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CHARGING INDIA'S BUS TRANSPORT

A Guide for Planning Charging Infrastructure for Intra-city Public Bus Fleet

Shyamasis Das, Chandana Sasidharan, Anirudh Ray

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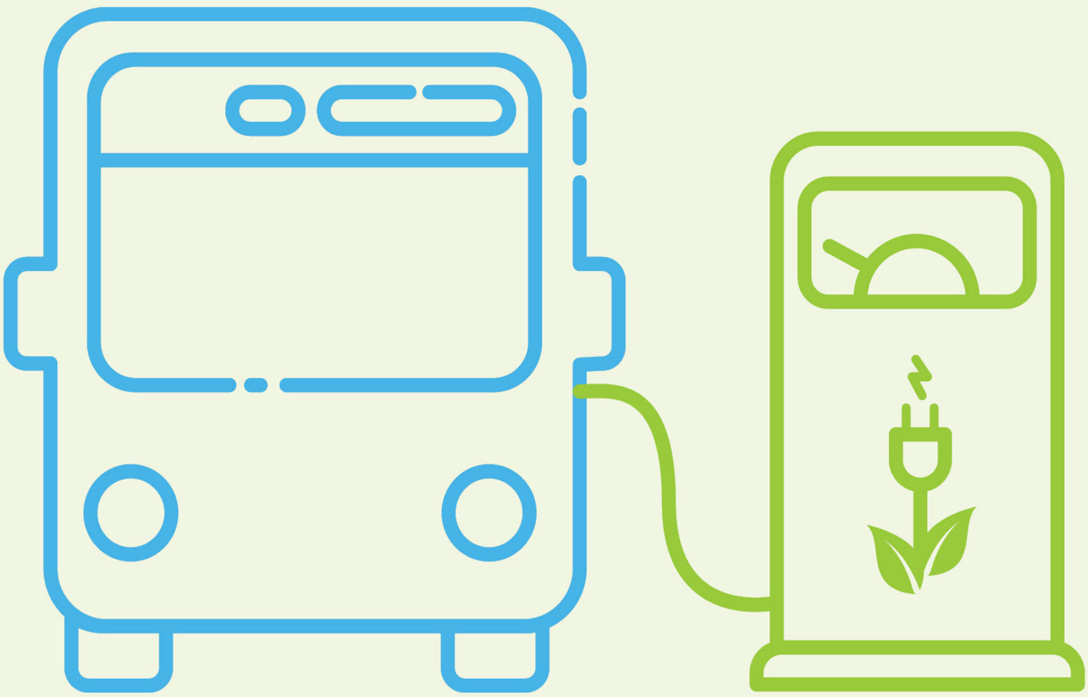

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1 Introduction and background

The National Electric Mobility Mission Plan (NEMMP) launched by the Government of India (GoI) in 2013 aims to realise around 6-7 million electric vehicles (EVs) on Indian roads by the year 2020 (Press Information Bureau, 2015).

GoI has also expressed its intent to achieve 100% EV sales by 2030. In the Union Budget for 2015-16, the government launched the FAME (Faster Adoption and Manufacturing of (Hybrid and) Electric Vehicles) scheme for 6 years till 2020. Phase-I of the scheme initially spanned over financial years 2015-16 and 2016-17 with a budget of ₹7950 million (Ministry of Heavy Industry and Public Enterprises, 2015). The Department of Heavy Industry (DHI), the nodal agency to operationalise the FAME scheme, subsequently extended the Phase-I till 31st March 2019 with an increased kitty of ₹8950 million. The initial phase of this scheme was chiefly concerned with incentivising the demand for EVs, development of a technology platform, setting up of charging infrastructure throughout the country, and execution of pilot projects. On 8th March 2019, DHI notified the next phase of FAME with a budget of ₹100 billion which becomes effective from 1st April 2019 for three years (Ministry of Heavy Industries and Public Enterprises, 2019). In Phase-II of the scheme, priority is given to public and commercial vehicle segments while offering the demand incentives.

In spite of the ambitious outlook of GoI towards electrification of vehicles, adoption of EV in the country is yet to pick up. Among different factors, high EV cost, range anxiety, primarily due to lack of charging stations, and EV charging time pose significant barriers to EV uptake. The perceived complexity and associated cost of EV-adoption deter the vehicle users to shift from an age-old, dependable transport technology *i.e.*, Internal Combustion Engine (ICE)-based vehicles to an entirely new format which has limited precedence in the country till now. On the flip side, an EV has a compelling competitive advantage over a comparable ICE-vehicle.

It is found that the Total Cost of Ownership (TCO)[1] of an EV could be considerably lower than an equivalent ICE-vehicle if the vehicle usage level (total distance travelled by a vehicle over the lifetime) is sufficiently high. The reason being the savings from the lower operating cost of an EV due to less energy consumption per km can potentially offset the higher upfront cost of an EV (University of Central Florida, Orlando, FL, 2018). This cost-advantage is envisaged to improve further in the near future with the decline in the price of a lithium-ion battery.

As the TCO of an EV becomes more attractive with higher usage, there is a strong driver for specific vehicle segments in India which are generally characterised with high per vehicle annual distance travel to adopt electric technology. Considering the competitive advantages of an EV and the current range anxiety, intra-city public buses in India merit consideration to switch to electric – an opinion echoed by an existing study titled “The Case for All New City Buses in India to be Electric” (Khandekar *et al.*, 2018).

On the ground also, one can observe that the effort towards electrification of intra-city public bus fleets is gaining traction. For instance, on 31st October 2017 DHI issued an Expression of Interest (EoI) soliciting proposals from states or city administrations for multi-modal electric public transport and also solely electric buses. The selected cities are eligible to receive funding under the FAME scheme.

THE STATE ROAD TRANSPORT UNDERTAKINGS (SRTUS) IN INDIA MANAGE OVER 1,00,000 BUSES ACROSS INDIA REGISTERING OVER 524 BILLION PASSENGER-KM ANNUALLY

The State Road Transport Undertakings (SRTUs) in India are an essential stakeholder in this transition because of the fact that they manage over 1,00,000 buses across India registering over 524 billion passenger-km annually (Ministry of Statistics and Programme Implementation, 2017). From the points of view of reducing fuel consumption and local air pollution and meeting climate goals, making the transition to electric buses from conventional diesel-run buses[2] also augurs well for the government considering state-owned public bus fleets account about 14% of total diesel consumption in the transport sector (Press Information Bureau, 2014). Hence, the state-owned public bus segment is regarded as a sweet spot of the nation-wide effort to shift to electric mobility. Apart from SRTUs, in many Indian cities, a significant share of public bus fleets is operated by the private sector. Because of the high upfront cost to procure buses and set up charging stations, at present private bus operators may hesitate to migrate to electric technology; however, in view of the declining cost of EV battery which would improve the bus TCO further, it is matter of time this segment of public bus fleet would gradually shift to electric format.

Irrespective of whether the transition to electric format happens today or tomorrow, extreme care must be taken while rolling out electric buses (e-buses) – any major disruption in the service of the public bus network in a city could have grave implications. It is worthwhile to mention here that a majority of the public transport demand in India, in both rural and urban areas, is met through bus transport. This is evident from the findings of the National Sample Survey Office (NSSO) in 2016 which states that 66% and 62% of the households in rural and urban areas respectively reported expenditures on bus transport (NSSO, 2016).

1 TCO includes capital and operating costs of a vehicle.
2 Some cities like Delhi have CNG buses.

INSTANCES OF ELECTRIFICATION OF PUBLIC BUS FLEETS IN INDIA

In recent times, SRTUs in major Indian cities are contemplating to introduce e-buses in their vehicle fleets. In response to DHI's Expression of Interest (EoI) dated 31st October 2017 which invited proposals from million-plus cities and special category states, 44 cities submitted 47 proposals for multi-modal electric public transport, out of which 11 cities were selected for pilot projects. The government has sanctioned a total of 390 buses wherein Delhi, Ahmedabad, Bengaluru, Jaipur, Mumbai, Lucknow, Hyderabad, Indore and Kolkata will be given subsidy for 40 buses each, while Jammu and Guwahati will get subsidy for 15 buses each (UITP, 2018). Telangana State Road Transport Corporation (TSRTC) has already procured 5 e-buses of 12 m standard length for its fleet in Hyderabad.

APPROXIMATELY 161 E-BUSES ARE ALREADY PLYING ON INDIAN ROADS AS IN MARCH 2019

It is worth mentioning here that before the aforesaid EoI was floated, there have been few instances of commercial operation of e-buses for public transport. For example, Himachal Pradesh Transport Corporation (HPTC) procured fully electric buses (Figure 1) from the erstwhile Goldstone-BYD joint venture and started operating them on the Kullu - Manali - Rohtang Pass route since September 2017. The Goldstone-BYD (now Olectra-BYD) tie-up had also conducted trials of their buses in Delhi, Mumbai, Bengaluru, Hyderabad, Chandigarh and Rajkot (The Hindu BusinessLine, 2018). In Mumbai, Brihanmumbai Electric Supply and Transport (BEST) has acquired hybrid electric buses from Tata Motors and fully electric buses from Olectra-BYD and is operating these buses on select routes since March 2018 (The Hindu, 2018).

FIGURE 1: 9 M LONG ELECTRIC BUS DEPLOYED IN HIMACHAL PRADESH [SOURCE: (SWARAJYA STAFF, 2017)]

It is reported that approximately 161 e-buses are already plying on Indian roads as in March 2019 (Balakrishnan, 2019). Many of the e-buses are operational without availing subsidy benefits under FAME scheme. The Pune Mahanagar Parivahan Mahamandal Limited (PMPML) recently deployed 25 e-buses of 9-m length under gross cost contract model (Bengrut, 2019). The Kerala State Road Transport Corporation (KSRTC) has also started to operate 9-m long e-buses on both inter-city and intra-city routes (Radhakrishnan, 2019) (Dogra, 2019).

Few large-scale procurements of e-buses for public transport are also expected. For example, the Govt. of Delhi has approved the procurement of 1,000 e-buses in 2019. The Govt. of Tamil Nadu is also planning to procure 2000 e-buses (TOI, 2019). The Bangalore Metropolitan Transport Corporation (BMTC) is also reported to have decided to procure 80 e-buses (TNM, 2019).

NEED FOR INVESTIGATION – PLANNING OF CHARGING INFRASTRUCTURE

Electric mobility in India and around the globe is at its infancy and evolving rapidly. On the one hand, many of the vehicle, battery and charging technologies are yet to be tested sufficiently in the real-world situation, and some are still at a prototype stage. On the other hand, the consumers are trying to understand the nuances of using an EV and figure out how they can shift to this new format without disturbing their mobility and compromising with their travel preferences. Moreover, EV-transport is unique from the rest of the road transportation modes due to the fact that its implementation is inextricably linked with the electricity distribution sector. Connection to the required service voltage of the electricity distribution network and uninterrupted and inexpensive supply of electricity are some essential requirements for running charging stations.

EV-TRANSPORT IS UNIQUE FROM THE REST OF THE ROAD TRANSPORTATION MODES DUE TO THE FACT THAT ITS IMPLEMENTATION IS INEXTRICABLY LINKED WITH THE ELECTRICITY DISTRIBUTION SECTOR

As the public bus fleets in the cities are embarking on the electric journey, there is very little space to make errors as it may adversely impact the public transport system of the city. Rolling out e-buses may pose as a double-edged sword to the bus service providers[3].

Deployment of charging stations in a meticulous way is critical for a bus service provider to achieve smooth operation of its e-bus fleet and make the corresponding electrification investment worthwhile. In order to make a seamless transition to electric mode, it is imperative that the establishment of required charging infrastructure is planned in advance and with enough due-diligence. Among the different operating factors, the range of an e-bus and charging time could potentially impact the service of a public bus fleet.

Currently, the bus service providers are not familiar of the e-bus operation and the charging technologies and do not have the necessary technical and commercial know-how to manage e-bus fleets, especially to plan and set up charging infrastructure. Also, the OEMs or third-party operators in India are on a learning curve – they are yet to garner sufficient hands-on experience in supporting bus service providers to operate fully electric bus fleets. This engenders the need to carry out comprehensive research on the current e-bus market and study the operation of a typical intra-city bus fleet in an Indian city in light of possible electrification.

3 Include SRTUs and private bus operators

2 Objective, scope and approach

The study **"Charging India's Bus Transport"** intends to facilitate the transition of the public bus mobility in a Tier-I or Tier-II city in India to a fully electric format by shedding interesting insights into the e-bus and charging technology market and providing definitive guidance to set up charging infrastructure for an intra-city e-bus fleet. This is arguably the most detailed study undertaken on e-bus transport in the Indian context.

To this end, the exercise sets three main objectives:

1. To develop a tool for evaluating the suitability of different charging technologies and making an objective decision to select the *"best-fit"* technology for charging a typical intra-city public e-bus fleet
2. To formulate a framework for examining the optimum charging capacity required to meet the charging demand of an intra-city public e-bus fleet on a route
3. To create tools which would serve as a useful guide to set up charging stations for an e-bus fleet

The study recognises the need to take a holistic approach to achieve the set objectives, *i.e.*, to take into cognizance the types of charging technologies and their technical and commercial details, the available electricity distribution network, the current e-bus specifications, the intra-city bus operation and route features, and the space requirement, all together.

The investigation entails the following main steps:

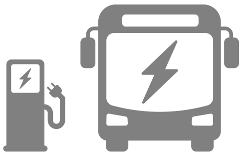
- Understanding the different categories of EV charging technologies prevalent in matured EV markets and developing a classification framework specially curated for the Indian scenario
- Carrying out a comparative assessment of the e-bus charging options and identifying the plausible charging technologies for the Indian bus fleet
- Reviewing the specifications of the e-bus models and the principal features of an intra-city bus transport network in a Tier-I or Tier-II Indian city
- Identifying the possibilities of charging of a public e-bus fleet in a city on a route
- Developing a unique Multi-Criteria Decision Matrix for selection of best-fit charging technology for each charging possibility
- Assessing different possible cases of routes of a public e-bus transport network, based on the relation of headway with average charging time for an e-bus
- Formulating relations between the operation parameters to evaluate the optimum charging capacity required to meet the charging demand of an intra-city public e-bus fleet on a route in the given cases
- Testing the effectiveness of the devised relations by applying real-world values
- Providing a much-needed overview of the technical, financial, spatial and management aspects which are critical from the point of view of planning the establishment of charging stations for a public e-bus fleet

The outcome of this exercise should be considered in the context of the specifications of the e-bus models[4] and charging technologies currently available in the market, and the principal features of an intra-city bus transport network in a Tier-I or Tier-II Indian city.

It should be borne in mind that the recommendations on the selection of charging technology and the planning of charging stations are based on the intra-city public bus network features commonly seen in the Indian cities. The purpose of this report is to provide general guidance for setting up charging infrastructure for public buses in an Indian city, and the outcome of this study should not be construed as specific to a city. The concerned bus service provider is advised to plan the charging infrastructure for its bus fleet according to the existing bus network and the route features of a particular fleet.

4 Only fully electric bus models have been considered.

3 Review of e-bus charging technologies



Charging technology, often known as a type of Electric Vehicle Supply Equipment (EVSE) refers to the apparatus required to re-charge the battery of an EV. A charger is effectively the interlink between the electricity distribution network and an EV and primarily consists of an electricity transfer equipment, a communication system and connector(s).

Charging technologies currently deployed worldwide for charging e-buses are diverse in their method of electricity transfer, power output levels, control and communication capabilities, *etc.* (IEA, 2018). The lack of international standards for EVSEs makes it challenging to compare the different charging technologies available in the market in a consistent way and make an appropriate decision to select a suitable charging option for e-buses. Given this challenge, at the very outset, this study intends to create a framework to categorise the EV charging technologies for e-buses based on certain salient features such as their method of electricity transfer, power output levels, *etc.* This would help perform objectively a comparative assessment of a range of charging technologies in the context of e-bus charging.

AN OVERVIEW OF EVSE CLASSIFICATION PRACTICES WORLDWIDE

NO UNIVERSAL STANDARD: The design parameters of an EVSE depend equally on the available electricity distribution network as much as the charging requirements of an EV. As neither the electricity grid design is uniform internationally, nor the EV charging requirements are identical across vehicle segments, there is no established universal standard to classify the charging technologies. However, one can observe certain regional standards in prominent EV markets, including the US, Europe and China. An overview of the standardisation attempts for classifying EVSEs is presented below.

US: One of the recognised classification standards for EVSEs is based on the charging power levels or simply "Levels"[5]. As early as 1996, three EVSE levels were defined in the US. The functionality and safety requirements were set for each level (Morrow, Karner, & Frankfort, 2008). Level 1 and Level 2 charging were defined for single-phase voltage available in residential and commercial buildings whereas charging at three-phase voltage, via AC or DC, was classified as Level 3. The initial US classification covered electricity transfer by both conduction and induction within the prescribed Levels. Subsequent revisions of the standard have diluted the classification based on power levels, shifting focus to the method of electricity transfer [6] (National Electric Code Commitee, 2016). The details of the original three Levels defined for EVSEs are presented in Table 1.

TABLE 1: PRESCRIBED STANDARD FOR EVSES IN THE US

EVSE Levels	Voltage rating (V)	Current range (A)	Power range (kW)
Level 1	120	15 - 20	1.4 - 2.4
Level 2	240	20 - 100	4.8 - 24
Level 3	480 V or above	60 - 400	50 - 350

EUROPE: Europe defines four charging Modes[7] as shown in Table 2 based on the charging rates, output power levels as well as the communication between EV and EVSE (Spöttle *et al.*, 2018). Europe's Modes for EVSE are different from US Levels as the former gives adequate consideration to EV-EVSE communication. The 120V voltage level is not prevalent in Europe and there is no European counterpart for US Level 1. Both single-phase and three-phase AC connections are allowed under the first three modes. Mode 3 covers smart charging aspects such as controlled charging and vehicle-2-grid functionality (Vesa, 2019). Europe also defines a separate subclass for DC charging under Mode 4.

TABLE 2: STANDARD FOR EVSES IN EUROPE

Modes	Description	Voltage rating (V)	Maximum current rating (A)	Power range (kW)
Mode 1	Slow AC charging in households	250 / 480	16	3.7-11
Mode 2	Slow AC charging with semi-active connection to vehicle to communicate for safety purposes	250 / 480	32	7.4-22
Mode 3	AC charging with active connection between charger and vehicle for safety and communication for smart charging	250 / 480	32	14.5-43.5
Mode 4	DC fast charging, active connection between charger and vehicle	600	400	38-170

CHINA: The charging standards established in China are primarily for conductive charging via AC or DC. China had adopted erstwhile European standards[8] and subsequently developed its own charging standards[9] for conductive charging system. Hence, the Chinese standard for conductive electricity transfer encompasses the four European charging Modes

5 As defined by the Infrastructure Working Council formed by Electric Power Research Institute (EPRI) and subsequently codified in the National Electric Code (NEC) under article 625
6 The latest revision of NEC (NFPA 70E) separates provisions related to conductive and inductive power transfer and carves out another subclass for DC charging
7 The modes are defined in the international industry norm DIN IEC 61851
8 GBT 18487.3.2001 and GB/T 20234.2.2001 adopting International Electrotechnical Commission (IEC) standards
9 GB/T 18487.1.2015 covering Electric Vehicle Conductive Charging System, and GB/T 20234.1, GB/T 20234.2 and GB/T 20234.3 for connection set for conductive charging

described above. China is also reported to be working along with CHAdeMO[10] association to work on a DC fast charging standard for charging power up to 900 kW suitable for large vehicles including electric buses (Boyd, 2018).

REST OF THE WORLD: Other than the major three EV markets, the attempts at standardisation of EVSEs are quite limited or rudimentary. For example, South Korea is an interesting market for e-buses, which has seen the implementation of pilot projects using wireless charging and battery swapping technology. However, the country has no established standard for either of the technologies. The existing standardisation for EVSEs in South Korea pertains only to conductive charging, as described in Table 3 (Park, 2016).

TABLE 3: EVSE CLASSIFICATION IN SOUTH KOREA

Charging	Type	Voltage rating (V)	Power rating (kW)
Mini	AC charging	220	<2
Standard	AC Charging	220	3-8
Rapid	DC Charging	100-450	>50

POSSIBLE WAYS TO CLASSIFY CHARGING TECHNOLOGIES

Charging technologies deployed all over the world can be categorised based on the following four major aspects:

- Technology used in electricity transfer
- Power output of the charger
- Communication and protection protocols
- Type of connection

1. **TECHNOLOGY FOR ELECTRICITY TRANSFER:** The primary characterisation of EVSEs can be done based on the method of electricity transfer. EVSE charging can be performed through a wired connection *i.e.*, by conduction or wirelessly *i.e.*, via induction. In the case of the former, the electricity transfer can be achieved using AC or DC. Battery swapping is the third method of electricity transfer where a fully charged battery replaces a depleted battery. Both battery swapping and inductive technologies have seen limited commercial deployment, and hence, standardisation efforts for both these technologies are yet to mature[11].
2. **POWER OUTPUT:** The power output of the charger can be either AC or DC[12]. However, the power output range of an EVSE is inextricably linked to the supply voltage which is readily available in the distribution network, the maximum output current rating allowed at each voltage and the charging requirement of an EV.
3. **COMMUNICATION AND PROTECTION PROTOCOLS:** The third aspect that has governed the characterisation of an EVSE is communication technology and protection protocols. It is seen that with the progressive increase in charger power output, the associated communication and protection protocols also get more complex. Improved communication technologies between EVSE and EV facilitates the application of smart charging functions.

10 CHAdeMO association is an e-mobility collaboration platform which is involved promotion of the CHAdeMO DC charging standard

11 IEC 61980-1:2015 for wireless charging and IEC 62840-1:2016 for battery swapping systems are the international standards available for the technologies

12 It is important to note that EVSE that facilitates AC charging which requires On-board charger on the Electric Vehicle. DC charging is performed in cases where the vehicle charger is not On-Board.

4. **CONNECTION BETWEEN EV AND EVSE:** In the case of conductive charging, an EVSE has two types of designs - plug-in or pantograph. Plug-in connectors[13] are common and used in both AC and DC charging. Pantograph connectors are mostly used in charging at high power using DC. There is no physical connection between EV and EVSE in case of inductive charging and battery swapping.

A snapshot of the possible charging technology characterisation is presented in Figure 2.

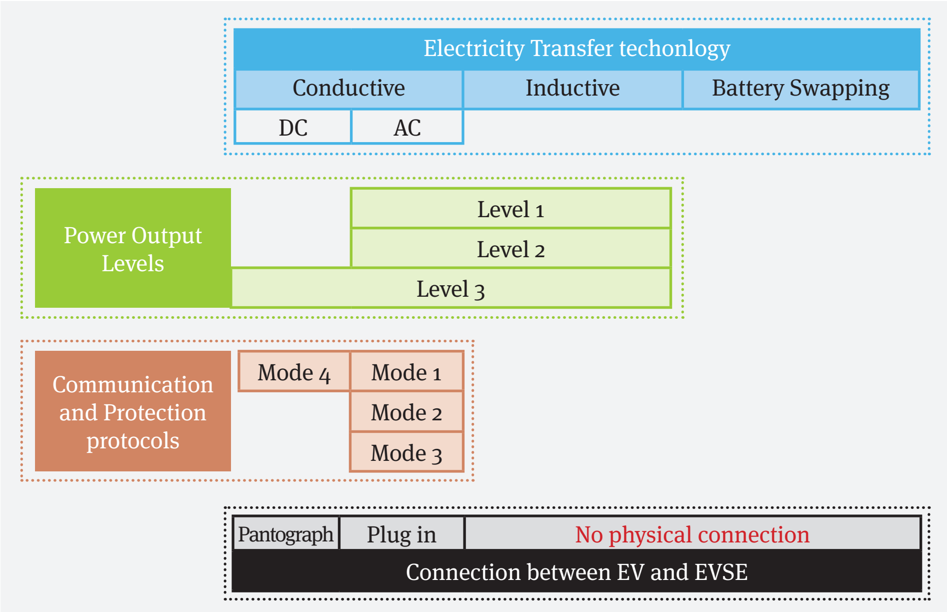


FIGURE 2: WAYS OF CHARACTERISING DIFFERENT TYPES OF CHARGING TECHNOLOGIES

CLASSIFYING CHARGING TECHNOLOGIES FOR ANALYSES

Charging technologies currently deployed in different parts of the world greatly vary with functional attributes and applications. Absence of a global standard of these technologies makes it a challenging task to evaluate and distinguish them under appropriate categories or sub-categories. To make an objective assessment of these different technologies, it is therefore deemed critical to develop a suitable framework for classifying the charging technologies based on the key attributes. The proposed framework also considers the standard practices followed in India's distribution network, wherever applicable[14]. The proposed approach for classifying the available charging technologies is presented in Figure 3. The details of the categories are given below.

13 Type 1/Type 2/CCS/CHAdeMO/GB-T are common plug-in connectors used in different protocols for AC/DC charging. They are accounted for under plug-in type of connectors.
14 Standard Voltages of 230V single phase circuit, and 415/11000/33000 for three phase circuits.

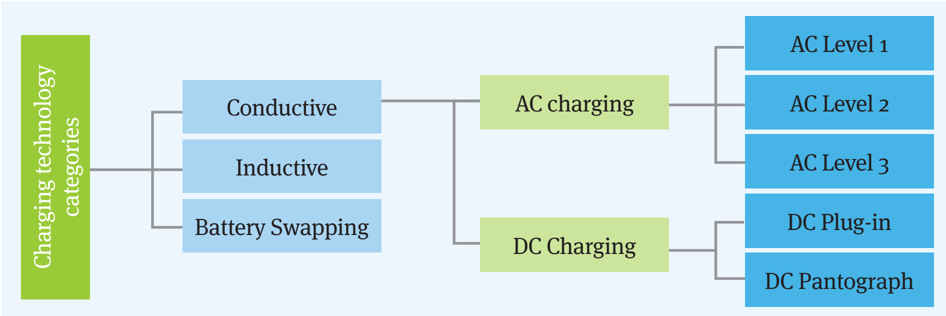


FIGURE 3: CATEGORIES OF CHARGING TECHNOLOGIES

AC CHARGING

An EV can be charged by conductive AC charging technology provided the former has an on-board charger which can convert supplied AC to DC power for charging the vehicle battery. AC charging is the most prevalent type of charging since the grid supplies the electricity in AC. Also, AC charging technology offers better economy of service in comparison with DC charging, where the cost of the converter and other auxiliary equipment adds to the charger cost. However, AC charging is only possible when the vehicle has an on-board charger, and the capacity of the on-board charger limits the capacity of AC charging. AC Charging can be categorised into three levels: Level 1, Level 2 and Level 3 considering the standard service voltages available worldwide. The classification broadly follows the Level-based standard of US, with less stress on the associated communication and protection requirements. The upper limits for power output in relevant cases are set using standard practices[15] applicable to the Indian distribution grid.

CASE STUDY: SHENZHEN, CHINA

The Chinese city of Shenzhen is the pioneer in adopting electric mobility to fight air pollution (Guardian, 2018). The city has successfully electrified its e-bus fleet of over 16,000 buses operated by three bus companies: Shenzhen Eastern Bus Company, Shenzhen Western Bus Company and Shenzhen Bus Group (ISGF, 2018) (Hall, Cui, & Lutsey, 2018). The e-bus operators collaborated with charging infrastructure providers to establish charging facilities at depots and the bus routes maintaining a 1:3 charger-to-bus ratio (Lu, Xue, & Zhou, 2018). Both AC and DC charging technologies are employed for charging the e-buses in the city (Eurabus, 2017). One of the most common chargers employed for BYD-supplied buses is an AC charger rated at 80 kW, 415 V, three phase supply (ISGF, 2018). The typical charging time reported in case of overnight charging at the depot is around 2 hours. However, there are also charging stations installed en-route, which are reported to charge the buses in approximately 40 minutes (Eurabus, 2017). The lead time for setting up the charging stations in 13 depots with 20 to 40 charging stations at each depot was reportedly around three months, while the process of grid connection took six months. It is also reported that current transformer stations were built at the depots in order to adjust the charging Voltage (Eurabus, 2017).

15 Maximum current in 230 V single phase AC circuit is considered as 32 A in accordance with the rating of highest single pole MCB available

AC LEVEL 1

AC Level 1 charging takes place at the lowest service voltage prevalent in some parts of the world. The salient technical specifications of Level 1 charging are stated in Table 4.

AC Level 1 charging is an established charging method for EVs as it is a simple plug and play charging which needs no ancillary infrastructure. Hence, the capital cost of charging equipment is negligible. The area required for AC Level 1 EVSE is also minimal as they are generally wall mounted. However, the applicable service voltage level is not available in the Indian grid. Also, there is no reported case of charging of e-buses at AC Level 1.

TABLE 4: AC LEVEL 1 TECHNICAL SPECIFICATIONS

Voltage (V)	120
Input current (A)	15 - 20
Output power (kW)	1.4 - 2.4

AC LEVEL 2

AC Level 2 charging entails single-phase charging performed at the most common service voltage in the world, as shown in Table 5. There is a case for Level 2 charging in India as single-phase connections at 230 V is typical in electricity distribution.

TABLE 5: AC LEVEL 2 TECHNICAL SPECIFICATIONS

Voltage (V)	230
Input current (A)[16]	6 - 32
Output power (kW)	1.4 - 7.6

AC Level 2 charging is also a simple plug and play charging using chargers on board the EV, and it generally requires no ancillary infrastructure. The cost estimates of the EVSE and ancillary infrastructure are shown in Table 6. Most of the AC Level 2 chargers at the given power level are wall mounted like AC 1 chargers. The availability of service voltage, almost no technical complexity and insignificant capex requirement makes AC 2 a suitable option for charging most vehicle segments in India. However, there is no confirmed case of AC Level 2 charging of e-buses globally at these power levels[17].

TABLE 6: COST ESTIMATES FOR AC LEVEL 2

Cost of charging equipment (₹)	8,000-64,000
Cost of ancillary infrastructure (₹)	Nil
Total cost of EVSE (₹)	8,000-64,000

AC LEVEL 3

AC Level 3 is the category which considers vehicle charging at three-phase AC distribution voltage level. The minimum voltage level associated with AC 3 charging in the Indian context is 415 V. Table 7 lists the salient technical specifications covering a range of AC Level 3 chargers currently available in the Indian market. The converter that is on board the EV limit the maximum power output of the EVSE in this category (Navigant, 2018).

TABLE 7: AC LEVEL 3 CHARGER TECHNICAL SPECIFICATIONS

Voltage range (V)	415 or above
Power output (kW)	20 - 80[18]

16 The maximum current is restricted to 32A considering the rating of highest single pole MCB prevalent in India, though US Level 2 charging allows currents till 100 A. Maximum Power is also calculated at 32A

17 The minimum power level reported for charging of fully electric buses is 20 kW, which will be a 3-phase charging according to Indian standards (ZeEUS, 2017).

18 Lowest range and highest range set according to rating of AC charger available for e-bus in market (BYD, 2019; ZeEUS, 2017)

The AC Level 3 chargers (Figure 4) available in the market are generally designed for wall-mount with minimal area requirement. However, those delivering high charging power require additional ancillary equipment including step down transformers, associated HT and LT switchgear, cables, protection system and SCADA system. AC Level 3 chargers with smart charging capability will have additional equipment to facilitate the communication and control functions needed for smart charging. The cost-estimates of AC Level 3 EVSE are presented in Table 8 (Spöttle, *et al.*, 2018).

TABLE 8: COST ESTIMATES FOR AC LEVEL 3

Cost of charging equipment (₹)	3,50,000 -6,40,000
Cost of ancillary infrastructure (₹)	2,50,000 -4,00,000
Total cost of EVSE (₹)	3,50,000[19]-10,40,000

ONE SHOULD BEAR IN MIND THAT AC LEVEL 3 CHARGING IS ONLY FEASIBLE IF THE E-BUS HAS AN ON-BOARD CHARGER.

AC Level 3 charger with output power as low as 22 kW is typically used for charging plug-in hybrid e-buses as seen in the European market (ZeEUS, 2017). However, the focus of this study is on fully electric vehicles, and hence, a charger of higher power output rating is selected for further analysis. The technical specifications of a typical AC charger[20] for e-bus are presented in Table 9 (BYD, 2019) (ISGF, 2018) (V6 News Telugu, 2017). One should bear in mind that AC Level 3 charging is only feasible if the e-bus has an on-board charger.

TABLE 9: SPECIFICATIONS OF A TYPICAL AC 3 BUS CHARGER CONSIDERED FOR ANALYSIS

Input voltage (V)	415
Output voltage (V)	415
Maximum output current (A)	126
Maximum output power (kW)	80

FIGURE 4: AC III E-BUS CHARGERS IN THE UK [SOURCE: (IAN, 2018)]

DC CHARGING

DC chargers can be classified into two categories based on the design of the charging systems - plug-in or pantograph. This categorisation is irrespective of the charging power level. A key advantage of DC charging over AC charging is the former does not require on-board charger in the EV. Only in case of continuous charging via catenary, on-board chargers would be necessary[21] (Siemens, 2017).

19 Lower cost is defined without considering cost of ancillary equipment as at lower power levels ancillary equipment is not necessary
20 The specifications are presented for 80kW (2x40kW) chargers employed by BYD in charging electric buses
21 Refer to Case study: On-Line charging via catenary in Vienna

CASE STUDY: ON-LINE CHARGING VIA CATENARY IN VIENNA

The city of Vienna is home to a unique bus charging case where the existing electricity infrastructure for tram-system is utilised. Since October 2012, the transport company, Wiener Linien has started commercial operation of e-buses in two bus routes with 12 buses which are charged continuously via catenary (Figure 5). The buses have on-board DC-DC converters and bottom-up pantograph systems that facilitate DC charging at 60 kW. The electricity is drawn to the on-board battery-charging system from the existing overhead line of the tram system. Besides, batteries of the buses are charged at the respective terminals of the bus routes. Each bus with 96 kWh battery reportedly takes 6 - 8 minutes for charging per cycle (Siemens, 2014). The Italian bus manufacturer Rampini and Siemens formed the consortium to execute this project (Siemens, 2017)

FIGURE 5: ELECTRIC BUS CHARGING VIA CATENARY USING AN ON-BOARD BOTTOM-UP PANTOGRAPH SYSTEM IN VIENNA [SOURCE: (WIKIMEDIA, 2013)]

DC PLUG-IN

DC plug-in charging entails DC charging by a plug-in connection. The minimum voltage level associated with this type of charging is 415 V in the Indian context. The primary technical specifications for the range of DC plug-in chargers (Figure 6) currently available in the market (ZeEUS, 2017) are presented in Table 10.

TABLE 10: DC PLUG-IN TECHNICAL SPECIFICATIONS

Output voltage range (V)	150 - 750
Power output (kW)	50 - 150

Cost-estimates shown in Table 11 show that DC plug-in chargers are generally costlier than AC chargers (Spöttle *et al.*, 2018) (Elin, 2016). Just like an AC Level 3 charger with high output power, DC plug-in charging at higher power level would require additional ancillary equipment including step down transformers, associated HT and LT switchgear, liquid cooled cables, protection system and SCADA system. The estimated minimum area requirement for a DC plug-in charger is 2 sq.m.

TABLE 11: COST-ESTIMATES FOR DC PLUG-IN

Cost of charging equipment (₹)	16,00,000 - 22,00,000
Cost of ancillary infrastructure (₹)	2,50,000 - 4,00,000
Total cost of EVSE (₹)	16,00,000[22] - 26,00,000

50 kW DC plug-in chargers are commonly reported to be used for charging e-buses (Siemens, 2017) (Proterra, 2016). 150 kW DC plug-in chargers capable of charging three e-buses sequentially are also available in the market (ABB, 2018). Nevertheless, the DC plug-in charger with 70 kW[23]

TABLE 12: SPECIFICATIONS OF A TYPICAL DC PLUG-IN BUS CHARGER

Input voltage (V)	415 or above
Maximum power (kW)	70

22 Lower cost is defined without considering cost of ancillary equipment as at lower power levels ancillary equipment is not necessary.

23 Additional details are not available in public domain for the 70 kW chargers deployed by Tata Motors in Kolkata (Charger manufacturer is Mass-Tech)

rating which found mention in a recent e-bus tender result in India has been considered for further analysis in this study (Khandekar *et al*, 2018) (refer to Table 12).

FIGURE 6: DC PLUG-IN CHARGER FOR AN E-BUS IN THE UK [SOURCE: (JORAIR, 2017)]

DC PANTOGRAPH

This category includes DC charging via pantograph with on-board bottom-up (Figure 5) or off-board top-down (Figure 7) configuration (Krefeld, 2015) (Siemens, 2017). The minimum voltage required for this type of charging is 415 V in the Indian context. The salient technical specifications for the range of DC pantograph chargers currently available in the market are stated in Table 13 (ABB, 2017) (ZeEUS, 2017).

TABLE 13: DC PANTOGRAPH TECHNICAL SPECIFICATIONS

Output voltage range (V)	150 - 750
Power output (kW)	150 - 650

It is worthwhile to mention here that DC pantograph charging technology is expensive and requires auxiliary infrastructure including distribution transformer (DT), associated LT and HT switchgear, cables, protection system, SCADA system, *etc.* (Mäkinen J. , 2016). The estimated cost of the charging system is to the tune of over ₹12 million (refer to Table 14) (Elin, 2016) (Spöttle *et al.*, 2018). Typical area requirements for a DC Pantograph system and a DC Plug-in system are considered to be similar.

TABLE 14: COST ESTIMATES FOR DC PANTOGRAPH

Cost of charging equipment (₹)	32,00,000 - 1,12,50,000
Cost of ancillary infrastructure (₹)	6,00,000 - 12,50,000
Total cost of EVSE (₹)	38,00,000 - 1,25,00,000

DC pantograph systems are found to be employed for charging e-buses with off-board chargers or on-board converters[24] (Siemens, 2017). E-buses having ultra-capacitors as energy storage options are also found to be charged via DC pantograph. DC pantograph systems rated 150 kW or above

24 Refer to Case study: On-Line charging via catenary in Vienna

are deployed mostly in the European markets (ZeEUS, 2017). The e-buses observed in such cases also have corresponding arrangements that facilitate charging via pantograph method. The salient technical specifications for a typical DC Pantograph charger considered for this study are stated in Table 15.

TABLE 15: SPECIFICATIONS OF A TYPICAL DC PANTOGRAPH BUS CHARGER

Input voltage (V)	415 or above
Output voltage (V)	150-750
Maximum output current (A)	500
Maximum output power (kW)	300

FIGURE 7: DC PANTOGRAPH CHARGING OF E-BUS USING AN OFF-BOARD BOTTOM-DOWN ARRANGEMENT IN LUXEMBOURG [SOURCE: (KYLE, 2017)]

CASE STUDY: DC PANTOGRAPH CHARGING IN THE CITY OF GENEVA

The city of Geneva employs DC pantograph-based technology for charging trolley e-buses (ABB, 2019). The city's public transport operator, Transports Publics Genevois (TPG) along with Swiss bus manufacturer HESS and charging infrastructure provider, ABB piloted e-buses on the route connecting the city's airport to suburban areas (Wagenknecht, 2017). The 18m long TOSA e-buses operate without catenary and are charged at selected bus stops, terminals and depots instead. The e-buses are charged at three different output power levels: 600 kW, 400kW and 45 kW. The 600 kW 'flash' charging stations which provide a quick power boost in a short span of 15-20 seconds are reportedly the fastest in the world. The 400 kW and 45 kW charging stations charge the battery for 5 and 30 minutes respectively.

INDUCTIVE CHARGING

The inductive charging category includes all charging technologies which achieve wireless transfer of electricity, either by static or dynamic induction. The minimum voltage required for this type of charging is 415 V in the Indian context. The salient technical specifications for a range of inductive chargers currently available in the market are presented in Table 16 (Wave, 2019).

TABLE 16: INDUCTIVE CHARGING TECHNICAL PARAMETERS

Output voltage range (V)	415 or above
Power output (kW)	50-250

As far as economics is concerned, inductive charging technology using underground power delivery systems are found to be expensive, although the required area for installation is minimal. These systems require auxiliary infrastructure including special high-frequency transformer, associated LT and HT switchgear, cables, protection system, SCADA system, vehicle alignment monitoring system, *etc.* The estimated cost of an inductive charging system is more than ₹ 22 million (refer to Table 17) (Elin, 2016).

TABLE 17: COST ESTIMATES FOR INDUCTIVE CHARGING

Cost of charging equipment (₹)	2,25,00,000 or above
Cost of ancillary infrastructure (₹)	3,80,000 - 7,20,000
Total cost of EVSE (₹)	2,28,80,000 or above

Wireless charging is not a conventional technology for charging of e-buses. Wireless transfer technology is also prone to electromagnetic interference related challenges (Ahn, 2017). In most cases, the technology is used for range extension of EVs (Wave, 2019) (Stewart, 2014). However, the technology merits consideration in the context of e-bus charging given the implementation of On-Line Electric Vehicle (OLEV) systems at Gumi and Sejong in South Korea. The Milton Keynes Demonstration Project is another example of inductive charging (Miles & Potter, 2014). The technical specifications of a typical charger considered for analysis are based on the Korean OLEV system (refer to Table 18) (Ahn, 2017).

TABLE 18: SPECIFICATIONS OF TYPICAL INDUCTIVE BUS CHARGER CONSIDERED FOR ANALYSIS

Input voltage (V)	415
Maximum current (A)	200
Maximum power (kW)	200

CASE STUDY: WIRELESS CHARGING IN GUMI

The city of Gumi, South Korea debuted in e-bus operation in 2014, where the fleet is charged via induction (Ahn, 2017). The Korea Advanced Institute of Science and Technology (KAIST) developed the proprietary magnetic resonance technology used for charging e-bus batteries under a $69 million funding from the government (Yeon-soo, 2019). Every On-Line Electric Vehicle (OLEV) e-bus is equipped with a special receiver which can collect electric power wirelessly from the underground power supply while in motion or at the stationary condition. An inductive charging station (Figure 8) with a rated output power of 200 kW also has special equipment which converts the electricity received from the grid to high-frequency currents (Suh, 2014). The project has a total 144m underground power supply system in the 24 km route which was installed post a regulatory revision allowing power line installation on the road. The OLEV systems are reported to operate at an efficiency of 85%.

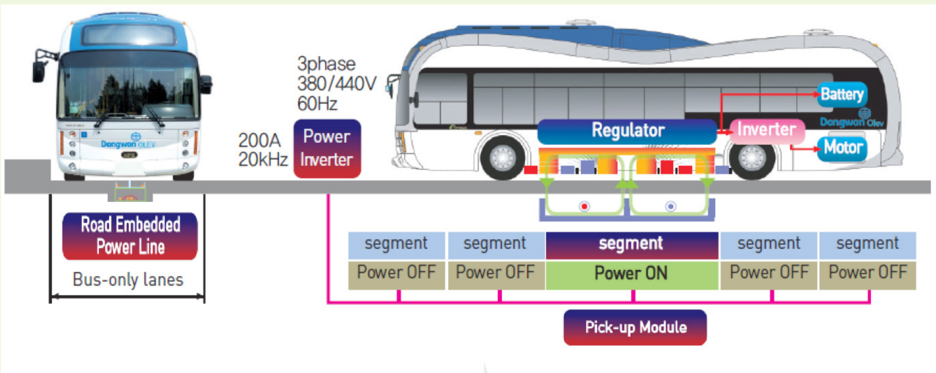


FIGURE 8: INDUCTIVE CHARGING OF E-BUS IN KOREA

BATTERY SWAPPING

Battery swapping based charging entails cases where depleted vehicle batteries are swapped with fully charged batteries. This is not a common technology in practice for charging of e-buses. A few trials of battery swapping in the bus segment have been reported in China (Hua, 2012), South Korea (Park, 2016) and Taiwan (Alees, 2014). On the other hand, a pilot e-bus project involving battery swapping is underway at Ahmedabad in India (Wangchuk, 2019) (John, 2019) (Sun Mobility, 2018).

Battery swapping system consists of the battery charging system and the battery swapping mechanism. Hence, the technical parameters for a battery swapping system would depend on both the charging point for batteries and the swapping infrastructure. Hardly any information is available on the power requirement for swapping operation. The minimum voltage required for this type of charging is considered to be 415 V in the Indian scenario.

The time required for swapping may range between 2.5 minutes to 10 minutes (Wangchuk, 2019) (Alees, 2014). Battery swapping technology requires special equipment such as battery-swapping arms and battery movement system, along with the battery charging system, which would potentially increase the capital and operating costs. The ancillary infrastructure would also include distribution transformer, associated LT and HT switchgear, cables, protection system and SCADA system. The estimated cost for battery swapping infrastructure is presented in Table 19 (Spöttle, *et al.*, 2018).

TABLE 19: COST ESTIMATES FOR BATTERY SWAPPING

Cost of charging equipment (₹)	3,20,00,000 or above
Cost of ancillary infrastructure (₹)	2,50,000-4,00,000
Total cost of EVSE (₹)	3,22,50,000 or above

CASE STUDY: JEJU ISLAND

South Korea is a unique market for e-buses where charging by conductive, inductive and battery swapping technologies have been employed. E-buses with battery swapping technology operate on Jeju Island (Park, 2016). The e-buses used in this project has 51 kWh battery bank which is mounted on the roof of the bus. The battery swapping stations (Figure 9) located at the bus-stops have battery charging facilities and robotic systems for swapping. At the swapping station, there are two automatic robotic systems to remove the depleted battery from the bus and attach a fully charged battery. The swappable batteries used in this project weigh approximately 760 kg and has a special shock absorption design feature (Begins, 2019).

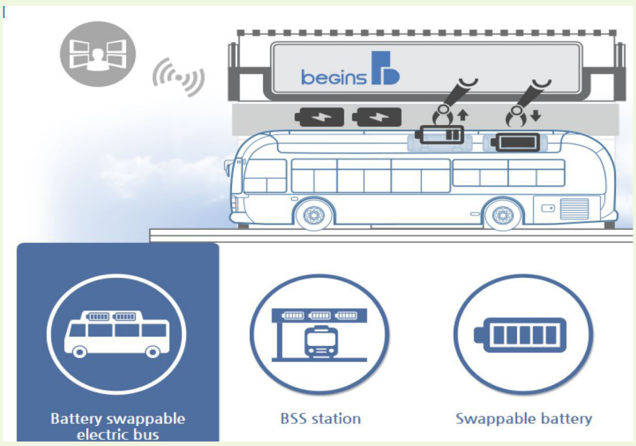


FIGURE 9: SCHEMATIC REPRESENTATION OF BATTERY SWAPPING STATION IN JEJU ISLAND, KOREA [SOURCE: (BEGINS, 2019)]

CASE STUDY: AHMEDABAD

The city of Ahmedabad can be considered as an outlier in India's e-bus landscape. It is the only city which is carrying out a trial of 'battery swap' technology (Figure 10). The city is the home to a unique Bus Rapid Transit system which is used as the test bed for the demonstration of this technology. However, battery swappable buses only constitute one-third (18 out of 50) of e-buses currently deployed in the city (Vora, 2019). The initial trial of the battery swappable model with smaller, lighter battery packs (Wangchuk, 2019) and shorter range (Shyam, 2018) is planned to service a 31km route in BRTS (Indian Express, 2019). Bus manufacturer, Ashok Leyland has collaborated with the energy service provider, Sun Mobility to implement the battery charging infrastructure and swapping system (Sun Mobility, 2018).

FIGURE 10: BATTERY SWAPPING DEMONSTRATION FOR THE E-BUS MODEL USED IN AHMEDABAD, INDIA [SOURCE: (REHAAN, 2018)]

4 Comparative assessment of the charging options

Taking into cognizance that it may not be plausible to employ every available charging technology to recharge the entire range of EV segments (*e.g.*, 2- and 3-wheelers, 4-wheeler passenger cars, buses, light commercial vehicles, *etc.*), the study undertakes a thorough comparative assessment of the above-mentioned charging options using a set of critical parameters to identify the ones which could be practically employed for charging e-buses in India (refer to Tables 20(a) and 20(b)). The values and details of the parameters are considered based on the technical and financial specifications observed in the market and are applicable in India's context.

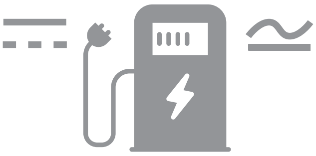
TABLE 20 (A): COMPARATIVE ASSESSMENT OF THE AVAILABLE OPTIONS FOR CHARGING ELECTRIC BUSES

Parameters	AC Level 1	AC Level 2	AC Level 3
Input voltage from grid (V)	120 [a]	230 [b]	415 or above [b]
Output range of chargers available in market (kW)	1.4 - 2.4 [d]	1.4 - 7.6 [e]	20 - 80 [f]
Output power considered for analysis (kW) [h]	2.2 [i]	6.8 [i]	80 [j]
Charging/ Swapping time[n]	55 - 65 hours [o]	17 - 20 hours [o]	1.5 - 2 hours [o]
Electricity connection required [q] (HT/ LT)	Required service voltage is not available in India	LT	HT
Ancillary infrastructure required [r]	No ancillary infrastructure required (simple plug and play)	No ancillary infrastructure required (simple plug and play)	Distribution Transformer, HT / LT switchgear, cables, protection relays and SCADA
Auxiliary energy consumption	Nil	Low	Low
Area requirement per EVSE (m^2)	0.09 (wall mounted)	0.8	0.8
Capital cost of charging technology [s] (₹)	Negligible	8,000 - 64,000	3,50,000 - 6,40,000
Cost of ancillary infrastructure [s] (₹)	0	0	2,50,000 – 4,00,000
Cost of electricity for charging	Required service voltage is not available in India	As per LT connection norms	As per HT connection norms
Maintenance cost (%)	10% of installation cost for periodic maintenance [t]; 2% of installation cost for regular maintenance [t]		
Ease of drawing electricity from the distribution network	Service voltage is not available in India	Not difficult; service voltage is available from a regular wall outlet	Moderately difficult; possible to draw electricity through a DT connected to a HT line
Established precedence for charging buses	No	No	Yes

TABLE 20 (B): COMPARATIVE ASSESSMENT OF THE AVAILABLE OPTIONS FOR CHARGING ELECTRIC BUSES

Parameters	DC Plug-In	DC Pantograph	Inductive charging	Battery swapping
Input voltage from grid (V)	415 or above [b]	415 or above [b]	415 or above [b]	415 or above [b, c]
Output range of chargers available in market (kW)	50 - 150 [g]	150 - 650 [g]	50 - 250 [g]	Data not publicly available [c]
Output power considered for analysis (kW) [h]	70 [k]	300 [l]	200 [m]	No typical value assumed [c]
Charging/ Swapping time[n]	1.7 - 2 hours [o]	~ 25 minutes [o]	Not reported	2.5 - 10 minutes [p]
Electricity connection required [q] (HT/ LT)	HT	HT	HT	HT [c]
Ancillary infrastructure required [r]	Distribution Transformer, HT / LT switchgear, liquid cooled cables, protection relay and SCADA	Distribution Transformer, HT /LT switchgear, liquid cooled cables, protection relays and SCADA	Distribution Transformer, HT / LT switchgear, road embedded cables, protection relay and SCADA	Distribution Transformer, HT /LT switchgear, cables, protection relays and SCADA
Auxiliary energy consumption	Low	Medium	High	High
Area requirement per EVSE (m^2)	2	2	2	No typical value assumed [c]
Capital cost of charging technology [s] (₹)	16,00,000 – 22,00,000	32,00,000 – 1,12,50,000	2,25,00,000 or above	3,20,00,000 or above
Cost of ancillary infrastructure [s] (₹)	2,50,000 – 4,00,000	6,00,000 – 12,50,000	3,80,000 – 7,20,000	2,50,000 – 4,00,000
Cost of electricity for charging	As per HT connection norms	As per HT connection norms	As per HT connection norms	As per HT connection norms
Maintenance cost (%)	10% of installation cost for periodic maintenance [t]; 2% of installation cost for regular maintenance [t]			
Ease of drawing electricity from the distribution network	Moderately difficult; possible to draw electricity through a DT connected to a HT line	Difficult; must be drawn only from an 11/33 kV substation which is not as accessible as a HT line	Moderately difficult; possible to draw electricity through a DT connected to a HT line	Moderately difficult; possible to draw electricity through a DT connected to a HT line
Established precedence for charging buses	Yes	Yes	Limited [u]	Limited [u]

a Voltage set according to parameters specified in the National Electric Code (NEC), USA (Morrow, Karner, & Frankfort, 2008)
b Voltage set at the typical single phase and three phase AC distribution in India
c Depends on both charging point for battery and the swapping infrastructure
d Power range set considering 12-20A input current range specified in NEC (Morrow, Karner, & Frankfort, 2008)
e Power range set considering 16-32A input current range for the Indian context, which also follows European modes defined for AC charging (Spöttle *et al.*, 2018)
f Lowest range and highest range set according to of rating of AC charger available for e-bus in the market (BYD, 2019; ZeEUS, 2017)
g Power range set according to the range of e-bus chargers available in the market (ZeEUS, 2017) (ABB, 2017) (Siemens, 2017) (Wave, 2019)
h Considering charging requirement for one e-bus at a time
i Highest possible power considered at power factor 0.9
j Rating of BYD e-bus charger available in the market (BYD, 2019)
k Rating of TATA electric charger as per the tender information available (Khandekar A. *et al.*, 2018)
l Assumed based on the study of e-bus chargers in the market (ZeEUS, 2017; ABB, 2017)
m Rating of OLEV electric charges in South Korea (Park, 2016)
n For rated battery capacity of 200 kWh
o Refer Appendix A - Charging time estimation for more details
p Swapping time set based on available details (Wangchuk, 2019) (Alees, 2014)
q Connection requirement is assessed as per India's grid code
r Requirement assessed based on industry accepted standards (Mäkinen J., 2016)
s Costs are estimated based on available literature and market values (Spöttle *et al.*, 2018) (Navigant, 2018) (EVConnectors, 2019) (SPDCTL, 2018) (IndiaMART, 2019)
t Periodic maintenance every four years and regular maintenance every year
u Few pilot cases of inductive charging and battery swapping for electric buses have been reported.



THE PLAUSIBLE CHARGING TECHNOLOGIES FOR BUSES ARE AC-III AND DC CHARGING

Based on the practicality-assessment (as summarised in Table 20), it is found that:

- AC-I technology requires a service voltage which is not prevalent in India.
- There is no confirmed case of AC-II charging of e-bus globally at India's power level (<7.4kW).
- Adoption of battery swapping technology for e-buses is at a pilot scale. The complexity of the operation of the technology, high cost of installation and operation, and the requirement for significant modification of the bus design are some of the significant hurdles in its implementation.
- Inductive charging is not preferred due to the complex nature of the system, high cost of installation, the necessity for modification of roads and low efficiency in energy transfer (Ahn, 2017).

Thus, this study has shortlisted the plausible charging technologies for buses, which are AC-III and DC charging. The latter has two sub-classes depending on the EVSE design – Pantograph and Plug-in. These are further examined to select the *"best-fit"* against a charging requirement of an intra-city e-bus fleet.

5 Setting the context for e-bus operation in the Indian cities

This study is based on a practical context that takes into account the specifications of e-buses currently available in India and the bus transport networks which are prevalent in the Tier-I and Tier-II Indian cities.

INTRA-CITY PUBLIC BUS NETWORK CHARACTERISTICS

The study aims to deduce a model set of e-bus specifications and intra-city bus network features for analysis of charging requirements. To this end, the study reviews the principal features of a typical intra-city public bus transport network commonly seen in Tier-I and Tier-II cities in India. The research identifies the following key features.

1. The network may be with/ without a dedicated corridor.
2. The bus network consists of depots/ terminals (generally referred to as nodes) where the bus trips begin or end.
3. There are separate nodes for the start and end of a bus trip.
4. Certain portions of different bus routes may overlap.
5. The nodes currently act as spaces for:
    - i. Repairing and servicing the buses
    - ii. Parking buses overnight
    - iii. The drivers and conductors to rest post completion of a trip before they start on their next trip
    - iv. Boarding or de-boarding of passengers who are beginning or finishing their trips at the depot
    - v. Fleet operators to run their day-to-day operations

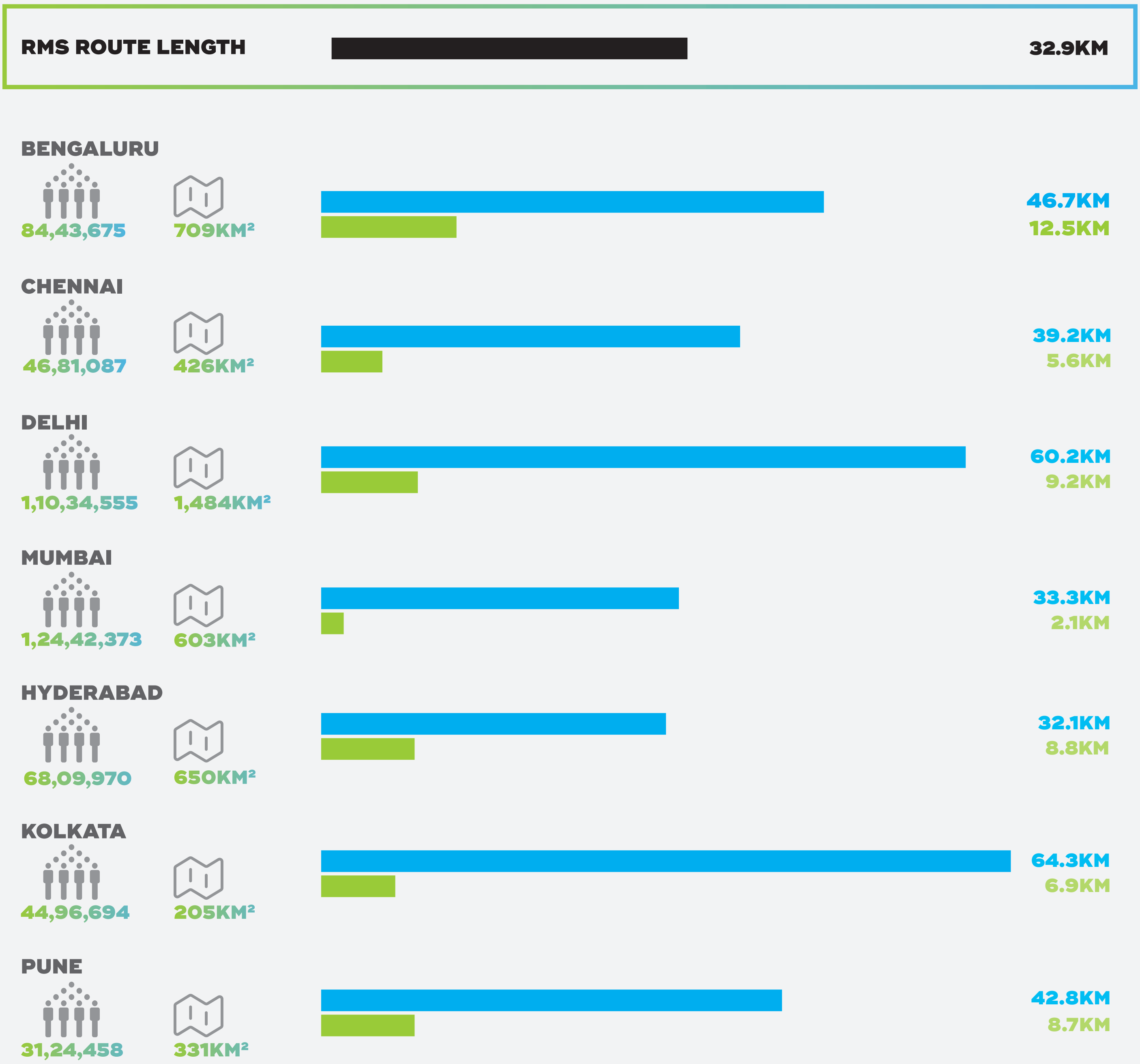
IT IS FOUND THAT AN INTRA-CITY BUS IN THESE CITIES COVERS A ROOT-MEAN-SQUARE (RMS) DISTANCE OF 32.9 KM IN A SINGLE TRIP, WHICH CAN BE ROUNDED OFF TO THE NEAREST HIGHER INTEGER - 33 KM.

For a public e-bus fleet, the nodes could be potentially the primary places for charging e-buses considering the following factors:

- Ease of setting up the charging station
- Less requirement for charging during operation hours of the bus fleet
- Supporting the range of an e-bus on a long route

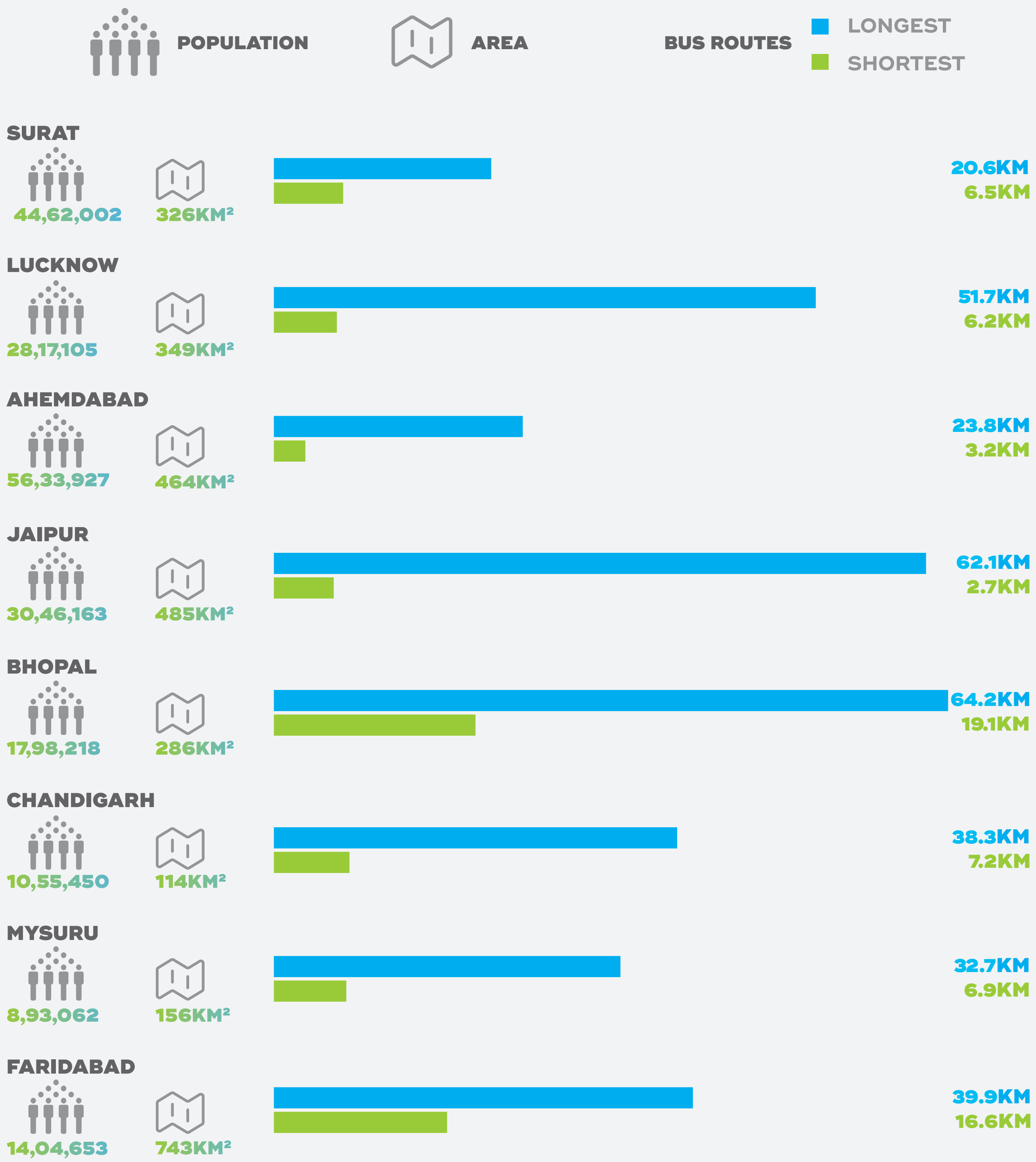
An e-bus route could also consider a multi-leg trip whereby after completing a leg, the bus would halt at an intermediate halting point equipped with the

LONGEST AND SHORTEST BUS ROUTES OF TIER-I AND TIER-II INDIAN CITIES



charging equipment. Important boarding/ de-boarding locations within the bus transport network qualify as the intermediate halting points. In such a case, the halting time would be longer than usual. Hence, an intermediate charging station should only be considered when the range of the e-bus is not sufficient to cover the entire route length.

Route lengths are a critical factor for planning the establishment of charging infrastructure for public e-bus transport. This study has assessed the longest and shortest bus routes of the Tier-I and Tier-II Indian cities.



It is found that an intra-city bus in these cities covers a root-mean-square (RMS) distance of 32.9 km in a single trip, which can be rounded off to the nearest higher integer - 33 km. The RMS distance has been considered as the best indicator of the central value for the data available on route lengths of the cities as mentioned above because if the data have a significant number of outliers, the calculation of the average of the route lengths will lead to a skewed and possibly a lower value.

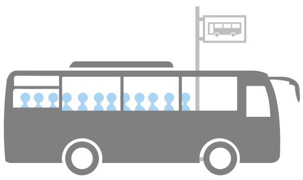
ELECTRIC BUS SPECIFICATIONS

AVAILABLE E-BUS MODELS

The study has taken into account the e-bus models as listed in Table 22 which are currently available in the Indian market.

TABLE 22: E-BUS MODELS CONSIDERED IN THE STUDY

S. No.	Bus model	Length of bus (m)	Manufacturer
1	Starbus Ultra Electric 9/12 EV	12	Tata Motors
2	Starbus Ultra Electric 6/9 EV	9	Tata Motors
2	Eco-Life (12m)	12	JBM
3	Eco-Life (9m)	9	JBM
4	eBUZZ K9	12	Olectra-BYD
5	eBUZZ K7	9	Olectra-BYD
6	Skyline Pro-E	9	Eicher Motors
7	12FP150	12	Foton-PMI
8	9FP102	9	Foton-PMI
9	CircuitS	12	Ashok Leyland
10	e-Cosmo – T32	8	Mahindra & Mahindra
11	e-Cosmo – T36	9	Mahindra & Mahindra
12	e-Cosmo – T40	10	Mahindra & Mahindra



THE PASSENGER-CARRYING CAPACITY OF A PUBLIC E-BUS FLEET ON A ROUTE SHOULD REMAIN AT PAR WITH THE BASELINE *I.E.*, THE BUS FLEET PRE-ELECTRIFICATION

The analyses of the e-bus models have been summarised below.

SIZE OF AN E-BUS

A critical fundamental premise of the study is the passenger-carrying capacity of a public e-bus fleet on a route should remain at par with the baseline *i.e.*, the bus fleet pre-electrification. This implies that a 9-meter ICE bus should be replaced at least by a 9-meter e-bus and a 12-meter ICE bus should at least be replaced by a 12-meter e-bus to maintain the same level of service post electrification. Consequently, the frequency of service on a particular bus route would either decrease (in case of acquisition of higher capacity e-buses) or remain the same (in case of acquisition of similar capacity e-buses), thereby warranting no change in the operation of the bus fleet. Replacement by a lower capacity e-bus would result in a higher frequency of service, thereby requiring a higher number of vehicular, infrastructural and support units and resulting in higher traffic on the route. Availability of 12-meter e-bus in the market is not a challenge. In this study, e-buses of 12-meter length have been considered for further analyses.

BATTERY CAPACITY OF E-BUSES

The currently available e-bus models with 12-meter length mostly have battery capacities of 300 kWh (ISGF, 2017). The price of a bus powered by a 300 kWh battery is almost four times the price of a comparable diesel bus and nearly ten times the price of a similar capacity CNG/ LNG bus. This makes 300 kWh e-buses economically unattractive when pitted against their diesel and alternate fuel counterparts considering their TCO values (ISGF, 2017).

One should explore the possibility of adopting a lower battery capacity for an intra-city e-bus fleet considering that battery accounts 50% to 60% of the cost of an e-bus and also the average bus-route length, slow traffic speed and cases where an HVAC (Heating, Ventilation and Air-Conditioning) system is not deployed in the baseline. Hence, two battery capacities have been considered for further analyses - 100 kWh and 200 kWh which are the other battery options for e-buses currently.

Maximum depth of discharge (DoD) is an important parameter to gauge the performance of a battery and in turn, of the EV. Each battery has a rated battery capacity (RBC), which is the total amount of energy that the battery contains. In practice, this energy does not correspond to the total energy available for usage (XDADevelopers, 2014). Going by the thumb rule for lithium iron phosphate ($LiFePO_4$) batteries (commonly called LFP batteries) which are prevalent worldwide and in India in EVs, it can be considered that around 30% of a battery's rated energy capacity is non-usable and must be reserved in the battery to maintain health of the battery (Buchmann, 2016). Therefore, as soon as a battery is discharged to approximately 30% of its rated capacity, it automatically shuts off and allows no further discharge (Buchmann, 2016). Thus, a battery can sustain a DoD up to 70% *i.e.*, minimum state of charge (SoC) of 30%.

It is worthwhile to highlight here that this 70% of the rated battery capacity is displayed as 100% on the display panels of the EVs and is called the displayed battery capacity (Buchmann, 2016).

Of the available 70%, it is recommended that the battery of an e-bus should never be discharged below 15% (ideally) or in extreme cases, below 10% to avoid any possibility of getting stranded.

This implies that for the 100 kWh and 200 kWh battery capacities, the total energy that would practically be available for running an e-bus would be 70 kWh (*i.e.*, 70% of 100 kWh) and 140 kWh (*i.e.*, 70% of 200 kWh) respectively.

Of the 70% energy that is available in both capacities of batteries, 15% has to be reserved as the minimum energy (charge) left in a battery when an e-bus arrives at a charging station in order to avoid range anxiety.

Therefore, the usable energy in a battery with rated capacity x kWh is (70-(70*15%))%* x kWh (Figure 11). Thus, for a battery rated 100 kWh, usable energy is estimated to be 59.5 kWh whereas it is 119 kWh for a battery rated 200 kWh.

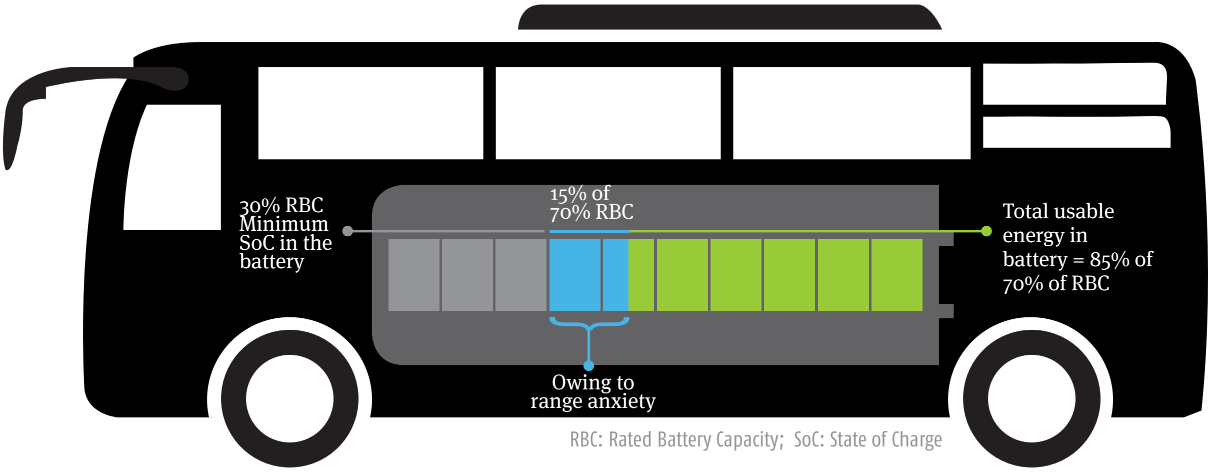


FIGURE 11: ENERGY CHARACTERISTICS OF AN EV BATTERY

ENERGY CONSUMPTION AND DRIVING RANGE OF E-BUSES

BYD, Tata Motors and Ashok Leyland, which are the major OEMs in the e-bus segment in India, have quoted the energy consumption values per km (Table 23) by their e-bus models when in operation.

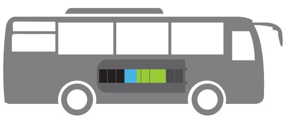
TABLE 23: ENERGY CONSUMPTION VALUES AS QUOTED BY DIFFERENT E-BUS MANUFACTURERS

S. No.	e-Bus length (m)	Manufacturer	HVAC system (present/ absent)	Energy consumed per km (kWh/ km)
1	9	Tata Motors	Absent	0.7 - 0.8
2	9	Tata Motors	Present	0.9* - 1.1*
3	9	Olectra-BYD	Absent	0.7 – 0.8
4	12	Tata Motors	Absent	1.3 - 1.4
5	12	Tata Motors	Present	1.7* - 2.0*
6	12	Ashok Leyland	Absent	1.2 - 1.3
7	12	Ashok Leyland	Present	1.8 - 1.9
8	12	Foton PMI	Present	0.83
9	9	Foton PMI	Present	0.85

* According to Tata Motors, e-buses fitted with HVAC systems consume 30%-40% more energy than e-buses without HVAC systems.

Sources: ISGF's Report on Implementation Plan for Electrification of Public Transportation in Kolkata, Model Details and Technical Specifications of Foton PMI and Olectra-BYD Buses

Note: The values for e-buses of Foton PMI seem to be outliers when compared to other e-bus models of same lengths and equipped with HVAC systems. Also, an anomaly has been detected in the fuel economy values of Foton PMI e-buses as a 12m e-bus appears to consume less energy per kilometre than a 9m e-bus.



CONSIDERING THE BUS ROUTE LENGTHS IN CITIES IT CAN BE CONCLUDED THAT A 200 KWH RATED BATTERY IS MOST SUITED FOR A 12-M E-BUS INTRA-CITY FLEET IN INDIA.

For further analyses, a range of mileage values (energy consumption per km) have been taken into account. The maximum and minimum values for energy consumption per km are considered to be 2 kWh and 0.83 kWh respectively.

The values listed above have been taken into consideration irrespective of the e-bus models being equipped or not with the HVAC system.

Based on the above energy consumption values for e-buses, a battery rated 100 kWh would allow an e-bus to travel a maximum distance of 74.4 km and a minimum distance of 29.8 km. On the other hand, a 200 kWh battery-powered e-bus would offer a driving range between 59.5 km and 148.8 km.

Considering the RMS of bus route lengths in the given cities which is approximately 33 km, it can be concluded that a 200 kWh rated battery is most suited for a 12-m e-bus intra-city fleet in India. This battery capacity would also help keep the capital expenditure on acquisition of e-buses fairly low for bus fleet operators (ISGF, 2017). A conservative value of the driving range has been considered *i.e.*, 59.5 km for all subsequent analyses. It is worthwhile to mention here that further investigation is necessary to evaluate the driving range profile of an e-bus as it depends on several design and operational factors such as the efficiency of drivetrain, the kerb weight, the average and maximum gradient of the route, the climatic condition, *etc.*

6 Possibilities of bus charging and selection of *"best-fit"* charging technology

Successful roll-out of a public e-bus fleet in a city hinges on careful planning of charging infrastructure.

To plan charging infrastructure for an e-bus fleet, it is imperative to take into account three key elements:

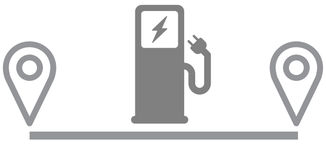
- Where to charge *i.e.*, at the depots (nodes) and/ or en-route
- When to charge *i.e.*, overnight and/ or during operating hours
- How to charge *i.e.*, identifying type(s) of charging technology to be adopted

These three elements should ensure that charging the fleet does not negatively affect the regular bus service on the concerned bus route. Considering the present operation of an intra-city public bus network and the ease of setting up charging stations (which depends on availability of bus-bays for charging, space for installing chargers, control and monitoring, *etc.*), the investigation understands that the origin and destination nodes (depots) are the most suitable locations for charging e-buses on a particular route. The bus charging at the depots/ terminals can be attended post-completion of trips during the operating hours of the bus transport network in the city or overnight when the bus transport pauses for hours. The role of overnight charging is to reduce the requirement for charging during operational hours of the bus fleet and thus, to make sure that the charging time does not negatively affect the service frequency of the concerned route.

Against this background, this study examines the following possibilities of charging an e-bus fleet on a route.

- Charging at the depots of the public bus transport network post completion of trip(s)
- Charging at the depots overnight
- Charging at an intermediate charging station between the origin and destination nodes during a multi-leg trip

IT IS NOT NECESSARY TO SET UP INTERMEDIATE/ EN-ROUTE CHARGING STATIONS.



Of the possibilities listed above, the purpose of en-route charging at an intermediate charging station is to replenish an e-bus with sufficient charge to reach the destination depot if a case arises where the range of the bus may not be adequate to make the trip. In its assessment of the intra-city bus routes in India, this research estimates that the minimum possible driving range of an e-bus considered for this study is 59.5 km which is greater than the RMS route length (33 km) by a comfortable margin. This implies that an e-bus with the proposed range would be able to complete a trip successfully without requiring a charge en-route. As any need to charge an intra-city e-bus fleet between the origin and destination nodes is not envisaged, it is not necessary to set up intermediate/ en-route charging stations.

The identified charging possibilities set the stage for the selection of *"best-fit"* charging technology among the available options in the market, followed by analyses of different cases to devise inter-relations between the operation parameters of an e-bus fleet which would guide the planning of establishment of charging infrastructure for an e-bus fleet.

Selection of a charging technology for a particular charging possibility of a specific vehicle segment is a costly riddle to solve since the effectiveness and feasibility of deployment and use of a charging technology hinge on a range of factors, both technical and economic. On the one hand, the technology should be suitable to satisfy the criteria for charging the vehicle (*e.g.*, charging time, grid infrastructure needed, *etc.*) and on the other hand, its establishment and operation should be cost-effective. Considering that charging and battery technologies are still evolving, it is possible that none of the charging options currently available in the market would satisfactorily meet all the preferences and hence, the selection of a suitable charging technology may involve trade-offs. However, to objectively decide on the trade-offs is a complex task and a framework would be useful in this regard. Taking into cognizance the possible complexity to identify the *"best-fit"* technology for charging of e-bus at a depot overnight or during operating hours, the study develops composite Multi-Criteria Decision Matrices (MCDMs), consisting of a set of techno-economic parameters, each assigned a weight based on the assessed degree of importance using the following scale (refer to Figure 12).

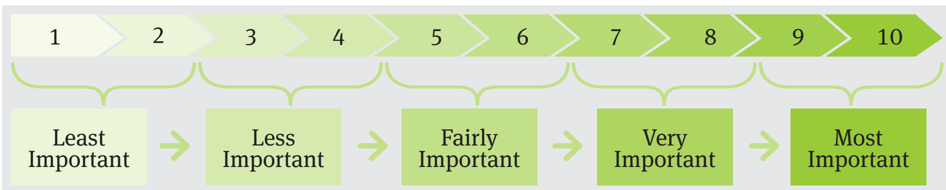


FIGURE 12: SCALE FOR ASSESSING THE IMPORTANCE OF A PARAMETER

It is worthwhile to state here that the set of technical and economic parameters considered in the composite MCDMs, and their assigned weights vary with charging possibilities as the criteria to evaluate *"best-fit"* also change. While considering the technical or economic parameters and assigning their respective weights, one should treat them in isolation from other contesting parameters and in the context of the given charging possibility. Each charging technology is ranked against individual parameters whereby the technology which satisfies most the ideal value for a parameter is ranked highest (*e.g.*, Out of four charging technologies, the most suited technology against a particular parameter will have rank "4"). Thus, one arrives at a normalised weighted rank for a technology. The charging technology which notches up the highest normalised weighted rank would qualify as the most preferred option. The least normalised weighted rank would determine the least preferred option.

The e-bus market in India is still at its infancy and the vehicle/ battery-features as well as charging technologies are evolving rapidly, which may impact the technical and economic viability of the concerned charging technologies. Therefore, it is critical to bear in mind that the given rankings of the charging options are reflective of the present scenario only and may change in the future. It is advisable that the stakeholders take a fresh look at the Decision Matrices and revise them after a period to make appropriate decisions.

As explained above, an e-bus fleet on a route may require to be charged post completion of trips as well as overnight to maintain the service frequency of the route. However, in the face of the contrasting trade-offs offered by the charging technologies against the commonly-used performance standards (such as charging time, capital cost, operational expenditure, input grid power, *etc.*), a particular charging technology may not be the *"best-fit"* option for charging e-buses post completion of trips as well as overnight. Hence, this study deems it important to evaluate the charging technologies in the contexts of bus charging post completion of trips and overnight separately. To this end, separate multi-criteria decision matrices have been constructed.

The technical and economic parameters and their weights considered in the multi-criteria decision matrices to assess the suitability of charging technologies for charging at a depot post the completion of the trip(s) or overnight are illustrated in Table 24 and Table 25.

TABLE 24: TECHNICAL PARAMETERS FOR MULTI-CRITERIA DECISION ANALYSIS FOR SELECTION OF CHARGING TECHNOLOGY

S. No.	Parameter	Ideal value	Justification of the ideal value	Depot charging during operating hours	Depot charging overnight
1.	Charging time	20 minutes	Considering the 3-C rate of charging a Li-ion battery	**Weight:** 10 **Justification:** It is of paramount importance as it will limit the charging time and help maintain the service frequency. Hence, this parameter is given the maximum weight.	**Weight:** 4 **Justification:** The practice of overnight charging would play a supportive role to charging during operating hours of the fleet. Also, during overnight charging, the demand for charged vehicles would not be immediate. Therefore, charging time here has less importance.
2.	Effectiveness to maintain service headway of a bus route	Headway of the concerned route	The headway of a route may vary considerably according to the attributes of the bus network and the route itself. The charging technology which charges faster is more suited to maintaining service headways.	**Weight:** 10 **Justification:** This parameter is deemed critical as maintaining service headway at the pre-electrification level is a pre-requisite. The importance of this parameter has to be treated in isolation and in light of the context *i.e.*, depot charging of e-buses post completion of trips.	**Weight:** 4 **Justification:** The purpose for overnight charging of e-buses is to complement charging during operating hours of the fleet; there is no immediate requirement to maintain service frequency of the route. Hence, less importance *i.e.*, the weight has been given here.

S. No.	Parameter	Ideal value	Justification of the ideal value	Depot charging during operating hours	Depot charging overnight
3.	Grid voltage required	415 V	3-phase AC distribution voltage has been prescribed here since it is easy to access based on the available service voltage in India's distribution network.	**Weight:** 6 **Justification:** If the voltage required for the vehicle charging is the same as the grid voltage, then no additional infrastructure is necessary for charging station installation.	
5.	Area required per EVSE (including allied infrastructure)	-	Minimum area requirement is most preferred.	**Weight:** 4 **Justification:** Lower the area required per EVSE, less would be the space constraint and hence, more convenient it would be to place an EVSE. Also, less area requirement would help lower the establishment cost for a charging station. However, it would not be a significant challenge in this case, as depots usually have sufficient space to accommodate infrastructural changes.	

The specifications of the concerned e-bus model should be considered while selecting a charging technology as the performance of the latter may vary.

TABLE 25: ECONOMIC PARAMETERS FOR MULTI-CRITERIA DECISION ANALYSIS FOR SELECTION OF CHARGING TECHNOLOGY

S. No.	Parameter	Ideal value	Justification of the ideal value	Depot charging during operating hours	Depot charging overnight
1.	Capital cost per EVSE	₹ 3,50,000	This value has been considered taking into account the minimum price of the EVSE suitable for bus charging.	**Weight:** 10 **Justification:** Cost of EVSE is the largest component of the developer's capital investment. This would have an important bearing on the economic feasibility of the project.	
2.	Cost of electricity for charging an e-bus by an EVSE	Minimum tariff applicable	The charging system which attracts the lowest electricity tariff would get the highest rank. Amount of electricity consumption at system-level is considered to be fixed.	**Weight:** 10 **Justification:** Cost of electricity for charging is the main operational expenditure to run a charging station. Here, only energy charge (/ variable cost) is considered. Demand charge (/ fixed cost) is not accounted as HT connection would be required to charge buses by both AC-III and DC fast charger.	
3.	Cost of ancillary infrastructure	Minimum cost	Cost of ancillary infrastructure depends on the type of EVSE. The one which entails least ancillary cost would be awarded the highest rank.	**Weight:** 5 **Justification:** Requirement of ancillary/ supporting infrastructure differs with EVSEs. Individual major cost heads are listed below: • AC-III charging system requires a dedicated DT to operate at full capacity. • Fast chargers require a cooling system for the converters/ cables to keep operating at high power without heating up, which eventually could slow them down. Any cost not to be directly incurred by the charging station developer has not been accounted for.	
4.	Maintenance cost per EVSE	₹ 42,000/ annum	Based on industry practices. Minimum cost is desirable.	**Weight:** 2 **Justification:** Maintenance cost which is a recurring cost includes servicing, repairing and inspection costs. Its share in total operating cost is expected to be low. 2% of capex equals regular maintenance cost and 10% of capex equals periodic (every 3 years) maintenance cost.	

Based on the listed technical and economic parameters and their ideal values, with the help of the Multi-Criteria Decision Matrix tool, the study assesses the charging technologies which are suitable for charging e-buses and presently available in the market. Table 26 presents the Multi-Criteria Decision Matrix for selection of charging technology for depot charging of e-buses post completion of the trip(s).

TABLE 26: MULTI-CRITERIA DECISION MATRIX FOR SELECTION OF CHARGING TECHNOLOGY FOR CHARGING OF E-BUSES DURING OPERATING HOURS

Parameters	Criteria	Weight (W)	AC-III		DCFC			
					Pantograph		Plug-in	
			R_{AC-III}	$W*R_{AC-III}$	R_{DCP}	$W*R_{DCP}$	R_{DCC}	$W*R_{DCC}$
Technical Parameters	Charging time	10	2	**20**	3	**30**	2	**20**
	Effectiveness to maintain service headway of a bus route	10	2	**20**	3	**30**	2	**20**
	Grid voltage required	6	3	**18**	1	**6**	3	**18**
	Area required per EVSE (including allied infrastructure)	4	3	**12**	1	**4**	2	**8**
Economic Parameters	Capital cost per EVSE	10	3	**30**	1	**10**	2	**20**
	Cost of electricity for charging a bus by an EVSE	10	3	**30**	1	**10**	3	**30**
	Cost of ancillary infrastructure	5	3	**15**	1	**5**	3	**15**
	Maintenance cost per EVSE	2	3	**6**	1	**2**	2	**4**
	Sum	**57**	**151**		**97**		**135**	
	Normalised Weighted Ranks		**2.65**		**1.70**		**2.37**	

W = Weight of a criterion for a particular charging requirement of a specific vehicle segment

R = Rank of a charging technology against a particular criterion

The charging technology which notches up the highest normalised weighted rank would qualify as the most preferred option. The least normalised weighted rank would determine the least preferred option.

AC-III CHARGING TECHNOLOGY IS MOST SUITABLE FOR CHARGING E-BUSES AT TERMINALS/ DEPOTS DURING OPERATING HOURS

The above MCDM shows that AC-III EVSE gets the highest normalised weighted rank. This implies that AC-III charging technology is most suitable for charging e-buses at terminals/ depots during operating hours post the completion of trips.

Table 27 shows the Multi-Criteria Decision Matrix for selection of charging technology for charging of e-buses overnight.

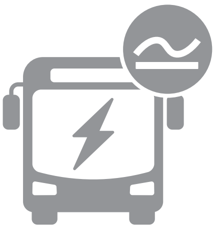
TABLE 27: MULTI-CRITERIA DECISION MATRIX FOR SELECTION OF CHARGING TECHNOLOGY FOR CHARGING OF E-BUSES OVERNIGHT

Parameters	Criteria	Weight (W)	AC-III		DCFC			
					Pantograph		Plug-in	
			R_{AC-III}	$W*R_{AC-III}$	R_{DCP}	$W*R_{DCP}$	R_{DCC}	$W*R_{DCC}$
Technical Parameters	Grid voltage required	6	3	**18**	1	**6**	3	**18**
	Charging time	4	2	**8**	3	**12**	2	**8**
	Effectiveness to maintain service headway of a bus route	4	2	**8**	3	**12**	2	**8**
	Area required per EVSE (including allied infrastructure)	4	3	**12**	1	**4**	2	**8**
Economic Parameters	Capital cost per EVSE	10	3	**30**	1	**10**	2	**20**
	Cost of electricity for charging a bus by an EVSE	10	3	**30**	1	**10**	3	**30**
	Cost of ancillary infrastructure	5	3	**15**	1	**5**	3	**15**
	Maintenance cost per EVSE	2	3	**6**	1	**2**	2	**4**
-	Sum	**45**	**127**		**61**		**111**	
	Normalised Weighted Ranks		**2.82**		**1.36**		**2.47**	

W = Weight of a criterion for a particular charging requirement of a specific vehicle segment

R = Rank of a charging technology against a particular criterion

The charging technology which notches up the highest normalised weighted rank would qualify as the most preferred option. The least normalised weighted rank would determine the least preferred option.



AC-III CHARGING SYSTEM IS MOST SUITED FOR CHARGING E-BUSES OVERNIGHT AT DEPOTS. HOWEVER, AC CHARGING IS ONLY POSSIBLE WHEN THE VEHICLE HAS AN ON-BOARD CHARGER OF SUITABLE CAPACITY.

From the normalised weighted ranks in the above MCDM, one could infer that AC-III charging system is most suited for charging e-buses overnight at depots. However, it is essential to remember that AC charging is only possible when the vehicle has an on-board charger of suitable capacity. Thus, charging by AC III EVSE would add the cost of an on-board charger to the cost of the e-bus. However, the associated charging infrastructure for AC III charging is much less than that for DC charging.

7 Framework for evaluation of required charging capacity at a depot

To plan the charging capacity at a bus depot for a route, the study sets some critical objectives to achieve. These are:

- To achieve maximum possible utilisation of installed EVSEs serving the charging demand of the route at the depot. This study considers that the optimal average Capacity Utilisation Factor (CUF) of the EVSEs serving a route, *i.e.*, the percentage of time in a day the EVSEs are plugged in to EVs, can be 85%. It is not possible to achieve 100% CUF given the time losses due to several reasons such as manoeuvring of e-buses into and out of parking bays, plugging in of e-buses, maintenance, *etc.* Moreover, the daily charging demand may not be too high. This implies that the EVSEs would be in active service for 85% of the time designated for charging per day on an average.
- To maintain the service frequency of the route at par with the baseline
- To charge an e-bus only when it cannot undertake another full trip on the remaining battery charge
- To replace the existing ICE buses on a route with an equal number of e-buses *i.e.*, the fleet size remains the same

To estimate the requisite charging capacity, *i.e.*, the number of AC-III EVSEs required for a route, the study has developed a framework in the form of a set of relations involving some key operational parameters.

h_n = Time-gap (headway) between two consecutive buses on n^{th} route (in minutes). It is the inverse of the service frequency. This variable is applicable to any route operating from the depot.

h_{min} = Time-gap (headway, in minutes) between two consecutive buses on the highest frequency route (amongst all routes operating from a depot). It is the inverse of the highest service frequency at a depot.

r = Ratio of total time designated for charging e-buses in a day to total daily operating hours of the bus network. This ratio directly impacts the number of EVSEs required for charging e-buses on a route.

d = Length of the route (in kilometers) from origin depot to destination depot

n = Number of trips completed by an e-bus before charging is needed. It can be calculated by dividing the driving range of the e-bus by the route length.

t_c = Effective charging time for an e-bus (in minutes). An e-bus may be left with some energy in the battery every time it reaches a depot.

The energy requirement of the e-bus at the time of charging is equal to n(d+Δ)2 kWh, where 2 represents the fuel economy of the e-bus in kWh/km and Δ represents a friction factor[25] of the route, due to which the e-bus may lose some additional energy which is assumed to be 10% of the energy required to complete one trip.

The effective charging time would depend on the energy requirement of the e-bus, the output power and the CUF of the EVSE and the ratio of time designated for charging to operating hours. Therefore, the effective charging time for an AC-III EVSE (output power = 80 kW) is:

$$t_c = \frac{n \times (d+\Delta) \times 2}{80 \times r \times 0.85} \times 60 \qquad \text{---- Eqn. 1}$$

Whether the time headway on a route is greater or less than the effective charging time of an e-bus is the most critical aspect that needs to be taken into account to evaluate the required charging capacity at a depot.

Hence, two separate cases have been studied in this regard.

CASE I: TIME HEADWAY ON THE MOST FREQUENT ROUTE IS GREATER THAN/ EQUAL TO EFFECTIVE CHARGING TIME FOR AN E-BUS

Mathematical expression: $h_{min} \geq t_c$ ---- Eqn. 2

In such a case, **one EVSE per bus route would be enough to serve the charging demand of the route at the depot.** Also, it is recommended to consider a common charging and boarding bay for an e-bus to allow the passengers to board the bus while it is being charged, an effective way to utilise the charging time.

An important possibility which should be explored is whether an EVSE can serve multiple routes provided its idle time is enough. To find the answer, one has to consider some operational sub-scenarios which are as follows.

If the headway of a route is less than twice of the headway of the highest frequency route of the depot, *i.e.*

$$1 \leq \frac{h_n}{h_{min}} < 2 \qquad \text{---- Eqn. 2.1}$$

then the idle time of an EVSE would not be sufficient to accommodate the charging demand of another route.

However, in case the ratio of the headways mentioned above is double or more (but less than three times), *i.e.*

$$2 \leq \frac{h_n}{h_{min}} < 3 \qquad \text{---- Eqn. 2.2}$$

then an EVSE would be able to serve two routes and not more. It is important to note here that both the routes must satisfy equation 2.2 *i.e.*, their headways have to be at least twice the headway of the highest frequency route but less than triple.

Generalising equations 2.1 and 2.2, the study concludes that if

$$m \leq \frac{h_n}{h_{min}} < m+1 \qquad \text{---- Eqn. 2.3}$$

where m is a positive integer, an EVSE would be able to serve routes (and not more) provided these routes satisfy equation 2.3.

25 In urban transport, a particular 'friction factor' is attributed to a route, which is a result of the time lost in traveling due to forced delays, poor road (network) quality, barriers, congestion, *etc*. It is different at different times during the day and is the highest during the peak hours.

CASE II: TIME HEADWAY ON THE ROUTE IS LESS THAN THE EFFECTIVE CHARGING TIME FOR AN E-BUS

Mathematical expression: $h_n < t_c$ ----- Eqn. 3

Let $\frac{t_c}{h_n} = k$ ----- Eqn. 3.1

where $k > 1$

In such a case, $]k[$ number of EVSEs per route where $]k[$ is the least integer greater than or equal to would be required.

Meticulous planning is necessary to schedule the charging activities at the depot post completion of trips during operating hours as the charging time could easily disrupt the route headway. Considering route headway (h_n) and effective charging time (t_c) for an e-bus are the two most critical operational parameters for an e-bus fleet on a route, this study formulates certain relations to plan charging activities centred around these parameters, as explained below.

By the time the first bus gets fully charged in minutes to undertake a trip, the second e-bus in line acquires $(1 - \frac{1}{k})$ proportion of the total usable energy. The $]k[^{th}$ bus at the $]k[^{th}$ EVSE acquires $1/k$ proportion of the total usable energy.

After t_c minutes, when the next e-bus queues up for charging, the first EVSE would be idle to serve the bus. Similarly, after t_c x $(k + 1)/k$ minutes since the beginning of charging operation of the first EVSE, the second EVSE would be able to accommodate another e-bus for charging. In this manner, all the e-buses would be able to get fully charged and leave on time and the time headway between two consecutive buses on that route remains unaffected. **Therefore, it can be concluded that in such a case, the node would require]k[EVSEs per route**.

For all the other routes operating from the same depot, a similar analysis has to be carried out. It is possible that the analysis may yield different and values for each route.

If the service headway on another route (operating from the same depot) is less than or equal to the charging time of an e-bus, then one can evaluate the required serving capacity for that route using the relations of Case I.

PRACTICAL APPLICATIONS OF THE DEVISED RELATIONS

Are the devised relations effective and can they be practically applied? To test that, this study considers a number of “real world” bus routes from bus networks in Tier-I and Tier-II cities in India. The routes are identified in a way that both Case I and Case II can be appropriately simulated. The analysis rubric consists of:

- Selection of bus routes in Tier-I and Tier-II Indian cities
- Consideration of a constant average headway instead of a dynamic headway; in practice, the headway of a route may vary across the operating hours.
- Consideration of AC-III EVSE for e-bus charging and an e-bus with a rated battery capacity of 200 kWh

To make the analyses robust, this research adds another layer of complexity while applying the relations. Following two different scenarios are considered in each of the cases:

Scenario 1 Designated time for charging e-buses is the same as the network’s daily operating hours *i.e.*, there is no overnight charging

Scenario 2: Designated time for charging e-buses is full day *i.e.* 24 hours

SCENARIO 1: DESIGNATED TIME FOR CHARGING E-BUSES SAME AS THE NETWORK'S DAILY OPERATING HOURS

CASE I: TIME HEADWAY ON THE MOST FREQUENT ROUTE IS GREATER THAN/ EQUAL TO EFFECTIVE CHARGING TIME FOR AN E-BUS

This study explores route number 605 of DTC (Delhi Transport Corporation), which has bus service for 18 hours a day and 6 daily trips are undertaken with an average time headway of 180 minutes. The route is approximately 27 km long and two trips can be completed before the bus requires charging. To estimate the effective charging time for an e-bus on this route, this study applies equation 1, as shown below.

$$\frac{n \times (d + \Delta) \times 2}{80 \times r \times 0.85} \times 60 = \frac{2 \times (27 + 2.7) \times 2}{80 \times (\frac{18}{18}) \times 0.85} \times 60 = 104.8 < 180$$

Since the estimated effective charging time is less than the time headway of the route, i.e., here $h_n > t_c$, **1 number of AC-III EVSE at a depot would be sufficient to serve the concerned route.**

It is worthwhile to mention here that the possibility of sharing of an EVSE amongst multiple routes has not been considered. However, it is possible to determine it using the devised relations.

To extend the analysis to a Tier-II city, the study has considered route number 17 in Surat city, operated by Surat Sitilink Limited, which has a daily operating duration of 15 hours. The number of trips made on the route in a day are 5 and the average time headway is equal to 180 minutes. The route length equals 14.2 km and an e-bus can complete 3 trips before requiring additional charge. The effective charging time for an e-bus is estimated using equation 1.

$$\frac{n \times (d + \Delta) \times 2}{80 \times r \times 0.85} \times 60 = \frac{3 \times (14.2 + 1.42) \times 2}{80 \times (\frac{15}{15}) \times 0.85} \times 60 = 82.7 < 180$$

The study finds that the estimated effective charging time is lower than the route headway, or $h_n > t_c$. **This indicates that 1 number of AC-III EVSE at a depot would be enough to serve the concerned route.**

CASE II: TIME HEADWAY ON THE ROUTE IS LESS THAN THE EFFECTIVE CHARGING TIME FOR AN E-BUS

The study considers route number 623 of DTC. The daily number of trips made on this route are 74 and the average time headway is equal to 20 minutes. Also, this route is approximately 25 km long and two trips can be completed before additional charge is required. The effective charging time is calculated using equation 1, as shown below.

$$\frac{n \times (d + \Delta) \times 2}{80 \times r \times 0.85} \times 60 = \frac{2 \times (25 + 2.5) \times 2}{80 \times (\frac{18}{18}) \times 0.85} \times 60 = 97.05 > 20$$

It is found that the effective charging time is greater than the time headway of the route, *i.e.* $h_n < t_c$. The ratio of effective charging time and time headway is found to be (as per equation 3.1):

$$\frac{t_c}{h_n} = \frac{97.05}{20} = 4.85$$

Thus, the study finds that the route would require **5 number of AC-III EVSEs at a depot.**

The analysis then examines bus route number 15 of Surat city. The number of trips made on this route in a day are 215 and the average time headway is equal to 4 minutes 30 seconds. The route length is equal to 7.1 km and 7 trips can be completed before additional charge is required. Hence, the effective charging time turns out to be:

$$\frac{n \times (d + \Delta) \times 2}{80 \times r \times 0.85} \times 60 = \frac{7 \times (7.1 + 0.71) \times 2}{80 \times (\frac{15}{15}) \times 0.85} \times 60 = 96.5 > 4.5$$

Hence, the route headway is lower than the effective charging time, or $h_n < t_c$

The ratio of effective charging time and time headway is as follows:

$$\frac{t_c}{h_n} = \frac{96.5}{4.5} = 21.44$$

Thus, **22 number of AC-III EVSEs would be required at a depot to serve the route mentioned above.**

SCENARIO 2: DESIGNATED TIME FOR CHARGING E-BUSES IS FULL DAY *I.E.* 24 HOURS

CASE I: TIME HEADWAY ON THE MOST FREQUENT ROUTE IS GREATER THAN/ EQUAL TO EFFECTIVE CHARGING TIME FOR AN E-BUS

This study explores route number 605 of DTC. The number of trips made on the route in a day are 6 and average time headway is equal to 180 minutes. The route is approximately 27 km long and two trips can be completed before the bus requires additional charge. The effective charging time for an e-bus is estimated to be:

$$\frac{n \times (d + \Delta) \times 2}{80 \times r \times 0.85} \times 60 = \frac{2 \times (27 + 2.7) \times 2}{80 \times (\frac{24}{18}) \times 0.85} \times 60 = 78.6 < 180$$

Here, the time headway of the route is greater than the effective charging time for an e-bus, that is $h_n > t_c$. Hence, **1 number of AC-III EVSE at a depot would be enough to maintain the service headway on the concerned route.**

The analysis also examines route number 17 operating in Surat city. The number of trips made on the route in a day are 5 and average time headway is equal to 180 minutes. The route length equals 14.2 km and an e-bus can complete 3 trips before requiring additional charge. The effective charging time for an e-bus is estimated to be:

$$\frac{n \times (d + \Delta) \times 2}{80 \times r \times 0.85} \times 60 = \frac{3 \times (14.2 + 1.42) \times 2}{80 \times (\frac{24}{15}) \times 0.85} \times 60 = 51.7 < 180$$

The effective charging time for an e-bus is lower than route headway, *i.e.*, $h_n > t_c$.

Therefore, **1 number of AC-III EVSE at a depot would be sufficient to serve the concerned route.**

CASE II: TIME HEADWAY ON THE ROUTE IS LESS THAN THE EFFECTIVE CHARGING TIME FOR AN E-BUS

Route number 623 of DTC has been examined. The number of trips made on the route in a day are 74 and average time headway is nearly equal to 20 minutes. This route is approximately 25 km long and two trips can be completed before additional charge is necessitated. Effective charging time is calculated as follows:

$$\frac{n \times (d + \Delta) \times 2}{80 \times r \times 0.85} \times 60 = \frac{2 \times (25 + 2.5) \times 2}{80 \times (\frac{24}{18}) \times 0.85} \times 60 = 72.8 > 20$$

In this case, the time headway of the route is less than the effective charging time, *i.e.* $h_n < t_c$. The ratio of effective charging time and time headway is:

$$\frac{t_c}{h_n} = \frac{72.8}{20} = 3.64$$

Hence, the study finds that the route would require **4 AC-III EVSEs at a depot.**

The analysis also examines bus route number 15 of Surat city. The number of trips made on this route in a day are 215 and the average time headway is equal to 4 minutes 30 seconds. The route length is equal to 7.1 km and 7 trips can be completed before additional charge is required. Calculating the effective charging time, we get

$$\frac{n(d + \Delta)2}{80 \times r \times 0.85} \times 60 = \frac{7(7.1 + 0.71)2}{80 \times (\frac{24}{15}) \times 0.85} \times 60 = 60.3 > 4.5$$

Here, the effective charging time is greater than the service headway on the route, *i.e.* $h_n < t_c$. As

$$\frac{t_c}{h_n} = \frac{60.3}{4.5} = 13.4$$

Hence, **14 AC-III EVSEs would be required to serve the aforementioned route.**

The investigation finds that the above results, which are the outcome of the practical application of the devised relations are logical. Hence, the study is able to infer that the formulated framework for assessing the required charging capacity at a depot for a route is practical and comprehensive – it can be applied in all the possible scenarios and cases.

8 What it would take to set up charging stations

Setting up a charging infrastructure is a multi-dimensional challenge. The study likes to emphasise here that the infrastructure planning exercise for setting charging stations for a public e-bus fleet does not end with the assessment of the charging possibilities, the selection of *"best-fit"* charging technology or the determination of the required charging capacity.

While the objective to satisfy the mobility demand should be at the core of this exercise, it is critical to consider other elements. The aspects of EV charger specifications and corresponding electricity grid connection and ancillary infrastructure requirements, cost of installation, and necessary spatial provision are some of the vital pieces of the planning puzzle. Not to mention, to crack this, it would require an understanding of a range of issues and involvement of a number of actors.

Hence, it is crucial to shed light on these aspects. To this end, this study on e-bus charging infrastructure has prepared a Reference Sheet on charging station and proposed a model layout (plan) for setting up charging stations at a depot. They can potentially serve as a useful guide to establish charging infrastructure at a depot. The Reference Sheet takes into account the identified *"best-fit"* charging technologies, which are AC III charger and other key results of this research (refer to Table 28).

TABLE 28: REFERENCE SHEET FOR AC III CHARGER

Aspects	Parameters	Data for AC – III
Charger specifica-tions	Input voltage to EVSE (V)	415
	Maximum output power from EVSE (kW)	80
	Charging time for buses (battery rated 200 kWh)	1.5-2 hours [a]
Grid connection requirement	Electricity connection required (HT/ LT)	HT
	Ancillary infrastructure required	Distribution Transformer
		HT/ LT Switchgear
		Cables
		Protection relay
		SCADA
	No. of chargers that can be supplied from a 1 MVA transformer	10
Cost Estimates	Capital cost of charging technology (₹)	3,50,000 – 6,40,000
	Cost of ancillary infrastructure (₹)	2,50,000 – 4,00,000
	Cost of electricity for charging (energy and demand charge as per connection)	Energy charge and demand charge as per HT (415V)
	Maintenance cost (%)	10% of installation cost as periodic maintenance
		2% of installation cost as regular maintenance
Charging facility space requirements (for a 12m e-bus)	Parking Bay Type	Angular
	Parking Bay Area (m^2)	39
	Parking Bay Angle (°)	45
	Maintenance Bay Type	Sawtooth
	Maintenance Bay Area (m^2)	36
	Maintenance Bay Entry Angle (°)	15
	Maintenance Bay Exit Angle (°)	30
	Marking specifications	Dashed lines at entry/ exit of station
		Solid lines between bays for non-negotiable movement
	Area required for EVSE (m^2)	0.8
	Area required for ESS (m^2)	80 [26]
	Area required for 3-phase pole mounted DT (m^2)	9
	Covered waiting area (per fully occupied 40-seater bus) (m^2)	30 [27]
	Minimum Entry/ Exit Lane Widths (m)	8
	Parking Area Lane Widths (m)	7.5 [b]
	Inner Turning Radius (Path Traced by the Inside Front Wheel) (m)	6.5 [b]
	Outer Turning Radius (To Clear the Outside Rear Overhang) (m)	13.2 [b]
	Area of Enquiry, Pass and Ticket Counter (m^2)	42
	Area Required for Ancillary Infrastructure (m^2)	600
	Area of Administration and Operation Office (m^2)	600
	Area of Depot Office (m^2)	600
	Area of Canteen (m^2)	80
	Area of Washroom (m^2)	20
	Area of Maintenance Room and Repair Workshop (m^2)	322
	Gradient of Sub-Level Parking Ramp (%)	10 [b]
	Total Depot Area (Ha)	5.89
	Plot Frontage (m)	423
	Curb Type	Barrier
	Curb Height (cm)	30 [b]
	Bus Stop Area (m^2)	10
	Empty Bay Indicators	Optic
	Canopy Area (m^2)	6430

[a] Refer Appendix A- charging time estimation for details
[b] C. S. Papacostas and P. O. Prevedouros 'Transportation Engineering & Planning', PHI, New Delhi

26 Master Plan Delhi – Modification 2021 (modified till 31/03/2016), Delhi Development Authority
27 Best Practice Guidelines – Airport Service Levels Agreement Framework, International Air Transport Association (IATA) Airport Development Reference Manual, IATA-ACI (Airports Council International)

DC PLUG-IN SHOULD BE USED IF ON-BOARD CHARGERS ARE MISSING FROM BUSES

Considering that an AC III charger can be adopted only if the e-bus has an on-board charger, a bus fleet operator can opt for DC plug-in which is the second-best option as per the Multi-Criteria Decision Matrices. Hence, a separate Reference Sheet has been prepared for DC plug-in charger (refer to Appendix B).

The suggested model layout/ plan (refer to Figure 13) is considerate of the charging infrastructure requirements at the bus depot.

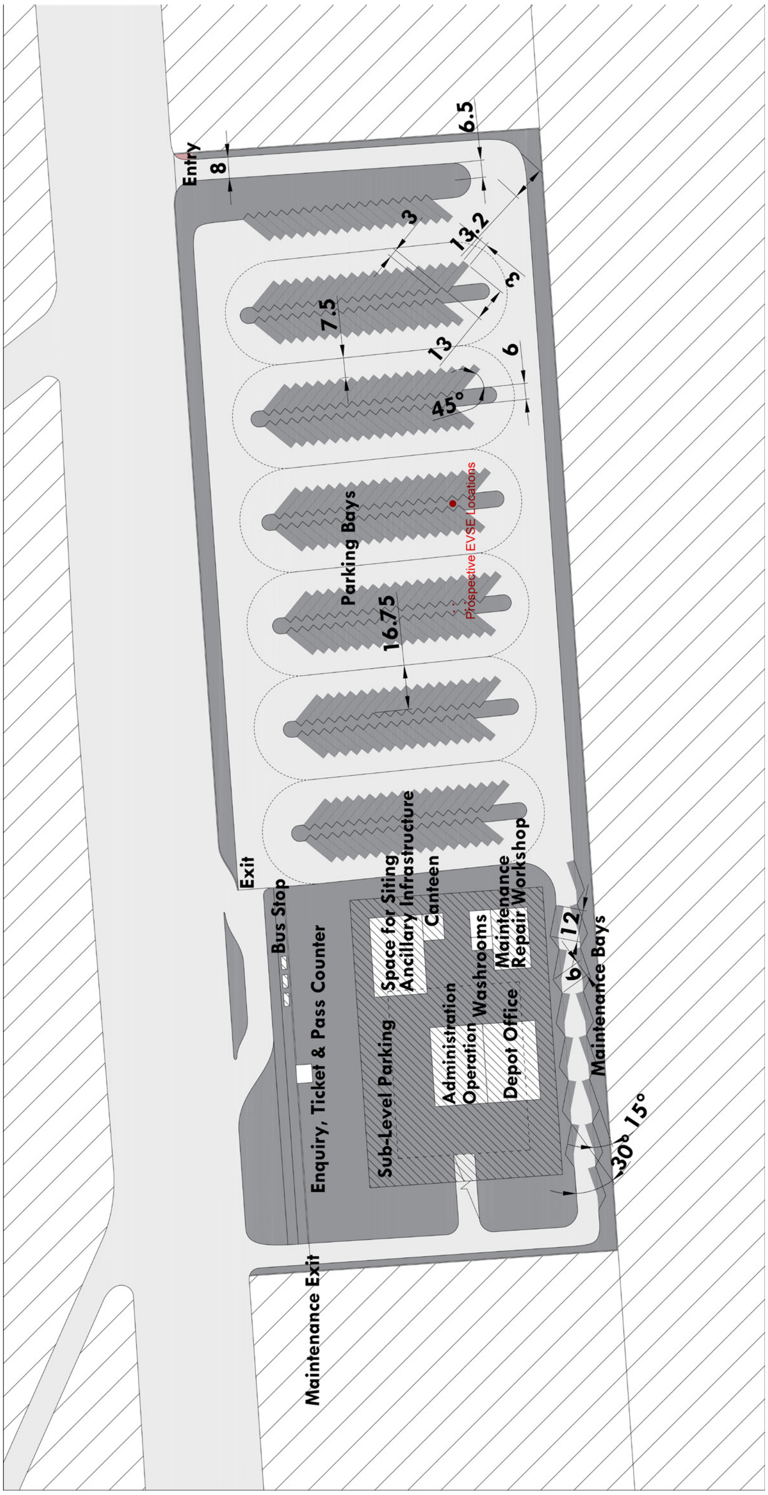


FIGURE 13: MODEL E-BUS DEPOT PLAN

This study has also developed a Roles and Responsibilities (R&R) Matrix (refer to Table 29) which highlights the kind of engagement of respective stakeholders required in the charging infrastructure planning exercise. This, however, does not take into account a particular implementation or business model adopted by the bus service provider. In this context, it should be bear in mind that the analyses and the results of this study should not be considered universally applicable and hence, it is essential that every bus service provider taking cues from this study and leveraging the developed frameworks carries out necessary charging infrastructure planning for their bus fleets.

TABLE 29: ROLES & RESPONSIBILITIES MATRIX REGARDING CHARGING INFRASTRUCTURE PLANNING

Key activities in charging infrastructure planning	Bus service provider	Bus OEM	Charging technology supplier	DISCOM
Understanding intra-city public bus network characteristics in the context of e-bus roll-out	P	S		
Examining the requisite e-bus size, battery capacity, driving range for a route	P			
Identifying suitable sites for siting charging stations for a route	P		S	
Understanding the specifications of different charging technologies	P	S		S
Examining the capex and opex for different charging technologies	P			
Evaluating the charging technologies using MCDMs and selection of "*best-fit*" charging option	P			S
Assessing the relation between time headway and e-bus charging time	P		S	
Examining the optimum charging capacity to be deployed for a route	P		S	
Assessing the necessary grid connection	S		S	P
Evaluating the charging facility space requirements	P		S	

P: Primary responsibility; S: Secondary responsibility

THOUGH THE BUS SERVICE OPERATOR HAS THE PRIMARY RESPONSIBILITY FOR THE ACTIVITIES, SUPPORT FROM EXTERNAL EXPERTS OR AGENCIES WOULD BE BENEFICIAL TO EFFECTIVELY CARRYING OUT THE PLANNING

From the R&R Matrix, it is quite evident that a bus service provider would have the primary responsibility to attend the bulk of the identified preparatory activities to set up the charging infrastructure for its e-bus fleet. However, undertaking these activities could be a tough challenge to a bus service provider since this is a new template for them, and they may not have the necessary experience and knowledge. Support from external experts or agencies would be beneficial to the bus service provider to effectively carrying out the planning. Not to mention the importance of the roles of other stakeholders, namely the bus OEMs, the charging technology suppliers and the DISCOMs in developing the plan for rolling out charging infrastructure for e-bus fleets. The fact that the success of the plan hinges on the close coordination among the stakeholders cannot be overstated.

Appendix A
Charging time estimation

Charging time calculation of EV batteries is a challenging exercise, as the charging time depends on the charger output power as well as the battery characteristics. Batteries themselves are complex energy storage devices wherein the available energy, the chemistry, configuration within the battery pack and the safe operating limits would determine the charging rate and time. Hence, a simplified estimation method[28] is developed to co-relate the energy required for charging with the maximum output power.

For the purpose of this study, industry-accepted standards applicable for e-buses and Lithium-ion (LFP) batteries[29] are considered to estimate the charging time. Charging time for a bus is estimated[30] taking into account, 200 kWh rated battery pack capacity (refer to Table 30). The two primary considerations that determine the charging energy requirement are the maximum allowed depth of discharge of the battery and the supplementary energy required to overcome range anxiety.

- Applying a thumb rule of the minimum state of charge of 30% to maintain the health of batteries, the maximum depth of discharge is 70%. The maximum charging energy requirement for the battery bank corresponds to the maximum available useful energy. For a 200 kWh battery, it is estimated to be 200 x 0.7 = 140 kWh.
- It is also recommended that the battery of an e-bus should never be discharged below 15% of the available useful energy avoid any possibility of getting stranded. The minimum charging energy requirement is estimated as 200x 0.7x(1-0.15) = 119 kWh.

The charging time is estimated at charging energy requirements of 119 kWh and 140 kWh respectively.

TABLE 30: CHARGING TIME ESTIMATION

EVSE Category	AC Level 1	AC Level 2	AC Level 3	DC Plug-in	DC Pantograph
Charger output power (kW)	2.2	6.8	80	70	300
Charging time (hours)	55-65	17-20	1.5–2	1.7-2	0.4-0.5

28 Charging time is estimated assuming a charging rate of 1C. Generally, the capacity of batteries is also rated at 1C
29 Lithium Iron Phosphate (LFP) batteries are the most common EV batteries.
30 Charging time is not estimated for battery swapping technology.

Appendix B
Reference Sheet for DCFC Plug-in Charger

Aspects	Parameters	Data for DCFC Plug-in Charger
Charger specifications	Input voltage to EVSE (V)	415
	Output power from EVSE (kW)	70
	Charging time for buses (battery rated 200 kWh)	1.7-2 hours
Grid connection requirement	Electricity connection required (HT, LT)	HT
	Ancillary infrastructure required	Distribution Transformer
		HT/LT Switchgear
		Liquid cooled cables
		Protection Relay
		SCADA
	No of chargers that can be supplied from a 1 MVA transformer	11
Cost Estimates	Capital cost of charging technology (₹)	16,00,000 – 22,00,000
	Cost of ancillary infrastructure (₹)	2,50,000 – 4,00,000
	Cost of electricity for charging (energy and demand charge as per connection)	Energy charge and demand charge as per HT (415V)
	Maintenance cost (%)	10% of installation cost as periodic maintenance
		2% of installation cost as regular maintenance
Charging facility space requirements (for a 12m e-bus)	Bay area and dimensions (m x m) (angular parking bay - 45^0)	13 x 3
	Manoeuvring lane width (m) (angular parking bay - 45^0)	15
	Bay dimensions (m x m) (sawtooth parking bay)	12 x 6
	Entry angle (sawtooth parking bay)	15^0
	Exit angle (sawtooth parking bay)	30^0
	Manoeuvring lane width (m) (sawtooth parking bay)	8
	Turning radius (m)	29
	Marking specifications	Dashed lines at entry/ exit of station
		Solid lines between bays for non-negotiable movement
	Area required for EVSE (m^2)	2
	Area required for ESS (m^2)	80
	Area required for 3-Phase Pole Mounted DT (m^2)	9
	Covered waiting area (per fully occupied 40-seater bus) (m^2)	30

a Refer Appendix A– charging time estimation for details

REFERENCES

CEA. (2018). Guidelines for Distribution Utilites for Development of Distribution Infrastructure. New Delhi: Central Electricity Authority.

ABB. (2017). Library. Retrieved from ABB: https://library.e.abb.com/public/c09e6e5078914efe874925c24b56f772/ABB_EVI_ProductLeaflet_HVC-OpportunityCharging_nd_web.pdf

ABB. (2018). Electric Vehicle Infrastructure: Overnight charging for electric buses and trucks. Retrieved from ABB EV Infrastructure: https://search-ext.abb.com/library/Download.aspx?DocumentID=9AKK107045A5070&LanguageCode=en&DocumentPartId=&Action=Launch

ABB. (2019, March 7). ABB flash-charging eBus solution reaches a new milestone of half a million km. Retrieved from ABB: https://new.abb.com/news/detail/17282/abb-flash-charging-ebus-solution-reaches-a-new-milestone-of-half-a-million-km

Ahn, S. (2017). Retrieved from Greentechlatvia: http://greentechlatvia.eu/wp-content/uploads/bsk-pdf-manager/2-5a_OLEV_Project_and_Technology_(Ahn)_rev_a_15.pdf

Alees. (2014). Battery Swapping System. Retrieved march 6, 2019, from Alees: http://www.aleees.com/en/component/k2/item/319-electricity.html

Balakrishnan, P. (2019, April 2). E-buses gaining traction on Indian roads. Retrieved from The Hindu BusinessLine: https://www.thehindubusinessline.com/opinion/columns/e-buses-gaining-traction-on-indian-roads/article26713920.ece

Begins. (2019). Electric Bus. Retrieved from Begins: http://www.begins.co.kr/en/business/ebus#bus

Bengrut, D. (2019, March 17). Rs 62 lakh earned in 45 days: e-buses in Pune a hit . Retrieved from Hindustan Times: https://www.hindustantimes.com/pune-news/rs-62-lakh-earned-in-45-days-e-buses-in-pune-a-hit/story-BAhQ842AufZhqW1bVsFzaM.html

Blanci, S. (2017, August 31). The U.S. Just Spent $84M On Electric Buses. Retrieved from Forbes-Transportation: https://www.forbes.com/sites/sebastianblanco/2018/08/31/84-million-electric-buses/#31ea41ea5e40

Boyd, J. (2018, December 17). IEEE Spectrum. Retrieved from IEEE: https://spectrum.ieee.org/energywise/transportation/efficiency/a-global-charging-standard-for-evs

Buchmann, I. (2016). Batteries In A Portable World. Battery University.

BYD. (2019, March 5). Retrieved from ICCT: https://www.theicct.org/sites/default/files/BYD%20EV%20SEDEMA.pdf

Dogra, S. (2019, March 20). Kerala Gets 5 New Electric Buses Promising A 300 Km Range On A Single Charge. Retrieved from Indiatimes: https://www.indiatimes.com/technology/news/kerala-gets-5-new-electric-buses-promising-a-300-km-range-on-a-single-charge-362783.html

Elin, K. (2016). Charging Infrastructure for electric city buses. Stockholm: KTH.

Eurabus. (2017). Electric Bus Study China. Berlin: Eurabus GmbH. Retrieved from https://www.eurabus.com/app/download/6580859618/Electric%20bus%20study%20-%20China%202017.pdf?t=1518596558

Eurabus. (2017). Electric Bus Study China . Berlin: Eurabus GmbH.

EVConnectors. (2019). EV prodicts. Retrieved march 8, 2019, from EVconnectors: https://evconnectors.com/

Guardian. (2018, December 12). Shenzhen's silent revolution: world's first fully electric bus fleet quietens Chinese megacity. Retrieved from The Guardian International Edition-Cities: https://www.theguardian.com/cities/2018/dec/12/silence-shenzhen-world-first-electric-bus-fleet

Hall, D., Cui, H., & Lutsey, N. (2018, October). Electric vehicle capitals: Accelerating the global transition to electric drive. Retrieved from International Council on Clean Transportation: https://www.theicct.org/sites/default/files/publications/EV_Capitals_2018_final_20181029.pdf

Hua, J. (2012). US China Workshop. Retrieved from Argonne National Lab: http://www.cse.anl.gov/us-china-workshop-2012/pdfs/session3b_demos_standards/hua_3B-4-HUA-Tsinghua%20Univ-Progress%20in%20Battery%20Swapping%20Technolo.pdf

Ian. (2018, June 26). Do Londoners dream of electric buses? Retrieved from IanVisits: https://www.ianvisits.co.uk/blog/2018/06/26/do-londoners-dream-of-electric-buses/

IEA. (2018). Global EV Outlook 2018. International Energy Agency.

ISGF. (2017). Implementation Plan for Electrification of Public Transportation in Kolkata. New Delhi: India Smart Grid Forum.

IndiaMART . (2019). Schneider SCADA Systems. Retrieved January 26, 2019, from IndiaMART InterMESH Ltd.: https://www.indiamart.com/proddetail/schneider-scada-systems-13202900712.html

Indian Express. (2019, January 17). Express News Service. Retrieved from Indian Express: https://indianexpress.com/article/cities/ahmedabad/on-display-at-vibrant-gujarat-trade-show-brts-e-buses-5542219/

ISGF. (2018, April 27). Electric Bus Revolution of Shenzhen City in China. Retrieved from India Smart Grid Forum: http://www.indiasmartgrid.org/reports/ISGF%20-%20Visit%20to%20Shenzhen%20Eastern%20Bus%20Company%20Ltd%20on%2016th%20April%202018.pdf

John, P. (2019, 1 21). City-Ahmedabad. Retrieved from Times of India: https://timesofindia.indiatimes.com/city/ahmedabad/city-to-run-e-bus-with-battery-swap-tech/articleshow/67616051.cms

JorAir. (2017, August 31). York's Park & Ride to be fully charged. Retrieved from JorAir: http://jorair.co.uk/2017/08/31/yorks-park-ride-to-be-fully-charged/

Khandekar, A., Rajagopal, D., Abhyankar, N., Deorah, S., & Phadke, A. (2018). The Case for All New City Buses in India to be Electric. Lawrence Berkeley National Laboratory. Retrieved from https://escholarship.org/uc/item/7d64m1cd

Khandekar, A., Rajagopal, D., Abhyankar, N., Deorah, S., & Phadke, A. (2018, December 07). The Case for All New City Buses in India to be Electric. Retrieved February 12, 2019, from eScholarship - Open Access Publications from the University of California: https://escholarship.org/uc/item/7d64m1cd

Krefeld. (2015, 4 20). mobility. Retrieved march 5, 2019, from siemens: https://www.siemens.com/press/pool/de/events/2015/mobility/2015-06-uitp/presentation-ebus-e.pdf

Kyle. (2017, February 14). Luxembourg City Electrifies Bus Routes With New ABB Fast Chargers. Retrieved from Cleantechnica: https://cleantechnica.com/2017/02/14/abb-fast-chargers-enable-hybrid-electric-bus-routes-luxembourg-city/

Liévano, A. B. (2019, February 4). Latin American cities finally embrace Chinese electric buses. Retrieved from Dialogo Chino- World: https://dialogochino.net/21995-latin-american-cities-finally-embrace-chinese-electric-buses/

Lu, L., Xue, L., & Zhou, W. (2018, 4 4). How Did Shenzhen, China Build World's Largest Electric Bus Fleet? Retrieved from World Resources Institute: https://www.wri.org/blog/2018/04/how-did-shenzhen-china-build-world-s-largest-electric-bus-fleet

Mäkinen, J. (2016). Fundamentals of electric bus charging. ABB.

Mäkinen, J. (2016, May 3). Fundementals of Electric bus charging. Retrieved from ABB: https://ecv-fi-bin.directo.fi/@Bin/162798bc24e229c4f0a05c8e45d8a5fd/1551777463/application/pdf/215749/19_16_NEBI2_Session5_M%C3%A4kinen_ABB.pdf

Miles, J., & Potter, S. (2014). Developing a viable electric bus service: the Milton Keynes demonstration project. Research in Transportation Economics, 357–363. doi:https://doi.org/10.1016/j.retrec.2014.09.063

Ministry of Heavy Industries and Public Enterprises. (2018, September 27). Extension of Fame-India Scheme up to 31st March 2019. Retrieved from FAME India Scheme: https://www.fame-india.gov.in/WriteReadData/userfiles/file/fame-3-3.pdf

Ministry of Heavy Industries and Public Enterprises. (2019, March 8). Publication of notification in Gazette of India(Extraordinary) regarding Phase-II of FAME India Scheme. New Delhi: The Gazette of India. Retrieved from Department of Heavy Industries: https://dhi.nic.in/writereaddata/UploadFile/publicationNotificationFAME%20II%208March2019.pdf

Ministry of Heavy Industry and Public Enterprises. (2015). Notification - Scheme for Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles in India - FAME India . New Delhi.

Ministry of Statistics and Programme Implementation. (2017). Motor Vehicles - Statistical Year Book India 2017. Retrieved 2018, from Ministry of Statistics and Programme Implementation: http://www.mospi.gov.in/statistical-year-book-india/2017/189

Morrow, K., Karner, D., & Frankfort, J. (2008). Plug-in hybrid electric vehicle charging infrastructure review. US Department of Energy-Vehicle Technologies Program.

National Electric Code Commitee. (2016). NFPA 70: National Electrical Code. National Fire Protection Association.

National Sample Survey Office. (2016). Key Indicators of Household Expenditure on Services and Durbale Goods. New Delhi: NSSO. Retrieved October 2018, 11

Navigant. (2018). EV Charging Equipment Market Overview. Boulder: Navigant Consulting, Inc.

Park, J. (2016). KOTI workshop report. Retrieved from https://citynet-ap.org/wp-content/uploads/2016/02/KOTI-Workshop-Report.pdf

Press Information Bureau. (2014, January 28). M/s Nielsen submits All India Study Report to PPAC on sale of Diesel and Petrol. Retrieved 2018, from Press Information Bureau: http://pib.nic.in/newsite/PrintRelease.aspx?relid=102799

Press Information Bureau. (2015). Anant Geete Launch's the Scheme for Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles in India – Fame India. Retrieved January 2019, 02, from http://pib.nic.in/newsite/PrintRelease.aspx?relid=118088

Press Information Bureau. (2016, November 23). Press Information Bureau, GoI. Retrieved November 14, 2018, from pib.nic.in: http://pib.nic.in/newsite/PrintRelease.aspx?relid=154119

Proterra. (2016). (Proterra) Retrieved March 5, 2019, from Proterra: https://www.proterra.com/technology/chargers/

Radhakrishnan, A. (2019, January 19). BEVs to ply between capital, Ernakulam. Retrieved from The Hindu: https://www.thehindu.com/news/national/kerala/bevs-to-ply-between-capital-ernakulam/article26039369.ece

Rehaan. (2018, February 12). https://www.team-bhp.com/forum/commercial-vehicles/195366-ashok-leyland-circuit-s-bus-auto-expo-2018-a.html. Retrieved from Team BHP: https://www.team-bhp.com/forum/commercial-vehicles/195366-ashok-leyland-circuit-s-bus-auto-expo-2018-a.html

Shyam, A. R. (2018, 2 19). Industry-Auto. Retrieved from Economic Times: https://economictimes.indiatimes.com/automotive/ashok-leylands-new-electric-bus-may-turn-focus-on-battery-swaping/articleshow/62845416.cms

Siemens. (2014). Wiener Linien Electric Bus. Berlin: Siemens AG. Retrieved from http://www.siemens.com/mobility

Siemens. (2017). E bus charging. Retrieved from Siemens: https://www.siemens.com/press/pool/de/events/2015/mobility/2015-06-uitp/presentation-ebus-e.pdf

SPDCTL. (2018). Cost Data: FY 2018-19. Hyderabad: Southern Power Distribution Company of Telangana, Limited.

Spöttle, M., Jörling, K., Schimmel, M., Staats, M., Grizzel, L., Jerram, L., . . . Gartner, J. (2018). Research for TRAN Committee – Charging infrastructure for electric road vehicles. European Parliament, , Policy Department for Structural and Cohesion Policies. European Parliament, Policy Department for Structural and Cohesion Policies, Brussels: European Parliament. Retrieved from http://bit.ly/2JBVvHq

Stewart, J. (2014). Retrieved from BBC: http://www.bbc.com/future/story/20141028-the-bus-that-recharges-on-the-go

Suh, N. P. (2014). A Solution to Energy and Global Warming: Electrification of Ground Transportation Systems Based on OLEV and SMFIR. Tel Aviv: Fuel Choices Initiative.

Sun Mobility. (2018, 5 2018). Retrieved from Youtube: https://youtu.be/4uNkKx-Kp4A

Swarajya Staff. (2017, September 22). Himachal Pradesh Becomes First Hill State To Run Electric Buses. Retrieved from Swarajya: https://swarajyamag.com/insta/himachal-pradesh-becomes-first-hill-state-to-run-electric-buses

The Hindu. (2018, March 22). Hybrid-electric buses prove to be a hit in Mumbai. The Hindu, p. 2. Retrieved February 15, 2018, from https://www.thehindu.com/news/cities/mumbai/hybrid-electric-buses-prove-to-be-a-hit/article23315490.ece

The Hindu BusinessLine. (2018, January 10). Goldstone electric buses flagged off by HP transport corporation. The Hindu BusinessLine, p. 2. Retrieved February 15, 2019, from https://www.thehindubusinessline.com/news/national/goldstone-electric-buses-flagged-off-by-hp-transport-corporation/article9868484.ece

TNM. (2019, February 17). BMTC decides to buy electric buses instead of leasing them, loses 75CR in subsidies. Retrieved from The News Minute: https://www.thenewsminute.com/article/bmtc-decides-buy-electric-buses-instead-leasing-them-loses-rs-75-cr-subsidies-96889

TOI. (2019, 2 9). After red fleet, buses to go 'green' in Tamil Nadu. Retrieved from Times of India: https://timesofindia.indiatimes.com/city/chennai/2000-e-buses-for-tn/articleshow/67908085.cms

UITP. (2018). 11 CITIES SELECTED FOR PILOT PROJECT OF MULTI-MODAL ELECTRIC PUBLIC TRANSPORT UNDER FAME INDIA. Retrieved January 2nd, 2019, from UITP India: https://india.uitp.org/articles/dhi-funding-pilot-electric-projects-11-cities

University of Central Florida, Orlando, FL. (2018, September 30). Project 6: Electric Vehicle Life Cycle Cost Analysis. Retrieved February 12, 2019, from Electric Vehicle Transportation Centre: http://evtc.fsec.ucf.edu/research/project6.html

V6 News Telugu. (2017, 2 9). Retrieved from Youtube: https://youtu.be/aIIt0UUiMGA

Vesa, J. (2019, March 3). SESKO. Retrieved from https://www.sesko.fi/files/671/EV-charging_standards_may2016_Compatibility_Mode_.pdf

Vora, R. (2019, Januray 24). Auto Focus. Retrieved from The Hindu Business Line: https://www.thehindubusinessline.com/specials/auto-focus/ashok-leyland-ahmedabad-electric-bus/article26082273.ece

Wagenknecht, T. (2017, October 11). TOSA: Geneva's electrical bus innovation. Retrieved from Intelligent Transport: https://www.intelligenttransport.com/transport-articles/71567/tosa-bus/

Wangchuk, R. N. (2019, 2 9). Retrieved from The Better India: https://www.thebetterindia.com/171736/india-ebus-electric-vehicle-costs-features-how-long-run/

Wave. (2019). home. Retrieved from Wave: https://waveipt.com/

Wikimedia. (2013, April 6). File:Vienna Electric Bus April 2013 - 1 (8635457634).jpg. Retrieved from Wikimedia Commons: https://commons.wikimedia.org/wiki/File:Vienna_Electric_Bus_April_2013_-_1_(8635457634).jpg

XDADevelopers. (2014, January). XDA Developers Forum. Retrieved from XDA Developers: https://forum.xda-developers.com/showthread.php?t=1391186

Yeon-soo, K. (2019, 3 24). ICT minister nominee accused of wasting research money. Retrieved from The Korea Times: https://www.koreatimes.co.kr/www/tech/2019/03/325_265924.html

ZeEUS. (2017, October 24). Publications. Retrieved from ZeEUS: http://zeeus.eu/uploads/publications/documents/zeeus-ebus-report-internet.pdf

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