the share of female heads of department within the transport sector in Almaty

[11] Source: European Bank for Reconstruction and Development, 2022. GRCF2 W2: Almaty Electric Public Transport (Final). European Bank for Reconstruction and Development

7.4 Urgench, Uzbekistan[12]

Figure 15 Škoda bus in Urgench Uzbekistan (Source: Transitphoto.org https://transphoto.org/photo/1948658/)

Urgench is a city in Uzbekistan, serving as the capital of the Khorezm Region. It is situated in western Uzbekistan, near the Amu Darya River and the Shavat canal. As of 2021, Urgench has an estimated population of approximately 145,000. Urgench is divided into several smaller administrative districts or neighborhoods, it is known as a district- level city within the Khorezm Region.

Trolleybus Service Overview

The trolleybus line has been operational since 1997, marking it as a long-standing transportation link. The line spans approximately 33 kilometers, connecting Urgench to the historical city of Chiva, an oasis along the Silk Road and a UNESCO World Heritage Site. This route initially aimed to facilitate access for tourists to Chiva, linking key entry points such as the railway station and the airport in Urgench to the north and west gates of Chiva. While initially catering to tourists, the trolleybus service has increasingly served the local population over the years.

Technical and Operational Aspects

The service is maintained with a fleet of trolleybuses provided by Skoda Electric, which replaced an older generation of vehicles. These trolleybuses, delivered in 2013, do not have an auxiliary drive and are thus dependent on the overhead lines.

Depot Facilities: The trolleybuses are housed and maintained at a depot in Urgench, where older vehicles from the initial fleet are also stored, albeit in a deteriorated condition.

Current Operations: The trolleybus runs daily from approximately 6:30 AM to 6:30 PM, with a frequency of a bus every 20 minutes.

Operational Practices: Stops are made at designated points and upon request along the route. The service competes with local minibuses, adopting flexible stopping strategies to attract passengers.

Challenges and Resilience

Sustainability of Service: Despite various challenges, including changes in national transport policy and economic conditions, the trolleybus line in Urgench- Chiva continues to operate. It stands out as a resilient form of public transportation in the region, contributing to both local mobility and environmental sustainability.

[12] Source: Budach, D. (2023). Surrounded by the desert: Uzbekistan's last trolley bus service. Urban Transport Magazine. Disponible en: https://www.urban-transport-magazine.com/en/surrounded-by-the-desert-uzbekistans-last-trolley-bus-service/ (Consultado: 24 Abril 2024).

8 Potential Trolleybus Use-Cases as Alternatives to Planned BEB Systems

8.1 Medellin, Colombia

The BRT project in Medellín with trolleybuses is set within a context of increasing concern for sustainability and energy efficiency in urban transportation. Medellín, a city experiencing significant population growth and challenging topography, has faced high levels of air pollution and traffic congestion. The traditional BRT (Bus Rapid Transit) system has utilized diesel buses, contributing to these environmental issues. The initiative to incorporate trolleybuses into the BRT system aims to leverage the advantages of transportation electrification, significantly reducing CO2 emissions and other pollutants.

The project includes the installation of an overhead wire infrastructure along the BRT routes, enabling trolleybuses to operate continuously and efficiently on exclusive lanes. Modern trolleybuses, equipped with high-efficiency AC motors and advanced traction systems, offer a robust and sustainable solution. Additionally, these vehicles are designed to handle Medellín's steep slopes more effectively than diesel buses, providing more reliable and comfortable transportation for users.

8.2 Istanbul, Turkey

The Istanbul Bus Rapid Transit (BRT) project aims to address the city's significant transportation challenges by transitioning from diesel buses to a more sustainable and efficient trolleybus system. Istanbul, a densely populated metropolis, suffers from severe traffic congestion and high levels of air pollution, exacerbated by the extensive use of diesel buses. The current BRT system, which operates along a 52-kilometer route and serves approximately 340 million passengers annually, is under pressure to meet increasing demand while reducing its environmental footprint. The proposed trolleybus system offers a compelling alternative by leveraging electric power, thereby reducing dependence on imported fossil fuels and cutting greenhouse gas emissions. Trolleybuses, which draw electricity from overhead wires, provide continuous and reliable service without the range limitations of battery electric buses. This system's energy efficiency is enhanced by regenerative braking technology, which recaptures energy during stops.

The project entails significant initial investments in infrastructure, including the installation of overhead contact lines and substations, but these costs are offset by the long-term savings from lower operational expenses and maintenance costs. Moreover, the adoption of trolleybuses aligns with Istanbul's sustainability goals, contributing to improved air quality and reduced noise pollution, thus enhancing the overall quality of urban life.

8.3 Amman, Jordan

The evaluation of deploying low-carbon buses for the bus rapid transit (BRT) system in Amman, Jordan, includes a comparison of various bus options such as hybrid, plug-in hybrid, opportunity charging, trolleybus, and battery electric buses against the baseline of diesel buses. The study highlights the significant contribution of the transport sector to greenhouse gas (GHG) and air pollutant emissions, emphasizing the urgency of adopting low-carbon buses. The analysis covers the technical, operational, and financial aspects of these bus options, assessing their respective advantages and disadvantages. This comprehensive evaluation aims to identify the most suitable low-carbon bus option for Amman's BRT system, considering factors like upfront capital costs, infrastructure requirements, energy and maintenance costs, and overall environmental impact.

8.4 Jinan, China

The Shandong Spring City Green Modern Trolley Bus Demonstration Project is situated in Jinan City, the capital of Shandong Province, People's Republic of China (PRC). The project aims to establish a modern trolleybus system to improve the urban transport environment, reduce emissions, and alleviate road congestion. The project, supported by a $150 million loan from the Asian Development Bank (ADB), involves constructing a 111.2 km zero-emission Bus Rapid Transit (BRT) network served by electric trolleybuses. This initiative is part of Jinan's broader urban development strategy, which includes enhancing public transport services to address traffic congestion and pollution. Jinan is in the middle part of Shandong Province, approximately 400 km south of Beijing. The city is bordered by Liaocheng to the southwest, Dezhou to the northwest, Binzhou to the northeast, Zibo to the east, Laiwu to the southeast, and Tai'an to the south. Jinan is known as the "City of Springs" for its numerous natural springs, and it plays a crucial role as a transportation hub with well-developed railway, highway, and aviation networks.

8.5 Technical and Operational Comparison

Aspect	Medellín, Colombia	Istanbul, Turkey	Amman, Jordan	Jinan, China
Bus Type	Trolleybus vs Battery Electric Bus	Trolleybus vs Diesel Bus	Trolleybus vs Battery Electric Bus	Modern Trolleybus vs Battery Electric Bus
Energy Consumption	Trolleybus: 1.2 kWh/km BEB: 1.2 kWh/km	Trolleybus: 3 kWh/km (10.8 MJ/km) Diesel: 21.66 MJ/km	Trolleybus: High efficiency, no batteries BEB: Battery powered, energy loss	Trolleybus: 89 kWh/100km BEB: 160 kWh/100km
Passenger Capacity	Trolleybus: 105 BEB: 64	Trolleybus (double articulated): 221 Diesel: 120-150	High capacity, continuous operation vs flexible but limited range	12m and 18m trolleybuses for high capacity
Route Flexibility	Limited by overhead wires	Limited but off-wire auxiliary possible	BEBs more flexible, trolley limited	Trolleybus limited to wired routes, BEBs flexible
Performance on Slopes	Trolleybus excels on steep slopes	Not specified	Trolleybus better in urban context	Not specified
Noise Level	Both quiet	Lower noise for trolleybus	Quiet with zero tailpipe emissions	Zero tailpipe emissions for both

8.6 Financial and Environmental Aspects

Aspect	Medellín, Colombia	Istanbul, Turkey	Amman, Jordan	Jinan, China
Infrastructure Costs	€1M-3M/km for overhead wires	€38.7M overhead + substations + €387.1M vehicles	High upfront CAPEX for wires and buses	$377.1M total; $150M ADB; $227.1M local
Vehicle Purchase Costs	BEBs costlier due to batteries	Higher vehicle costs for trolleybus fleet	High upfront bus CAPEX for both types	Investment split between buses and infrastructure
Maintenance & Operating Costs	Lower for trolleybus infrastructure maintenance, varies for BEBs	Lower for trolleybuses vs diesel	Lower OPEX for trolleybuses, complex charging for BEBs	Lower operating cost for trolleybuses
Emission Reductions	Zero street emissions for trolleybuses	85-88% reduction in CO, NOx, PM, CO2 vs diesel	Zero tailpipe from trolleybuses and BEBs	Zero tailpipe emissions; emissions depend on grid mix
Energy Efficiency & Lifespan	Higher for trolleybuses on fixed routes	25% energy recovery by regenerative braking	Trolleybuses more energy efficient due to direct electricity	Trolleybus more efficient than BEBs
CO2 Savings	Significant for trolleybuses over diesel/BEB	Major reduction vs diesel	Lower GHG emissions with both types	Reduced emissions expected but depends on power source

8.7 Suitability and Strategic Insights

Medellín highlights trolleybuses' suitability for hilly terrain and consistent BRT routes with a local manufacturing advantage, offering cost savings and better energy efficiency at scale.

Istanbul benefits from trolleybuses' large passenger capacity and renewable integration through regenerative braking, though infrastructure investment is substantial.

Amman stresses the trade-off between initial investment and long-term operational costs, with trolleybuses favored for high-frequency consistent routes, while BEBs offer route flexibility but pose charging challenges.

Jinan demonstrates a large-scale investment in trolleybus BRT network to combat congestion and pollution, with advanced infrastructure enabling extensive zero-emission public transport, supported by international development financing.

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