Planning Tool for E-Bus Deployment

CENTER FOR STUDY OF SCIENCE, TECHNOLOGY & POLICY

SHAKTI SUSTAINABLE ENERGY FOUNDATION

Planning Tool for E-Bus Deployment

Center for Study of Science, Technology and Policy

December 2021

Designed and edited by CSTEP

Disclaimer

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

Contributors: Spurthi Ravuri, Dr Vinay Kandagal, Aswathy KP, Arunesh Karkun

This report should be cited as: CSTEP. (2021). Planning tool for e-bus deployment. (CSTEP-RR-2021-09).

December, 2021

Center for Study of Science, Technology and Policy

Bengaluru

18, 10th Cross, Mayura Street
Papanna Layout, Nagashettyhalli
RMV Stage II, Bengaluru 560094
Karnataka (India)
Tel.: +91 (80) 6690 2500
Email: cpe@cstep.in

Noida

1st Floor, Tower-A
Smartworks Corporate Park
Sector 125, Noida 201303
Uttar Pradesh (India)

Acknowledgements

Center for Study of Science, Technology and Policy (CSTEP) is grateful to Shakti Sustainable Energy Foundation (SSEF) for their support in developing E-Bus Depot Electrification Planning and Operations Tool (E-DEPOT).

The authors would like to thank Mr M N Srinivas, Chief Mechanical Officer (P), and his team at Bangalore Metropolitan Transport Corporation (BMTC), and officials from Bangalore Electricity Supply Company Limited (BESCOM), for providing their valuable time, data, and feedback on the Tool. We are also thankful to Dr Ravi Gadepalli for reviewing the functions of the Tool.

We specially appreciate the efforts of our colleagues at CSTEP, Anantha Lakshmi and Harshid Sridhar for the internal technical review, Sreerekha Pillai and Garima Singh for editorial review, and Bhawna Welturkar for graphical support. We also thank Dr Mridula Dixit Bharadwaj, former Sector Head – Materials and Strategic Studies, CSTEP, for initiating the study.

Last but not least, we express our gratitude to Dr Jai Asundi, Executive Director, CSTEP, and Thirumalai NC, Sector Head – Materials and Strategic Studies, CSTEP, for their constant support and encouragement.

Executive Summary

Phase II of the Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles (FAME) India is envisioned to introduce 7,000 e-buses across the country by 2024. This initiative has increased e-bus deployment at a rapid rate. However, the traditional bus operators are not yet familiar with the operational needs of e-buses. Unlike traditional buses that require refuelling, e-buses need frequent recharging to increase their operational range. This key difference calls for setting up the necessary electric infrastructure to meet the charging demand of e-buses.

Charging even a small e-bus fleet would have a significant impact on the local power demand handled by the distribution companies (DISCOMs). Therefore, estimating the additional power demand generated by charging e-buses is crucial for DISCOMs to plan their infrastructure.

E-DEPOT (E-bus Depot Planning and Operations Tool) has been developed to aid the decision-making process of state transport undertakings (STUs) and DISCOMs, regarding the deployment of e-buses. This version of the Tool aims to assess the depot-based charging requirements, considering the existing fleet operations. It performs a feasibility analysis to identify schedules (buses on a specific route) that are suitable for e-bus deployment. The resultant power and energy consumption in charging these e-buses at the selected depots is also estimated. Hence, with the relevant inputs, this generic Tool can formulate e-bus charging plans for different Indian cities.

The depots and schedules selected for operating e-buses are the key inputs for the Tool. The specifications of the e-bus and the charger models chosen, and the power-grid details are the other inputs. Using this data, the Tool provides a list of schedules that can be electrified, a charging timetable, the utilisation profile of each charger, the charging-demand profile, the peak power demand, the total charging energy consumed, and the cost of charging per day at each depot.

The functions of the Tool are demonstrated using data representing the public buses operating in Bengaluru. E-buses with specifications of 250 kWh of battery capacity and 200 km of operational range were considered to operate on these routes. These e-buses were considered to be charged with either a slow charger of 60 kW or a fast charger of 120 kW, depending on the halt duration available for charging.

Of the 311 schedules (operating on 24 routes) used to demonstrate the Tool, only 72 are feasible and the remaining 239 are infeasible. While 72 of the infeasible schedules do not have halts at the selected depots, 161 have route lengths longer than the operational range supported by the battery, and six do not have sufficient halt time to completely charge the battery. The Tool shows that for the 72 feasible schedules operating from the four depots, a total of 16 slow chargers would be required. The electricity cost for charging these schedules, according to the corresponding charging timetables, is INR 60,360 per day. Based on the representative power-grid details used in the study, it was found that new feeders are not required for deploying e-buses at the selected depots.

Upon comparing this base case with scenarios of higher battery capacity and a provision of intermittent charging, it was observed that, for this case study, increasing the battery capacity (up to 325 kWh) is a more economically viable option than increasing the charging locations (up to 3 locations) for intermittent charging.

These findings indicate that the maximum battery capacity eligible for subsidy under the FAME II scheme may need to be increased. Currently, the scheme provides subsidies to e-buses with up to 250 kWh battery capacity. This is not sufficient for the bus-transit operations in metropolitan cities, where the average run is over 200 km per day. Alternatively, intermittent ultrafast charging (with power rating of at least 150 kWh) stations can be set up to cater to routes with higher daily run.

Contents

Tables

Figures

Abbreviations

2W	two-wheeler
3W	three-wheeler
4W	four-wheeler
BESCOM	Bangalore Electricity Supply Company Limited
BEV	battery electric vehicle
BMR	Bengaluru Metropolitan Region
BMRCL	Bengaluru Metro Rail Corporation Limited
BMRDA	Bengaluru Metropolitan Region Development Authority
BMTC	Bangalore Metropolitan Transport Corporation
CS	charging station
CSTEP	Center for Study of Science, Technology and Policy
DC	direct current
DHI	Department of Heavy Industries
DISCOM	distribution company
DTC	distribution transformer centres
EV	electric vehicle
EVSE	electric vehicle supply equipment
FAME	Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles
FC	fast charger
GoK	Government of Karnataka
HEV	hybrid electric vehicle
hr	hour
IIASA	International Institute for Applied Systems Analysis
INR	Indian rupee
KERC	Karnataka Electricity Regulatory Commission
km	kilometre
KSRTC	Karnataka State Road Transport Corporation
kWh	kilowatt-hour
min	minute
MoP	Ministry of Power
PCS	public charging stations
PHEV	plug-in hybrid electric vehicles
R&D	research and development
SC	slow charger
SoC	state of charge
SSEF	Shakti Sustainable Energy Foundation
STU	state transport undertaking
TCO	total cost of ownership
TOD	time of day
TTMC	traffic and transit management centres

1. Introduction

With Phase II of the Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles in India (FAME India) Scheme seeking to support and introduce 7,000 new e-buses across the country (Press Information Bureau Delhi, 2020a), electric bus (e-bus) deployment in India has increased at a rapid rate. As of November 2021, 6,265 e-buses have been sanctioned under this scheme (Press Information Bureau Delhi, 2020b). These e-buses are likely to replace the aging fossil-fuel-powered buses in the near future. E-buses differ significantly from traditional buses due to their design. While traditional buses rely on refuelling, e-buses need to be recharged. A key aspect of this difference, therefore, is the requirement for setting up the necessary electrical infrastructure to serve the charging needs of e-buses. Most public and private bus-fleet operators in the country are experienced in deploying and operating traditional buses, using a well-established refuelling infrastructure, but are not familiar with the infrastructure needs of e-buses. This is, therefore, a major shift in paradigm for most bus–fleet operators in the country.

1.1. Need for the study

Due to the requirement of electrical infrastructure, bus-fleet operators need to work closely with electrical utilities, primarily the power distribution companies or DISCOMs. In terms of size, e-buses form one of the largest categories of electric vehicles (EVs). Based on the FAME II notification, we can assume the energy-storage capacity of the on-board battery of an e-bus to be about 250 kWh, which is equivalent to the capacity of 50 electric 3-wheelers (e-3Ws), or about 17 electric cars (e-cars) (DHI, 2019). Further, assuming that chargers of 60 kW[1] are being used to charge these e-buses, charging even a small fleet of such e-buses will have a significant impact on the local power demand experienced by the DISCOMs. Thus, estimating the addition of this substantial demand (generated by e-bus charging) can be crucial in helping DISCOMs to plan better and be well-prepared to deal with future power-demand requirements at the local level.

To this end, *E-DEPOT (E-bus Depot Planning and Operations Tool)*[2] seeks to bridge the gap between the transport and power sectors, by converting the electrification of buses and their respective operational schedules, into the power and energy demand likely to be experienced due to the charging of these e-buses. This is in direct continuation with the work done in a previous CSTEP-SSEF project titled 'Implementation Plan for Electrification of Public Bus Transport in Bengaluru' (CSTEP-SSEF, 2018), in which 164 Bangalore Metropolitan Transport Corporation (BMTC) bus routes were identified for immediate electrification at the most efficient and economical terms (i.e., without the need to upgrade the existing power-supply infrastructure at the charging locations). While the earlier analysis was limited to the study area within Bengaluru, the tool developed under the current project seeks to not only improve on the previous work, but also enable bus-transport operators and DISCOMs anywhere in India to perform similar analyses.

1.2. Aim

The aim of this project is to develop a simulation tool for public-transport utilities, which can be used in coordination with DISCOMs to plan the depot-based charging infrastructure required to operate e-buses within their transport networks.

---

[1] The DC (direct current) charging power output commonly used for charging e-buses ranges from 50 to150 kW (Das et al., 2019).

[2] Hereafter referred to as the Tool.

1.3. Objectives

The key objectives of this project are:

1. To enable bus-fleet operators to perform a feasibility analysis of operational schedules to assess:
    a. the potential electrification solutions best suited to their needs and constraints
    b. the power and energy consumed due to e-bus charging at depots
    c. the cost of electricity for charging e-buses
2. To enable DISCOMs to estimate and plan for the additional demand resulting from e-bus charging, based on an analytical framework.
3. To ensure the tool is generic and can generate charging plans for different Indian cities, using relevant inputs.

1.4. Scope and limitations

The Tool considers that e-buses are recharged once every day at the depot, and their operational range (distance covered) is limited to the range capability of the fully-charged on-board battery.

Approximations have been made to estimate charging behaviour. Charging of batteries under real-world conditions are also affected by temperature and capacity degradation over time, and typically the rate of charging is non-linear. However, in this Tool, due to the absence of data and detailed models, charging profiles have been assumed to be linear ("2012 Index IEEE Transactions on Power Systems Vol. 27," 2012).

While this Tool requires manual iterations, users may find that results obtained through multiple runs of the Tool (to test different hypothetical scenarios) provide meaningful insights. It may be possible to arrive at and test the boundary conditions for a particular e-bus and its charger specifications by using this Tool, which could assist the user in making decisions at the time of technology selection and procurement.

2. Review of the Existing E-bus Planning Tools

Several tools have been developed globally to assist in e-bus deployment, each with specific objectives. While most of these tools are not available online or not accessible publicly, those accessible were studied to understand the flow of data, the expected outputs, and the user interface. These are explained in Table 1. The outputs from these tools include recommending the optimal fleet size, charging typologies, number of charging stations, operational timetable for different bus types, and the consequent energy consumption.

Cactus-Electromobility, developed by Fraunhofer and Silesian University, recommends the selection and optimal application of battery charging and switching technologies by comparing the technical, economic, and ecological aspects of the solutions (Naumann et al., 2015). The *Software Tool for Planning of City Bus Transport Electrification,* developed by Topic et al., (2018), optimises the e-bus fleet-charging management and performs techno-economic comparisons with the conventional fleet. Another tool, the *BeWhere-Bus* tool, developed at the International Institute for Applied Systems Analysis (IIASA), optimises the distribution of charging stations for e-buses in a city (International Institute for Applied Systems Analysis, 2018). However, this tool does not discuss the type and scale of the charging infrastructure required. The *EV Fleet Analyzer* is one of the first tools that predicts the energy consumption of EVs on the basis of road and vehicle characteristics (ViriCiti and Simacan, 2018). *EVI-Pro* or the *Electric Vehicle Infrastructure Projection Tool* uses attributes of traffic, EV, and charging technology to predict the scale and type of charging infrastructure for supporting a city's EV transition (U.S. Department of Energy, 2018). While the first three tools mentioned above have been specifically designed for e-buses, the *EV Fleet Analyzer* was designed for e-trucks and can be tried for e-buses.

Table 1: Description of EV-deployment tools

Tool name	Target EV type	Expected outputs	Open-source availability
Cactus-Electromobility	Electric Bus (BEV/HEV/PHEV)	• An optimal operations plan which is energy efficient and economical • The timetable for each bus type equipped with charging technologies	Yes
Software Tool for Planning of City Bus Transport Electrification	Electric Bus (BEV/HEV/PHEV)	• Energy consumption from travelled distance profile • Energy demand • Required number of e-buses & charging stations • Total cost of ownership (TCO) & sensitivity analysis	Yes
BeWhere-Bus	Electric Bus (BEV/HEV/PHEV)	Charging station types and quantity required	No
EV Fleet Analyzer	Electric Trucks (BEV/HEV/PHEV)	Energy consumption per route and the most feasible route for EV travel	No
EVI-Pro	Light-duty EVs (2W, 3W, 4W)	Charging plugs, charger type (slow or fast), location, and number of charging stations	Yes

The usability and success of a tool depends on the nature and quality of the available local data. Limited access to bus-wise drive cycle data in India makes it difficult to explore the above discussed tools, and necessitates the development of a tool that is compatible with the data available. Such a tool has also to be customised to suite the operations of Indian state transport undertakings (STUs), and this requires close engagement with the bus operators.

3. Tool Description

The Tool uses data from the bus-fleet operators as well as the DISCOMs as inputs. The analysis performed can be divided into two parts: one that involves identifying the feasible schedules (in the input data) that are fit to be operated through e-buses, and the other that involves analysing the charging requirement at a selected depot. Figure 1 depicts the main activities, the flow of information inside the Tool, and its key outputs.

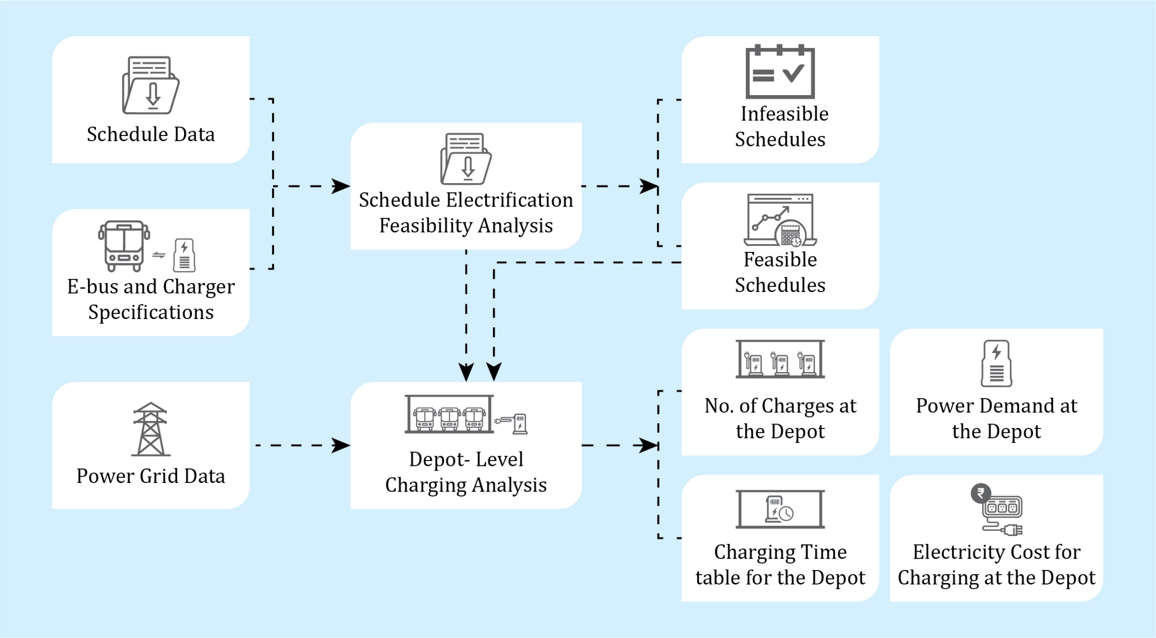


Figure 1: Overview of the Tool

Based on suggestions from various stakeholders, some more features like intermittent charging and TCO calculations were incorporated to update the Tool as Version 2.0. The features of Version 1.0 are discussed in this section and the features of the updated version are described in Appendix VI.

Moving ahead, this section describes the functions and the associated processes of the Tool. First, the operations of the subsystems are defined, and then the necessary inputs, the feasibility criteria, and the simulation process are explained.

3.1. Definition of subsystems

The Tool assesses the operations of the public bus transit system and the impact of its electrification on the power distribution system. The operations of the two systems are described below:

3.1.1. Public bus transit system

As shown in Figure 2, the primary component of a public bus transit system is a depot where the administrative, operational, and maintenance functions related to the buses are carried out. Each depot in the transit network is responsible for the operations of several routes. Each route is defined by an origin and a destination (covering a specific distance) and a set of bus stops.

A number of buses (or schedules) operate on a given route at a predefined frequency, based on the demand for mobility between the origin and destination. As these buses[3] make several trips between the origin and the destination through the day, they halt intermittently at the designated locations for crew rest/change. Most of the buses return to the assigned depot for resting during non-operational hours.

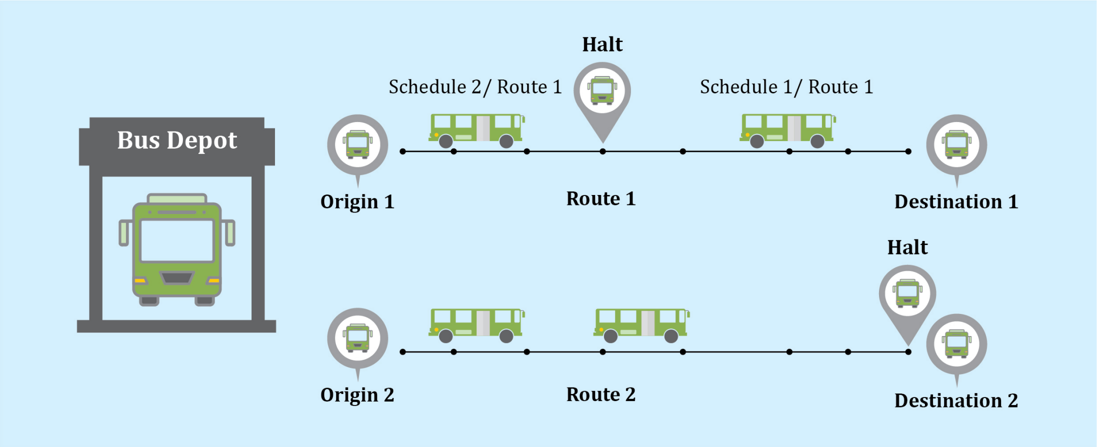


Figure 2: Public bus transit system: Schematic representation

3.1.2. Power distribution system

The power generated at the power plants is transmitted to the substations and then distributed to the consumers via feeders and distribution transformers (Figure 2). Most of the energy-generating plants are currently coal-based, with a small proportion fuelled by gas and renewable sources such as solar and wind energy. The energy generated is transmitted at high voltages via a network of wires/towers over long distances that form the transmission network. Substations in this network receive the bulk of the electricity, and distribute it further (at lower voltages) to serve the local demand. Electrical feeders are power lines that distribute power from a substation to different transformers, which, in turn, distribute it to the end users. The network of transformers, along with the accompanying wires/supporting structures, form the distribution grid. In case a certain consumer (such as a commercial or industrial consumer) demands considerable power, a dedicated feeder may be required to serve the load. Similarly, when a charging infrastructure is installed at a depot, the energy demand at the corresponding feeder needs to be assessed. Understanding the historical load profile (hourly and daily) of the feeder helps analyse the impact of the new charging infrastructure on the power grid network and recommend an infrastructure upgrade, if necessary.

---

[3] For the sake of clarity, buses serving a given route will be referred to as ‘schedules’, within the scope of this report.

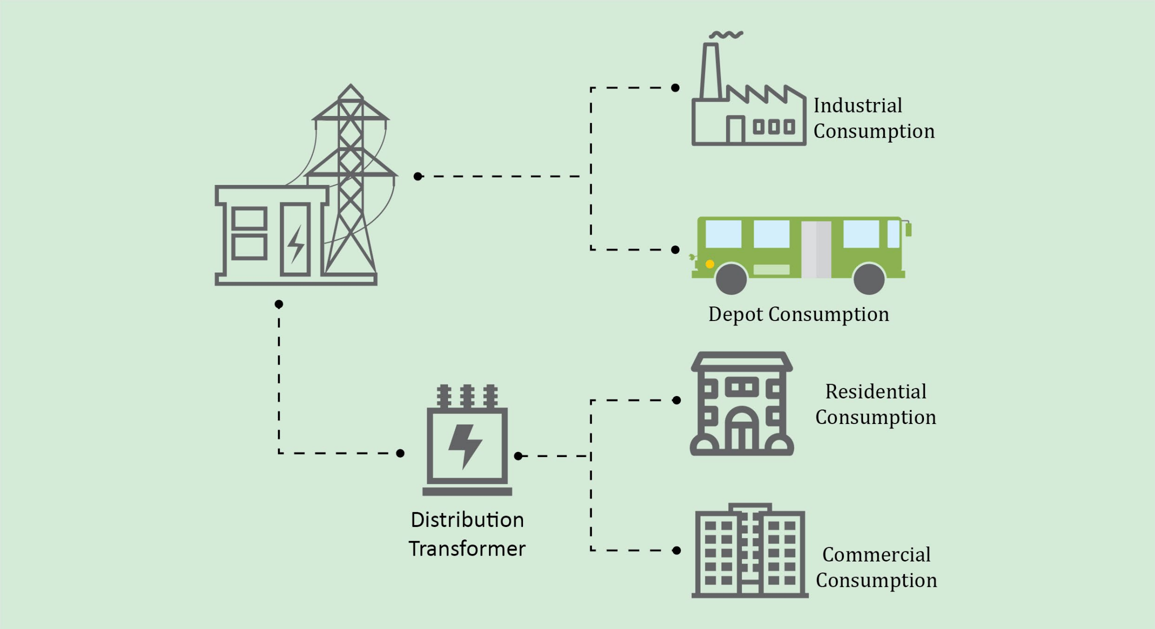


Figure 3: Power distribution system: Schematic representation

3.2. Inputs required

The Tool requires the user to provide certain inputs that are specific to the operator or service area. The inputs include the specifications of the electric bus model considered, the bus-transit network operations, the charging technology chosen, and the power-grid details. The inputs required are detailed in Table 2.

Table 2: Inputs required by the Tool

Schedule data*	
Route No.	a unique code associated with each route
Schedule No.	a unique code associated with each schedule/bus operating on a route
Trip No.	a trip is a single journey between the origin and the destination. The trip number represents the sequence of the schedule operations
Origin	the origin of the corresponding trip
Destination	the destination of the corresponding trip
Trip length	the distance travelled (km) by the bus between the origin and the destination for the corresponding trip
Trip start time	the time at which the bus begins the trip from the origin
Trip end time	the time at which the bus ends the trip at the destination
Halt duration	the duration (min) for which the bus halts at the destination before starting the next trip
E-bus specifications*	
Battery size	the maximum energy storage capacity (kWh) of the on-board battery of an e-bus
Usable capacity	the percentage of the battery capacity that can be used for operations, considering the health of the battery
Operational range	the distance (km) an e-bus model is expected to travel at full charge

Energy consumption	the amount of energy consumed for travelling one kilometre (kWh/km)
Charger specifications*	
Charger type	fast or slow
Charging power	the power rating (kW) of each e-bus charger
Buffer time	the time required (min) to manoeuvre to and fro the charging bay in the depot
Electrification scenario*	
Depots to electrify	the list of depots that the user would like to electrify and generate results for
Initial assumed number of chargers	the charger type and number to be installed at each selected depot
Power-grid details	
Substation limit	the maximum power that can be drawn from the substation
Historical peak demand	the maximum power demand experienced by the particular feeder historically
Time of the historical peak	historical peak demand: the time of day at which peak demand is witnessed
TOD (time of day) tariff	the tariff slabs on units consumed; will have the same value in case of no TOD tariff
* mandatory data	

The power-grid-related details input, such as the historical peak demand and the TOD tariff for the chosen city/state, have to be specific to the city/state considered, and hence, need to be input accordingly. This widens the applicability of the Tool, enabling it to cater to different geographical areas.

3.3. Schedule feasibility criteria

The schedules uploaded by the user are checked for feasibility on the basis of the following criteria:

Criteria 1: The schedules should have at least one trip with the destination at any of the selected depots and halt there for more than the buffer time (as provided by the user).

Criteria 2: The total distance travelled by a schedule over one day should be less than or equal to the operational range capacity of the e-bus (maximum distance that can be covered in a single charge).

Criteria 3: The halt duration of the schedules should be sufficient to completely charge the battery, using a fast charger.

Only those schedules that pass all the three criteria are considered for planning the charging infrastructure at the selected depots (depicted schematically in Figure 4).

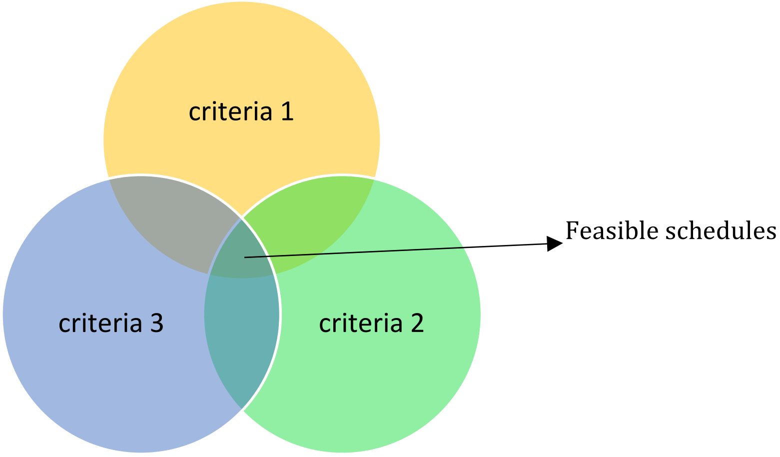


Figure 4: Schematic representation of feasible schedules

3.4. Simulation framework

As mentioned earlier, the Tool aims to estimate the number of schedules feasible for electrification, as well as the charging-infrastructure requirement at a selected depot, based on the incoming schedules. The set of key inputs and outputs are summarised in Table 3. A user-friendly interface is designed to facilitate the input/output interaction with the Tool (Appendix III).

Table 3: Key inputs and outputs from the Tool

Key Inputs	Key Outputs
E-bus specifications	Schedules that can be electrified
Charger specifications	Schedules that cannot be electrified and why
Schedule data	The total number of chargers (slow & fast) required at each selected depot
Power-grid details and the tariff	Charging-energy profile and the related costs

The Tool involves a dynamic simulation to estimate the charging-infrastructure requirement and is composed of two main entities or agents:

- charging station (CS) at a depot
- electric buses arriving at the selected depot

A charging station consists of a number of charging guns. These could be a combination of slow and fast chargers. The user is required to input an initial number of the slow and fast chargers. The states of the above-mentioned agents change with time, as well as due to their interaction with each other. The different states taken by the agents during the course of the simulation are mentioned in Table 4.

Table 4: Different states occupied by the charging station and electric buses over time

A charger gun in the CS	An e-bus at the select depot
Occupied	Ready to charge
Unoccupied	Charging (on-going)
	Finished charging

The main steps in the simulation are listed in Table 5 and illustrated in Appendix I.

Table 5: Main steps in the simulation

1. A schedule's itinerary is read from the input file uploaded by the user.
2. The feasibility of the arriving schedule/bus is assessed according to the criteria explained in Section 3.3.
3. The number of slow and fast chargers (within the charging station) is assigned (by the user) before the start of the simulation.
4. The simulation starts with the arrival of the first schedule and ends with the departure of the last bus.
5. For each schedule, the battery state of charge (SoC) and the time required for both slow and fast charging are estimated (refer Appendix II).
6. If a schedule has enough time to halt at the depot, slow charging is prioritised, else fast charging is considered.
7. Based on the charging preference (as determined in step 6), a slow/fast charging gun, if vacant, is immediately assigned to the schedule.
8. If the corresponding slow/fast gun is not immediately available, the schedule is held in queue till it reaches the maximum wait time, after which it is assigned to a fast charger (if a slow charger is still unavailable).
9. If a schedule is unable to occupy a charging gun (immediately or at the end of queuing time), it is considered an unsuccessful simulation. The user is then required to restart the simulation with a higher number of charging guns.
10. By iterating the steps above (starting from step 4) while varying the number of fast and slow chargers, one can arrive at the minimum number of chargers (fast and slow) for the selected depot [this process is depicted in the flow diagram in Figure 6].

Figure 5 explains the simulation process (steps 5 to 9). The red- and green-coloured circles in the charging station represent occupied and unoccupied charging guns, respectively.

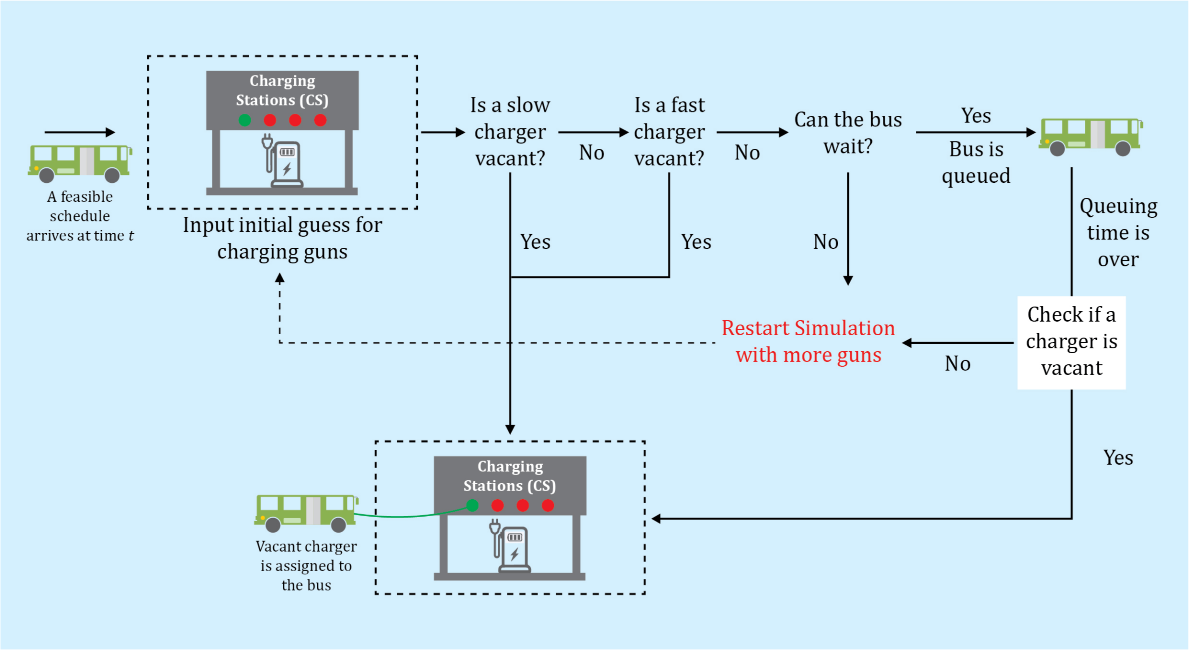


Figure 5: Overview of the simulation

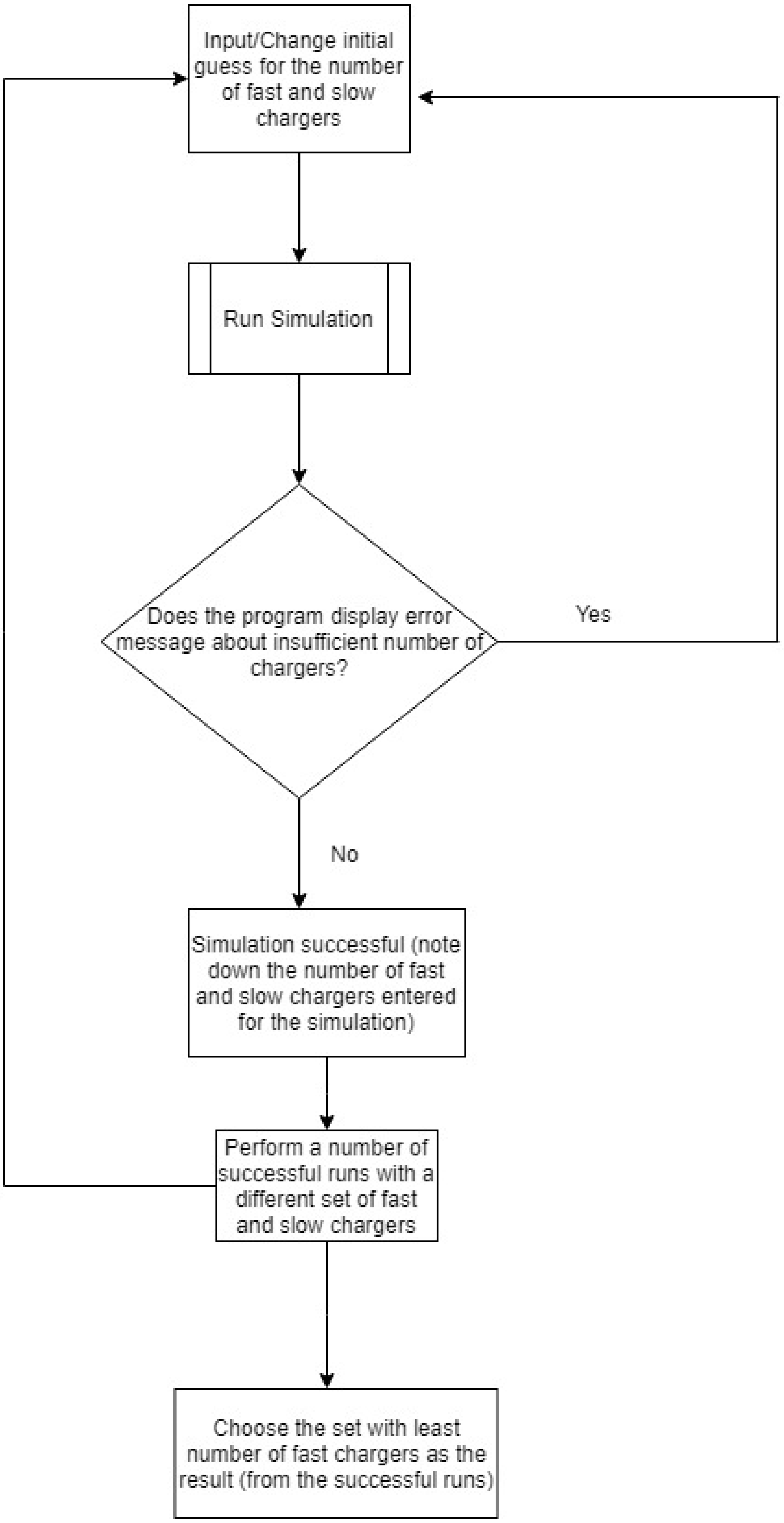


Figure 6: Steps involved in iterating the simulation

3.5. Simulation outputs

Based on the inputs, the model is expected to provide the outputs listed in Table 6.

Table 6: Details of the Tool: Outputs

For all schedules	Total schedules entered
	Total feasible schedules (number and list)
	Total infeasible schedules (number, list, and reason)
For the depots selected	Total no. of schedules arriving at the depot
	No. of schedules that can be electrified
	Charging timetable
	Minimum no. of fast chargers required
	Minimum no. of slow chargers required
	Charger utilisation rate for each charger
	Charging-demand profile
	Peak power demand due to charging (kW)
	Substation/feeder grid code limit exceeded? (yes/no)
	By how much has the limit been exceeded? (subject to user input)
	Total charging energy consumed per day (kWh)
	Total cost of charging per day (INR)

4. Case Study: Electrification of 300 Buses by BMTC

In 2019, the Bengaluru Metropolitan Transport Corporation (BMTC) initiated the process of operationalising 300 AC e-buses in Bengaluru. These buses were to serve 24 routes from four depots (HSR Layout, Hebbal, KR Puram, and Whitefield) where appropriate charging technology would be installed (Bengaluru Metropolitan Transport Corporation, 2019a). Of these routes, 58 run to and fro the airport with an average trip length of 40 km, while 253 run normal trips within the city with an average trip length of 22 km. Each e-bus was expected to run 200-250 km without recharging. The authority was interested in understanding the feasibility of charging these buses at the selected depots and its impact on the power-grid system of the city.

4.1. Public bus-transport network - BMTC

BMTC and Karnataka State Road Transport Corporation (KSRTC) are responsible for facilitating urban mobility in the Bengaluru Metropolitan Region (BMR) through a bus system (Egis Geoplan Private Limited and BMRDA, 2016). BMTC is the fleet operator for the intracity services, while KSRTC caters to the intercity transport needs. Currently, BMTC operates on 2,500 routes (6,161 schedules) with 6,661 buses to carry more than 45 lakh daily passengers (Bengaluru Metro Rail Corporation Limited, 2019; Bengaluru Metropolitan Transport Corporation, 2020a). With an average trip length of about 12 km, the buses cover approximately 11.39 lakh kilometres per day (Bengaluru Metropolitan Transport Corporation, 2020b). The average occupancy of the buses has been decreasing due to the increase in private-vehicle dependency, and now stands at 71.5% (Bengaluru Metro Rail Corporation Limited, 2019). The operations are handled by 10 traffic and transit management centres (TTMC), 45 bus depots, and 58 bus stations (Bengaluru Metropolitan Transport Corporation, 2020a). Of these, the Majestic bus terminal serves the maximum ridership—about 70,000 passengers per day (Bengaluru Metro Rail Corporation Limited, 2019). Approximately three lakh litres of diesel was consumed per day by the BMTC fleet during 2017-18 (Bengaluru Metropolitan Transport Corporation, 2019b).

In accordance with the initiatives for a more sustainable urban transport system, BMTC plans to gradually convert all the diesel-fuelled buses to electric ones.

4.2. Power distribution system – BESCOM

Bangalore Electricity Supply Company Limited (BESCOM) is responsible for distributing electric power in urban Bengaluru and seven other surrounding districts. Currently, it serves the city with around 1,600 feeders (Ministry of Power, 2016). In the financial year 2018-19, it served 118 lakh customers with 3.5 lakh distribution transformer centres (DTC).

BESCOM has created the 'Smart Grid and Electric Vehicle Cell', which, along with other responsibilities, will oversee the implementation of EVs, charging stations, and tariff structure (Bangalore Electricity Supply Company, 2020). As a first-of-its-kind initiative in the country for a public-utility-run charging infrastructure, it had set up 80 EV charging stations with 126 charging units, by February 2020 (The Hindu, 2020). The cost of charging at these self-serviced stations will be around INR 4.85 per unit (Karnataka Electricity Regulatory Commission, 2019).

4.3. Data collection

The inputs related to the bus and charger specifications were collected from the relevant literature and through discussions with BMTC officials. Form IV, which contains the schedule-level data for each route, was collected from BMTC for the selected routes, and translated into the required format. For the purpose of data privacy, we have replaced the actual names of depots, routes, and schedules with representative ones. The four depots will be referred to as Depots 1, 2, 3, and 4, hereafter.

4.4. Inputs and assumptions

The important parameters used for this case are shown in Table 7. Two types of chargers—fast and slow—with specifications mentioned in the table, were used during the simulation. The feeder historical peak demands used in the simulation are only representative.

Table 7: Inputs and assumptions

	Parameters	**Values**
Electric Bus Specifications*	Operational range	200 km
	Battery capacity	250 kWh
	Usable capacity	80 %
	Energy consumption	1 kWh/km
Charging Specifications	Slow charger power	60 kW
	Fast charger power	120 kW
	Buffer time	5 min
	Charger efficiency	90%
Electrification Scenario	Depots to be electrified	Depots 1, 2, 3, 4
General Simulation Parameters	Minimum time required to charge	60 min
Power-grid details	TOD tariff	INR 5/kWh**

* The Tata Starbus 4/12m has been considered as a reference for the case study. The battery capacity considered in this model is eligible for subsidy under FAME II.

** BESCOM charges the same tariff at all times of the day.

4.5. Feasibility analysis of schedules

At the start of the simulation, 311 schedules were analysed, of which 72 schedules were found feasible for being charged at any of the selected depots – Depot 4, Depot 3, Depot 2, and Depot 1. This means that they halt at either of these locations for a minimum duration (buffer time), run for 200 km or less over the day, and have sufficient time at the depot for a complete recharge using a fast charger. The feasible schedules arriving at the selected depots are listed in Appendix IV.

Of the 239 infeasible schedules, 72 do not have halts at the selected depots (criteria 1), 161 have route lengths longer than the operational range supported by the battery (criteria 2), and 6 do not have sufficient halt duration to completely charge the battery (criteria 3). The infeasible schedules and the associated reasons are listed in Appendix V.

4.6. Simulation results

The feasible schedules were then simulated for each depot to prepare the charging plans and assess the associated power requirement.

4.6.1. Depot 1

To arrive at the minimum number of chargers required at Depot 1, several manual iterations were made, as described in Table 8. The simulations were unsuccessful when the number of chargers input was insufficient to charge the feasible schedule arriving at the depot. Of the successful simulations, the one with the least number of fast chargers is selected for further analysis.

Table 8: Summary of manual iteration to arrive at minimum number of chargers

Trial No.	FC (fast charger)	SC (slow charger)	Comments
1	0	3	Simulation unsuccessful
2	1	3	Simulation successful
3	0	4	Simulation successful
4	1	4	Simulation successful

Hence, to charge the 15 feasible schedules arriving at Depot 1, four slow chargers are required, as shown in Table 9.

Table 9: Summary of results at Depot 1

Parameter	Output
Total no. of schedules arriving at the depot	30
No. of schedules that can be electrified	15
No. of fast chargers required	0
No. of slow chargers required	4
Peak power (kW) during charging	240
Feeder grid code limit exceeded?	No
Total charging energy required per day (kWh)	2,813
Total cost of charging per day (INR)	14,067

The bus arrival profiles are displayed in Figure 7. Of the 30 buses that arrive at the depot throughout the day (represented by the blue line), only 15 can be charged here (represented by the orange line). This is either because the halt duration here is not sufficient to charge the schedule using a fast charger, or because the schedule has a long route length (more than 200 km) that cannot be operated using the specified 250 kWh battery.

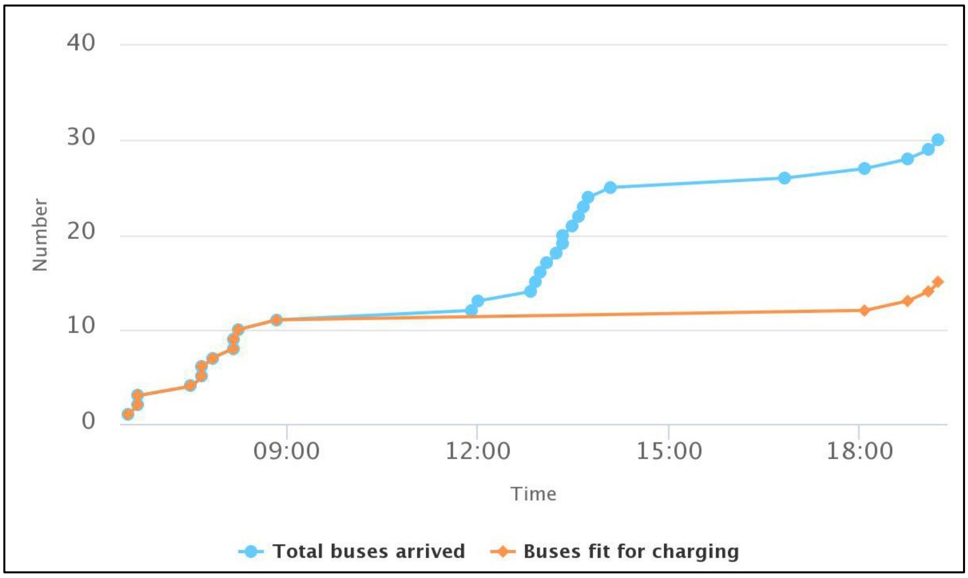


Figure 7: Bus arrival profiles at Depot 1

Source: CSTEP Research

The charging profiles of the buses charging at this depot are displayed in Figure 8. When a schedule arrives at the depot for charging (represented by the orange line), it is either charged (represented by the green line) when there is a charger vacant, or is queued (represented by blue line) till one becomes vacant. At any point of time, the number of schedules represented by the blue and green lines should together be equal to the number of schedules represented by the orange line.

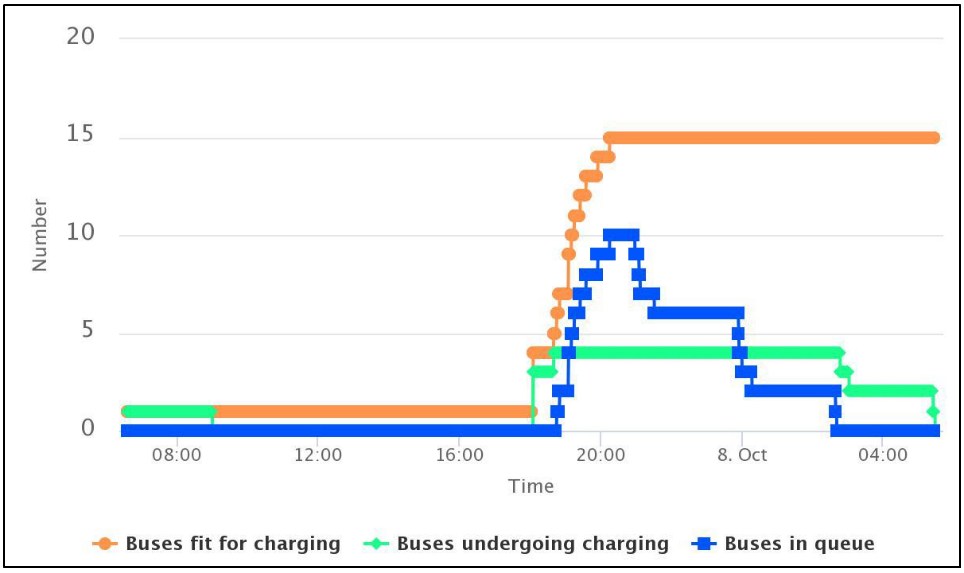


Figure 8: Charging profile of buses at Depot 1

Source: CSTEP Research

Table 10 shows the details of the charging plan. These schedules take between 2.5 and 3 hours (2.8 hours on an average) to recharge the battery to its full capacity.

Table 10: Charging plan at Depot 1

Schedule No.	Schedule Length (km)	Halt Start Time	Halt End Time	Halt Duration (min)	Charging Start Time	Charging End Time	Charging Duration (min)	Queueing Duration (min)	Charging Mode
GHI-1/5	164.8	19:15	07:35	745	21:31	00:17	166	136	Slow
GHI-1/6	172.1	18:05	06:25	745	18:05	20:58	173	0	Slow
GHI-3/4	169.2	19:05	07:25	745	21:05	23:55	170	120	Slow
XYZ-1/33	163.8	19:10	07:35	750	23:54	02:39	165	284	Slow
XYZ-1/34	163.8	19:55	07:55	725	00:17	03:02	165	262	Slow
XYZ-2/53	165.6	18:50	07:25	760	21:07	23:54	167	137	Slow
XYZ-2/54	165.6	19:35	07:55	745	00:00	02:47	167	265	Slow
XYZ-2/55	165.6	20:15	08:35	745	02:41	05:28	167	386	Slow
XYZ-2/64	144.4	06:35	18:55	745	06:35	09:00	145	0	Slow
XYZ-3/23	165.2	19:25	08:00	760	02:39	05:25	166	434	Slow
XYZ-3/28	165	18:45	07:50	790	23:55	02:41	166	310	Slow
XYZ-4/2	169.7	18:40	07:15	760	18:40	21:31	171	0	Slow
XYZ-4/3	178.9	18:05	06:25	745	18:05	21:05	180	0	Slow
XYZ-4/4	180.9	18:05	06:25	745	18:05	21:07	182	0	Slow
XYZ-7/3	180.9	19:05	07:25	745	20:58	00:00	182	113	Slow

The utilisation of the four slow chargers and the resultant charging demand is illustrated in Figure 9 and Figure 10, respectively.

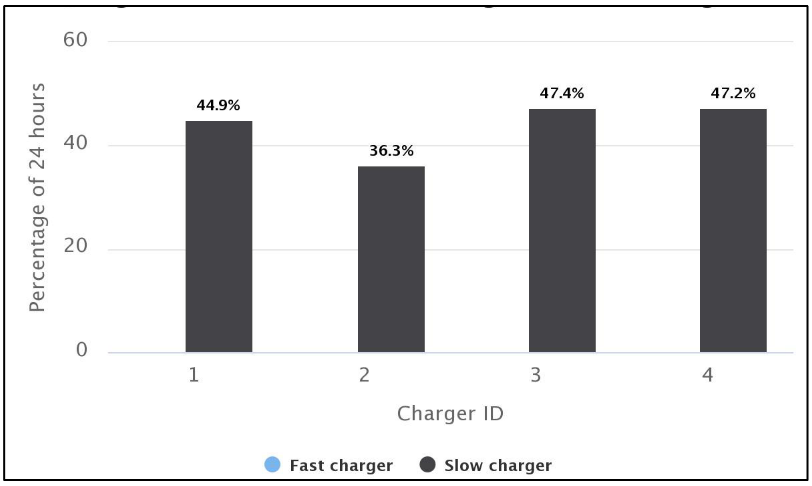


Figure 9: Utilisation of chargers at Depot 1
Source: CSTEP Research

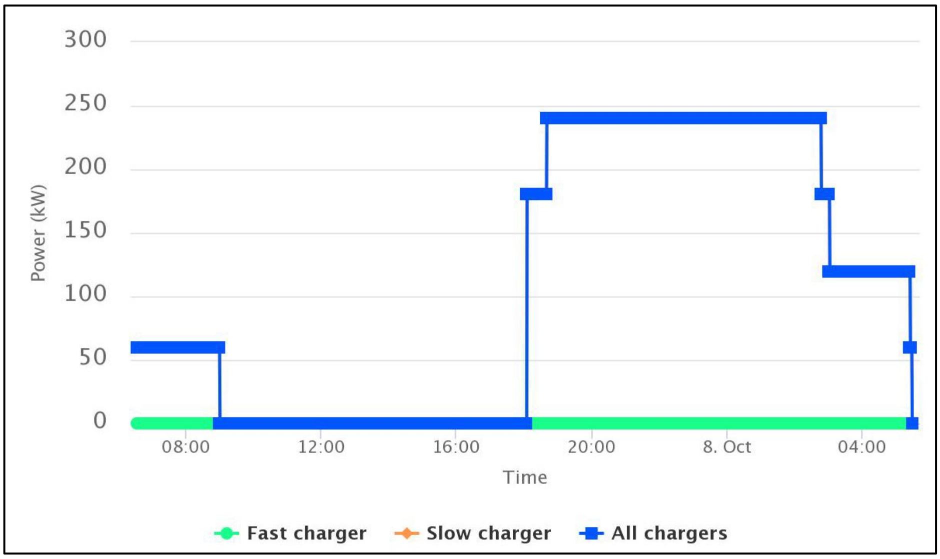


Figure 10: Charging-demand profile at Depot 1

Source: CSTEP Research

Figure 11 explores the power-grid-planning-related characteristics. It compares the peak-load values of the relevant feeder, as well as the maximum load capacity (termed as grid code limit). The peak load in this example represents values on a daily basis, which were collected over some months (This is one of the formats in which the data has been collated by the local DISCOM).

The orange points depict the sum of the peak-load data of the relevant feeder and the power demand due to e-bus charging (from Figure 10), at the corresponding time instants of the entered (peak load) data points (total load). Hence the orange points (total load) represent the shift in the load on the feeder due to charging, though limited to the number of input points. This total load, as well as the highest peak during charging, is then compared with the grid code limit to assess if the feeder capacity is exceeded during charging. For this method to be effective, a large number of peak-load data points are essential as initial input.

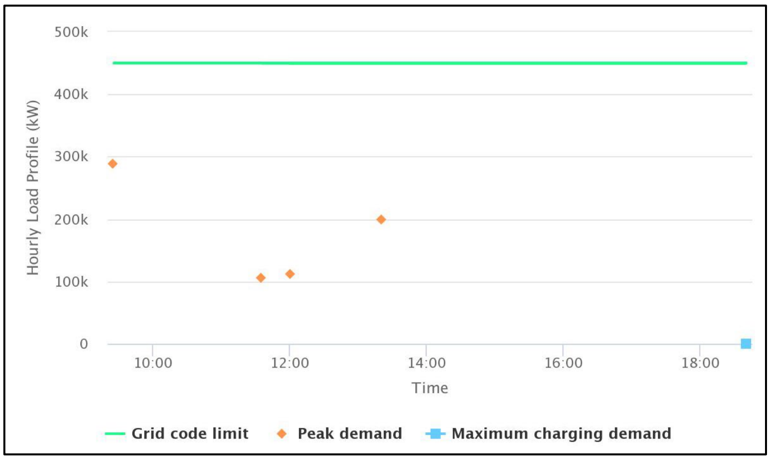


Figure 11: Feeder-limit profile at Depot 1

Source: CSTEP Research

The feeder limit at the substation is 450 kW and the peak demand at this depot is only 240 kW (Figure 11). Hence, the existing feeder is sufficient to provide electricity for the charging needs at Depot 1. The total cost of charging is INR 14,067 per day (Figure 12).

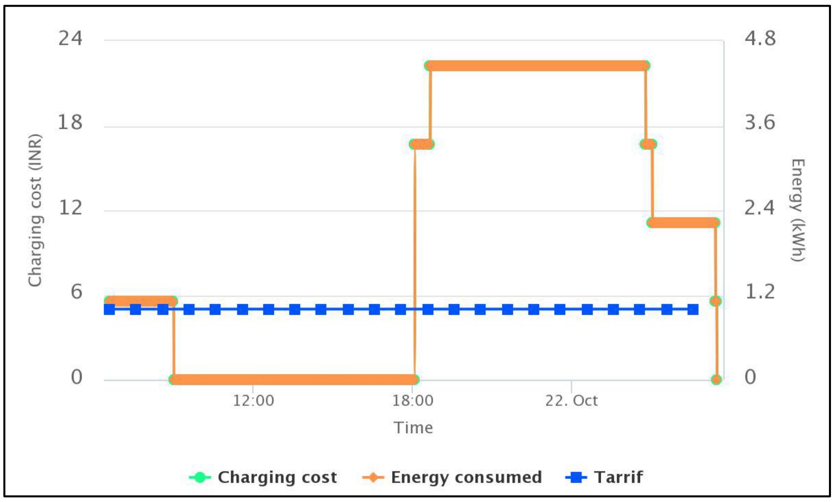


Figure 12: Charging cost at Depot 1

Source: CSTEP Research

4.6.2. Depots 2, 3, and 4

Simulations were performed for the other three depots in a similar manner. The summary of the simulations is discussed in Table 11. The power-grid details were not available for these depots and hence the feeder-impact-related outputs were not generated.

Table 11: Summary of results for Depots 2, 3, and 4

Parameter	**Outputs**		
	Depot 2	**Depot 3**	**Depot 4**
Total no. of schedules arriving at the depot	153	84	29
No. of schedules that can be electrified	20	34	3
No. of fast chargers required	0	0	0
No. of slow chargers required	4	7	1
Peak power (kW) during charging	240	420	60
Feeder grid code limit exceeded?	N/A	N/A	N/A
Total charging energy required per day (kWh)	2,983	5,858	419
Total cost of charging per day (INR)	14,913	29,290	2,093

The charging demand at these depots is displayed in Figure 133. It shows that charging mostly happens between 1800 hours and 0900 hours every day.

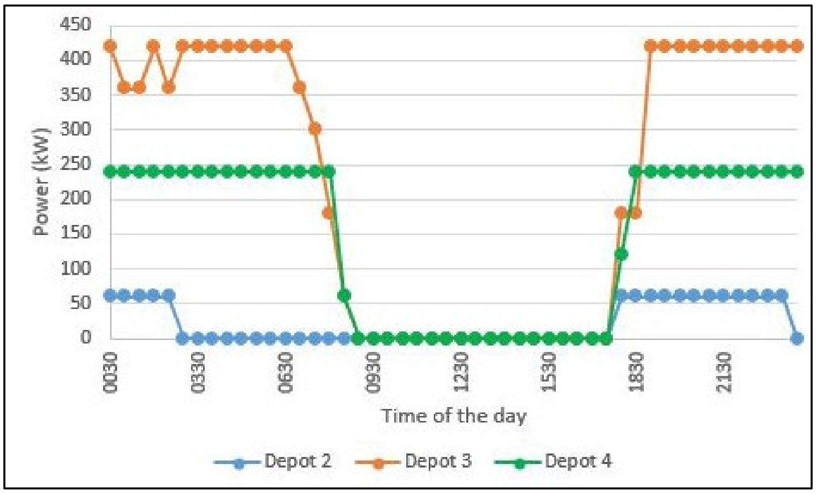


Figure 13: Charging-demand profiles at Depots 2, 3, and 4

Source: CSTEP Research

To summarise, for operating the 72 feasible e-buses on the selected routes from the four depots, a total of 16 slow chargers (60 kW) are required. This is because the long-halt durations (viz. 12 hours on an average) of the feasible schedules support charging using a slow charger. The electricity cost for charging these schedules, according to the corresponding charging timetables, is INR 60,360 per day. Based on the representative power-grid details used, it was found that new feeders are not required to deploy these e-buses at the selected depots.

4.6.3. Comparison with other scenarios

The Tool was run with the same representative data to compare various scenarios of higher battery capacity or more charging locations. The above example was considered as the base scenario. Scenario 1 retained the battery capacity in the base scenario and added three more locations for intermittent charging of the e-buses. Scenario 2 used e-buses with higher battery capacity (325 kWh and 260 km range) and charging infrastructure at the same four depots. The observations from the simulations are summarised in Table 12.

Table 12: Comparison of charging scenarios

Scenarios	**Base**	**1**	**2**
Battery capacity (kWh)	250	250	325
Effective range (km)	200	200 (+ up to 75)	260
Overnight / full-charging charger power (kW)	60/120	60/120	60/120
Intermittent charging charger power (kW)	NA	60/120	NA
Overnight / full-charging depots	Depots 1,2,3, 4	Depots 1,2,3, 4	Depots 1,2,3, 4
Intermittent charging locations	NA	IC1, IC2, IC3*	NA
No. of feasible schedules	72	137	131
Number of chargers required	8 fast, 18 slow	28 fast, 28 slow	19 fast, 29 slow
Capital cost (lakh INR)	5,312	10,410	9,748
Operational cost (lakh INR)	883	1,812	1,676

* Representative names of BMTC bus stations where e-buses can undergo intermittent charging.

Note: Capital cost includes the cost of the e-buses, chargers and the battery replacement. Operational cost includes the electricity cost of charging the e-buses and the maintenance of the e-buses and chargers.

From the above table, it can be inferred that in this case study, increasing the battery capacity is a more economically viable option than increasing the charging locations for intermittent charging though the number of feasible schedules would be slightly (and insignificantly) lower.

5. Conclusions and Recommendations

5.1. Conclusions

Recently, the Department of Heavy Industries (DHI) has sanctioned a subsidy of INR 3,545 crore for over 7,000 e-buses to be deployed across the country. Preparing for this large-scale deployment requires the involvement of the bus-fleet operators, as well as the electricity-distribution companies. In this context, the Tool attempts to combine the fleet-planning and grid-planning activities. Currently, the Tool focusses on estimating the charging requirements at specific depots.

First, the Tool checks the feasibility of the schedules inputted by the user. The list of feasible schedules helps the user check whether the schedules input are in accordance with the proposal or they require revision or reconsideration. The list of infeasible schedules helps the user understand why certain schedules cannot be electrified. If the schedule does not halt at the selected depot for the minimum time required, the user can consider rerouting or rescheduling it. If the schedule does not have sufficient operational range to run, the user can consider using a different bus model with an extended operational range. Where the schedule does not have sufficient charging time, the user can either increase the power of the charger considered or revise the schedule to have a longer halt duration.

Later, the depot-level simulation generates a summary table for a selected depot, using the number of fast and slow chargers inputted. This table helps the user decide, at a glance, whether the existing power-distribution infrastructure can support the charging infrastructure or not. Similarly, the DISCOMs can understand and plan for the power-infrastructure requirement at the depot. The charging timetable can be used to plan for and train the human resources required to operate the charging infrastructure. This table will be more useful where the user wishes to automate the charging process. The charger utilisation plot helps the user identify the charger(s) that is sparsely used over the day, and decide if avoiding such charger(s) would still be feasible. The charging-demand profile is useful for DISCOMs in understanding how much power should be available at the depot for charging and when. The feeder-impact plot indicates that if the charging demand at a particular depot exceeds the load capacity of a feeder at any point of time, a dedicated feeder would be required to serve the depot. This would help them decide if the existing feeder would be sufficient to cater to the charging requirements at the depot or a new feeder should be drawn from a nearby substation. The graph displaying the charging-cost profile informs the bus-fleet operator of the operational electricity cost involved in deploying the charging infrastructure at the depot.

Of the 311 schedules used to demonstrate the Tool, only about 40% cover less than 200 km a day, rendering the remaining schedules (about 60%) infeasible on using the chosen e-bus model (with 250 kWh battery capacity). This indicates the need to use e-buses with higher battery capacities. However, such a measure would lead to an increase in the capital costs.

The Tool demonstrates that for the 72 feasible schedules operating from the four depots, a total of 16 slow chargers would be required. The electricity cost for charging these schedules, according to the corresponding charging timetables, is INR 60,360 per day.

Upon comparing this base case with scenarios of higher battery capacity and a provision of intermittent charging, it was observed that increasing the battery capacity (up to 325 kWh) is a more economically viable option than increasing the charging locations (up to 3 locations) for intermittent charging.

Moving forward, the Tool could be evolved to demonstrate the operational feasibility of other charging technologies like battery swapping and pantograph charging. The network-planning aspect of public transit could also be included in the Tool, so that it can select/design operations favourable for e-bus deployment.

5.2. Recommendations

Based on the findings of the simulation performed by the Tool, the following recommendations are made:

Increase the maximum battery capacity eligible for subsidy under the FAME II scheme

The FAME II scheme provides a subsidy of about INR 20,000 per kWh of battery used for e-buses with battery capacities up to 250 kWh. However, as observed from the scenarios analysed, a battery capacity of more than250 kWh may be required (i.e. 325 kWh or above) for operating e-buses and meeting the e-bus adoption targets in metropolitan cities like Bengaluru. Hence, the DHI should reconsider the maximum battery capacity eligible for subsidy under the FAME II scheme.

Use intermittent plug-in charging

Higher battery capacities translate to higher capital costs and increased bus weight. This would, in turn, necessitate a reduced passenger load, resulting in lesser earnings per kilometre. Hence, for situations where a higher battery capacity cannot be used, an intermittent ultra-fast plug-in charger (with a power of at least 150 kW) could be considered. However, this could substantially increase the power demand. A techno-economic feasibility analysis of these charging stations may be necessary for efficient decision making. The state governments could consider supporting the setting up of intermittent ultra-fast charging stations.


23

6. References

2012 Index IEEE Transactions on Power Systems Vol. 27. (2012). *IEEE Trans. Power Syst., 27*(4), 2397–2431. https://doi.org/10.1109/TPWRS.2012.2230561

Bangalore Electricity Supply Company. (2020). *Smart grid & electric vehicle cell* [WWW document]. https://bescom.karnataka.gov.in/page/Departments+of+Corporate+Office/Smart%20Grid%20and%20Electric%20Vehicle/SG+&+EV/en

Bengaluru Metro Rail Corporation Limited. (2019). *Comprehensive mobility plan for Bengaluru* (Draft for public consultation). Bengaluru: Author.

Bengaluru Metropolitan Transport Corporation. (2020a). *BMTC at a glance* [WWW document]. https://mybmtc.karnataka.gov.in/info-1/BMTC+Glance/en

Bengaluru Metropolitan Transport Corporation. (2020b). *Performance indicator* [WWW document]. https://mybmtc.karnataka.gov.in/info-1/Perfomance+Indicator/en

Bengaluru Metropolitan Transport Corporation. (2019a). *Proposal for availing incentives under Fame India Scheme Phase II for deployment of electric buses on operational cost model basis* (Proposal). Bengaluru: Author.

Bengaluru Metropolitan Transport Corporation. (2019b). *Annual administration report 2017-18* (Report No. 21). Bengaluru: Author.

Center for Study of Science, Technology and Policy & Shakti Sustainable Energy Foundation. (2018). *Implementation plan for electrification of public bus transport in Bengaluru*. https://cstep.in/drupal/sites/default/files/201901/CSTEP_RR_Implementation_plan_for_electrification_of_public_bus_transport_in_Bengaluru_April2018.pdf

Das, S., Sasidharan, C., & Ray, A. (2019). *Charging India's bus transport*. Alliance for an Energy Efficient Economy. https://shaktifoundation.in/wp-content/uploads/2019/07/Full-Report_Charging-Indias-Bus-Transport-2.pdf

Department of Heavy Industries (2019). *Notification of FAME India Scheme Phase-II*. New Delhi: Author.

Egis Geoplan Private Limited, BMRDA (2016). *Bangalore metropolitan region revised structure plan 2031*. Bengaluru: Author.

International Institute for Applied Systems Analysis. (2018). *BeWhere-bus* [WWW document]. https://iiasa.ac.at/web/home/research/modelsData/Bewhere/BeWhere_Bus.html

Karnataka Electricity Regulatory Commission. (2019). *Annual report of Karnataka Electricity Regulatory Commission* (Report No. 20). Bengaluru: Author.

Ministry of Power. (2016). *Registered feeders in Karnataka* [WWW document]. Urja Mitra.http://www.urjamitra.com/app/RegisteredFeederWithMapCircle.html?sid=33&disid=97

Naumann, S., Sebastian, H., Krawiec, K., Markusik, S., Łazarz, B., Janecki, R., Karoń, G., & Sierpinski, G. (2015). *Cactus Electromobility+* [WWW document]. Cactus Electromobility. http://www.cactus-emobility.eu/description.html

Press Information Bureau. (2020a). *Promotion of electric vehicles* [Press release]. file:///C:/Users/spurthi/Zotero/storage/Z7WFC89X/PressReleaseIframePage.html.

Press Information Bureau. (2020b). *670 new electric buses and 241 charging stations sanctioned under FAME scheme* [Press release]. https://pib.gov.in/PressReleasePage.aspx?PRID=1658900

Bescom sets up 80 electric vehicle charging stations. (2020, February 5). *The Hindu.* https://www.thehindu.com/news/cities/bangalore/bescom-sets-up-80-electric-vehicle-charging-stations/article30743515.ece

Topić, J., Maletić, F., Škugor, B., & Deur, J. (2018). *Software tool for planning of city bus transport electrification* [Conference session]. International Conference on Science and Traffic Development. https://bib.irb.hr/datoteka/967132.Software_Tool_for_Planning_of_City_Bus_Transport_Electrification.pdf

U.S. Department of Energy. (2018). *Electric Vehicle Infrastructure Projection Tool (EVI-Pro) Lite* [WWW document]. https://afdc.energy.gov/evi-pro-lite

ViriCiti, & Simacan. (2018). *EV Fleet Analyzer* [WWW document]. ViriCiti. https://viriciti.com/press-releases/first-energy-route-planner-for-electric-buses-and-trucks/


USO OBLIGATORIO
CINTURONES DE SEGURIDAD

7. Appendix I

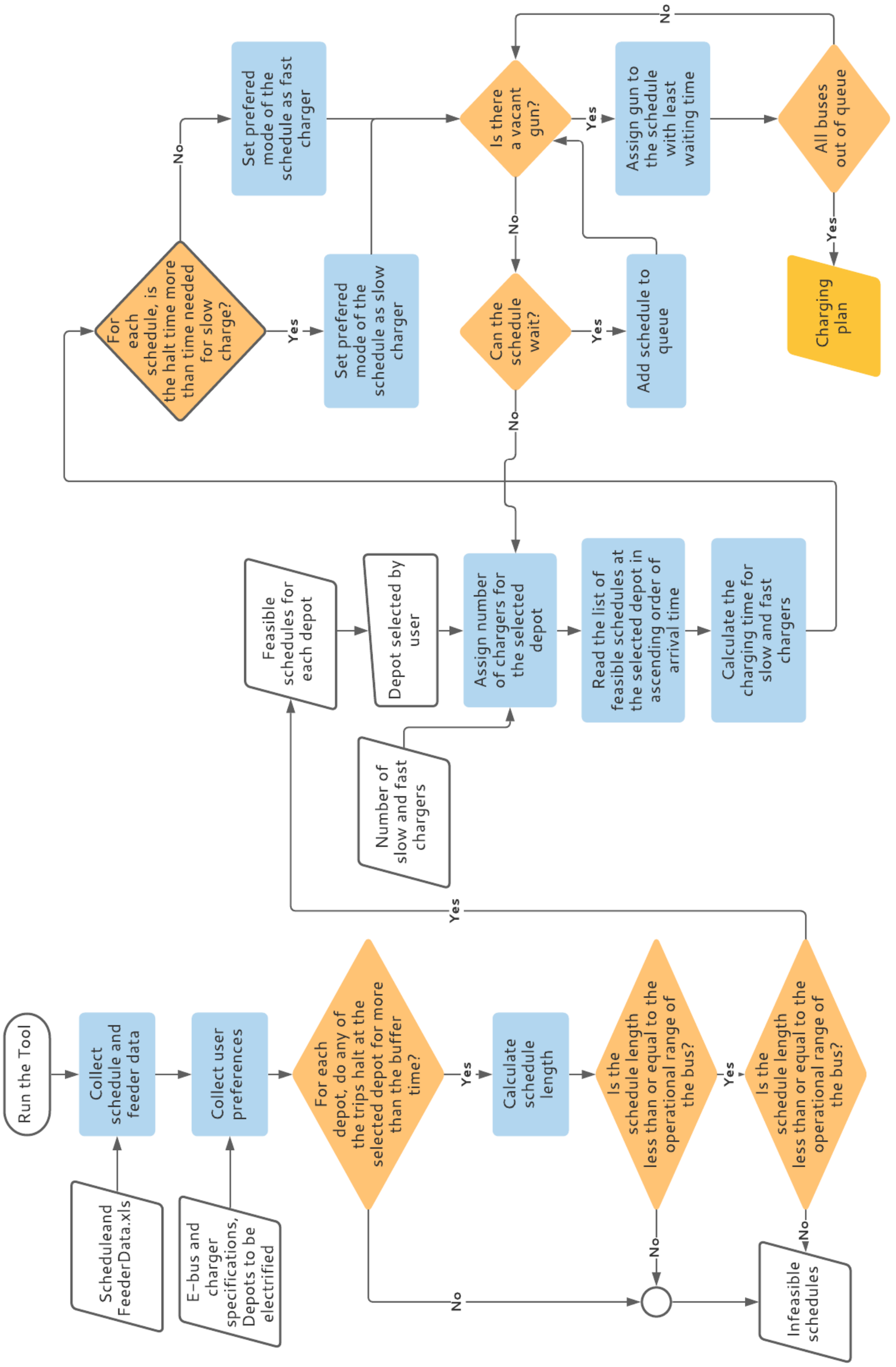


Figure 14: Flowchart of the Tool process

8. Appendix II

State-of-charge and charging-time calculations

Battery state-of-charge (SoC) calculation:

$$E_{Charge} = Q_{max} \times \left(\frac{D}{R}\right)$$

$$T_{Chrg} = \frac{E_{Charge} \times 60}{P_{Chrg}}$$

During charging

$$SoC_t = SoC_{max} - \left(\frac{P_{Chrg} \times \Delta t}{Q_{max} \times 60}\right)$$

In the above equations:

E_{Charge} = energy requirement for charge; Q_{max}= maximum battery capacity; D = total distance covered by the e-bus; R= maximum range covered by the e-bus per full charge; T_{Chrg} = time for charging an e-bus; P_{Chrg}= power of a charging gun; Δt= time lapse up to the instant t; SoC_t= battery state-of-charge at the current instant (t); SoC_{max}= maximum battery SoC.

9. Appendix III

User Manual

The Tool can be accessed at this link: https://beta.cstep.in/evroute/#/

To start the analysis, the user has to log in (Figure 155) to the platform using the credentials provided.

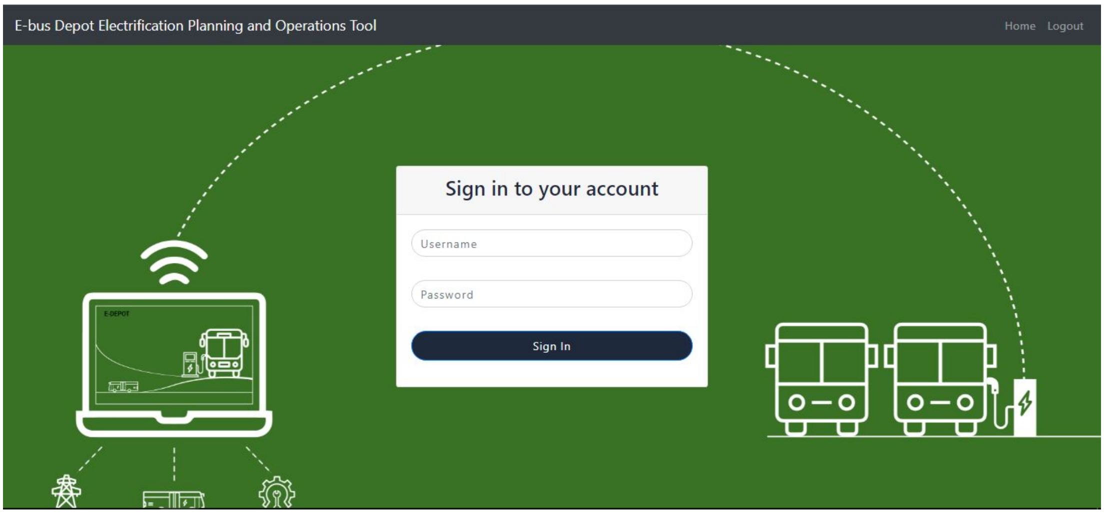
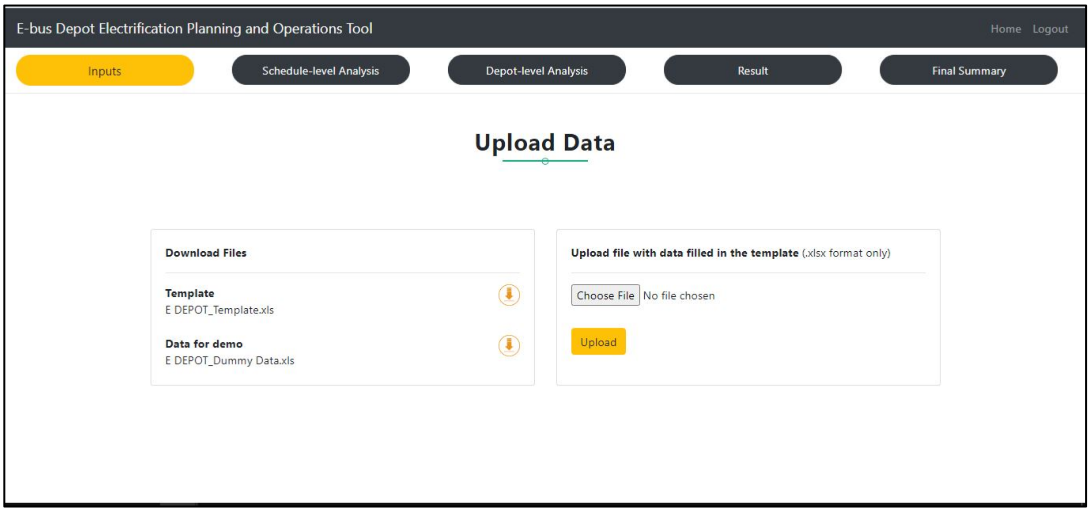


Figure 15: Log-in screen of the Tool

The user then has to provide the schedule and feeder data in an Excel file (.xls). He/she has to download the template and upload it after filling in the required details (Figure 16).

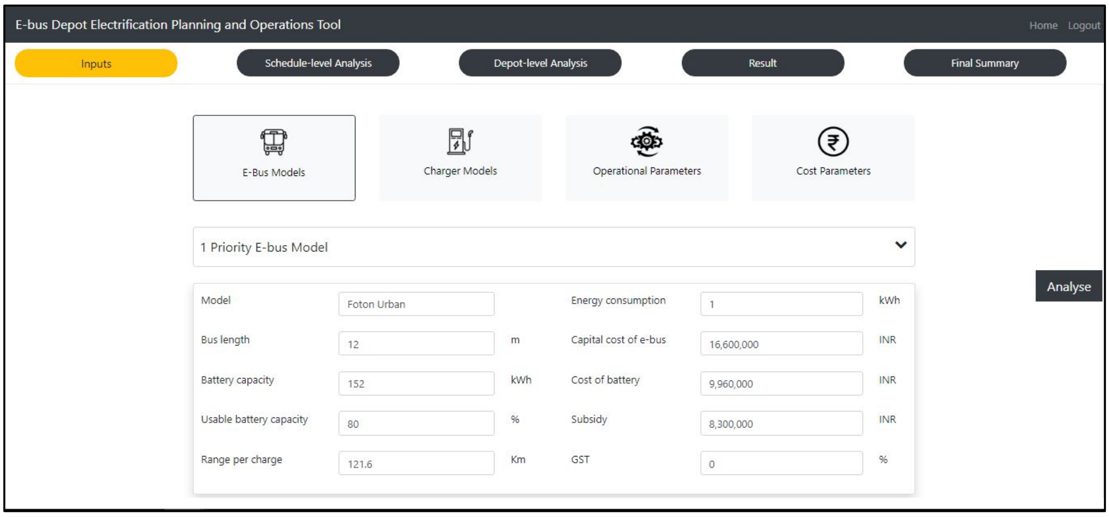


The details related to the schedules are recorded in an Excel file (.xls). The user will need to download the template shown in Figure 17 and fill in the required details.

	A	B	C	D	E	F	G	H	I
1	**Route No.**	**Schedule No.**	**Trip No.**	**Origin**	**Destination**	**Trip length**	**Trip Start Time**	**Trip End Time**	**Halt Duration**
2									
3									
4									
5									

Figure 17: Schedule data entry template

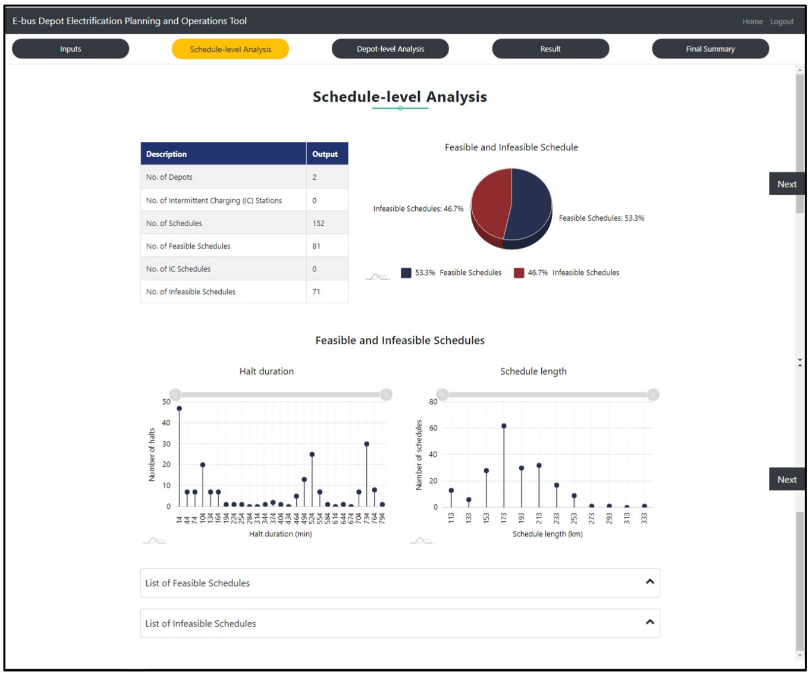
The charger specifications, e-bus specifications, operational parameters, and cost parameters are read from the uploaded excel file. The user can view the summary of the inputs under the associated tab, as shown in Figure 18



1 Priority E-bus Model

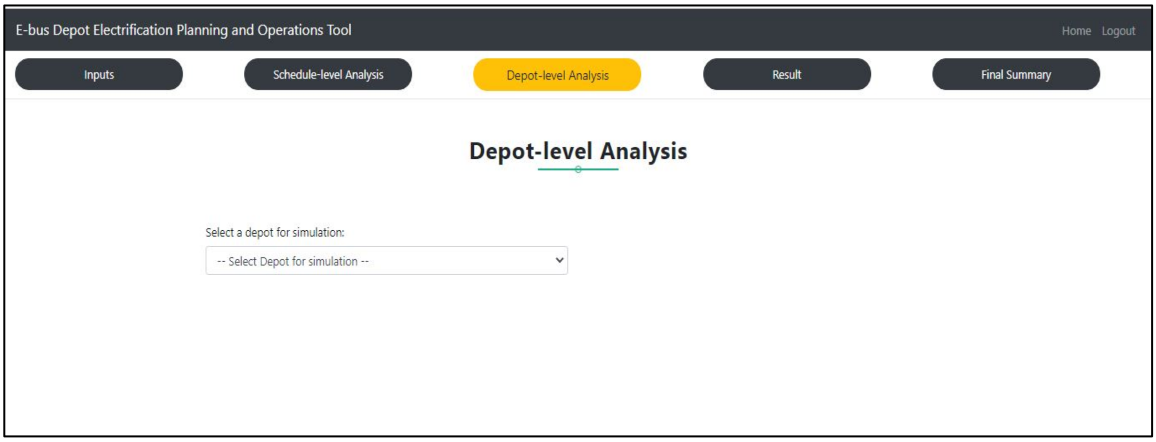
Model	Foton Urban		Energy consumption	1	kWh
Bus length	12	m	Capital cost of e-bus	16,600,000	INR
Battery capacity	152	kWh	Cost of battery	9,960,000	INR
Usable battery capacity	80	%	Subsidy	8,300,000	INR
Range per charge	121.6	Km	GST	0	%

The next screen (Figure 19) displays the summary of the schedule-level analysis.



Description	Output
No. of Depots	2
No. of Intermittent Charging (IC) Stations	0
No. of Schedules	152
No. of Feasible Schedules	81
No. of IC Schedules	0
No. of Infeasible Schedules	71

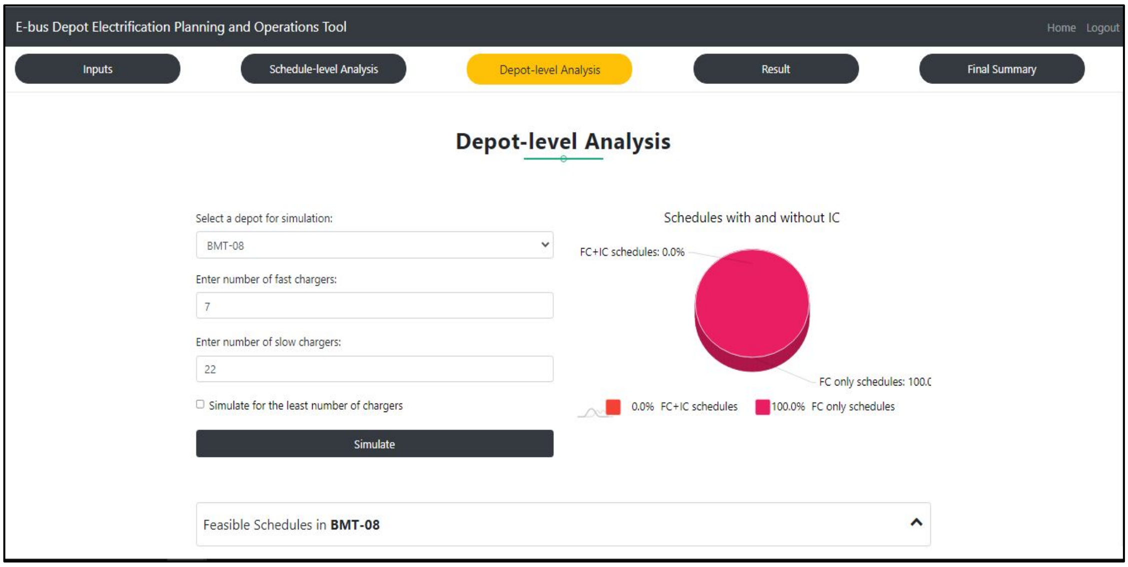
In the next screen (Figure 20), the user is asked to select one depot from those selected for the simulation.



Select a depot for simulation: -- Select Depot for simulation --

Figure 20: Depot selection screen

The summary of the selected depot is displayed on the next screen (Figure 21). The user is required to either provide the number of slow and fast chargers proposed (if known) at this depot, or simulate the results for the suggested number of chargers, or select the option to simulate the least number of chargers required (as explained in Appendix VI).



Select a depot for simulation: BMT-08

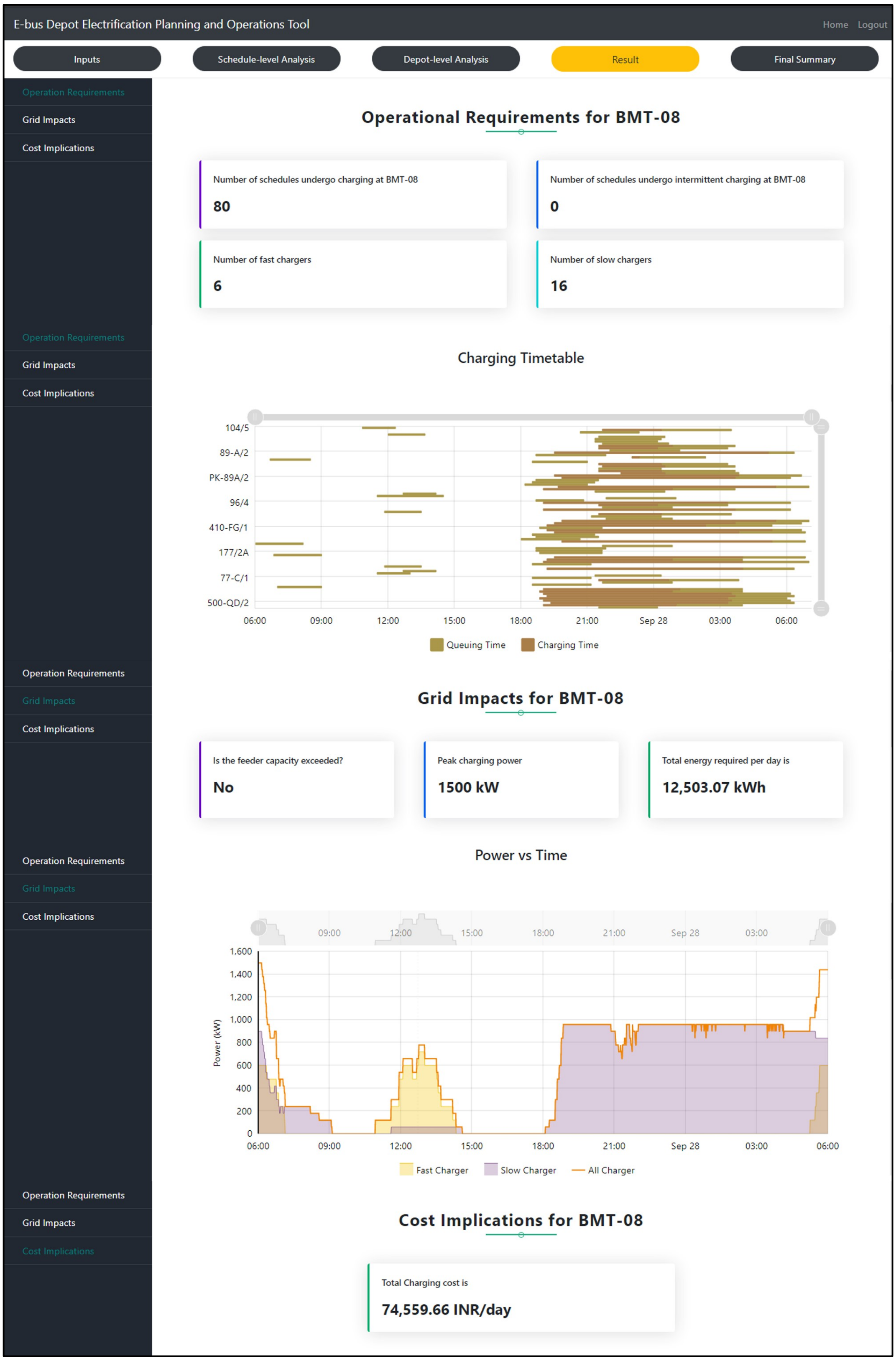
Enter number of fast chargers: 7

Enter number of slow chargers: 22

☐ Simulate for the least number of chargers

Feasible Schedules in **BMT-08**

Upon choosing to simulate the analysis at the selected depot, the results for the corresponding depot are displayed (Figure 22). These results are displayed under three sections – Operational Requirements, Grid Impacts, and Cost Implications.



Operational Requirements for BMT-08

Number of schedules undergo charging at BMT-08
80

Number of schedules undergo intermittent charging at BMT-08
0

Number of fast chargers
6

Number of slow chargers
16

Grid Impacts for BMT-08

Is the feeder capacity exceeded?
No

Peak charging power
1500 kW

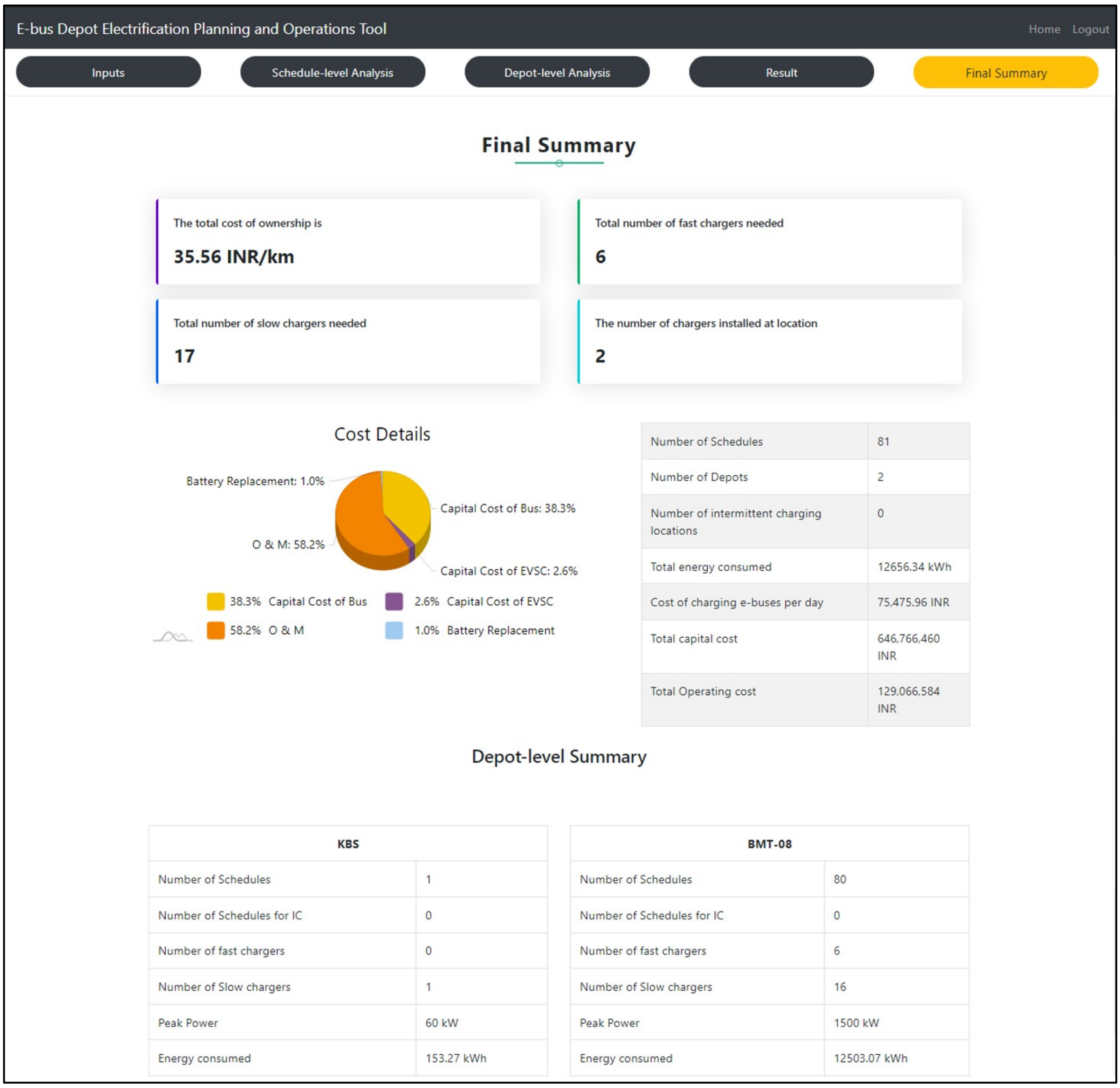
Total energy required per day is
12,503.07 kWh

Cost Implications for BMT-08

Total Charging cost is
74,559.66 INR/day

Figure 22: Results for the selected depot

Once the results for all the selected depots are simulated, the summary of all the simulations can be displayed under the 'Final Summary' tab (Figure 23), which summarises the TCO (Appendix VI) and infrastructure requirements for all the depots together.



Final Summary

The total cost of ownership is
35.56 INR/km

Total number of fast chargers needed
6

Total number of slow chargers needed
17

The number of chargers installed at location
2

Cost Details

Number of Schedules	81
Number of Depots	2
Number of intermittent charging locations	0
Total energy consumed	12656.34 kWh
Cost of charging e-buses per day	75,475.96 INR
Total capital cost	646,766,460 INR
Total Operating cost	129,066,584 INR

Depot-level Summary

KBS	
Number of Schedules	1
Number of Schedules for IC	0
Number of fast chargers	0
Number of Slow chargers	1
Peak Power	60 kW
Energy consumed	153.27 kWh

BMT-08	
Number of Schedules	80
Number of Schedules for IC	0
Number of fast chargers	6
Number of Slow chargers	16
Peak Power	1500 kW
Energy consumed	12503.07 kWh

Figure 23: Final summary

10. Appendix IV

List of feasible schedules

The feasible schedules arriving at the four depots (Depot 4, Depot 3, Depot 2, and Depot 1) are listed in Table 13.

Table 13: List of schedules to be charged at each selected depot

Route No.	Schedule No.	Halt Start Time	Halt End Time	Halt Duration (mins)	Schedule Length (km)	Selected Charging Location
ABC-1	ABC-1/5	17:55	08:00	850	153.4	Depot 2
ABC-2	ABC-2/17	17:50	07:55	850	183.9	Depot 3
ABC-2	ABC-2/18	03:25	19:25	965	163	Depot 3
ABC-2E	ABC-2E/6	18:25	09:40	919	189.8	Depot 2
DEF-1	DEF-1/11	18:50	07:10	745	165	Depot 3
DEF-2	DEF-2/3	18:50	07:15	750	167.3	Depot 2
GHI-1	GHI-1/5	19:15	07:35	745	164.8	Depot 1
GHI-1	GHI-1/6	18:05	06:25	745	172.1	Depot 1
GHI-2	GHI-2/6	19:50	08:10	745	116.1	Depot 2
GHI-2	GHI-2/8	19:20	07:40	745	122.1	Depot 2
GHI-3	GHI-3/11	19:00	07:20	745	187.9	Depot 2
GHI-3	GHI-3/12	19:30	07:50	745	187.9	Depot 2
GHI-3	GHI-3/13	19:50	08:10	745	187.9	Depot 2
GHI-3	GHI-3/14	20:10	08:30	745	187.9	Depot 2
GHI-3	GHI-3/4	19:05	07:25	745	169.2	Depot 1
GHI-4	GHI-4/10	18:55	07:15	745	168.1	Depot 3
XYZ-1	XYZ-1/12	19:05	08:10	790	127.8	Depot 2
XYZ-1	XYZ-1/13	18:50	07:10	745	173.6	Depot 2
XYZ-1	XYZ-1/18	18:55	07:15	745	174.5	Depot 3
XYZ-1	XYZ-1/28	19:15	08:00	770	163.8	Depot 3
XYZ-1	XYZ-1/33	19:10	07:35	750	163.8	Depot 1
XYZ-1	XYZ-1/34	19:55	07:55	725	163.8	Depot 1
XYZ-1	XYZ-1/4	18:35	07:35	784	127.8	Depot 2
XYZ-2	XYZ-2/16	18:50	07:45	780	162	Depot 3
XYZ-2	XYZ-2/17	20:00	08:20	745	167	Depot 3
XYZ-2	XYZ-2/18	20:15	08:35	745	167	Depot 3
XYZ-2	XYZ-2/19	19:50	08:10	745	113	Depot 3
XYZ-2	XYZ-2/23	20:30	08:55	750	167	Depot 3
XYZ-2	XYZ-2/30	20:05	08:25	745	113	Depot 3
XYZ-2	XYZ-2/33	20:55	09:15	745	113	Depot 3
XYZ-2	XYZ-2/35	18:45	07:30	770	173.2	Depot 2
XYZ-2	XYZ-2/4	19:15	08:00	770	167	Depot 3
XYZ-2	XYZ-2/45	19:50	08:15	750	174.5	Depot 2

XYZ-2	XYZ-2/46	20:10	08:45	760	174.5	Depot 2
XYZ-2	XYZ-2/48	21:05	09:25	745	113	Depot 3
XYZ-2	XYZ-2/49	21:15	09:35	745	113	Depot 3
XYZ-2	XYZ-2/5	21:10	09:30	745	167	Depot 3
XYZ-2	XYZ-2/50	18:05	06:25	745	178.9	Depot 3
XYZ-2	XYZ-2/52	19:25	07:45	745	167	Depot 3
XYZ-2	XYZ-2/53	18:50	07:25	760	165.6	Depot 1
XYZ-2	XYZ-2/54	19:35	07:55	745	165.6	Depot 1
XYZ-2	XYZ-2/55	20:15	08:35	745	165.6	Depot 1
XYZ-2	XYZ-2/60	18:45	07:30	770	167	Depot 3
XYZ-2	XYZ-2/61	19:40	08:20	765	167	Depot 3
XYZ-2	XYZ-2/62	18:50	07:10	745	167	Depot 3
XYZ-2	XYZ-2/63	18:55	07:20	750	167	Depot 4
XYZ-2	XYZ-2/64	06:35	18:55	745	144.4	Depot 1
XYZ-3	XYZ-3/19	19:25	07:45	745	185.4	Depot 2
XYZ-3	XYZ-3/20	20:00	08:40	765	183.9	Depot 2
XYZ-3	XYZ-3/22	18:50	07:25	760	128	Depot 3
XYZ-3	XYZ-3/23	19:25	08:00	760	165.2	Depot 1
XYZ-3	XYZ-3/24	19:10	07:45	760	128	Depot 3
XYZ-3	XYZ-3/28	18:45	07:50	790	165	Depot 1
XYZ-3	XYZ-3/29	19:15	08:15	784	165	Depot 3
XYZ-3	XYZ-3/30	19:15	07:55	765	165	Depot 3
XYZ-3	XYZ-3/32	19:35	07:55	745	128	Depot 3
XYZ-3	XYZ-3/39	19:50	08:10	745	128	Depot 3
XYZ-3	XYZ-3/45	20:05	08:25	745	175.6	Depot 2
XYZ-3	XYZ-3/57	18:15	07:00	770	170.1	Depot 2
XYZ-3	XYZ-3/58	06:00	19:25	810	127.8	Depot 2
XYZ-3	XYZ-3/59	03:35	18:30	900	157.2	Depot 3
XYZ-4	XYZ-4/2	18:40	07:15	760	169.7	Depot 1
XYZ-4	XYZ-4/3	18:05	06:25	745	178.9	Depot 1
XYZ-4	XYZ-4/4	18:05	06:25	745	180.9	Depot 1
XYZ-5	XYZ-5/20	18:45	07:10	750	160.4	Depot 3
XYZ-5	XYZ-5/22	18:15	06:55	765	160.4	Depot 3
XYZ-6	XYZ-6/5	18:35	06:55	745	172.9	Depot 4
XYZ-6	XYZ-6/6	19:05	07:25	745	168.5	Depot 3
XYZ-7	XYZ-7/2	19:00	07:30	755	122	Depot 4
XYZ-7	XYZ-7/3	19:05	07:25	745	180.9	Depot 1
XYZ-7	XYZ-7/6	18:50	07:40	775	159	Depot 3
XYZ-7	XYZ-7/7	18:55	07:25	755	164.8	Depot 3

11. Appendix V

List of infeasible schedules

The infeasible schedules, with their respective reasons for infeasibility, are listed in Table 14. However, the infeasible schedules can be made feasible in the following ways:

For the schedules that are infeasible due to **insufficient battery operational range**, the battery size needs to be increased. The desired battery size can be calculated as:

$$battery\ size\ = \frac{schedule\ length\ \times energy\ consumption}{usable\ \ capacity}$$

For example, in Table 14 below, ABC-3/1 is infeasible because of its long schedule length of 400 km. Given the depth of discharge (80%) and energy consumption (1 kwh/km) (as specified in Table 7), the desired battery size for this schedule, calculated using the above equation, would be 500 kWh.

For the schedules that are infeasible due to **insufficient halt duration at the depot**, the halt duration needs to be increased. The minimum halt duration required can be calculated as:

$$charge\ duration\ = \frac{schedule\ length\ \times energy\ consumption\ \times 60}{rated\ power\ of\ fast\ charger}$$

For example, in Table 14 below, DEF-1/2 halts at Depot 1 for 30 min rendering it infeasible. Using the above equation, the minimum time required to completely charge the battery using a fast charger of 120 kW (as specified in Table 7) would be 84 min.

For the schedules that are infeasible because there is **no halt at the selected depot**, rerouting such that it halts at the depot is required.

Table 14: Infeasible schedules

Schedules with an insufficient battery operational range				
ABC-3/1	ABC-2/13	XYZ-8/3	XYZ-3/53	XYZ-1/31
ABC-3/2	ABC-2/14	XYZ-3/1	XYZ-3/54	XYZ-1/5
ABC-3/3	ABC-2/15	XYZ-3/11	XYZ-3/55	XYZ-1/6
ABC-3/4	ABC-2/16	XYZ-3/12	XYZ-3/56	XYZ-1/7
ABC-3/5	ABC-2/2	XYZ-3/13	XYZ-3/6	XYZ-1/8
ABC-3/6	ABC-2/3	XYZ-3/14	XYZ-3/7	XYZ-1/9
ABC-4/1	ABC-2/4	XYZ-3/15	XYZ-3/8	XYZ-2/1
ABC-4/2	ABC-2/5	XYZ-3/16	XYZ-3/9	XYZ-2/10
ABC-4/3	ABC-2/6	XYZ-3/17	XYZ-5/23	XYZ-2/15
ABC-4/4	ABC-2/7	XYZ-3/18	XYZ-5/35	XYZ-2/2
ABC-4/5	ABC-2/8	XYZ-3/2	XYZ-5/36	XYZ-2/24
ABC-4/6	ABC-2/9	XYZ-3/21	XYZ-5/37	XYZ-2/25
ABC-4/7	ABC-2E/1	XYZ-3/25	XYZ-5/4	XYZ-2/27

ABC-4/8	ABC-2E/2	XYZ-3/26	XYZ-5/7	XYZ-2/3
ABC-4/9	ABC-2E/3	XYZ-3/27	XYZ-5/8	XYZ-2/32
ABC-5/1	ABC-2E/4	XYZ-3/3	DEF-1/13	XYZ-2/36
ABC-5/2	ABC-2E/5	XYZ-3/31	DEF-1/20	XYZ-2/37
ABC-5/3	GHI-1/1	XYZ-3/34	DEF-1/22	XYZ-2/47
ABC-5/4	GHI-1/2	XYZ-3/35	GHI-4/14	XYZ-2/56
ABC-5/5	GHI-1/3	XYZ-3/36	XYZ-1/1	XYZ-2/6
ABC-5/6	GHI-1/4	XYZ-3/37	XYZ-1/10	XYZ-2/66
ABC-6/1	GHI-5/1	XYZ-3/38	XYZ-1/11	XYZ-2/7
ABC-6/2	GHI-5/2	XYZ-3/4	XYZ-1/14	XYZ-2/8
ABC-6/3	GHI-5/3	XYZ-3/40	XYZ-1/15	XYZ-2/9
ABC-6/4	GHI-5/4	XYZ-3/41	XYZ-1/17	XYZ-4/1
ABC-6A/1	GHI-2/1	XYZ-3/42	XYZ-1/19	XYZ-6/3
ABC-6A/2	GHI-2/2	XYZ-3/43	XYZ-1/21	XYZ-6/4
ABC-6A/3	GHI-2/3	XYZ-3/44	XYZ-1/25	XYZ-7/1
ABC-6A/4	GHI-6/2	XYZ-3/46	XYZ-1/26	XYZ-7/4
ABC-2/1	GHI-6/3	XYZ-3/47	XYZ-1/27	XYZ-7/5
ABC-2/10	GHI-3/15	XYZ-3/5	XYZ-1/3	XYZ-7/8
ABC-2/11	XYZ-8/1	XYZ-3/50	XYZ-1/30	XYZ-7/9
ABC-2/12				
Schedules with no halt at the selected depot				
ABC-1/1	XYZ-5/11	XYZ-5/6	GHI-4/6	XYZ-2/31
ABC-1/2	XYZ-5/12	DEF-1/1	GHI-4/7	XYZ-2/34
ABC-1/3	XYZ-5/14	DEF-1/14	GHI-4/8	XYZ-2/38
ABC-1/4	XYZ-5/16	DEF-1/15	GHI-4/9	XYZ-2/39
GHI-6/5	XYZ-5/17	DEF-1/6	XYZ-2/11	XYZ-2/40
GHI-6/6	XYZ-5/2	DEF-1/8	XYZ-2/12	XYZ-2/41
GHI-3/2	XYZ-5/24	GHI-4/1	XYZ-2/13	XYZ-2/42
GHI-3/5	XYZ-5/25	GHI-4/11	XYZ-2/14	XYZ-2/43
GHI-3/6	XYZ-5/26	GHI-4/12	XYZ-2/20	XYZ-2/44
GHI-3/7	XYZ-5/27	GHI-4/13	XYZ-2/21	XYZ-2/51
GHI-3/8	XYZ-5/28	GHI-4/2	XYZ-2/22	XYZ-2/57
XYZ-8/2	XYZ-5/29	GHI-4/3	XYZ-2/26	XYZ-2/58
XYZ-8/4	XYZ-5/34	GHI-4/4	XYZ-2/28	XYZ-6/2
XYZ-5/1	XYZ-5/38	GHI-4/5	XYZ-2/29	XYZ-6/9
XYZ-5/10	XYZ-5/5			
Schedules with a halt duration insufficient to fully charge the battery				
DEF-1/2	DEF-1/7	XYZ-1/16	XYZ-1/2	XYZ-1/20
XYZ-1/35				

12. Appendix VI

Version 2.0: Updated Features

The features updated in version 2.0 of the Tool are discussed in detail in this section.

Intermittent charging

Most STUs operating e-buses in India, fully charge the buses overnight (full charging or FC) at the selected depots. This method of charging is preferred because it requires fewer locations for installing charging infrastructure and the buses can be charged with chargers of lower power (up to 60 kW). However, for common battery capacities (up to 250 kWh), this method creates range anxieties and renders a large number of schedules infeasible due to long travel distances. This calls for larger battery sizes that would sustain energy for a day of operations.

A solution for addressing this range anxiety is to charge these buses intermittently during the daily operations. In this case, those buses that cannot return for full charging without completely discharging the battery, can be charged at dedicated locations during mid-day crew change or other longer halts. These events of intermittent charging (IC) usually use higher-power chargers (above 60 kW). In some cases, the same depots can be used for IC, while in some others a different location (bus station or depot) can be used. This alternative charging method involves higher capital costs for installing the infrastructure at the additional locations and for the use of higher power chargers.

For schedules that require intermittent charging (those that are run longer than the effective range given by the e-bus model), the location for intermittent charging is assigned considering the following:

1. The schedule has to stop at least at one of the pre-selected locations during its operations, for a minimum amount of time (buffer time). (*Note: This halt is different from the long halt at the end of the schedule's operations.*)
2. The SoC of the battery upon arrival at such a location should be greater than the minimum SoC.
3. The schedule should halt at such a location for a duration long enough to recharge the entire amount of battery capacity discharged.

Schedules that require intermittent charging but do not have any locations that fulfil the above criteria, will be infeasible for electrification, given the chosen e-bus and charger models.

All schedules feasible for intermittent charging will have one depot assigned for full charging and one location for intermittent charging.

The charging requirements can be simulated separately for the depot locations and for intermittent charging locations.

Charger quantity estimation

The depot-level analysis simulates the charging requirements at the selected depot, for a given number of fast and slow chargers.

In the previous version of the Tool, the user had to manually enter the number of slow and fast chargers for the depot-level simulation. In this updated version, the user is provided with an indicative number of fast and slow chargers. These numbers are estimated based on the number of buses arriving at the location for charging, number of buses that require slow and fast chargers, average charging time with slow and fast chargers, and the average halt duration. This estimation does not consider queuing of the e-buses, and hence, is often an overestimation. The user can overwrite these numbers with those indicated by the operator/bidder. Alternatively, the user can choose to simulate for a minimum number of chargers (by checking the radio button option). In this case, the number of chargers is iteratively reduced till a combination of slow and fast chargers is arrived at, such that they are sufficient to charge the schedules arriving at the location.

In either case, the charging requirements, grid planning, and cost-implications related results are displayed according to the choice of the user.

Total cost of ownership (TCO)

In this version of the Tool, a TCO module has been incorporated that estimates the overall cost of owning all the feasible schedules, along with their charging requirements. The main components involved in the module are displayed in Figure 24.

As shown, TCO involves both the upfront costs as well as the operational costs of the fleet.

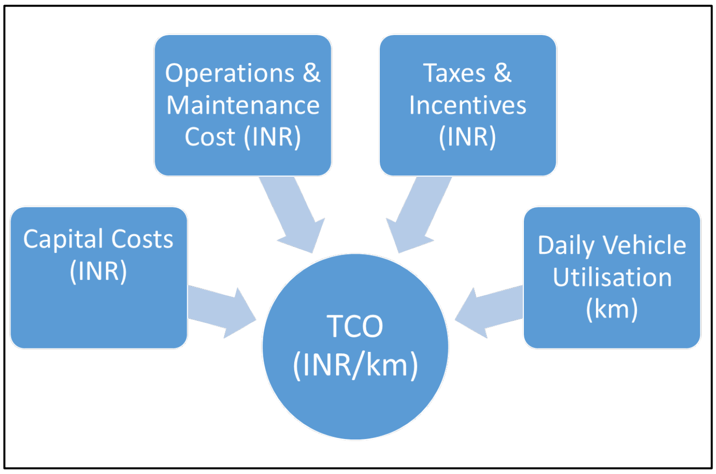


Figure 24: Components of the TCO Module

Here, both capital costs and operation and maintenance costs of e-buses and chargers, along with the battery replacement costs have been considered. The capital costs of e-buses and chargers include their purchase costs, and relevant taxes and subsidies/funds. The operational and maintenance costs include the labour and installation cost for the chargers at the depot, cost of electricity for charging, e-bus maintenance cost, charger maintenance cost, and data-related services and staff costs.

TCO is estimated using the following equation:

$$TCO\left(\frac{INR}{km}\right) = \frac{A}{D} = \frac{I \times CRF + Q}{D}$$

$$CRF = \frac{d(1+d)^N}{(1+d)^N - 1}$$

Where

A = Annual revenue (INR/Yr)
Q = Operational costs (INR / Yr)
I = Initial investment (INR)
D = Annual distance covered (km/Yr)
d = Discount rate
N = Time period of the project (Yr)
CRF= Capital recovery factor

Stakeholder Feedback on Version 2.0

The updated version of the Tool was demonstrated to four STUs to understand the usefulness of the Tool and to receive feedback on its features. The four STUs were Bengaluru Metropolitan Transport Corporation (BMTC), Kerala State Road Transport Corporation (KSRTC), North-West Karnataka Road Transport Corporation (NWKRTC), and Pune Mahanagar Parivahan Mahamandal Ltd (PMPML).

The feedback was positive and the usefulness of the Tool in the planning process, in general, was acknowledged.

Officials at BMTC acknowledged that the results from the Tool would help them during the tendering process and asked CSTEP to perform the simulation for the proposed BMTC metro feeder e-buses. The results of this simulation have been shared in Section 4.

Officials at NWKRTC and KSTRC mentioned that the Tool will be useful to understand the grid impact of charging the e-buses, when they procure more number of e-buses in the future. Similarly, PMPML was interested in looking into charger infrastructure planning to optimally decide on the quantum of chargers, quantum of sanction load, etc.

CENTER FOR STUDY OF SCIENCE, TECHNOLOGY & POLICY

Bengaluru
#18 & 19, 10th Cross, Mayura Street,
Papanna Layout, Nagashettyhalli (RMV II Stage),
Bengaluru-560094, Karnataka, India

Noida
1st Floor, Tower-A, Smartworks Corporate Park, Sector-125,
Noida-201303, Uttar Pradesh, India

---

www.cstep.in
☎ +91-8066902500
cpe@cstep.in
@cstep_India