Charging Technology Options for E-Buses in Bengaluru

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SHAKTI
SUSTAINABLE ENERGY FOUNDATION

Charging Technology Options for E-Buses in Bengaluru

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Shakti Sustainable Energy Foundation seeks to facilitate India's transition to a sustainable energy future by aiding the design and implementation of policies in the areas of clean power, energy efficiency, sustainable urban transport, climate change mitigation, and clean energy finance.

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Executive Summary

Electric buses (e-buses) have caught the attention of the Indian public transport operators due to their ability to address the issues of rising greenhouse gas emissions, and air and noise pollution caused by conventional fuel buses. The Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles (FAME) II scheme envisages the deployment of 7,000 e-buses by 2024. In order to make this a seamless transition, an efficient charging infrastructure is imperative. Currently, depot-based plug-in charging is the most common method of charging e-buses in India. Though it is preferred for its low capital cost and use of low-power chargers—and also because it draws power during off-peak hours—there are several challenges associated with this technology. For instance, it can be installed only at a few designated locations, requires long charging durations, causes high range anxiety, and demands dedicated space. Several manufacturers, operators, and decision-makers are keen to explore other charging alternatives, therefore.

In this context, this study explores three alternative charging technologies: battery swapping, opportunity charging, and battery-assisted trolleybus systems.

The aim of this study was to assess the technical feasibility of deploying these charging technologies in Bengaluru. A framework was developed to compare the technical parameters of the three e-bus charging technologies. Through the framework, the study seeks to create awareness among stakeholders regarding the benefits and limitations of these technologies.

First, a literature review of the key technical parameters of the three charging technologies was performed and a comparison matrix was prepared. Later, some routes were selected and analysed to evaluate the key parameters of each charging technology. These parameters were then compared to identify the most feasible e-bus charging technology for the route.

For demonstrating the framework, four Bengaluru Metropolitan Transport Corporation (BMTC) air-conditioned (AC) bus routes were chosen: two from the airport AC routes, and two from the Vajra (non-airport AC routes) routes. Trip origins and destinations, trip start and end times, halting locations, and distance travelled for one representative schedule (for each of the two routes), were considered for analysis. Technology parameters (like battery capacity, charging power, maximum power requirement, and total energy demand); operational parameters (like number of recharging locations, number of daily recharges required, and minimum area requirement); and financial parameters (like the operational cost in terms of electricity used, the capital cost of the bus, battery, and infrastructure) were compared for the selected routes.

As the cost of battery and charging-infrastructure components constitutes a major share of the total capital cost of operating an e-bus, the trade-off between battery size and the number of charging locations decides the type of charging technology to be chosen. The comparison showed that battery swapping is suitable for shorter routes (trip length between 25 km and 30 km) that are associated with a larger depot and require relatively low investment. Opportunity charging was found to be suitable for longer routes (50 km or more) but with more charging locations. It is especially preferred when the space for queuing and charging the buses in the depot is limited. Battery-assisted trolleybuses were found to be suitable for shorter or longer routes and can be deployed where tram systems are prevalent, since they have a higher infrastructure cost.

The analysis concluded that while converting a large fleet of traditional fuel-based buses to e-buses, a combination of charging technologies should be considered. However, since the feasibility of employing the technologies depends on city-specific characteristics such as traffic, and bus-transit network and operations, a common incentive scheme (such as the one under FAME or those under state-level EV policies) may not be applicable to all cities or states across the country. For a successful transition to e-mobility on a large scale, cities should prepare customised action plans for e-bus deployment, considering the characteristics discussed in this study. The central agencies should then evaluate the proposals and initiate necessary actions.

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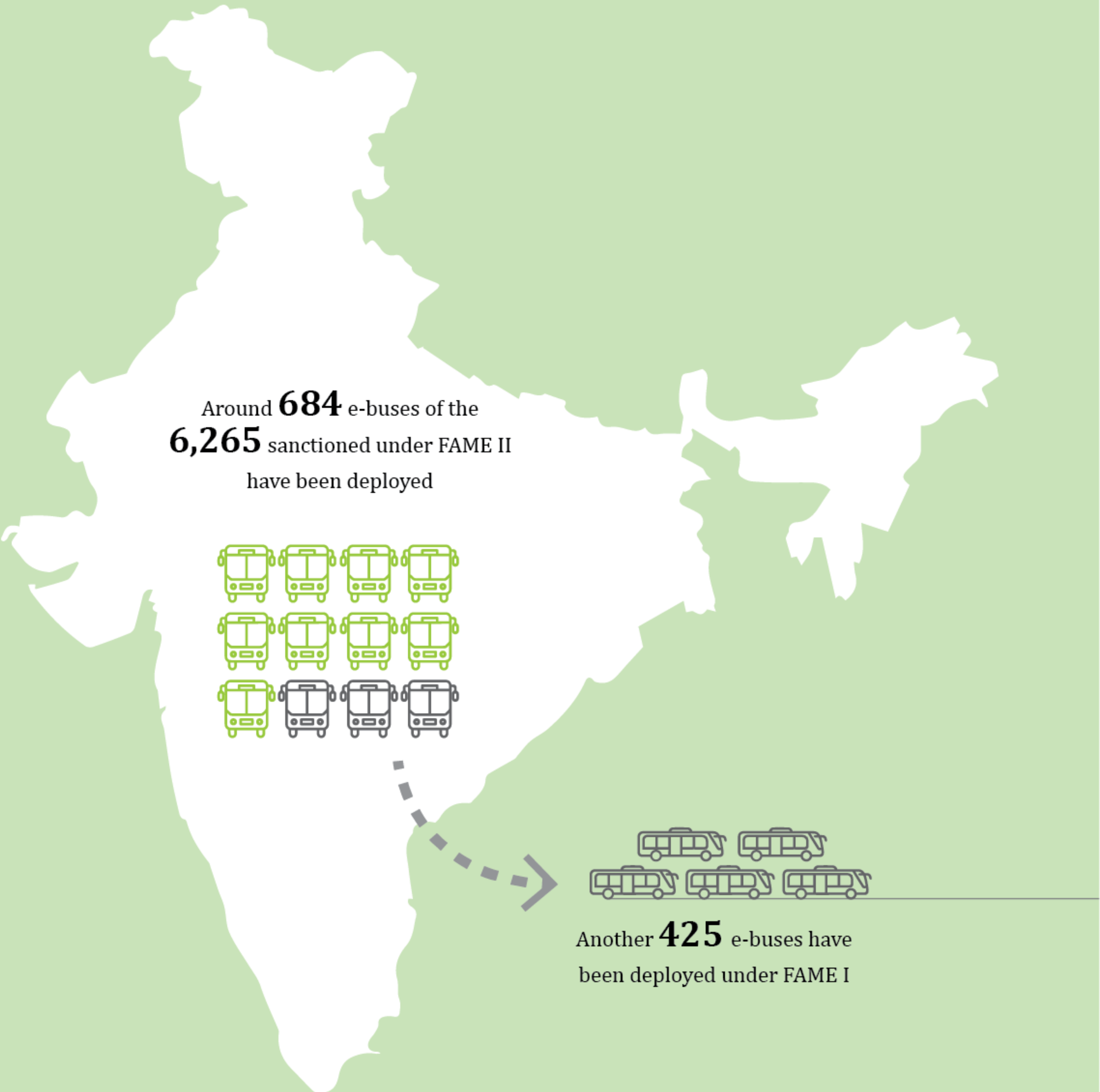
Abbreviations

AC	air conditioned
ARAI	Automotive Research Association of India
BIS	Bureau of Indian Standards
BMR	Bengaluru Metropolitan Region
BMTC	Bangalore Metropolitan Transport Corporation
CCS	combined charging system
CNG	compressed natural gas
CSTEP	Center for Study of Science, Technology and Policy
DC	direct current
EV	electric vehicle
EVSE	electric vehicle supply equipment
FAME	Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles
FC	fast charger
FCB	fluid-cooled batteries
GST	Goods and Services Tax
hr	hour
IMC	in-motion charging
INR	Indian rupee
km	kilometre
KIAS	Kempegowda International Airport Service
kWh	kilowatt-hour
LTO	lithium titanium oxide
min	minute
MoHUA	Ministry of Housing and Urban Affairs
MoP	Ministry of Power
NEMMP	National Electric Mobility Mission Plan
PCS	public charging stations
SC	slow charger
SGST	State Goods and Services Tax
SPV	special purpose vehicle
sq.m	square kilometre
TTMC	Traffic and Transit Management Centres

1. Introduction



In recent years, electric buses (e-buses) have gained prominence as a substitute to the traditional diesel and compressed natural gas (CNG) buses in India. Phase II of the Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles (FAME) India Scheme aims to support the deployment of 7,000 e-buses across the country, of which 6,265 have been sanctioned, as of November 2021 (Ministry of Heavy Industries & Public Enterprises, 2019). Given the benefits of reduced local air and noise pollution, lower greenhouse gas emissions, and comparable total costs of ownership that e-buses offer, their growing popularity is not surprising (CSTEP-SSEF, 2018; Global Green Growth Institute & Center for Study of Science, Technology and Policy, 2015).

Karnataka's Bangalore Metropolitan Transport Corporation (BMTC), which has been at the forefront of e-bus adoption in the country, plans to induct 300 e-buses for its regular service (Bengaluru Metropolitan Transport Corporation [BMTC], 2019a) and 90 e-buses for its metro-feeder service (Menezes, 2020). In our previous study "Implementation Plan for Electrification of Public Bus Transport in Bengaluru", the Center for Study of Science, Technology and Policy (CSTEP) worked closely with BMTC to draft an e-bus fleet implementation plan. Key outputs of the project included the identification of suitable e-bus routes for installing electric vehicle supply equipment (EVSE), and a cost-benefit assessment framework for e-bus variants (including fully electric and hybrid buses) (CSTEP-SSEF, 2018).

The present study builds on these foundations, by examining some key innovative charging solutions for e-buses and testing their applicability to Bengaluru. The most common method of charging e-buses is depot-based plug-in charging. However, there are many challenges associated with this method, such as captive charging, long charging durations, high range anxiety, and space availability issues. Therefore, to allow for more flexibility in operating e-buses, it is important that alternatives to depot-based plug-in charging be explored. In this context, the study explores three other e-bus charging technologies: battery swapping, opportunity charging, and battery-assisted trolleybus systems. Each of these solutions has different characteristics, which have been explored in detail.

1.1 Need for the study

In India, only plug-in charging is eligible for subsidy under Phase II of the FAME India Scheme (Department of Heavy Industries, 2019) (Appendix I). However, many states, such as Telangana, Kerala, Delhi, and Karnataka, have released electric vehicle (EV) policies to encourage battery swapping, and India's first e-bus battery swapping station has been set up in Gujarat (Parikh, 2019; WRI India, 2019). Thus, there is a visible willingness among Indian policymakers to evaluate and encourage the use of innovative charging solutions.

1.2 Aim

The aim of this study is to assess the technical feasibility of deploying battery swapping, opportunity charging, and battery-assisted trolleybus systems, alongside the prevalent depot-based plug-in charging systems in Bengaluru.

1.3 Objectives

The key objectives of the study are:

- Preparing a framework to compare and assess the feasibility of the e-bus charging technologies.
- Creating stakeholder awareness regarding the benefits and limitations of these alternative e-bus charging technologies.

1.4 Scope and limitations

The scope of this study extends to developing a framework for assessing the feasibility of the e-bus charging technologies. The framework identifies the operational parameters and constraints of each technology. However, the practical challenges involved in setting up and operating these technologies are not explored here. Also, due to a lack of contextual studies, the impact of traffic conditions, topography, and the eventual degradation of batteries have not been considered in estimating the effective range of e-buses.

The framework is demonstrated on four selected routes but can be used for other routes and cities, and the findings can be utilised to assist/strengthen decision-making for the charging requirements of large-scale e-bus deployment.

2. Global and Indian Experience

The features of battery swapping, opportunity charging, and battery-assisted trolleybuses, as learnt from various case studies, are presented in this section. The basic method of charging e-buses—depot-based plug-in charging—involves the installation of EVSEs, commonly known as chargers, at bus depots. The chargers installed at the depots are used to replenish the depleted on-board batteries of e-buses, using a plug-in method. The time taken to charge the batteries (2-3 hours) with this technology is significantly longer than the time taken by diesel buses to refuel (5-10 minutes). Due to this, e-buses have to undergo charging post operational hours or during overnight halts (Das et al., 2019). Though this ensures that the operations of the buses are not affected, there may be cases where the battery capacity is insufficient to allow the e-bus to arrive at the depot for charging. The possibility of such cases prompts bus fleet operators to consider alternative charging technologies, some of which are discussed below.

2.1. Battery swapping

An alternative to plug-in charging systems for e-buses is the replacement of the depleted battery itself with a fully charged battery. This is known as battery swapping (An et al., 2020). Depending on manufacturers' designs, swappable battery packs can be placed at the bottom, at the sides, at the rear, or at the top of the e-bus (An et al., 2020; Gao & Wu, 2014; Park, 2016). In this technology, the process of removing discharged batteries from the bus and replacing them with charged batteries from the containers with the help of robots is referred to as a 'swapping event'. The time taken by each swapping event (turnaround time) is usually 2-10 min (Li, 2016; Wangchuk, 2019).

Pros and cons

The main advantage of this technology is that it allows for an extremely quick turnaround time (less than 10 min) as compared to plug-in charging which might need a few hours. Other benefits include the ability to charge batteries slowly and during preferred periods (such as when time-of-day tariffs are favourable or when power demand from the grid is less), and the slower rate of charge which can have a positive impact on battery life (An et al., 2020).

The main disadvantage of swapping is the requirement of land for building swapping stations. The amount of land required for a swapping station depends on the size of the e-bus fleet it needs to cater to, along with the batteries held in reserve for it (in the battery bank). This can be a significant constraint in cities where land is expensive. In order to mitigate expenses related to land, two possible alternatives can be explored. The first is to build smaller swapping stations; and the second is to build the swapping station in areas where land is cheaper, such as in suburban areas. However, both these solutions have drawbacks. While a smaller swapping station will cater to fewer buses, a swapping station located far from the routes will require e-buses to have more expensive batteries with larger energy-storage capacities to accommodate the detour. Therefore, the location and sizing of a swapping station require careful consideration (An et al., 2020).

Another major disadvantage of swapping is the significant additional cost associated with procuring additional battery packs that constitute the battery reserve for the fleet. The number of batteries required for a swapping model has to be 1.5 to 2 times the number of e-buses (Li et al., 2015), to ensure that there are no disruptions in e-bus services.

Technical parameters

India’s first project on battery swapping for e-buses is operated by Sun Mobility and is located in Ahmedabad, Gujarat. In 2019, eighteen e-buses were deployed with battery swapping technology in Ahmedabad. These e-buses operate on a 35 km Bus Rapid Transit System (BRTS) corridor. The batteries are swapped after a round trip. The swapping operation takes 3-4 min and is automated using a robotic arm (Parikh, 2019). According to the discussion with representatives from Sun Mobility, the station itself is built within a cargo container and thus can be transported to any site to directly begin operations. The swapping station takes 60% less space than a depot-based charging system and consumes only 33% of the energy required by a direct current (DC) fast-charging station. These details, as shared by Sun Mobility with CSTEP, are discussed in Table 1.

In order to gain further insights about e-bus swapping stations, two cases from China were studied. The first case is of Xuejiadao Station, located in Qingdao, Shandong Province, China. It was designed to serve six routes and requires eight minutes to complete a swapping event. The station (seen in Figure 1) can complete 540 swapping events in a day (Li et al., 2018).

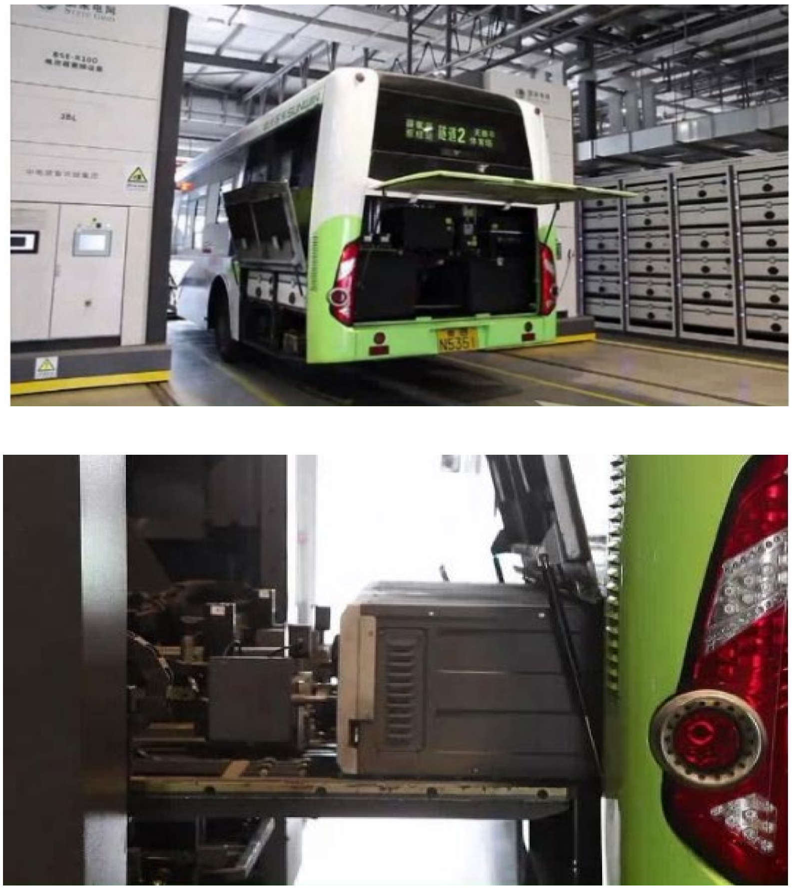


Figure 1: Swapping operations at the Xuejiadao Station in Qingdao

(Source: Li et al., 2018)

The second case is of the swapping station that was constructed for World Expo 2010 in Shanghai, China. The station serviced three routes with 120 e-buses (Li et al., 2015). The technical parameters of these stations have also been compared in Table 1.

Table 1: Technical parameters for swapping stations

Attributes	Xuejiadao Swapping Station, Qingdao	World Expo 2010 Swapping Station, Shanghai	Swapping Station, Ahmedabad, India
Number of e-buses serviced	180	120	18
Battery capacity	225 kWh		60-65 kWh
Average daily mileage	190 km	181 km	
Max range per charge	132.68 km	68 km	54-70 km
Energy consumption	1.2 kWh/km	NA	NA
Average daily swaps	2 per e-bus	2.7 per e-bus	NA
Average charging time for batteries	144 min	118 min	NA
Number of batteries	300	232	~27
Number of battery racks	120	NA	NA
Number of swapping units	6	8	12
Number of charging units	120	112	NA
Power per charging unit	90 kW	63 kW	60 kW
Charging power consumed by the station	8 MW	8 MW	NA

These technical requirements of battery swapping technology have been compared with those of opportunity charging and battery-assisted trolleybuses in Table 4.

Costs

A study by Jhunjhunwala (2017) estimates the cost of operating a swapping station to be INR 15.71 per km (battery and infrastructural costs being INR 8.8 per km; operational costs of electricity and manpower being INR 6.91 per km). Estimates made by the Alliance for an Energy Efficient Economy (AEEE) indicate a capital investment of at least INR 3.2 crore, and an additional cost of INR 2.5 to 4 lakh for the ancillary infrastructure, per swapping station (Das et al., 2019). Operational and infrastructural costs of swapping stations will, thus, vary according to factors like the expected size of the service fleet and location.

2.2. Opportunity charging

Opportunity charging is a process that aims to replenish a large amount of energy in short bursts. The purpose behind opportunity charging is range extension. Through frequent recharging events, the EV can sustain its state of charge, and thus its range capability, over a longer period of time (Electric Power Research Institute, 1999). In the case of opportunity charging, charging can take place at the bus stops in the network, at the terminals, or at the bus depots (Rogge et al., 2015). The process of connecting a charger (pantograph or wireless) to the bus and disconnecting it after charging is referred to as a 'recharging event'. In many cases, plug-in charging systems remain the primary technology for recharging e-buses while they are at rest for long periods (Zero Emission Urban Bus System [ZeEUS], 2018).

The time taken to charge via opportunity charging—though still more than that taken to refuel buses—is considerably less than the time taken by plug-in charging. It is important to note here that opportunity charging relies on the most advanced charging technologies and battery chemistries such as lithium titanate (LTO), or even technologies like supercapacitors, often leading to higher capital costs (ZeEUS, 2018). In this study, opportunity charging has been divided into two categories on the basis of the charging method. These are induction-based opportunity charging and pantograph-based opportunity charging (Clairand et al., 2019; ZeEUS, 2018).

Induction-based opportunity charging (or simply induction charging) relies on wireless energy transfer from an external source (wireless charging), without the requirement of any physical contact between the bus and the charger (Li & Mi, 2014), as shown in Figure 2.

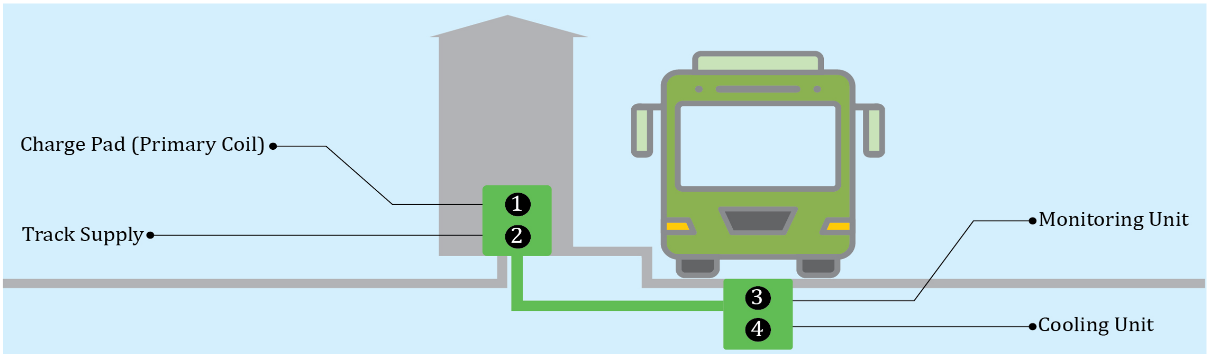


Figure 2: Schematic representation of induction charging

(Source: Swenja et al., 2020)

Pantograph-based opportunity charging (or pantograph charging) relies on high-powered charging through physical contact (Clairand et al., 2019) (as shown in Figure 3). The system can either be bottom-up, with a built-in pantograph on the e-bus roof or top-down, where the pantograph is installed at the charging location. In the former type, the pantograph ascends from its enclosure and makes contact with external contact rails, which, upon contact, initiate high-powered DC charging (Siemens, 2019). In the latter, the inverted pantograph descends from the charging hood to make contact with the on-board rails to initiate high-powered DC charging (ABB, 2019; Siemens, 2019).

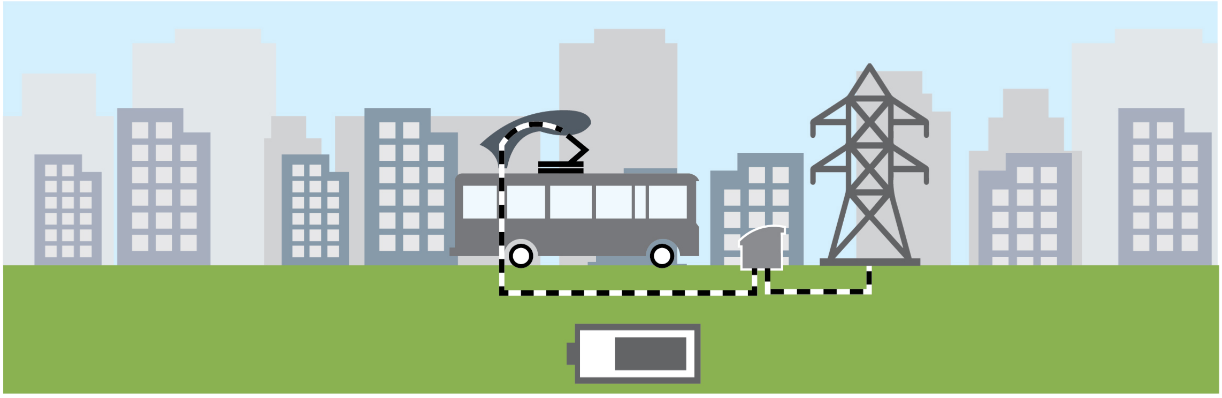


Figure 3: Schematic representation of pantograph charging

(Source: Siemens AG, 2015)

In both cases, the process of extending and withdrawing the pantographs is fully automated, and takes only a few seconds.

Pros and cons

Though opportunity charging is efficient in rapidly increasing the operational range of e-buses, most of them rely on plug-in charging at depots at the end of their daily operations, as the primary recharging event. The average charging time for such events is about four hours (ZeEUS, 2018).

While there is some evidence that wireless charging can reduce energy consumption and greenhouse gas emissions (Bi et al., 2015), the technology is limited by the low efficiency of energy transfer, high installation costs, and exposure of humans to magnetic fields and radio frequency radiation (Clairand et al., 2019; Musavi & Eberle, 2014).

It is important to note here that rapid opportunity charging results in battery heating, which may lead to reduced cycle life of the batteries. This can be mitigated through carefully designed cooling systems. However, evaluating the impact of opportunity charging on the overall cycle life is difficult because—depending on the effectiveness of temperature and overcharge control—the impact on batteries may or may not be beneficial (Electric Power Research Institute, 1999).

The frequent and high-power charging events constitute another drawback of this technology, as they increase the load on the grid. Additionally, these events occur during the usual peak hours of the day, increasing the cost of electricity consumed.

Technical parameters

Induction charging has been deployed across at least eight European cities, including Berlin, London, and Utrecht (ZeEUS, 2018). The average charging time for induction-based charging is approximately 5 to 7.5 min. The on-board batteries possess a battery capacity that typically lies between 60 and 75 kWh (ZeEUS, 2018).

Pantograph charging uses a power supply of up to 450 kW (Clairand et al., 2019). However, the latest designs can supply power up to 600 kW as well (Siemens, 2019). Thirty European cities, including Prague, Helsinki, Barcelona, and Stockholm have deployed e-buses that use pantograph charging. The typical capacity of the on-board batteries used in these e-buses is 80 to 90 kWh, and they take 5 to 13 min to charge through the pantograph (ZeEUS, 2018). As pantograph charging forms the more common category of opportunity charging, its technical requirements have been compared to the others in Table 4.

Costs

The capital cost for an induction charging system is over INR 2.25 crore, and the cost of ancillary infrastructure is between INR 3.8 lakh and 7.2 lakh (Das et al., 2019). For a DC pantograph charging system, the capital cost is between INR 32 lakh and 1.125 crore, and the cost of ancillary infrastructure is between INR 6 lakh and 12.5 lakh.

2.3. Battery-assisted trolleybuses

Battery-assisted trolleybuses or battery electric hybrid trolleybuses combine the advantages of e-buses and trolleybuses (Grygar et al., 2019). Trolleybuses are a popular public-transit option across the world, using an overhead electrical contact line as their source of power. Battery-assisted trolleybuses utilise an auxiliary power source in the form of an on-board battery, which allows the trolleybus to operate even when contact with the overhead wires is ended or severed (Trolley, 2013). The battery is charged while the trolleybus operates in contact with the overhead lines; this process is known as in-motion charging (IMC) and is shown in Figure 4 (Bartłomiejczyk, 2017).

Pros and cons

Contact lines restrict trolleybuses from operating cyclically on a fixed route along the lines installed. However, the availability of dual power sources in the case of battery-assisted trolleybuses makes them superior to traditional trolleybuses, as the dependence on expensive overhead contact lines can be reduced while allowing for flexibility in the deployment of these trolleybuses. Since charging happens en-route during operations, no turnaround time is required. There is also no requirement of land for setting up the infrastructure. However, as the on-board battery primarily relies on IMC, the length of the overhead contact lines must be sufficient to charge the on-board battery. Also, the on-board battery must store enough energy to ensure undisrupted travel between the sections where overhead lines are absent in the network (Bartłomiejczyk, 2017; Trolley, 2013).

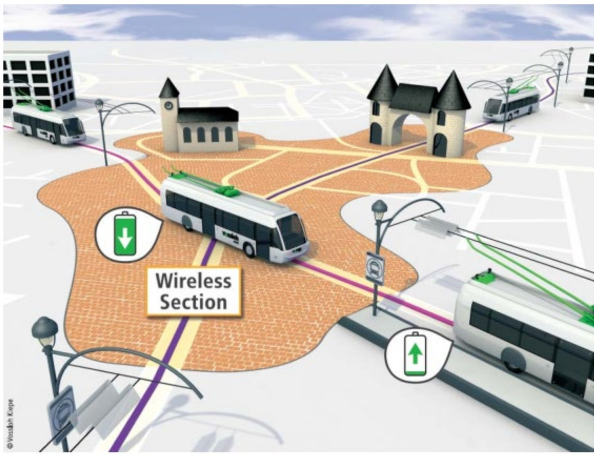


Figure 4: Schematic representation of in-motion charging systems

(Source: Bartłomiejczyk, 2017)

Technical parameters

Battery-assisted trolleybuses have been deployed in some European cities. These include Gdynia and Lublin in Poland; Lucerne and Geneva in Switzerland; Cagliari and Milan in Italy; and Plzen in the Czech Republic. Popular 12m bus models include the Solaris Trollino 12, Skoda 26 Tr, and the Ursus T70116. The size of the on-board batteries on these battery-assisted trolleybuses varies from 13.6 kWh (Ursus T70116. 18) to 69 kWh (Solaris Trollino 12) (ZeEUS, 2018).

The battery-assisted trolleybus system in Gdynia utilises Li-ion on-board batteries of 69 kWh, with an observed charging-discharging efficiency of 96%. The maximum charging power for the on-board battery is 120 kW while in motion, and 90 kW during the halt. Energy consumption is found to depend on external factors such as temperature (higher during winters due to heating load) and varied between 1.2 to 2.5 kWh/km. However, this value can go up to three times the average value, as the energy uptake from the catenary can be as high as 7 kWh/km (while recharging the on-board battery) in adverse weather conditions (Bartłomiejczyk, 2017). The energy consumption of the battery-assisted trolleybus is found to also vary depending on the mode of operation (catenary/battery), charging of the battery, as well as due to energy regeneration, as discussed in Table 2 (Bartłomiejczyk, 2017).

Table 2: Energy consumed by battery-assisted trolleybuses

Energy Consumption	Catenary Operation Mode	Battery Operation Mode
Total energy consumption	No battery charging: 1.45 kWh/km	1.27 kWh/km
	Battery charging (fast mode): 4.06 kWh/km	
Energy consumption with regeneration	0.84 kWh/km	1.01 kWh/km
Energy consumption without regeneration	1.45 kWh/km	1.6 kWh/km

Thus, the contact line must be supplied with power from a strong system in order to withstand this additional demand. The average operational speed of the trolleybuses varies between 12 and 18 kmph. These trolleybuses are able to cover up to 29 km while relying exclusively on auxiliary batteries. Technical details of the battery-assisted trolleybus system in Gdynia are given in Table 3 (Bartłomiejczyk, 2017).

Table 3: Technical details of a battery-assisted trolleybus model

Number of battery modules	3, connected in parallel
Total capacity of batteries	69 kWh
Technology	Lithium-ion
Producer	Impact Clean Power / EnerDel
Single module capacity	23 kWh / 36 Ah
Maximum voltage of a module	728 V
Maximum continuous output power of a module	64 kW
Maximum continuous power of module charging	38 kW

On the basis of these factors, the study estimated the theoretical minimum coverage of the overhead contact lines to fall within the range of 11% and 29%. The lower bound indicates low-speed conditions along the contact lines, and lower energy consumption; the upper bound indicates high speeds along the contact lines, and higher energy consumption (Bartłomiejczyk, 2017).

It can be learnt from the example of battery-assisted trolleybuses in Gdynia that the minimum catenary coverage depends on various operational and charging conditions (Figure 5).

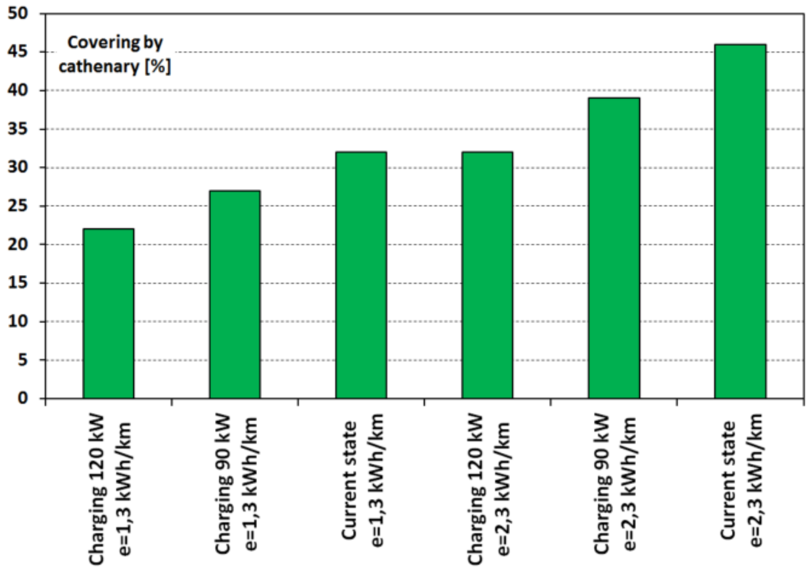


Figure 5: Minimum catenary coverage for various operating and charging conditions

(Source: Bartłomiejczyk, 2017)

Note: "Current State" implies a charging power of 70 kW, which was in use in Gdynia at the time of the study.

While the contact-line coverage may have a theoretical minimum of as little as 11%, it is generally safe to have a coverage of 50% in order to account for factors such as traffic obstructions en route. This is particularly useful for planning for trolleybus deployment in areas where it is difficult to have overhead contact lines. For every 1 km of catenary-free operation, 2 min and 30 sec of charging time must be assumed (and a minimum of 1 min 45 sec) (Bartłomiejczyk, 2017). These technical requirements of battery-assisted trolleybus systems have been compared to the others in Table 4.

It is important to note here that Gdynia has an average annual temperature of 7.1 °C, with a minimum of -2 °C (ZeEUS, 2018). This is far removed from the operating conditions in Bengaluru, where the average annual temperature is around 23.6 °C ("Bengaluru Climate", n.d.). Additional factors such as route profile will also have an impact on the design of the overhead contact lines and the performance of battery-assisted trolleybuses (Grygar et al., 2019).

Costs

Compiling the capital costs from case studies in Milan, Gdynia, and San Francisco, it can be estimated that the cost of each battery-assisted trolleybus would vary from INR 5.9 crore to 7.7 rore[1] ("City of Gdynia", 2018; SFMTA Board of Directors, 2017; "Solaris selling 80 trolleybuses to Milan", 2018)

Depending on various factors, implementation costs per kilometre for trolleybus contact lines can vary between EUR 1 million and 20 million (between INR 8.3 crore and 165 crore per km, as of April 2020). This includes the costs of preparatory studies, construction of bus depots, establishing the bus-operations centre, acquisition of trolleybuses and contact-line maintenance vehicles, electrical power network construction, installing urban infrastructure and technical networks (relaying cables, etc.), and operational integration (personnel training, trolleybus maintenance, and so on) (Trolley, 2013).

Such high costs will be a significant barrier in India, especially since the battery e-buses currently available in the Indian market usually cost almost INR 2 crore (UITP India, 2016).

[1] Assuming an exchange rate of INR 80 per EUR; INR 18.6 per PLN; and INR 64.5 per USD

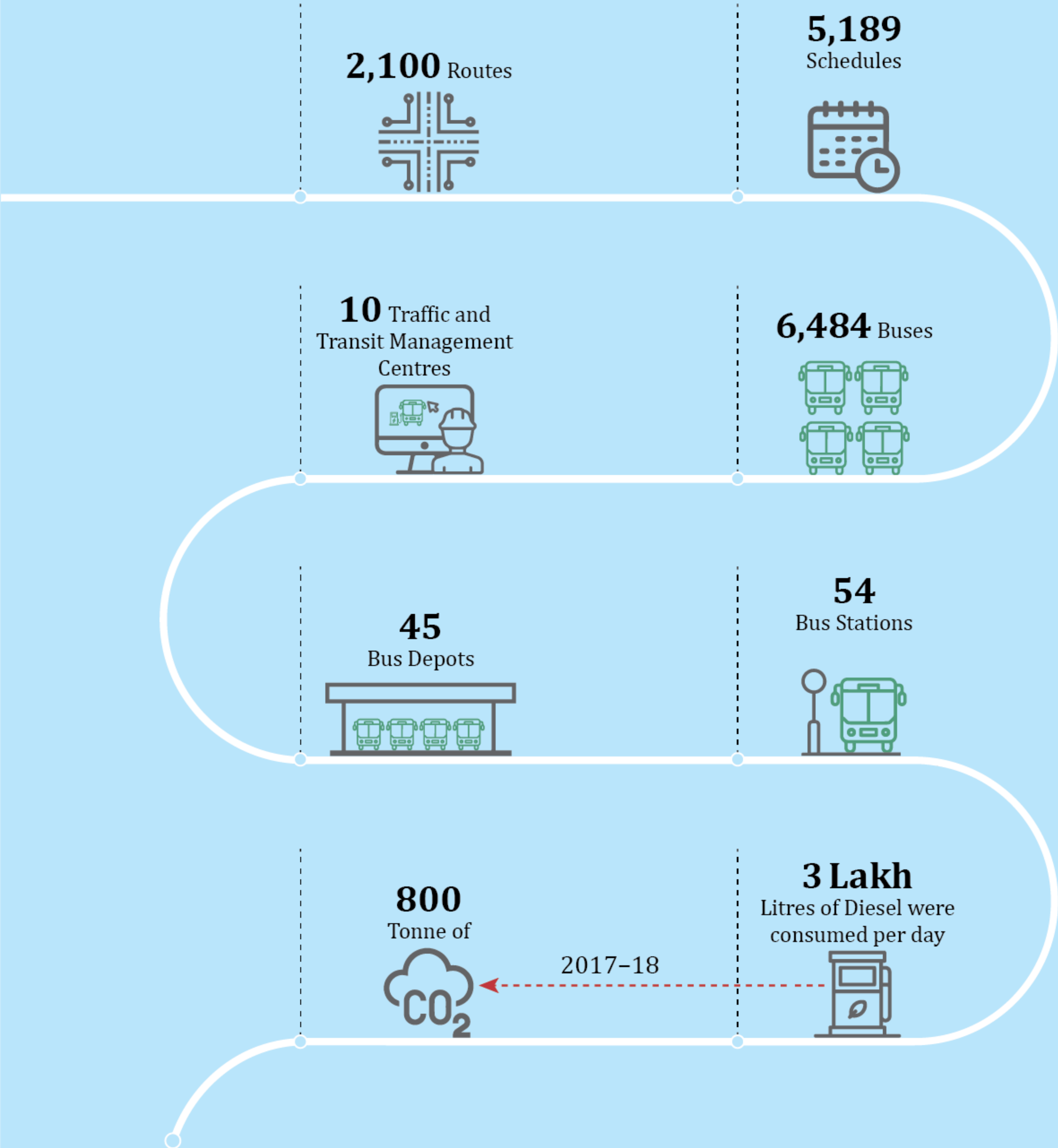
2.4. Summary

The technical requirements of the technologies reviewed through literature are summarised as a comparison matrix in Table 4.

Table 4: Comparison matrix of the technical requirements for the three technologies

Parameters	Battery Swapping	Opportunity Charging	Battery-assisted Trolleybus
Turnaround Time	2.5–10 min (Li, 2016; Park, 2016; Wangchuk, 2019)	3–10 min (ZeEUS, 2018)	No turnaround time required
Charging Power	9 kW–30 kW per charger (Li, 2016)	Up to 600 kW per charging point (Siemens, 2019)	70–120 kW for battery charging (600 V, 600A max) (Bartłomiejczyk, 2017)
Charger Efficiency	87% (Unda et al., 2012)	NA	96% (Bartłomiejczyk, 2017)
Battery Capacity	50 kWh (Park, 2016)	60–90 kWh (ZeEUS, 2018)	13.6–69 kWh (ZeEUS, 2018)
Number of Chargers Per Battery Pack	No. of batteries = 1.5 x No. of buses No. of chargers = 3 x No. of batteries	One 450 kW charger for 4.5 buses (ABB, n.d.)	Overhead contact lines required for charging
Costs	INR 3.5 crore per swapping station (Das et al., 2019)	INR 0.38–1.25 crore per pantograph system (Das et al., 2019)	INR 5.9–7.7 crore per bus ("City of Gdynia", 2018; SFMTA Board of Directors, 2017; "Solaris selling 80 trolleybuses to Milan", 2018;) INR 8.3–165 crore/km (Trolley, 2013)
Area Required	~75 sq.m per station (Ministry of Housing and Urban Affairs, 2019)	10 sq.m per charging unit at stops (Warren, 2017)	Area for infrastructure not required
Typical Range	5–35 km (Li et al., 2018; Wangchuk, 2019)	6–7 km per charge @ 450kW (ABB, n.d.)	Around 50% route length that has contact lines (Bartłomiejczyk, 2017)

3. Study Area



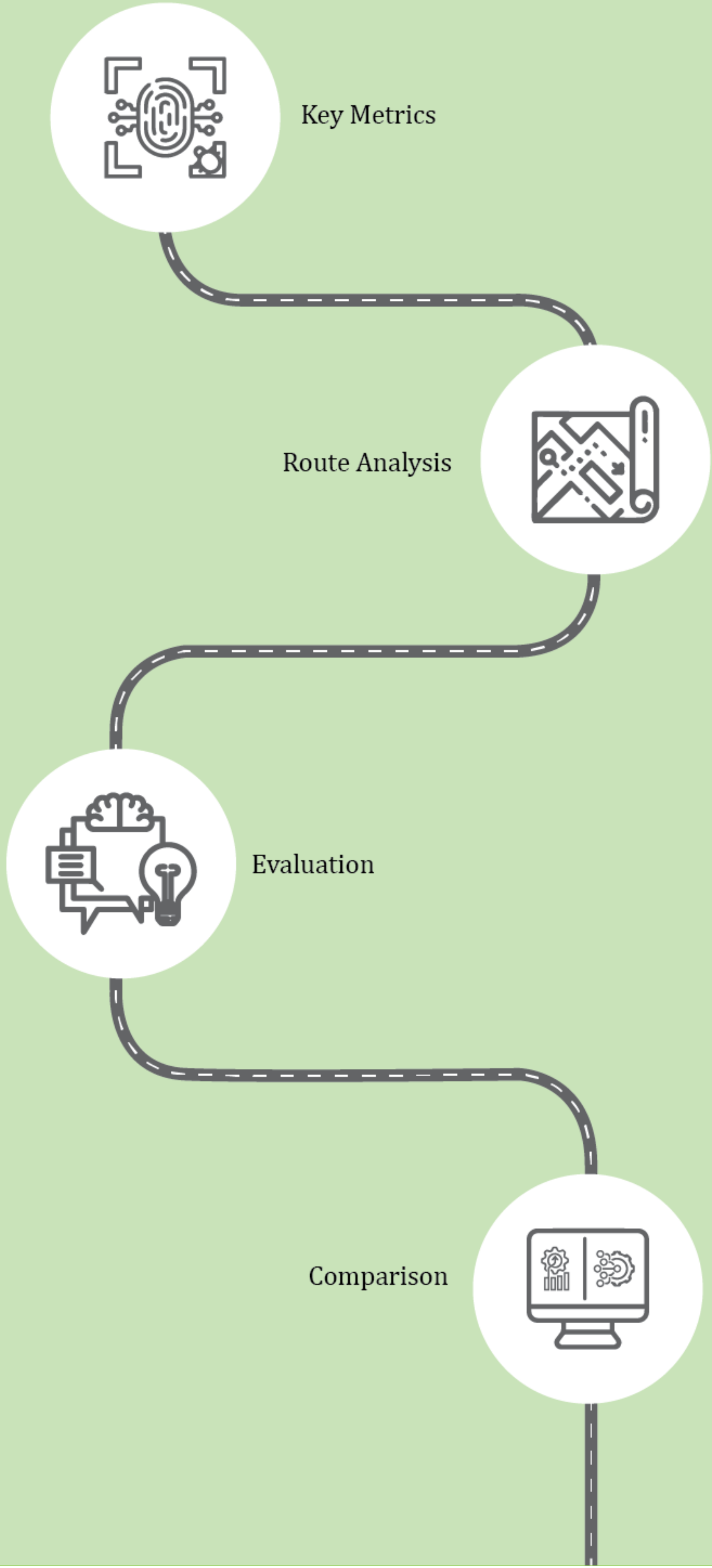
Study Area – Bengaluru City Transit Network

This study demonstrates the framework for assessing the technological suitability of the three technologies available for charging e-buses in Bengaluru.

BMTC is responsible for operating intra-city mobility services in the Bengaluru Metropolitan Region (BMR) through a bus system (Bangalore Metropolitan Region Development Authority, 2016). Currently, BMTC operates on 2,100 routes (5,189 schedules), with 6,484 buses (Bangalore Metro Rail Corporation Limited, 2019; BMTC, 2020). The operations are handled by 10 Traffic and Transit Management Centres (TTMC), 45 bus depots, and 54 bus stations (BMTC, 2020). Approximately 3 lakh litres of diesel were consumed per day by the BMTC fleet during 2017–18 (BMTC, 2019b). This would have accounted for about 800 tonne of CO_2 emissions from fuel combustion[2].

[2] Derived by using the carbon dioxide emission factor as 2.6 kg CO_2-e per litre of diesel (Ministry for the Environment, Government of New Zealand, 2019).

4. Approach



To assess the feasibility of the e-bus charging technologies for Bengaluru's city transit network, the requirements of each technology were compared at the route level, using key metrics. The steps for undertaking the comparison are illustrated in Figure 6.

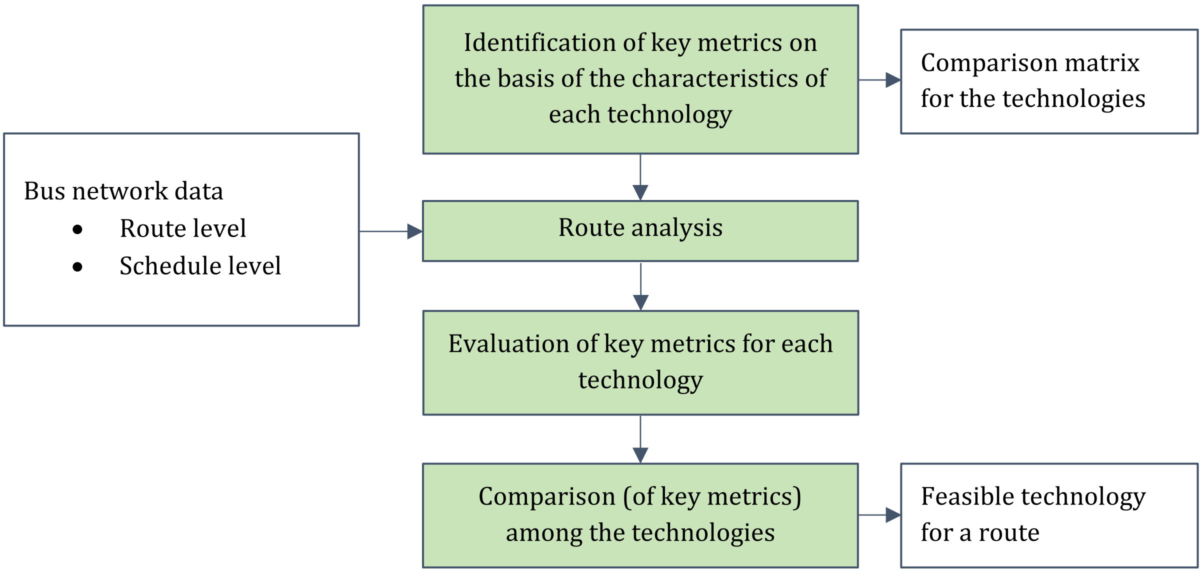


Figure 6: Feasibility assessment framework for e-bus charging technology

Thus, broadly, the assessment framework involved four major activities. The first activity was to develop a comparison matrix on the basis of the characteristics of each technology through an extensive literature review. For demonstrating the framework, BMTC network data was used to perform the route analysis. The identified key metrics of each technology were then evaluated for the selected bus routes. Finally, a comparison was done to identify the feasible technology for each route.

4.1 Identification of key metrics

The key metrics were identified after studying the operational characteristics of technologies. A comparison matrix (Table 4) was created to differentiate the technologies on the basis of their operational requirements and constraints.

4.2 Route analysis

For demonstrating the assessment framework, two routes were chosen from the airport air-conditioned (AC) routes, and two from the Vajra[3] routes selected by BMTC for electrification (BMTC, 2019a). The chosen routes are KIAS 7A, KIAS 4 (airport AC routes), and V 500D and V 500CA (Vajra routes). Trip origins and destinations, trip start and end times, halting locations, and distance travelled for the selected routes were considered for the analysis.

[3] Airport AC bus services (KIAS) connect the Bengaluru airport to the city; Vajra AC bus services connect major IT parks in Bengaluru to the city.

The total route length (or the total distance travelled by a bus in a day) was the main criteria for selecting the routes for demonstration as it decides the nature and frequency of charging required.

4.3 Evaluation of key metrics for each technology

Comparing the key metrics (including their economic feasibility and impact on the power infrastructure) of the technologies would help assess the feasibility of their implementation in Bengaluru. The metrics discussed in this section for each technology will be used to compare their deployment suitability at the route level.

The usable capacity of a battery (UBC, in kWh) is determined by the permissible depth of discharge (DoD) and the discharge limit (DL) (Das et al., 2019), and expressed as:

$$UBC = (DoD - (DoD \times DL)) \times BC \qquad \text{– Eq 1}$$

where BC is the rated battery capacity in kWh; DoD is the proportion of the battery capacity that can be discharged completely without compromising the health of the battery, expressed as a ratio; and DL is the recommended limit below which the battery should not be discharged to maitain a charge reserve, expressed as a ratio.

The effective range (R, in km) operable with each e-bus charging technology depends upon the usable capacity of the battery and energy consumption of the bus per kilometre. It can be calculated as:

$$R = \frac{UBC}{EC} \qquad \text{– Eq 2}$$

where UBC is the usable battery capacity in kWh; and EC is the energy consumption of the bus in kWh/km.

The technical requirements pertaining to each technology, and the associated key metrics as mentioned in Table 4, are discussed in the following sub-sections (4.3.1 to 4.3.4).

4.3.1 Battery swapping

In the case of battery swapping, the effective range (R) of the bus is limited by the battery size. Smaller battery sizes are preferred for swapping to ensure quicker and easier operations. The technical requirements (e.g. swapping time) have been discussed in Table 4.

The time required ($T_{charge,swap}$, in hr) to charge a battery at the swapping station is calculated as:

$$T_{charge,swap} = \frac{UBC}{CP \times eff} \qquad \text{– Eq 3}$$

where UBC is the usable battery capacity in kWh; CP is the power of the charger used in kW; and eff is the efficiency of the charger expressed as a ratio. $T_{charge,swap}$ determines the energy consumed during charging. The energy consumed (E_{swap}, in kWh) at the swapping station for charging batteries is expressed as:

$$E_{swap} = CP \times T_{charge,swap} \times N \qquad \text{– Eq 4}$$

where N is the number of batteries to be charged (equal to the number of swaps) in a day.

4.3.2 Opportunity charging

The turnaround time for pantograph-based opportunity charging ($T_{charge,opp}$) is usually considered as 3–10 min (Table 4). (This turnaround time does not consider the time taken to ascend and descend the pantograph since it is only about 10 seconds each).

The total energy consumed (E_{opp}, in kWh) at the charging location is expressed as:

$$E_{opp} = \sum_1^n CP \times T_{charge,opp} \qquad \text{– Eq 5}$$

where, $T_{charge,opp}$ is the time required to recharge the e-bus (expressed in hr); and n is the number of the charging locations on the route.

4.3.3 Battery-assisted trolleybuses

In the case of battery-assisted trolleybus, the length of the contact lines required for a given route will depend on the effective range (R) of the on-board battery of the bus (as derived in Eq 2). Thus, the range capability of the battery-assisted trolleybus must be greater than the distance the bus needs to travel while disconnected from the overhead contact lines.

When under the overhead contact lines, the power drawn by the bus can be divided into two categories: consumption and charging. It is to be noted that here it is assumed that the consumption component of power drawn by the battery-assisted trolleybus includes propulsion power, power required for heating/cooling, and power for running other auxiliary services. Therefore, the total energy consumed by the trolleybus per kilometre (E_{total}, in kWh/km), while under contact wires, can be represented as:

$$E_{total} = E_{consumption} + E_{charging} \qquad \text{– Eq 6}$$

Similarly, the total power consumed by the battery-assisted trolleybus while under contact wires (represented as P_{total}, and expressed in terms of kW) can be expressed as:

$$P_{total} = P_{consumption} + P_{charging} \qquad \text{– Eq 7}$$

Please note that when the trolleybus is in contact with the overhead power lines and the on-board battery is fully charged, $E_{charging}$ /$P_{charging}$ is zero.

Using the average speed[4] of the trolleybus (given as kmph), it is possible to derive the values for power (P)[5] while under contact wire and energy per kilometre (E) consumed by the bus:

$$E * speed = P \qquad \text{– Eq 8}$$

Using these equations, it is possible to calculate the values of $E_{consumption}$, $E_{charging}$, $P_{consumption}$, and $P_{charging}$. The total energy consumed by a trolleybus per trip ($E_{trolley}$) is given by:

$$E_{trolley} = \sum_{1}^{n}(E_{stop-stop} \times l_{stop-stop}) \qquad \text{– Eq 9}$$

where for n stops, l is the distance covered between two stops while in contact with the overhead contact lines; and E_{stop} is the energy consumed by the trolleybus while covering the distance l.

4.3.4 Depot-based charging

In the case of depot-based charging, the effective range (R) primarily depends on the model of the bus and the built-in battery capacity. The time taken for a recharging event ($T_{charge,depot}$) is determined by the distance travelled by the bus and is calculated as:

$$T_{charge,depot} = \frac{UBC \times \frac{d}{R}}{CP \times eff} \qquad \text{– Eq 10}$$

where d is the distance travelled by the bus before recharge (in km); and R is the effective range of the bus in km;.

The energy consumed (E_{depot}, in kWh) at the depot for charging the e-bus is expressed as:

$$E_{depot} = CP \times T_{charge,depot} \qquad \text{– Eq 11}$$

where $T_{charge,depot}$ is the time required to charge the e-bus (expressed in hr).

4.4 Comparison of charging technologies

The technologies were compared for technical, operational, and financial parameters to assess their feasibility for each route. The parameters used to compare the charging technologies across the selected routes are as follows:

Technical Parameters:

- Battery capacity
- Charging power
- Maximum power demand per bus
- Total energy required at all locations

[4] Average speed is calculated from the schedule data, i.e., from the distance between stops and time to cover the distance.
[5] The study considers an average power throughout while travelling under the wires. Also, the effect of topography has not been included due to the unavailability of relevant data.

Operational Parameters:

- Number of recharging locations/swapping stations
- Number of recharges required per day
- Total recharging time at all locations

Financial Parameters:

- Operational cost (in terms of electricity used)
- Capex cost of bus
- Capex cost of infrastructure

5. Feasibility Assessment on Selected Routes

As mentioned under Section 4.2, four routes were considered for assessing the feasibility of the charging technologies. Of the selected routes, particulars of one schedule each (KIAS 7A/1, KIAS 4/1, V 500D/1, and V 500CA/1) were considered for detailed analysis (assuming that the characteristics will remain same for all schedules of the route). The feasibility of the three technologies and depot-based charging for KIAS 7A/1 and V 500D/1 are discussed in the following sections.

The observations for the other two routes (KIAS 4 and V 500CA) are discussed in Appendix III.

5.1 Route analysis

The details of selected routes are given in Table 5. The airport route (KIAS 7A) is relatively long, with a trip length (distance between the end points) of 50 km and a total route length of 402 km, whereas the trip length of the Vajra route (V 500D) is 30.5 km and the total route length is 250.2 km. Both the routes majorly operate on arterial roads with sufficient road width. Most of the KIAS 7A route operates on the 65m-wide Bellary road while the V 500D route operates on the 45m-wide outer ring road. The KIAS 7A/1 bus operates with an average speed of 22.1 kmph, and an energy consumption of 1.27 kWh/km[6] (Jin et al., 2020); the V 500D/1 bus operates with a lower speed of 11.2 kmph, and an energy consumption of 1.35 kWh/km (Jin et al., 2020).

Table 5: Details of selected routes (KIAS 7A and V 500D)

Route	KIAS 7A	V 500D
Schedule	KIAS 7A/1	V 500D/1
Associated depot	Depot – 25	Depot – 28
Width of the road (m)	65	45
Origin	Kempegowda International Airport	Hebbal
Destination	HSR layout BDA complex	Silk Board
Trip length (km)	50	30.5
Total route length (km)	402	250.2
Dead km (km)	1.5	4
Number of bus stops	25	37
Number of trips per day	8	8
Average speed (kmph)	22.1	11.2
Energy consumption (EC) (kWh/km)	1.27	1.35

[6] The energy consumption values are taken from a simulation model result given in the reference mentioned here.

5.2 Evaluation of key metrics for each technology: KIAS 7A

The general assumptions considered for KIAS 7A for all charging technologies (based on the literature review in Section 2) are given in the Table 6.

Table 6: Assumptions considered for charging technologies: KIAS 7A

<table>
<tr><th></th><th>Battery swapping</th><th>Opportunity charging</th><th>Trolleybus</th><th>Depot charging</th></tr>
<tr><td colspan="5">Battery specification</td></tr>
<tr><td>Battery capacity (kWh)</td><td>120</td><td>80</td><td>69[7]</td><td>324</td></tr>
<tr><td>Depth of Discharge (DoD) (%)</td><td colspan="3">70</td><td>100</td></tr>
<tr><td>Discharge limit (DL) (%)</td><td colspan="3">15</td><td>20</td></tr>
<tr><td colspan="5">Charger Specification</td></tr>
<tr><td>Power of DC charger (kW)</td><td>60</td><td>150</td><td>60</td><td>120</td></tr>
<tr><td>Charging time (min)</td><td>5 [8]</td><td>10</td><td>-</td><td>130</td></tr>
<tr><td>Charger efficiency</td><td>0.95</td><td>-</td><td>-</td><td>0.95</td></tr>
</table>

The technology requirements and the resultant key metrics for each technology solution of KIAS 7A are discussed below.

5.2.1 Battery swapping

Use of the standard 60 kWh batteries would provide a range of only 28 km and the bus would run out of charge before reaching the end point. Hence, a higher battery capacity (120 kWh) was assumed.

Given the battery specifications in Table 6, the usable battery capacity is 71 kWh (Eq 1) and the effective range for the bus is 56 km (Eq 2).

Since the length of each trip on the KIAS 7A/1 route is 50 km, the battery will require a replacement at the end of each trip i.e., at HSR layout BDA Complex and Kempegowda International Airport. Consequently, it will require three batteries, one charging at each station and one in the bus. As the e-bus makes eight trips between the origin and destination in a day, it would require eight battery swaps, four each at HSR layout BDA Complex and Kempegowda International Airport. A total of 40 min a day is spent at the stations for swapping.

[7] Capacity of the auxiliary battery in the trolleybus
[8] 2.5–10 minutes is the turnaround time-range mentioned in Table 4. The time may vary depending upon the size of the battery. For the purpose of analysis, it is assumed as 5 minutes.

With the charger specifications given in Table 6, the time taken to charge a battery at a station is 107 min or 1.8 hr (Eq 3). The resultant energy consumed for charging four batteries at each station (given by Eq 4) is 429.5 kWh, and therefore the total (at both stations) is 859 kWh per day. This energy consumption would cost INR 2,083[9] at each station and INR 4,166 together per day.

A swapping station for serving an e-bus would require an area of approximately 75 sq.m (15 sq.m for the swapping station [Town and Country Planning Organisation, 2019] and 60 sq.m to accommodate the bus undergoing swapping).

Buses designed for swapping could cost between INR 1.5 crore and 3 crore. Assuming a unit of battery capacity costs INR 12,600 per kWh, the three batteries required for this technology would cost approximately INR 45 lakh. The cost of installing chargers and the ancillary infrastructure would be around INR 15 lakh, and INR 2.5 – 4 lakh respectively.[10]

5.2.2 Opportunity charging

Considering the battery specifications in Table 6, the usable battery capacity is 47.6 kWh (Eq 1) and the effective range for the bus is 37 km (Eq 2).

As the route length of the KIAS 7A/1 is 51.5 km (including dead km) and effective range with the given specifications is 37 km, this route requires two charging locations for the 'up' trip (KIAS to BDA complex). One charging location shall be at the starting point and the second could be at an intermediate bus stop location. Once the bus gets fully charged at the bus stop, it can run for another 37 km and needs to get charged at another intermediate bus stop location during the 'down' trip. In effect, to complete one round trip, the route requires three charging locations, one at the endpoint (KIA), and two at the intermediate bus stops.

To complete the daily trips (eight trips), this schedule would require 12 recharging events, four at each location. A total of 40 min a day would be spent at each location, resulting in a total recharging time of 120 min per day. The resultant energy consumed for recharging at each location is 100 kWh and a total of 300 kWh for the route. The cost of electricity consumed at the three locations together would be INR 1,455 per day. Also, to set up the charging location with one pantograph, the area required would be approximately 10.24 sq.m.

The procurement cost of an e-bus compatible with this technology would be INR 80 lakh – 2.5 crore. The cost of 150 kW DC fast chargers would range between INR 56 lakh and 74 lakh, while setting up a charging station (hardware setup) would cost INR 56 lakh to 75 lakh. Consequently, setting-up the three charging stations is estimated to cost INR 3.4 crore to 4.5 crore[11].

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[9] Considering a unit of electricity is charged at INR 4.85/kWh.

[10] The costs are estimated from various sources and market trends ("Ashok Leyland Buses Price List", n.d.; Pillai et al., 2018; Yadav, 2020; "The Price of an Electric Car Battery", 2020; Das et al., 2019)

[11] These cost are estimated from (Nelder & Rogers, 2019; Das et al., 2019; Hooftman et al., 2019; Pillai et al., 2018)

5.2.3 Battery-assisted trolleybuses

The operation of the route with trolleybus system is illustrated in Figure 7.

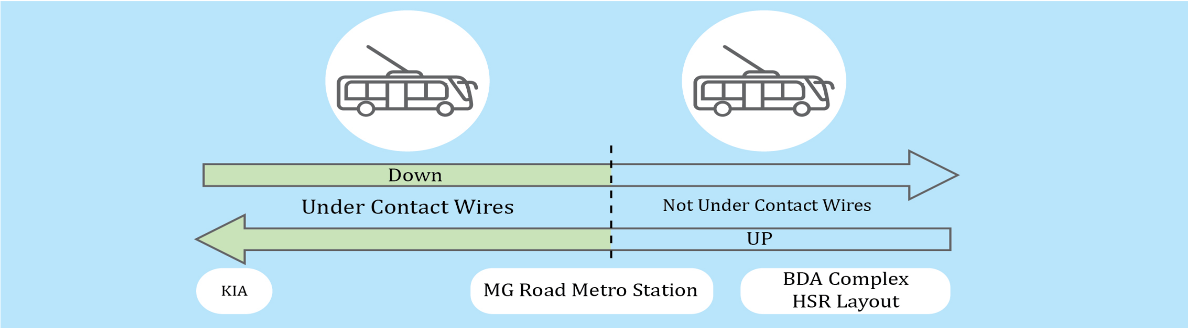


Figure 7: Overview of battery-assisted trolleybus operations on route KIAS 7A

(Source: CSTEP)

Considering the battery specifications in Table 6, the usable battery capacity is 41.1 kWh (Eq 1) and the effective range for the bus is 32.3 km (Eq 2).

In order to ensure smooth operations, 35.5 km of the 50 km route length (71% of route length) has been considered to be under contact wires (based on reasons given in 4.3.3). The overhead contact lines have been assumed to be installed between KIA and MG Road Metro Station, on both sides of the road (Figure 7). The total number of bus stops under the contact wires is 19 (out of 25 bus stops). Under this configuration, the battery will always retain a minimum of 2.5 kWh out of its usable stored energy before it is recharged again under the contact wires, and the bus must operate using energy stored in its battery for only 29% of the route length.

A bus operating on this route takes 110 min to complete the 'up' trip, and 120 min to complete the 'down' trip. Thus, the average speed for the 'up' trip is 26.8 kmph, whereas for the 'down' trip it is 24.6 kmph. Based on the energy consumption for the route, and the charging power required, the power and energy required are calculated in Table 7, as per Eq 6, Eq 7, and Eq 8.

Table 7: Energy consumed from overhead contact lines for KIAS 7A

Category	UP		DOWN	
	Energy consumed (kWh/km)	Power required (kW)	Energy consumed (kWh/km)	Power required (kW)
Propulsion (includes HVAC etc.)	1.27	34.1	1.27	31.2
Charging	2.2	60	2.4	60
Total (consumption + charging)	3.5	94.1	3.7	91.2

Thus, the average power demand expected for battery-assisted trolleybus operating on this route is 94.1 kW, and the maximum energy required is 3.7 kWh/km. However, as per the literature reviewed, it may be possible for these trolleybuses to require an energy supply of up to 7 kWh/km from overhead lines under peak conditions (Bartłomiejczyk, 2017). This would lead to a maximum power[12] demand of 188 kW for KIAS 7A/1.

As the bus makes a total of four round trips and two dead trips, the total energy required per bus is 794 kWh per day. The cost of the energy required per bus is INR 3,855 per day.

According to the literature review, the cost of one battery-assisted trolleybus would be around INR 6 crore. The capital expenditure for covering 35.5 km would be at least INR 295 crore[13]. This cost includes the costs of preparatory studies, construction of bus depots, adaptation of the bus operations centre, acquisition of trolleybuses and contact-line maintenance vehicles, electrical power network construction, adaptation of urban infrastructure and technical networks (relaying cables etc.), and operational integration (personnel training, trolleybus maintenance and so on) (Trolley, 2013).

5.2.4 Depot-based charging

Considering the battery specifications given in Table 6, the usable battery capacity is 259 kWh (Eq 1) and the effective range for the bus is 204 km (Eq 2).

This charging system would require one battery to be placed in the bus that gets recharged through a plug-in charger at the station. As the bus halts at HSR Layout (Depot 25) twice a day after a run of 200 km (four trips), the battery can be recharged during these halts.

Using the 120 kW DC charger (Table 6), it takes 134 min or 2 hr to charge the battery once (Eq 10). Each charging activity consumes 268 kWh (Eq 11) of energy, accounting for 537 kWh of energy consumption per day. The resultant electricity cost would be INR 2,600 per day.

This plug-in charging station would occupy 165 sq.m (105 sq.m for the charger set-up [Town and Country Planning Organisation, 2019] and 60 sq.m for the bus undergoing recharging).

The primary cost of this technology includes the costs of the e-bus and a plug-in charger, which would be INR 2-3 crore and INR 45 lakh, respectively. The supporting infrastructure could cost about INR 11 lakh.

[12] Power is subject to variation, depending on acceleration and deceleration behaviour. Maximum power could be drawn while accelerating. More undulations on the road fluctuate the power demand, which is not included in the scope of the study.

[13] Please note that these cost estimates have been converted from foreign currencies, and therefore will vary significantly should battery-assisted trolleybuses be manufactured or sold in India.

5.2.5 Comparison of technologies

From the discussion above, the key metrics of the technologies can be summarised as given in Table 8.

Table 8: Comparison of technologies for KIAS 7A

	Battery Swapping	Opportunity Charging	Trolleybus	Depot-based Charging
Battery capacity considered (kWh)	120	80	69	324
Charging power considered (kW) (DC charger)	60	150	60	120
Number of recharging locations/length of overhead contact lines	2	3	35.5 km	1
Number of daily recharges required/no of times bus connects to overhead lines	8	12	4	2
Total recharging time at all locations (min)	40	120	NA	268
Maximum power demand per bus (kW)	60	150	94.1	120
Total energy required at all locations (kWh)	859	300	794	537
Area required for each station (sq.m.)	75	10.2	NA	165
Total cost of electricity required (INR) per day	4,166	1,455	3,855	2,600
Capex cost of the bus (INR)	1.5 crore	0.8-2.5 crore	6 crore	2-3 crore
Capex cost of infrastructure (INR)	0.8-0.85 crore	3.4-4.6 crore	295 crore+	0.57 crore

To operate this route on electricity, the three technologies require a smaller battery size than that needed for depot-based charging. The charging infrastructure is required in more than one location for battery swapping and opportunity charging technologies as against one location with depot-based charging. In the case of trolleybuses, this infrastructure is required for 35.5 km. For all the stations, a total area of 150 sq.m for battery swapping and 31 sq.m for opportunity charging is required.

Despite requiring a higher number of recharging instances, the time spent for recharging/swapping at the locations is lower for these technologies than for depot-based charging. It is 85% less for battery swapping, and 55% less for opportunity charging. For trolleybuses, charging occurs while they are in motion. The maximum power drawn for battery swapping and trolleybuses is lesser (50% and 21.5% less, respectively) than that drawn by depot-based charging. Opportunity charging requires 25% more power as it uses high-powered fast chargers.

The total energy consumed and the resultant electricity cost for charging a bus is higher for battery swapping (60% higher), and trolleybuses (48% higher) than depot-based charging. However, for opportunity charging, the total energy consumed and the resultant electricity cost is 44% lower than depot charging. The cost of a trolleybus is about three times higher than that of a usual e-bus. The cost of infrastructure is also higher for the three technologies.

Trolleybus has the advantage of a smaller battery size, which is lighter and cheaper. However, the higher cost of procuring the bus and installing the required infrastructure makes it less feasible for operation. While opportunity charging allows for small battery size and smaller land requirement, the maximum power demand is high. The need for multiple recharging locations also increases the cost of infrastructure.

Serving this route with battery swapping technology will require a larger battery size than usual that could require a longer turnaround time at the swapping stations. Also, the energy consumed and the consequent electricity costs are higher. However, the relatively low capital costs and ease of operations make it more feasible than opportunity charging and trolleybuses. While in comparison to the common depot-charging solution, battery swapping requires higher capital investment for the charging infrastructure, while its impact on the power grid is lesser than depot charging. This is due to the use of chargers with lower power ratings in the case of swapping.

5.3 Evaluation of key metrics for each technology: V 500D

The general assumptions considered for V 500D for all charging technologies (based on the literature review in Section 2) are given in the Table 9.

Table 9: Assumptions considered for charging technologies: V 500 D

	Battery swapping	Opportunity charging	Trolleybus	Depot charging
Battery specification				
Battery capacity (kWh)	90	80	69	250
Depth of Discharge (DoD) (%)	70			100
Discharge limit (DL) (%)	15			20
Charger specification				
Power of DC charger (kW)	60	150	60	120
Charging time (min)	5 [14]	10	-	89
Charger efficiency	0.95	-	-	0.95

[14] 2.5-10 minutes is the turnaround time range mentioned in Table 4 . The time may vary depending upon the size of the battery. For the analysis purpose it is assumed as 5 minutes.

The technology requirements and the resultant key metrics for each technology solution of V 500D are discussed below.

5.3.1 Battery swapping

Using the standard 60 kWh battery would provide a range of only 26 km and the bus would run out of charge before reaching the endpoint. Hence, a higher battery capacity (90 kWh) was assumed.

Considering the battery specifications in Table 9, the usable battery capacity is 54 kWh (Eq 1) and the effective range for the bus is 40 km (Eq 2).

Since the length of each trip on the V 500D/1 route is 30.5 km, the battery will require a replacement at the end of each trip i.e., at Hebbal and Silk Board. Consequently, it will require three batteries, one charging in each station and one in the bus. As it makes eight trips in a day, it would require eight battery swaps, four each at Hebbal and Silk Board. A total of 40 min a day is spent at the stations for swapping.

With the charger specifications given in Table 9, the time taken to charge a battery at a station is 81 min or 1.3 hr (Eq 3). The resultant energy consumed for charging four batteries at each station, given by Eq 4, is 322 kWh, and therefore the total energy consumed at both stations is 644 kWh per day. This energy consumption would cost INR 1,562 at each station, and INR 3,124 together, per day.

Three batteries of 90 kWh each for this bus would cost INR 34 lakh. The other cost and area requirements are similar to those discussed for KIAS 7A in Section 0.

5.3.2 Opportunity charging

Considering the battery specifications given in Table 9, the usable battery capacity is 47.6 kWh (Eq 1) and the effective range for the bus is 38 km (Eq 2).

Since the route length of the schedule is less than the effective range, the bus would recharge at the end of each trip at the terminal stations, i.e. Hebbal, and Silk Board. To complete the daily trips (eight trips), this schedule would require eight recharging events, four at each location. A total of 40 min a day would be spent at each location. The resultant energy consumed for recharging at two locations is 200 kWh per day and this would cost a total of INR 970 per day for this schedule.

As this route requires only two charging locations, the infrastructure setup cost would range from INR 2.2 crore to 3 crore. The other cost and area requirements are similar to those described for KIAS 7A.

5.3.3 Battery-assisted trolleybuses

The details of route operation with trolleybus system are given in Figure 8.

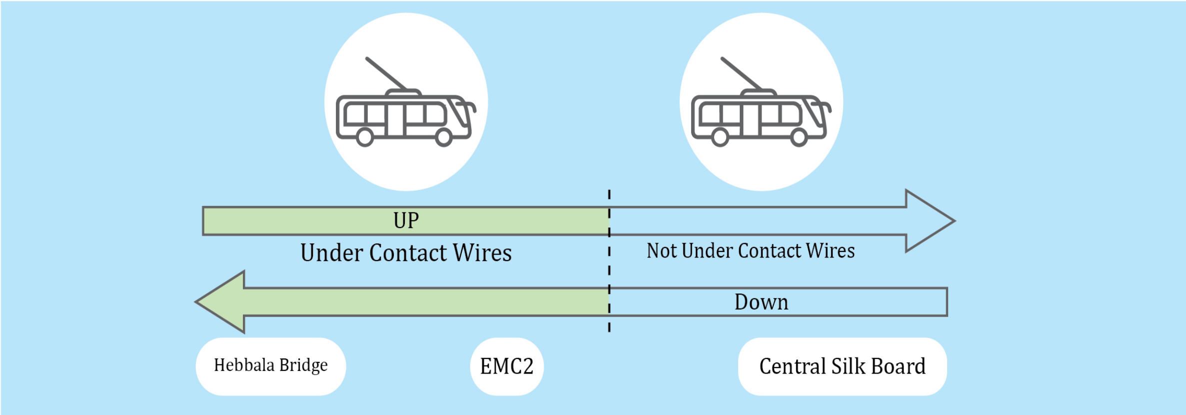


Figure 8: Overview of battery-assisted trolleybus operations on route V 500D

(Source: CSTEP)

Considering the battery specifications given in Table 9, the usable battery capacity is 41.1 kWh (Eq 1) and the effective range for the bus is 31.5 km (Eq 2).

In order to ensure smooth operations, 15.2 km of the 29.2 km route length (52% of route length) has been considered to be under contact wires (based on reasons given in 4.3.3). The overhead contact lines have been assumed to be installed between Hebbala Bridge (towards Tin Factory) and Bagmane Tech Park (EMC2), on both sides of the road. The number of bus stops under the contact wires is 23 (out of 37 bus stops). Under this configuration, the battery will always retain a minimum of 3.3 kWh out of its usable stored energy before it is recharged again under the contact wires, and the bus must operate using energy stored in its battery for 48% of the route length.

A bus operating in this route takes 100 min to complete the 'up' trip, and 115 min to complete the 'down' trip. Thus, the average speed for the 'up' trip is 17.5 kmph whereas for the 'down' trip it is 15.2 kmph. Based on the energy consumption for the route, and the charging power required, the power and energy required are calculated in Table 10, as per Eq 6, Eq 7, and Eq 8.

Table 10: Energy consumed from overhead contact lines for V 500D

Category	UP		DOWN	
	Energy consumed (kWh/km)	Power required (kW)	Energy consumed (kWh/km)	Power required (kW)
Propulsion (includes HVAC etc)	1.35	23.6	1.35	20.5
Charging	3.4	60	3.9	60
Total (propulsion + charging)	4.8	83.6	5.3	80.5

Thus, the average power demand expected for the battery-assisted trolleybus operating on this route is 83.6 kW, and the maximum energy required is 5.3 kWh/km. However, under peak conditions with high energy demand this would generate a possible maximum power demand of 123 kW for V 500D/1.

As the bus makes four round trips and two dead trips in all, the total energy required per bus is 417 kWh per day. The cost of the energy required per bus is INR 2,015 per day.

As per the literature review, the cost of one battery-assisted trolleybus would be around INR 6 crore. The capital expenditure for covering 15.2 km would be at least INR 126 crore.

5.3.4 Depot-based charging

Considering the battery specifications given in Table 9, the usable battery capacity is 200 kWh (Eq 1) and the effective range for the bus is 148 km (Eq 2).

This charging system would require one battery to be placed in the bus that gets recharged through a plug-in charger at the station. As the bus halts at Hebbal (Depot 28) twice a day after a run of 125 km (four trips), the battery can be recharged during these halts.

Using the 120 kW DC charger, it takes 89 min or 1.5 hr to recharge the battery once (Eq 10). Each recharge activity consumes 179 kWh (Eq 11) of electricity, amounting to 357 kWh of energy consumption per day. The resultant electricity cost would be INR 1,732 per day.

The area and cost requirements are the same as those discussed for KIAS 7A in Section 0.

5.3.5 Comparison of technologies

From the discussion above, the key metrics of the technologies can be summarised as shown in Table 11.

Table 11: Comparison of technologies for V 500D

	Battery Swapping	**Opportunity Charging**	**Trolleybus**	**Depot-based Charging**
Battery capacity considered (kWh)	90	80	69	250
Charging power considered (kW) (DC charger)	60	150	60	120
Number of swap/recharging locations or Length of overhead contact lines	2	2	15.2 km	1
Number of daily swaps/recharges required or No of times bus connects to overhead lines	8	8	4	2
Total swap/recharging time at all locations (min)	40	40	NA	179
Maximum power demand per bus (kW)	60	150	83.6	120

Total energy required at all locations (kWh)	644	200	417	357
Area required for each station (sq.m)	75	10.2	NA	165
Total cost of electricity required (INR) per day	3,124	970	2,015	1,732
Capex cost of the bus (INR)	1.5 crore	0.8 – 2.5 crore	6 crore	2-3 crore
Capex cost of infrastructure (INR)	0.7 – 0.72 crore	2.3 – 3 crore	126 crore+	0.57 crore

To operate this route on electricity, the three technologies require a smaller battery size than that needed for depot-based charging. The charging infrastructure is required in more than one location for the three technologies, as against one location with depot-based charging. In the case of trolleybuses, this infrastructure is required for 15.2 km. For all the stations, a total area of 150 sq.m for battery swapping, and 20 sq.m for opportunity charging, is required.

Despite requiring a higher number of recharging instances, the time spent for recharging/swapping at the locations is lower for these technologies than for depot-based charging. This is 77% less for both battery swapping and opportunity charging. For trolleybuses, charging occurs while in motion. The maximum power drawn for battery swapping and trolleybuses is lesser (50% and 30% less respectively) than that drawn for depot-based charging. Opportunity charging system requires 25% more power.

The total energy consumed and the resultant electricity cost for charging are higher for battery swapping (80%) and trolleybus (17%) than that for depot-based charging. However, for opportunity charging, the energy requirement is 44% lesser than that for depot charging. The cost of a trolleybus is about three times higher than that of a normal e-bus. The cost of infrastructure is also higher for the three technologies.

The lower electricity cost of operating a trolleybus on this route is outweighed significantly by the capital investment required for the infrastructure. Though the length of the contact wire is less than that of KIAS 7A due to its shorter route, the infrastructure cost is still considerably higher than that of the other technologies. Opportunity charging has a comparatively higher power demand due to the use of high-powered chargers on the way. The need for multiple recharging locations also increases the cost of infrastructure. However, this is lesser for the V 500D route than the KIAS 7A route, due to its shorter length.

Battery swapping consumes more energy and hence incurs the highest operating cost among all three technologies. However, the comparatively low capital costs and ease of operations make it the most feasible of the three charging technologies.

The analyses performed for the other two routes (KIAS 4 and V 500CA) show that the observations do not vary with the route length (Appendix III).

6. Conclusions

Battery Swapping

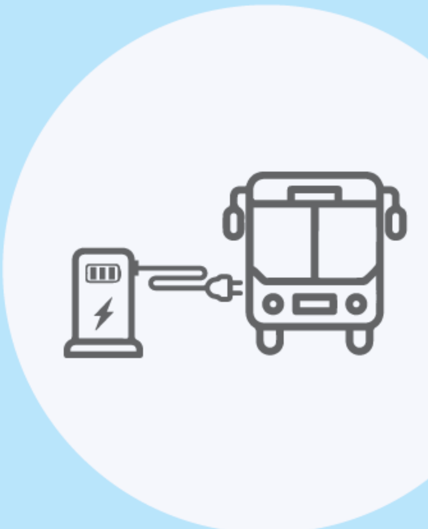
Short routes (like feeder routes) (25- 30 km)
Terminals can spare a bay for swapping station
Limited budget available

Opportunity Charging

Long Routes (>50 km)
Area availability at depot is a challenge
Intermediate bus stops have additional area of ~10 sqm.
Access to low-cost capital

Trolleybuses

Route length is not a constrain
Existing tram/trolleybus infrastructure
Travel speeds are low
Adequate funding



The study finds that the choice of technology largely depends on the characteristics of public transit operations (in terms of route length, halting durations, halting locations, the area available at the depot, etc.), route characteristics (in terms of road width, the topography of roads, etc.), power infrastructure (grid capacity), and the nature of investments. Some of these characteristics are detailed here to indicate how they help in determining the technology to be employed.

Route length

The trip length is the distance between the origin and destination. For routes with shorter average trip lengths (25 – 30 km), battery swapping would be the most suitable choice of charging technology. In case battery swapping cannot be used due to space constraints, opportunity charging can be considered with pantographs installed at each end station. For these two charging technologies, when the operations consume 1 kWh/km or more (on such short routes), the battery capacity required would be between 40 kWh and 75 kWh.

However, for using battery swapping on routes with longer average trip lengths (> 50 km), a larger battery size would be required, resulting in longer turnaround time, and compromising the convenience of this technology. Hence, for such routes, opportunity charging would be a more suitable charging solution with pantographs installed at strategic locations. When the operations consume 1 kWh/km or more (on such long routes), the battery capacity required would be above 80 kWh.

Battery-assisted trolleybuses could also be considered along any route length if sufficient road width (45 m or above) is available, or a supporting infrastructure (like tram/Metro corridor) is already existing along the route.

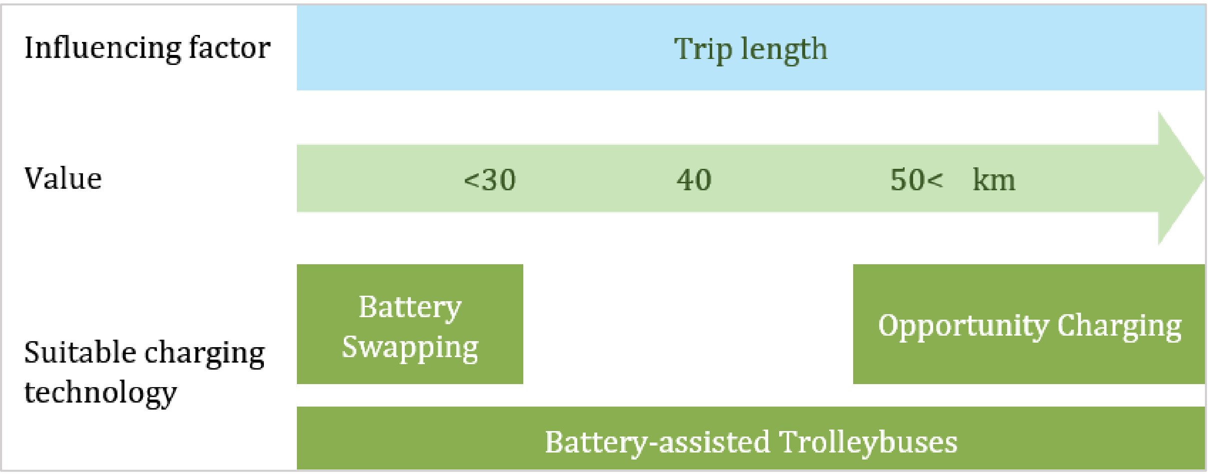


Figure 9: Choice of technology on the basis of trip length

Depot or charging station area

Battery swapping is suitable when the e-bus routes operate from depots that can allocate at least 75 sq.m (minimum area required for a bus to swap its battery) for installing the swapping infrastructure. In case area is a constraint, opportunity charging or battery-assisted trolleybuses could be considered. The former requires only 10 sq.m per pantograph at each charging location, while the latter requires dedicated lanes on the road with a width of at least 45 m.

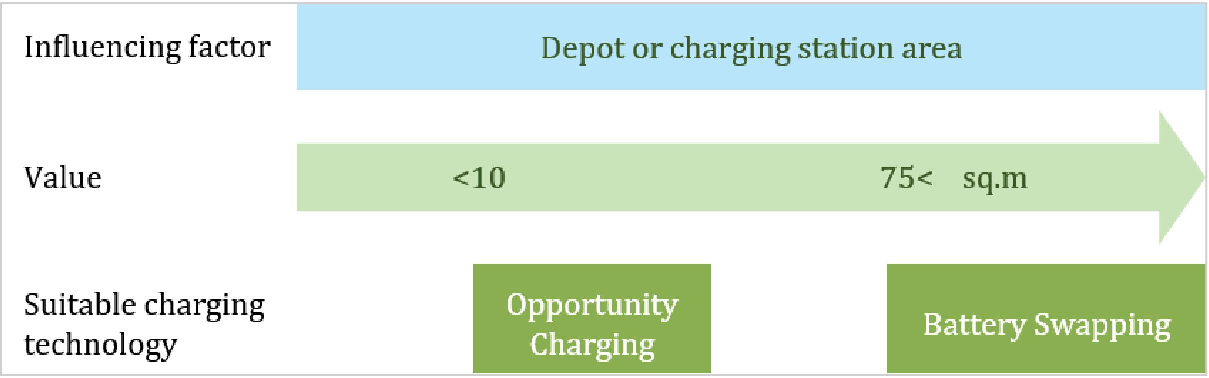


Figure 10: Choice of technology on the basis of depot or station area

Power infrastructure

For immediate deployment, battery swapping is a better option as it does not require any major grid upgradation, owing to the use of slow chargers (< 60 kW). The other two technologies require upstream power infrastructure upgrades. While battery-assisted trolleybuses use only around 80-90 kW, they require the power lines to be installed along the lane. Opportunity charging uses higher-power-rated chargers (150 kW or above) and thus would require a dedicated feeder, along with other power infrastructure upgradations.

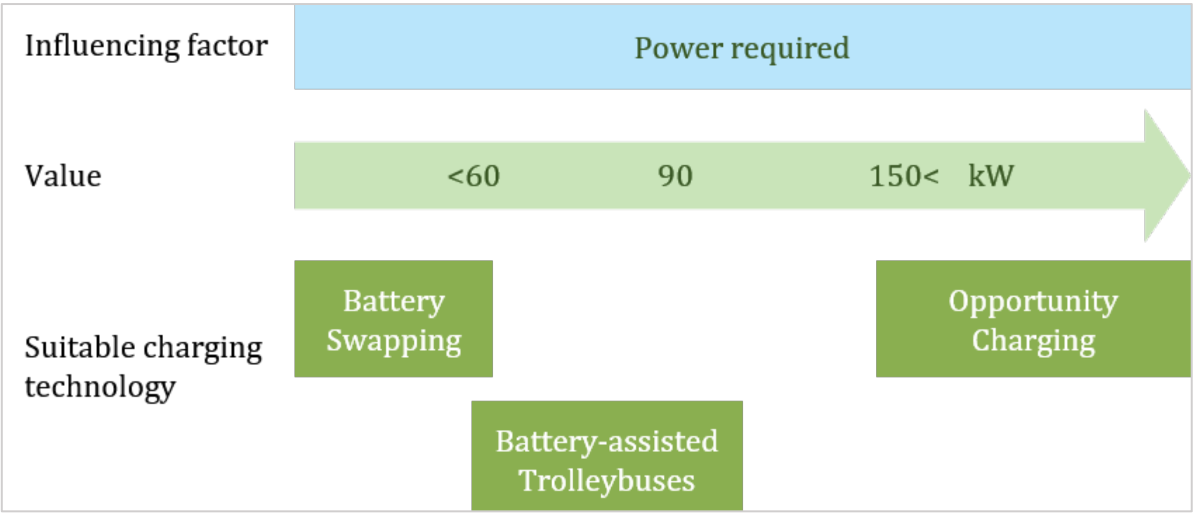


Figure 11: Choice of technology on the basis of power infrastructure requirements

Investment

Of the three technologies, battery-assisted trolleybuses require the highest capital investment on account of their extensive infrastructure.

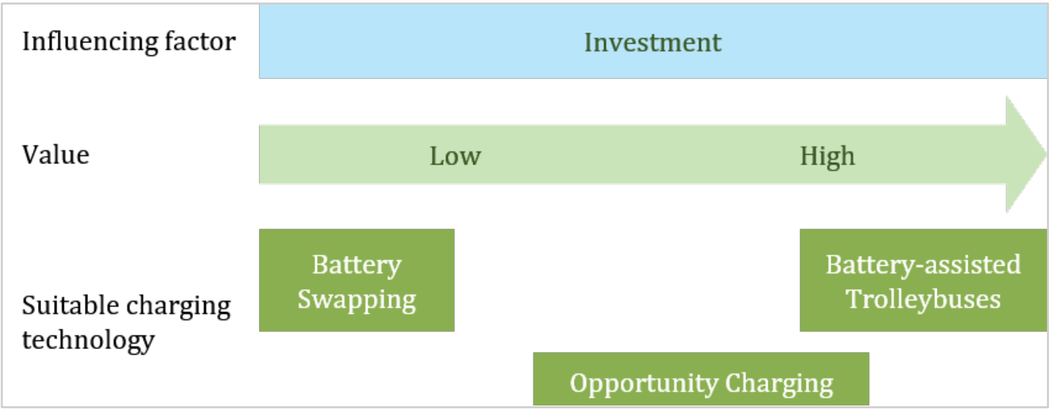


Figure 12: Choice of technology on the basis of capital investment

Battery swapping has a lower capital cost as compared to opportunity charging, although the operational costs (electricity) are higher.

As seen above, the feasibility of employing a certain technology depends on the bus transit network, its operations, and traffic characteristics. Since these parameters vary with each city, a common incentive scheme (such as the one under FAME or those under state-level EV policies) may not be applicable for different states/cities across the country. Instead, cities need to prepare customised action plans for deploying e-buses, taking into account the characteristics discussed in this study. The central agencies can evaluate the proposals, and initiate necessary actions. This would enable efficient deployment of e-buses, thus facilitating a smooth and successful transition to clean public mobility.

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8. Appendix I: Indian Policy Landscape of EV-Charging Infrastructure

Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles in India (FAME India)

FAME India was launched in 2015, as a part of the National Electric Mobility Mission Plan (NEMMP) 2020. The first phase, which was initially planned for two years (till 2017), got extended till 2019, with a total outlay of INR 895 crore. The second phase was notified in March 2019 for three years, with an outlay of INR 10,000 crore.

The first phase was aimed at creating demand, building technology platforms and charging infrastructure, and implementing pilot projects. This phase created a demand for around 2.87 lakh EVs through purchase subsidies. Also, with this scheme, 465 e-buses were sanctioned for operation in several cities.

The second phase focusses on demand incentives, establishment of a network of charging stations, and information, education and communication (ICT) activities. The demand incentives are capped at 40% (of the total cost) for e-buses, and at 20% for other vehicles. The demand is supported by 100% funding for establishing the charging infrastructure. In addition, one slow charger (SC) per e-bus and one fast charger (FC) for every 10 e-buses are also funded (Ministry of Heavy Industries and Public Enterprises, 2019).

Amendments to Model Building Bye-Laws, 2016

The Ministry of Housing and Urban Affairs (MoHUA) has amended the building bye-laws to accommodate the charging infrastructure for EVs in various building types. The amendment suggests that 20% of the total vehicle-holding capacity of the premise be provided for charging EVs. It also suggests that an additional power load be made available, to accommodate (the power required for) all charging points. The amendment specifies a minimum of one SC for plotted residential buildings; and one SC for every three 4-wheeler-EVs or one FC for every ten 4-wheeler-EVs; one SC for every two 3-wheeler-EVs as well as 2-wheeler-EVs; and one FC for every 10 e-buses. These charging stations shall provide open metering and on-the-spot payment options to the users (Ministry of Housing and Urban Affairs, 2019).

Electric Vehicle (EV) Charging Guidelines and Specifications

The specifications (Ministry of Power [MoP], 2018; MoP, 2019) were notified by the MoP in December 2018 and further modified in October 2019. The objective was to enable the schemes aimed at faster adoption of EVs in India through the provision of reliable, accessible, and affordable charging infrastructure. The guidelines state that the establishment of public charging stations (PCS) shall be a de-licensed activity. The scheme is planned to be piloted in mega cities, expressways, and highways in the first phase (1-3 years); and in state capitals, and union territory headquarters in the next phase (3-5 years).

The guidelines prescribe that an exclusive transformer with substation equipment and 33/11 KV lines/cables with associated equipment be provided for every PCS. The revision prescribes that for fast charging, the rated voltage shall be 200-500 V or higher for Combined Charging System (CCS) and CHAdeMO; and 380-415 V for Type–2 AC charger connectors, all with a single connector gun each. For slow or moderate charging, it specifies 230 V for Bharat AC-001 with three charging points and three connector guns of 3.3 kW each, and 48-72 V (or higher) for Bharat DC-001 with single connector gun each. In addition, for the charging infrastructure for heavy-duty EVs (like trucks and buses), at least two chargers of 100kW each (of CCS/CHAdeMO) or a fast charger with single connector gun is required. Fast charging stations may also have options for battery swapping. Further, for a fast-charging facility, appropriate liquid-cooled cables for on-board charging of fluid-cooled batteries (FCB), and climate-control equipment for fast charging of batteries (for swapping), are to be provided.

At least one PCS shall be provided in a grid of 3 km x 3 km, and one PCS for every 25 km on both sides of the road. To address the concerns of long-range travel and/or heavy-duty EVs, one fast charging station within the PCS for every 100 km on either side of the road shall be provided (MoP, 2018; MoP, 2019).

State EV Policies

In alignment with the initiatives of the central ministries, several states have formulated EV-related policies to promote their adoption. While the focus is on increasing the adoption rate through incentives and subsidies, these policies also promote the setting-up of research and development centres, manufacturing units, and charging-infrastructure services. The states also consider this transition to electric as an opportunity to attract investment and provide employment.

Through its EV policy, Karnataka has proposed the formation of a special purpose vehicle (SPV) to oversee the provision of charging facilities at all major residential and commercial development sites, based on Bureau of Indian Standards (BIS)/Automotive Research Association of India (ARAI) specifications (Commerce and Industries Department, Government of Karnataka, 2017). The policy also recommends an FC/swapping station at every 50 km on major highways. To facilitate these installations, the state aims to provide investment subsidies worth INR 15 lakh to 5 crore to EV-charging/swapping-infrastructure-manufacturing enterprises. This is in addition to the exemptions from stamp duty, registration charges, land conversion fees, and electricity duty.

Telangana also recommends setting up charging infrastructure at all transit stations, airports, parking lots, markets, malls, and on highways to major cities (one station for every 50 km) (Government of Telangana, 2017). The state would also support the setting-up of PCS with 75% reimbursement of goods and services tax (GST), and charging infrastructure at residential complexes with capital subsidies of INR 5-10 lakh. Along with similar incentives, Uttar Pradesh provides capital subsidy of up to 6 lakh per charging station for the first 100 stations in the state (Government of Uttar Pradesh, 2018), while Andhra Pradesh provides a capital subsidy of INR 30 thousand to 1 lakh for charging-infrastructure equipment/machinery, and up to INR 10 lakh for the first 50 swapping stations (Industries & Commerce Department, Government of Andhra Pradesh, 2018).

Similarly, Delhi encourages the use of electric 2-wheelers, 3-wheelers, and 4-wheelers for shared mobility (Government of the National Capital Territory of Delhi, 2018). The union territory provides up to INR 30,000 per charging point for setting up the first 10,000 private charging points. It has also planned to invite bids for the setting-up of charging/swapping infrastructure across the city. In the case of swapping infrastructure, reimbursement of 100% state goods and service tax (SGST) will be provided for advanced batteries.

Several other states, like Kerala (Transport Department, Government of Kerala, 2017), Maharashtra (Industries, Energy and Labour Department, Government of Maharashtra, 2018), and Tamil Nadu (Government of Tamil Nadu, 2019) also promote the setting-up of adequate charging infrastructure to facilitate the transition to electric mobility.

9. Appendix II: Battery Storage Technologies

Lithium batteries are globally accepted technologies for EVs and plug-in hybrid electric vehicles (PHEV). The performance characteristics of the six commonly-used lithium battery variants, along with their advantages and disadvantages, are detailed in Table 12

Table 12: Characteristics of common lithium battery variants

Lithium Battery Variants	Properties	Pros	Cons
Lithium Cobalt Oxide (LCO)	• Voltage – 3.6 V • Specific Energy – 150-200 Wh/kg • Charge rate – 0.7-1 C • Discharge rate – 1 C • Cycle life – 500-1000 cycles • Applications – mobile phones, tablets	• Very high specific energy	• Limited specific power • Cobalt is expensive
Lithium Iron Phosphate (LFP)	• Voltage – 3.2 V • Specific Energy – 90-120 Wh/kg • Charge rate –1 C • Discharge rate – 1 C • Cycle life –2000 cycles and higher • Applications – portable and stationary	• Very flat voltage discharge curve	• Low capacity • High self-discharge
Lithium Nickel Manganese Cobalt Oxide (NMC)	• Voltage – 3.6 V, 3.7 V nominal • Specific Energy – 140-200 Wh/kg • Charge rate – 0.7-1 C • Discharge rate – 1 C • Cycle life – 1000-2000 cycles • Applications – EV's	• High capacity • High power • Long cycle life	• Use of cobalt in the cathode makes it expensive • Safety aspect
Lithium Manganese Oxide (LMO)	• Voltage – 3.7 V • Specific Energy – 100-150 Wh/kg • Charge rate – 0.7-1 C • Discharge rate – 1 C • Cycle life – 300-700 cycles • Applications – electric power trains	• High power • Safer than LCO	• Less capacity • Free of cobalt

Lithium Nickel Cobalt Aluminum Oxide (NCA)	• Voltage – 3.6 V • Specific Energy – 200-250 Wh/kg • Charge rate –0.7 C • Discharge rate – 1 C • Cycle life –1000-1500 cycles • Applications – EVs, medical devices	• Outstanding specific energy	
Lithium Titanium Oxide (LTO)	• Voltage – 2.4 V • Specific Energy – 50-80 Wh/kg • Charge rate –1 C • Discharge rate – 10 C possible • Cycle life –1000-1500 cycles • Applications – UPS, electric power train	• Long life • Fast charge • Safest Lithium batteries • Wide temperature range • Ability to ultra-fast charge	• Low specific energy • Low voltage • High cost • **LTO is the anode Cathode can be LMO, LFP, NMC

("Types of Lithium-ion", 2020; Jaiswal, 2017; Zubi et al., 2018)

Among these variants, NMC and LFP are the most preferred batteries for EVs, due to their high specific energy, cell voltage, cycle life, and low cost. For opportunity charging, LTO batteries might be preferred due to their ultra-fast charging characteristic. However, they are expensive, when compared to other lithium battery types.

The feasibility of other lithium battery variants such as solid-state batteries, lithium sulphur, lithium air, and lithium metal batteries are being explored as alternative technologies for EVs. It is believed that the performance of these emerging technologies can be higher than that of the existing options.

10. Appendix III: Technical Comparison of Routes – KIAS 4 and V 500CA

A feasibility analysis (similar to the one done under Section 5) of the three technologies and depot-based charging, was performed for two more routes with different route characteristics. The details of the selected routes are given in Table 13.

Table 13: Details of selected routes (KIAS 4 and V 500CA)

Route	KIAS 4	V 500CA
Schedule	KIA 4/1	V 500CA/4
Associated depot	Depot – 18	Depot – 25
Width of road (m)	65	45
Origin	Kempegowda International Airport	Banashankari
Destination	HAL Airport Road	ITPL
Trip length (km)	55	27
Total route length (km)	330.9	167
Dead km (km)	0.9	10.5
Number of bus stops	30	41
Number of trips per day	8	8
Average speed (kmph)	27	16
Energy consumption (EC) (kWh/km)	1.27	1.3

The key metrics for comparing the technical parameters of the three technologies and depot charging is summarised in Table 14.

Table 14: Comparison of technologies for routes KIAS 4 and V 500CA

	KIAS 4/1				V 500CA/4			
	Battery Swapping	**Opportunity Charging**	**Trolleybus**	**Depot**	**Battery Swapping**	**Opportunity Charging**	**Trolleybus**	**Depot**
Battery capacity considered (kWh)	140	80	60	250	80	80	60	250
Charging power considered (kW) (DC chargers)	60	150	60	120	60	150	60	60
Number of recharging locations /length of overhead contact lines	2	3	40.1 km	2	2	2	13.2 km	1
Number of daily recharges required /number of times bus connects to overhead lines	6	10	4	2	6	6	4	1
Total recharging time at all locations (min)	125	100	NA	222	71	60	NA	230
Maximum power demand per bus (kW)	60	150	95.5	120	60	150	82.8	60
Total energy required at all locations (kWh)	752	250	540	443	429	150	281	230
Area required for each station (sq.m)	75	10.2	NA	165	75	10.2	NA	165
Total cost of electricity required (INR) per day	3,645	1,213	2,622	2,149	2,083	728	1,366	1,113
Capex cost of the bus (INR)	1.5 crore	0.8 – 2.5 crore	6 crore	0.8 crore	1.5 crore	0.8 – 2.5 crore	6 crore	0.8 crore
Capex cost of infrastructure (INR)	0.88 – 0.9 crore	3.4 – 4.6 crore	332 crore+	0.57 crore	0.65 – 0.68 crore	2.3 – 3 crore	109 crore+	0.57 crore

To operate both routes on electricity, the three technologies require a smaller battery size than that needed for depot-based charging. The charging locations required are more or less similar to those needed for depot-based charging. For all the stations, a total of 150 sq.m for battery swapping, and 20–30 sq.m for opportunity charging, is required. For trolleybuses, the infrastructure is installed along the length of the route (48%–73% of the length).

Though these technologies require a higher number of recharging instances, the time spent for recharging/swapping at the locations is lower, as compared to depot-based charging. The maximum power drawn per bus for charging batteries in battery swapping and battery-assisted trolleybus systems is less than that drawn in depot-based charging system. However, opportunity charging requires more power.

The total energy consumed and the resultant electricity cost for charging a bus is higher for trolleybuses and battery swapping technologies than what it is for depot-based charging system. However, for opportunity charging, the total energy consumed and the resultant electricity cost is less than that in depot charging. The cost of a trolleybus is about three times higher than that of a usual e-bus. The cost of infrastructure is also higher for the three technologies.

Serving these routes with battery swapping technology will require a larger battery module than usual, which could, in turn, require a longer turnaround time at the swapping stations. Also, though the electricity cost is comparatively higher, the infrastructure cost is less than that of opportunity charging and trolleybuses, making it more feasible than the other technologies.


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