Estimation of the energy consumption of battery driven electric buses by integrating digital elevation and longitudinal dynamic models: Malaysia as a case study

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HIGHLIGHTS

• The electric bus energy consumption is calculated by using spatial-temporal model.
• The varying energy losses among the grid and electric bus charging are considered.
• The proposed framework can be straightforwardly applied on various bus networks.
• The validation of this study is based on Bus-Rapid Kuala Lumpur data.
• A tracking system is used to obtain the speed measurement of the driving mode.

ARTICLE INFO

Keywords:
Energy consumption
Battery electric buses
Geographical Information System
Longitudinal dynamics model
Opportunity charging and overnight charging
Electrical power grid

ABSTRACT

This work proposes a generic framework to estimate the energy consumption and investigate the penetration impact of a distributed network of battery electric buses (BEBs). The core of this work builds on a novel framework to determine the energy demand of BEBs and their potential as a replacement for diesel-powered buses in transportation networks. This paper uses data mapping technology from the Geographical Information System to cover the potential analysis of BEB penetration for large-scale bus networks. State-of-the-art methods have previously estimated the energy consumption of a BEB by using simulator models for each driving cycle, but these studies have not considered the actual elevation data of a local bus route. In fact, the elevation of the bus route is considered the main factor that varies the energy consumption of BEBs. This study

Abbreviations: BEB, Battery Electric Bus; GIS, Geographical Information System; LDM, Longitudinal Dynamics Model; DEM, Digital Elevation Model; Rapid KL, Rapid Kuala Lumpur; PIS, Passenger Information System; GHG, Greenhouse gases; EV, Electric vehicle; EB, Electric bus; PTA, Public transport authority; EBIM, Malaysian Innovation of Electric Bus; STRM, Shuttle Radar Topography Mission; MRN, Malaysia Representative Network; UNECE, United Nations Economic Commission for Europe; NIMA, National Imagery and Mapping Agency; PMSM, Permanent Magnet Synchronous Machine.

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https://doi.org/10.1016/j.apenergy.2020.115873

Received 14 July 2020; Received in revised form 21 August 2020; Accepted 12 September 2020

Available online 5 October 2020

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developed a longitudinal dynamic model with a spatial version of a digital elevation model to determine the energy demand of a large-scale BEB network. Additionally, this work assessed two charging protocols—opportunity charging and overnight charging—according to the operating environments of electric buses. The application of the framework is validated in a case study to electrify the entire Rapid Kuala Lumpur bus (Bus Rapid KL) network in Malaysia. The proposed model used real-world data, which are typically available only to bus transit administration operators. In this paper, the data for bus route lines, bus station locations, and the number of passengers riding the Bus-Rapid KL were considered to formulate the forecasting longitudinal and temporal model by using passenger information system data. The results showed a penetration impact of the BEB charging demand during daytime and nighttime in an urban area in Kuala Lumpur. The proposed forecasting paradigm may permit power network operators to predict the optimal electric bus charging demand based on actual BEB consumption through the bus paths.

### Nomenclature

- $\phi$: Slope gradient
- $F_r$: Mechanical force
- $F_c$: Rolling resistance
- $C_r$: Coefficient of rolling resistance
- $M$: Total mass
- $g$: Acceleration due to gravity
- $F_a$: Force originating from the road slope
- $F_d$: Aerodynamic drag force
- $p$: Density of air
- $C_d$: Drag coefficient
- $F_t$: Transient force required accelerating
- $m_f$: Fictive mass of rolling inertia
- $E_T$: Total energy consumption

1. Introduction

Reducing carbon dioxide emission to mitigate climate change becomes one of the main concerns for the energy sector [1]. A number of technologies, such as carbon capture and storage (CCS), that could be used to mitigate climate change are deployed worldwide. In this context, there is significant interest in CCS for providing decarbonization energy systems and offering flexibility. Nevertheless, to apply CCS on large scale, a range of economic and technical obstacles must be tackled accordingly. In this context, one of the major economic barriers is the fact that CCS implementation requires large investment. CCS could be attractive with the existence of a stringent carbon policy and favorable CCS market conditions. On the other hand, carbon capture and utilization (CCU) is another emerging technology and has appeared as a feasible route in mitigating CO2 concentrations in the atmosphere. CCU makes it possible for CO2 waste emissions from large emitters is captured and used to produce new products and develop economic opportunities. However, the current worldwide consumption for chemical products does not have sufficient capacity to seize enough carbon emissions to share efficiently in addressing the CO2 mitigation targets [2,3]. Alternatively, the interdependency opportunities and increase of new technologies between electric power generation and electric vehicles (EVs) are evolving, with the shift on renewable energy resources for electricity generation. This new growth of renewable energy became the introduction of increasing EVs technologies to be considered a promising option for GHG issues.

Malaysia is responsible for 0.3% of global GHG emissions. Furthermore, Malaysia is the second largest per capita GHG emitter among the Association of Southeast Asian Nations (ASEAN) [4,5]. Thus, city buses emit 0.3 kg of CO2 per passenger mile, and a long-distance bus trip (more than 20 miles) emits 0.08 kg of CO2 per passenger mile. Therefore, the Malaysian government’s Bernama news agency reported that authorities are planning for the introduction of 2000 electric buses (EBs) and 100,000 EVs on Malaysian roads by 2020.

The key reasons for choosing BEBs over diesel-powered buses are zero tailpipe emissions, superior energy efficiency and reduced operating and servicing costs [6]. The better prediction of variations in energy consumption would improve the reliability of bus schedules and reduce unnecessary overloads of the electric grid due to concurrent recharging events [7]. Overload peaks can also be alleviated by installing more charging stations to share the charging load among multiple chargers, thus achieving significant savings in charging costs. The integrated planning of charging infrastructure for electric fast-charging bus systems has to consider various information, restrictions and constraints that can be structured in three different categories: bus operation, infrastructure, and technology.

In bus operation, information on the topology of the bus network and bus stop details must be captured to consider the cost interactions when fast-charging stations are installed. Moreover, data on daily operation hours and dwell times are required. Dwell times are determined by the bus route schedule and might vary according to the type of bus stop [8,9].

Regarding the infrastructure, data on the bus fleet configuration need to be considered to account for different specific electricity consumption and resulting infrastructure requirements. Furthermore, information on infrastructure availability in landmarked areas that lack energy grid capability is required. As a result, such information requires complete infrastructure planning because bus stops and routes have to be structured with sufficient charging stations [10,11].

Based on technology, data on charging power and battery specifications are needed, where the energy of an electric bus, which can be recharged at charging stations, depends on significant data such as the dwelling time of operational planning, the available charging infrastructure (i.e., the time of operation, grid power and charging power), and the battery type and its state of charge (SOC). In this context, a battery’s charging behavior in terms of charging power and the SOC can be described by a nonlinear function. Long-term charging behavior also depends on the depth of discharge (DOD), which is intended to be kept relatively low to improve the longevity of a battery [12].

As illustrated in Table 1, to estimate the energy demand of BEBs and manage various bus networks, the energy consumption of all bus routes is considered through diverse traffic conditions over an entire day. The forecasting energy demand models of EBs can be calculated by the kinematic energy consumption of a trip (E kWh/km) along with the bus specification parameters, such as the auxiliary power consumption from operating doors, powered steering and lighting [13,14]. Several researchers have applied a simulator model to determine the energy consumption for EBs, where a simulator model is used to determine the energy consumption of a traveling bus. A variety of simulations have been applied with this approach by using different software such as ADVISOR [15], CarSim [16], and Autonomie [17]. In [18], the charging time and energy consumed an electric bus in Daegu Metropolitan city, South Korea are modeled by using ADVISOR program, which is a MATLAB-based electric vehicle simulator. In [19], by using Autonomie software, a generic model of electric bus was developed in different driving cycles to evaluate the energy demand of electric buses. The main advantages of this model were fast computation times and the flexibility...
to simulate a large number of driving cycles, while the disadvantage was inaccuracy in the dynamic simulation.

In the literature, several driving cycle standards have been used to determine the energy consumption of BEBs. The traffic measurements of diverse districts are used to assess these driving cycles. The most common standardized driving bus cycles are Paris (France), New York City (U.S.), and Braunschweig (Germany). The characteristics of different driving bus cycles were presented in [20]. For example, in [21], the authors investigated a few standards of driving patterns and then used one of these standards based on the best match of the bus line characteristics to each line. In general, previous studies have illustrated that the average energy consumption ranges from 0.9 kWh/km to 1.6 kWh/km (for 12-meter electric buses) and from 1.7 kWh/km to 2.4 kWh/km (for 18-meter electric buses). Nevertheless, using a standard driving cycle approach in a dissimilar area will have an inaccuracy in the dynamic simulation.

In [22], the researchers studied the features in six driving cycle standards and then used one of these standards based on the best match of the bus line’s characteristics to each line. In general, previous studies have illustrated that the average energy consumption ranges from 0.9 kWh/km to 1.6 kWh/km (for 12-meter electric buses) and from 1.7 kWh/km to 2.4 kWh/km (for 18-meter electric buses). Nevertheless, using a standard driving cycle approach in a dissimilar area will have an inaccuracy in the dynamic simulation.

In [23], the authors evaluated the energy consumption and battery performance of city transit electric buses operating on real day-to-day routes in Knoxville, USA, which covered a mileage of nearly 71,500 km over 610 days, based on a developed framework tool that links bus electrification feasibility with real-world vehicle performance. In a case study of Putrajaya-Malaysia, the existing bus operation with conventional bus powered by diesel or gasoline was used to evaluate the electric bus performance based on different bus operation scenarios [24]. In [25], the tests were carried out using standard test cycles for heavy vehicles as well as routes developed based on actual road conditions. However, this approach is impractical for larger bus networks, and it requires field-test measurements, which are inherently limited with respect to their scalability.

However, due to the difficulty in directly measuring the road gradient of each individual bus route, the effect of the route gradients is neglected in various previous studies that applied for estimating energy consumption of BEB networks. Therefore, there is a gap in the understanding of the full effects of road gradients on estimation of the energy consumption of BEB network. In addition, the varying energy losses between the grid connection point and BEB charging is not sufficiently covered in the literature. In order to address these gaps, this paper proposes a novel framework based on digital elevation model (DEM) and longitudinal dynamics model (LDM) formulations. In this framework, the gradient values over a topographic surface are required for the bus routes. Thus, the proposed approach aims to address the challenges of large-scale bus networks and fills the research gap of understanding the full effects of road gradients on energy consumption. Besides, the varying energy losses between the grid connection point and BEB charging stations are also considered to obtain a highly accurate value of estimated energy consumption. Further records of the total number of passengers for each bus route, which can be collected from the operators of large-scale bus networks, are required to improve the framework accuracy. In this paper, the total energy of overnight and opportunity charging is systematically determined. These calculations are generalized by charging events to analyze the impact of BEB charging.

This study is presented to determine an energy consumption model to support the electrification plan of the large-scale bus networks comprehensively. The proposed framework provides the advantages of adaptability, where it can be straightforwardly applied to different large-scale bus networks and is predicted to perform with high accuracy. The important contributions of this paper are highlighted as follows:

1. The model addresses a lack of quantitative analysis (research gap) to study the effect of road gradients on the energy consumption of EBs. In this regard, a thorough study is performed to investigate the effect of road gradient on BEB energy consumption by using a DEM.
2. The model assesses the energy consumption of BEBs by using Geographical Information System (GIS) data to determine the gradient of the road with an interval of 30 m.

### Table 1

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Collection Type</th>
<th>Model Description</th>
<th>Case Study (Country/State/City)</th>
<th>Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>[21]</td>
<td>Consumption data</td>
<td>In this research, 12-meter length buses were compared. Diesel bus average consumption in Tampere City Transport (TKL) is 40 l/100 km and was used in the calculations.</td>
<td>Tampere City/Finland</td>
<td>The total consumption of the e-bus used in the calculations (9000 kg curb weight) was estimated to be on average 1 kWh/km.</td>
</tr>
<tr>
<td>[22]</td>
<td>Six different driving cycles with technical descriptions (BR, MAN, E11, HIS50, Line 18, and Line 51B)</td>
<td>The energy consumption of the different buses is defined with vehicle simulation by using Autonomous Vehicle Simulation Software, which offers a proven simulation environment for heavy vehicle studies.</td>
<td>Finland and USA-California USA</td>
<td>Total energy consumption in Finland driving cycles has no significant differences.</td>
</tr>
<tr>
<td>[23]</td>
<td>The data are representative of real-world routes driven by conventional diesel buses.</td>
<td>A framework tool was developed to link bus electrification feasibility with real-world vehicle performance, city transit service reliability, battery sizing and charging infrastructure.</td>
<td>Knoxville Area Transit (KAT) in Knoxville/U.S.</td>
<td>The average energy consumption of the electric bus is 1.35 kWh/km.</td>
</tr>
<tr>
<td>[24]</td>
<td>Tests employed two routes based on actual bus route data with a length of approximately 100 km.</td>
<td>The tests were carried out using standard test cycles for heavy vehicles as well as routes developed on the basis of actual road conditions.</td>
<td>Gdynia-Flat, Gdynia-Hills/Poland</td>
<td>Total energy consumption is 20.49 kWh/90 passengers for each 142.35 km.</td>
</tr>
<tr>
<td>[25]</td>
<td>The data was collected according to a city bus network of four bus routes.</td>
<td>A k-Greedy algorithm-based approach was proposed to determine the energy consumption for a bus journey.</td>
<td>Japan</td>
<td>The estimated energy consumption amount is 1.41 kWh/km.</td>
</tr>
<tr>
<td>[26]</td>
<td>On-board diagnostics (OBD) data Collectors.</td>
<td>Three BEB models were tested on-road while participating in the demonstration project.</td>
<td>Macao/ China</td>
<td>The battery uses 15.3 kWh of electricity over the entire 8.8 km route.</td>
</tr>
<tr>
<td>[27]</td>
<td>Operation time and existing bus schedule data were used.</td>
<td>The BEB was implemented by using MATLAB/Simulink software platform.</td>
<td>Penghu/Taiwan</td>
<td>The average energy consumption is 1.3 kWh/h for each kilometre travelled.</td>
</tr>
<tr>
<td>[28]</td>
<td>The data composed of technological and operational information.</td>
<td>Automatic pre-processing is conducted in the form of deadhead routing and energy consumption simulations for all service and deadhead.</td>
<td>Scenario A, in the German city of Aachen and scenario B, in the Danish city of Roskilde.</td>
<td>0.5 kWh / km is the energy consumption for type 1 bus (representing a low weight electric bus) and 0.9 kWh / km for type 2 buses.</td>
</tr>
</tbody>
</table>
Fig. 1. Generic framework of the total energy consumption model of the BEB integrated into the electric power distribution.
3. Moreover, a new methodology is proposed for calculating the power consumption and modeling the charging infrastructure for an electric bus based on large-scale network spatial–temporal real-world data.

4. The model applies a real data set of the entire bus network of the Klang Valley area in Malaysia.

5. The impacts of BEB charging demands on the Malaysia power system network are investigated.

The outline of the paper is as follows. In Section 2, the methodology of the system, which comprises four input models and a process model to obtain total energy consumption by integrating a dynamic-static model, is presented. Application of the framework to a case study of Malaysia is deeply discussed in Section 3. Next, important findings of this work are presented and thoroughly discussed in Section 4. The presented findings cover (1) the energy consumption of BEBs and (2) an investigation of the impacts of charging BEBs on a Malaysian representative distribution power network. Finally, Section 5 concludes the paper and provides a brief overview of future work.

2. A proposed novel framework for estimating the energy consumption of BEBs

The core concept of this study builds on providing a comprehensive generic framework of energy demand for electric buses and their potential as a replacement for diesel buses in transit operations. This framework contains an input model of real-world data integrated into dynamic and static models. The dynamic model consists of spatial–temporal models and an accumulated efficiency model (for powertrain losses), while the static model represents the type of charging (opportunity charging and static charging). The output of the framework is split into obtaining the energy consumption of an entire bus network and investigating the impacts of the distributed network, as shown in Fig. 1. The following sections describe in detail how the models are integrated.

2.1. Input model

In this section, highly accurate spatial and temporal data from a city bus network, the input and output characteristics of a BEB, the Space Shuttle Radar Topography Mission (SRTM), and a generic network representative of a heavily loaded distribution network are required. In this context, the application of the energy demand model considered real-world data to electrify a large-scale bus network.

2.1.1. Aggregated data from a city bus network

This section describes the characteristics of a city bus network based on geographical segmentation (spatial data), time-dependent examination (temporal data), and volume of traffic (VoT) (spatial–temporal data). In geographical segmentation, the data is individually collected associated with each bus route sections, such as number of bus stops and distance between bus stops. A time-dependent examination refers to the temporal data based on a bus traveling time which includes dwell time, idling time, and its frequency reaches per hour. The VoT is a function of both geographical and time-dependent segmentation data according to the spatial and temporal characteristics of the bus lines.

2.1.2. BEB characteristics

Buses can vary in design depending on regional requirements and generally can be classified as low-flow commuter buses, intercity coaches, and double-decker buses. It is important to designate BEBs with flexible battery sizes to establish a significant impact on energy demand (battery mass) and the feasibility of the chosen charging strategies. It is helpful to understand the impact of battery size, particularly together with appropriate emerging charging technologies (opportunity and overnight charging), on BEB applications along short and long routes. The exterior and interior aspects of the considered BEB, which include bus weight, average bus capacity, bus frontal area, bus drag coefficient, and rolling resistance, should be taken into account when calculating the BEB energy consumption model.

2.1.3. Space Shuttle Radar Topography Mission (SRTM) data

DEM data are acquired from the SRTM satellite, which are provided by the National Aeronautics and Space Administration (NASA). The SRTM is a satellite that was launched in 2000 to collect elevation data across the entire earth. The spatial resolution of these data is approximately 1 arc-second, or approximately 25 m, with near-global coverage (from 56°S to 60°N).

First, the route is digitized between each of the two main stations. Then, the DEM data are laid out to cross-collaborate the elevation data. The route is designed in polyline format, where a split function is applied on the polyline to divide it into equal lengths of 30 m (same as the DEM spatial resolution). The final step is to calculate the slope using the TAN function.

2.1.4. Representative electrical power grid data

A generic network representative data of a heavily loaded distribution network is required, as follow:

- Generation profile.
- The characteristics of high-voltage to medium-voltage transformer (HV/MV).
- Number of feeders.
- The characteristics of transmission lines.
- The characteristics of medium-voltage to low-voltage transformer (MV/LV).
- Load profile.

2.2. Dynamic-Static model

This section uses a dynamic-static model of a BEB to obtain the total energy consumption for one journey. The dynamic model presents three submodels (spatial, temporal, and accumulated) integrated into the LDM model. The output of the dynamic model is added to the static model, which consists of opportunity charging and overnight charging.

This study divides the calculation of the energy demand into sections 30 m in length. In addition, more precise input data are used (GPS-based measurements) to improve the reliability of the results. In addition, a submodel is added in this framework to calculate the varying energy losses between the grid connection point and BEB. Thus, the total energy demand is divided into two parts (Part one: Energy consumption of BEBs while the buses are in operation time. Part two: the energy losses between the grid connection points and BEB charging).

2.2.1. Digital elevation model (DEM): Spatial model

DEM refers to the quantitative model of the Earth’s terrain, which is in digital form [29,30]. Essentially, this model simulates the topographical geodatabase of a bus network area using the GIS environment. The bus routes are extracted and mapped with visualization tools. First, the slope gradient (\(\phi\)) is determined in terms of spatial planning for application in LDM equations in the following section. In fact, the geo-database describes the real-world scenario of the elevation value assigned to the bus routes (in meters above sea level).

In this model, a specialized database is obtained by using Google Earth Pro software, which represents the relief of a route surface between points (between each 30 m). The route network is first created by defining two stations, and then the route is exported into the GIS environment for further analysis. The exported route is divided into equal distances along the way with an interval of 30 m to determine the total energy consumption based on these intervals.

2.2.2. Longitudinal dynamic model (LDM)

To determine the dynamic energy consumption, a dynamic model of
the consumption pattern must be developed based on the longitudinal basic principle dynamic model for BEBs, as detailed in Appendix A. Based on Fig. 2, the total required mechanical energy at the wheels as a function of the kinematic parameters describing bus movement can be expressed in the vehicle dynamics equation:

\[
E = \eta \left[ \left( \frac{MgC_1 \cos \phi_1 + Mgsin \phi_1}{d_1} \right) + \left( \frac{1}{2} \rho \cdot \Delta (v - w)^2 \right) \right] + \left( (M + m_f) \frac{dv}{dt} \right) \cdot d_1
\]

where \( E \) is the mechanical energy required at the wheels to drive a distance \( d \) in kWh, \( d \) is the distance traveled (each 30 m), and \( \eta \) is the accumulated efficiency factor of the BEB (described in the next section).

Meanwhile, the total energy consumption \( E_T \) of a single BEB traveling from the first terminal to the last terminal can be determined according to the following approach:

\[
E_T = E_1 + E_2 + E_3 + \ldots + E_n
\]

Fig. 2. Total energy consumptions of a route bus for each 30 m.

![Block diagram of Battery Electric Bus (BEB).](image-url)

Fig. 3. Block diagram of Battery Electric Bus (BEB).
\[ E_n = \eta \left[ (MgC \cos \phi_n) + (Mg \sin \phi_n) + \left( \frac{1}{2} pACd(v - w)^2 \right) \right] + (M + m) \frac{dv}{dt} \]  

where \( E_n \) is the energy consumption measured at the last 30 m (at the last slope \( \phi_n \)) of traveled distance, as shown in Fig. 2.

2.2.2. Accumulated model

This section introduces the efficiency factor of BEB powertrain and auxiliary part to determine the energy losses while the bus is in operation duty. This model contains the motor, inverter, battery and auxiliary accord, as shown in Fig. 3. The accumulated efficiency factor can be expressed as follows:

\[ \eta = \eta_{PMSM} + \eta_{INV} + \eta_{BAT} + \eta_{AU} \]  

\( \eta_{PMSM} \) is the efficiency factor of the permanent magnet synchronous machine (PMSM), which consists of a rotor and stator, \( \eta_{INV} \) is the efficiency factor of the DC/AC convertor, \( \eta_{BAT} \) is the efficiency factor of the BEB battery, \( \eta_{AU} \) is the efficiency factor of the auxiliary load, including the air conditioner, pumps and radiator fan.

In addition, the auxiliary power \( P_{aux} \) required for various auxiliary services (such as air conditioning, powered steering, operating doors, rear lighting, and front lighting) needs to be considered. The auxiliary energy \( E_{aux} \) can be determined by applying the following formula:

\[ E_{aux} = (P_{aux})T \]  

where \( T \) is the total time of the trip.

2.2.4. Tracking System: Temporal model

The equations for determining the energy demand for acceleration, constant speed and deceleration phases are given as follows:

\[ E_{a+} = \eta \left[ (MgC \cos \phi) + (Mg \sin \phi) + \left( \frac{1}{2} pACd(v - w)^2 \right) \right] \]  
\[ E_0 = \eta \left[ (MgC \cos \phi) + (Mg \sin \phi) + \left( \frac{1}{2} pACv^2 \right) \right] \]  
\[ E_{a-} = \eta \left[ (MgC \cos \phi) + (Mg \sin \phi) - (pACd d_{d}) + \left( (M + m)a \right) \right] d_{d} \]  

where \( E_{a+}, E_0 \), and \( E_{a-} \) are the mechanical energies required for acceleration, constant speed and deceleration movements in kWh, where each \( E_n \) (2d) takes one of the forms in (5), (6) or (7) for the whole distance \( d_n = 30m \), while \( d_{d0}, d_{d1}, \) and \( d_{d2} \) represent the distances during acceleration, driving at constant speed and deceleration; \( v \) is the constant speed during the coasting phase. Each bus route begins with constant acceleration (\( a_+ \)) at distance \( d_{d0} \), followed by constant speed (\( v_+ \)) at distance \( d_{d1} \) and arrives at a standstill with constant deceleration rate \( a_- \) at distance \( d_{d2} \), as follows:

\[ D = d_{d0} + d_{d1} + d_{d2} \]  
\[ d_{d0} = \frac{v_+^2 - v_0^2}{2a_+} \]  
\[ d_{d2} = \frac{v_0^2 - v_-^2}{2a_-} \]
\[ d_1 = D - (d_{00} + d_{02}) \]  \hspace{1cm} (11)

where \( D \) is the total distance, \( v_f \) is the final speed and \( v_i \) is the initial speed.

2.3. Energy and power losses in BEB charging station

This section introduces a model to calculate the energy losses during the BEB charging operation with electricity transmission. As illustrated in Fig. 4, the lines and transformers in the BEB charging stations are
considered, where the BEB charging stations are provided with alternating current, and the voltage is adjusted based on the required level by using a DC/DC converter, as follow:

- High-voltage to medium-voltage transformer (HV/MV).
- Medium-voltage transmission line, 11 kV
- Medium-voltage to low-voltage transformer (MV/LV).
- Charger system that includes a three-phase rectifier and DC/DC converter.

To determine the power losses in the power supply system, equation (12) is used.

$$\Delta P = P_T \left( 1 - \prod_{i=1}^{n} \eta_i \right)$$

where $\Delta P$ (kW) is the power loss in the transmission system, $P_T$ (kW) is the power on the output terminals of the power supply point, $\eta_i$ is the efficiency of the $i$-th element of the power supply system, and $n$ is the number of components of the power supply system.

The energy loss $\Delta E$ (kWh) in the transmission system is determined by applying the following formula:

$$\Delta E = \Delta P \cdot T$$

where $T$ (s) is the time of electricity transmission during a day.

2.3.1. Cable losses
Cable losses play a significant role in the estimation of the accumulated energy consumption of BEBs during charging operations with electricity transmission. As a BEB is connected to the power supply through a long power cable, there is a considerable voltage drop occurring across this cable, as given by Equation (14):

$$\Delta P_c = \frac{3I^2R_c}{1000}$$

where $\Delta P_c$ (kW) is the electrical power loss of the cable, $I$ (A) is the required current, and $R$ (ohm) is the resistance of the power cable.

2.3.2. HV/MV and MV/LV transformers
In this study, the losses occurring in the transformer while the BEB is charging its batteries are considered to estimate the total energy required to operate BEBs in the existing power system network. Moreover, there are no-load losses that are fixed values and are unrelated to the load. First, these losses include hysteresis losses, eddy current losses, dielectric losses, and thermal losses due to no-load current. Second, there are load losses dependent upon the loading on the transformer. These load losses include the copper losses, which are proportional to the square of the current flowing into the transformer.

2.3.3. Power electronics devices (PEDs)
The losses of power electronics devices (PEDs) are calculated in this model, where these devices are used to convert the AC line voltage to the DC battery voltage. Three-phase rectifiers and DC/DC converters are considered the main parts of PEDs, which include cooling fans and other parasitic loads. The PED losses consist of two parts: stand-by losses inherent in the electronics and Joule effect losses proportional to the square current. Therefore, the current rate is one significant parameter for the PED power loss behavior.

Hence, the efficiencies and power losses of the respective elements in this section (cables, transformers, PEDs) were selected according to the datasheets and Malaysia power system standards.
3. Application of the framework to a case study of Malaysia

The aforementioned framework is applied to a bus transport operator of Kuala Lumpur, Malaysia (Bus-Rapid KL). Rapid KL is a public transportation system built by Prasarana Malaysia and is operated by its subsidiaries, covering the Kuala Lumpur and Klang Valley areas.

3.1. Data

Highly accurate spatial and temporal data from Bus-Rapid KL, Malaysian Innovation of Electric Bus (EBIM), the Space Shuttle Radar Topography Mission (SRTM), and the Malaysia Representative Network (MRN) are collected, processed and analyzed during this project. The dataset provided insight and illustrated the input data of the energy consumption framework. The application of the energy demand model used real-world data to demonstrate the large-scale Selangor network in Malaysia. The research uses actual GIS data to calculate the gradient of the routes for each 30-meter distance.

3.1.1. Aggregated data from Bus-Rapid KL

This section describes the characteristics of the Bus-Rapid KL routes in Malaysia, operating mainly in urban areas of the Klang Valley and covering six key areas (Area One to Area Six). Fig. 5 provides an example of the Bus-Rapid KL map illustrating the bus routes in Area One [31,32]. Specifically, Bus-Rapid KL operates a total of 10 city bus routes, 165 bus routes, 85 local bus routes, and 63 trunk bus routes, and the total number of bus hubs is 4,446. It currently has 11 bus depots spread across the Klang Valley with 1347 buses in operation, boasting an average daily ridership of 348,000. The data cover one record per stop at a bus stop for each single bus, with the aggregated sum of boarding and alighting passengers at that stop through on-board observations.

3.1.2. BEB characteristics using EBIM

In this work, the EBIM bus [33], as shown in Fig. 6, has a length of 12 m and can seat 40 passengers (EBIM is designed according to United Nations Economic Commission for Europe (UNECE) regulations provided by Automotive Engineering of Transport Department Malaysia for vehicle type approval). Table 2 shows the input and output characteristics of the EBIM bus, which is used to determine the Malaysian drive cycle model. CALB CAM 72 cells were selected for the battery pack requirements of the BEB, with specifications as shown in Table B.1.

3.1.3. Spatial-SRTM data

In this paper, the study area covers an area of approximately $514 \times 6$ km in the Ampang area in Malaysia, as shown in Fig. 7. The DEM model can be used to extract various topographic models such as slope, aspect, and curvature. In this study, a DEM model was used for calculating the bus route elevations, where each pixel represents an area of $30^\circ \times 30^\circ$ meters from the sea level, as shown in Fig. 7. The topography model of 15 bus routes in the Ampang area (such as AJ03, AJ04, A2B) was determined by applying various topographies from below sea level (SL) elevation routes, owing to subsidence, to hilly and mountainous regions, as shown in Fig. 8. This demonstrates the density of the bus network in the Ampang area and the number of possible travel routes to be assessed.

3.1.4. Malaysia representative network (MRN) data

In this study, MRNs of 33 kV/11 kV and 11 kV/0.4 kV are modeled by applying a robust statistical method and geometrical service area model to a set of residential networks. The network examined in this study is a distribution network in Selangor state (Malaysia) with an area of $9.221 \text{ km}^2$, which serves approximately 3000 customers, as shown in Fig. 9. The 11-kV network is a 132/33/11 kV transformation, with the 33-kV network as the primary distribution. The 11 kV feeders are designed as another connected network but operate as a radial with a normal off point (NOP). In this context, the transformers of the MRN are described as two 33/11 kV transformers, four 11 kV feeders <5 km in length, and four 11/0.4 kV feeders for each feeder.

Furthermore, more than 90% of the lines in the MRN are underground (UG) cables. Models of the trial networks were developed using Siemens PSS®E software based on a steady-state power system simulation application. This work uses this set of models and data as a foundation for the examination of BEB load impacts.

3.2. DEM, PIS, and MRN models

In the following subsection, we will elaborate on the structures of the DEM, PIS, and MRN models in Malaysia.
3.2.1. **DEMxxx**

This paper simulates the topographical geodatabase of the Klang Valley area using DEM-based grid data within the GIS environment. The Bus-Rapid KL routes were extracted and mapped with powerful GIS algorithms and geovisualization tools. DEM can be determined by using the following steps:

**Step 1: Indicating Bus Routes-Bus Stops**

This work navigates the Bus-Rapid KL network (bus routes and bus stops) by using Google Earth Pro software.

**Step 2: Earth Explorer- United States Geological Survey (USGS)**

In this step, the Earth Explorer-USGS is used to obtain the elevation data of SRTM-DEM 1 arc-second global 30 m, where the Earth Explorer user interface is an online search, discovery, and ordering tool developed by the USGS. Earth Explorer supports the searching of satellite, aircraft, and other remote sensing inventories through interactive and textual-based query capabilities.

**Step 3: GIS Software**

By using ArcGIS software, DEM can be expressed as Raster with grid of matrix form. In addition, the route networks were extracted and mapped with ArcGIS software by applying geo-visualization tools. These features were used to create a topographical geo-database for the route bus networks.

**Step 4: Slope calculations**

The bus routes were divided into equal distance along the way with an interval of 30 m in order to determine the buses energy consumptions for each 30 m. The following formula is applied to determine the slope ($\phi$) of each 30 m:

$$\phi = \tan^{-1} \frac{\Delta y}{\Delta x}$$  \hspace{1cm} (15)

3.2.2. **PIS model**

The acceleration and deceleration of the driving mode can be obtained with a PIS, which is provided by Rapid KL Klang Valley and Kuala Lumpur. The PIS is part of a four-component project under Prasarana’s Fleet Tracking system, where the PIS and GPS systems are implemented on buses, and trunk radios allow drivers to communicate directly with the Bus Control Centre (BCC). Every bus is fitted with GPS, allowing the control center located at the Bus-Rapid KL headquarters on Old Klang Road to monitor bus movements. This GPS system covers all 169 routes serviced by Bus-Rapid KL buses throughout the Klang Valley.

The PIS provides real-time tracking of bus location by installing a GPS unit onboard the bus. GPS tracking devices collect information regarding the vehicle, including the vehicle’s geographical location (i.e., longitude and latitude), speed and driving direction at regular time intervals. GPS-based services include bus satellite navigation and tracking systems to enable the operator to support online tracking and monitoring services, as shown in Fig. 10.

3.2.3. **MRN model**

To investigate BEB load impacts on the Malaysia network, the described framework is applied to real-world data, where the bus routes have been classified into opportunity charging and overnight charging. It is important to model the Malaysia distribution networks, which have been developed by using Siemens PSS@E. As illustrated in Fig. 11, the number of BEBs that need to be charged depends on nonused nodes in the MRN model. Based on current distribution networks, operational schedules, and the number of bus routes, the charging schedule of all buses is coordinated according to the MRN peak demand over 24 h.

3.3. **Opportunity and overnight charging**

The individual packs are comprised of CALM CAM 72 (Ah) 3.2 LiFePO4 cells arranged in two parallel sets of 66 in series. This configuration was assumed for a BEB engaged in opportunity charging, which provides a peak voltage of 211 V nominal with 30 kWh of storage capacity and an approximate mass of 500 kg. In contrast, the battery pack configuration for a BEB engaged overnight charging was set up as 3 parallel strings of 3 packs in series, and this arrangement provides a peak voltage of 633 V nominal with 270 kWh of storage capacity and an approximate mass of 3000 kg.

4. Results and discussion

4.1. **Energy consumption**

The route gradients and passenger masses are considered the main factors that contribute to the energy consumption of BEBs. In addition to the gradient variations of the routes (each 30 m), the total BEB mass of a city bus can vary significantly during a route due to variations in the number of passengers. However, exact real-time data on passenger
loading are applied in a statistical manner to obtain an exact value of BEB energy consumption for the Bus-Rapid KL.

In Fig. 12, the BEB energy consumption model is obtained by applying different bus routes. In fact, the presented values are based on the energy consumption results of real-world data, which is assumed to be proportional to the trip distance.

The result in Fig. 13 compares the energy consumption by applying Equation (7) in four scenarios according to four bus routes—U30, UB103, U28, and U29. The actual driving case is executed in the first scenario (brown bar), where the energy consumption value is obtained by using equation 2d. The second scenario (blue bar) is determined by using formula 2d in case the buses are empty in terms of the passenger’s weight (number of passengers = 0). Based on the third scenario (yellow bar), the energy consumption value is calculated by assuming that the elevation of bus routes is neglected (Ø = 0). Finally, in the fourth scenario (purple bar), the energy consumption value is calculated by considering the elevation of bus routes neglected (Ø = 0) with empty buses (number of passengers = 0).

The boxplots in Fig. 14 show the SoC levels of the whole bus routes for the Ampang area (Area One) before the charging process and after the charging process. In this context, during the discharging process, the state of the charger (SOC) is obtained by applying Equation (16) as follows:

$$\text{SOC}_i = \text{SOC}_0 - \frac{1}{C} \int_{t_0}^{t_i} \text{idt}$$  \hspace{1cm} (16)

where SOC$_i$ is the present value of the SOC, SOC$_0$ is the initial value of the SOC, C is the total capacity of the battery, and $\int_{t_0}^{t_i} \text{idt}$ is the integral of discharge current during the discharge process.

Focusing on the boxplot of each subfigure, the vertical dimension of the boxes shows the data variation, i.e., the top line of the boxes refers to the 75th percentile of the data, while the bottom line of the box is the 25th percentile. Note that the horizontal bold line located inside the box is the median or the 50th percentile. The ends of the whiskers (lines extending vertically from the boxes) represent the minimum and maximum values of all of the observations.

Specifically, the boxplots in Fig. 14(a) and (c) show the SoC levels of the battery at the beginning of a charging event to be processed with overnight charging and opportunity charging. The boxplots in Fig. 14(b) and (d) show the SoC levels at the end of a charging event by
overnight charging and opportunity charging. In the case of overnight charging, the SoC observations have a lower index compared to the SoC of opportunity charging status with the same battery size because opportunity charging is available in the bus terminals, which allows the buses to be charged after one journey. These diverse SoC levels result in a diverse range of charging profiles used in this study to create the spatial–temporal model. In this context, the main purpose of Fig. 14 is to classify the bus routes into two groups, where the first group of bus routes could be charged with opportunity charging and the second group of bus routes could be charged with overnight charging. This classification is presented based on the energy consumption results of the real-world data, which are assumed to be proportional to the trip distance. Therefore, the bus routes with low values of energy consumption per trip, which require a small battery size, could be charged with an opportunity charging approach. In addition, the bus routes with high values of energy consumption per trip, which require a large battery size, could be charged with an overnight charging approach.

4.2. Applying the energy consumption model to the existing Malaysia networks

4.2.1. MRN voltage constraints

This work demonstrated the potential impacts of voltage variations on the MRN to reduce the impact on the distribution networks. The voltage constraint of the MRN is identified by setting the upper and lower limits to correspond with the standard voltage regulation limits set by the Malaysia network. The voltage variation is set to ±5% ($V_{\text{min}} = 0.95\text{p.u}$ and $V_{\text{max}} = 1.05\text{p.u}$) for steady-state voltage levels of 6.6 kV, 11 kV and 33 kV under normal conditions [34].

$$V_{\text{min}} \leq V_i \leq V_{\text{max}}, \text{ for } i = 1, \ldots, n$$

(17)

where $i$ is the bus number, $n$ is the total number of buses or nodes, $V_{\text{min}}$ is the minimum voltage and $V_{\text{max}}$ is the maximum voltage.

4.2.2. Distribution network

The MRN is developed to study the impacts of BEB charging by
Fig. 13. Comparison of the energy consumption values in four scenarios according to bus routes U30, U103, U28, and U29.

Fig. 14. The SoC levels of the whole bus routes in Area One, (a) SoC levels before charging for buses using overnight charging, (b) SoC levels after charging for buses using overnight charging, (c) SoC levels before charging for buses using opportunity charging, (d) SoC levels after charging for buses using opportunity charging.
scheduling buses based on opportunity charging and an overnight charging approach. The total residential loads distributed through 108 low-voltage nodes and 16 nodes at 400 V feeders represent a selected central state in Malaysia. In this study, the 400 V feeder has four branches covering different districts with electric bus charging stations and one 11 kV feeder connected separately to the electric bus station hub. A total of nine charging nodes and 16 residential feeders were supplied from the main bus via 11 kV/0.400 kV and 33 kV/11 kV distribution transformers.

Fig. 15 shows the voltage profile based on the typical residential load profile for all nodes in Fig. 9 (before installation of the charging station), recorded at each hour over a 24 h period. As seen from Feeder 2, which contains five unused nodes, the voltage magnitude (p.u.) is at a maximum value of 1 because no load is connected at that particular feeder (voltages at the primary and secondary terminals of the transformer are equal). Meanwhile, in Feeder 1, three nodes (nodes 1101, 2601, 2801) are already utilized for residential purposes, where the voltage magnitude is 0.980 p.u. – 0.995 p.u. In addition, the voltage at the first node of the feeder is observed to be higher than the subsequent nodes, as the voltage tends to drop due to an increase in cable length (increase in impedance) from the first node to the fifth node. Next, in Feeder 3, four nodes are already utilized for residential purposes. Since more nodes are being utilized, the voltage (p.u.) of the nodes in Feeder 3 is observed to be lower than that of Feeder 1, i.e., in the range of 0.970 – 0.995. Moreover, the voltage magnitude is observed to be higher during the daytime (08.00 to 18.00) than at night (18.00 to 08.00). This is particularly due to high load demand during the nighttime.

Fig. 16. Bus voltages based on scheduled opportunity charging and overnight charging.
According to the voltage profile in Fig. 16, the estimated demand of BEBs in Section II has been scheduled (where the bus routes have been classified into opportunity charging and overnight charging) to be connected to the five 11 kV feeders, as illustrated Table C.1. The scheduling time is suggested based on the surveillance profile voltage in Fig. 16. In doing so, the charging opportunity (fast charging) is presented during the daytime, where the load is low during the daytime in the selected area (residential area network). However, overnight charging (slow charging) is offered at night, where the load is high at night.

By comparing Fig. 15 and Fig. 16, it can be clearly seen that there is an observable change to the voltage after integration of the BEBs to the grid. The scheduling of opportunity charging is revealed to have a greater impact on the distribution system performance compared to overnight charging. Focusing on the day-time period between 07:00 AM to 19:00 PM, the voltage profile is observed to have dropped significantly, with the worst voltage value of 1p.u. recorded at node 5701 (refer to Appendix D). The lowest voltage recorded during the daytime is 0.975p.u., which is still compliant with the minimum voltage regulation limit of 0.95p.u. The main finding of opportunity charging shows that there is a serious impact on the grid voltage. Therefore, based on this impact, overnight charging is not recommended in this research.

For overnight slow charging, it can clearly be seen that the voltage magnitude is not significantly affected, even at times between 22:00 PM and 12.00 AM (where the load demand is the highest in the residential area). For instance, the voltage magnitude for the worst affected node 10,201 (refer to Appendix D) still remains at 0.955p.u. According to the main findings obtained for overnight charging, it can be recommended that the unused nodes at Feeders 1, 2 and 3 of the current MRN distribution network can potentially be utilized as overnight charging stations for battery electric buses (BEBs) by considering the suggested schedule.

5. Conclusion

Planning for the installation of BEBs in the current public transport systems requires cautious considerations, which include but are not restricted to identifying the best routes for electrification, selecting a BEB model, the battery size and the suitable charging policy. Nevertheless, the initial important stage in the installation plan is to estimate the energy required to operate the electric buses in the existing bus lines. Practically, this will be very challenging because of the shortage of readily obtainable data, especially for large transportation networks.

This paper presents an integrated model that integrates digital elevation and longitudinal dynamics models to overcome these issues while enabling the utilization of current real system-wide data.

A novel framework has been successfully developed in this paper to estimate the energy demand of BEBs using real-world data. The charging strategy has been classified into opportunity and overnight charging to be integrated into a residential distribution network. A case study was used to investigate the impact of the uptake of BEBs on distribution networks.

There are still many challenges remaining as electric bus charging unfolds in future Malaysian distribution systems. For example, the unmanaged charging topology that occurs in random arrivals and departures of the electric bus in residential networks has a large impact on the current distribution system. Some electric buses may require opportunity charging during the morning despite a higher electricity tariff during the peak load hours, whereas this charging should occur through normal (overnight) charging. The next step of this study proposes an electric bus management system (EBMS) that considers the affected parameters that could impact the distribution network or bus efficiency, including an electricity tariff. It is also possible to install renewable energy-based charging stations to relieve the harmful influence of opportunity charging systems. Based on the simulated result, it is recommended that the number of opportunities charging connections be reduced during the hours of 22:00 – 23:00 h. In future work, an optimization algorithm would be developed to find the optimum size of photovoltaic-grid-BEB charging components, which could be used for supporting load balancing, regulating voltage and frequency, reducing peak-loads, and increasing the adoption of renewable energy.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors would like to thank and acknowledge the Universiti Tenaga Nasional (UNITEN) BOLD Publication for funding this research. Funding: This work was supported by Universiti Tenaga Nasional BOLD Publication Fund [grant number RJ010436494/IRMC/Publication/2019.

Appendix A

The total required mechanical force (F_r) at the wheels, as a function of the kinematic parameters describing vehicle movement, can be expressed in the bus dynamics equation according to Newton's second law.

\[ F_r = F_r + F_a + F_g + F_i \]

where \( F_r \) is the rolling resistance, which is the frictional resistance offered by the road due to the motion of the wheels:

\[ F_r = C_r M g \cos \phi \]

\( C_r \) is the coefficient of rolling resistance; \( M \) is the total mass (bus mass and passenger weights) of the bus in \( k_e \); \( g \) is the acceleration due to gravity9.81 m/s\(^2\); and \( \phi \) is the angle of inclination (in rad).

Hence, the value of \( \phi \) is obtained by applying the DME of the spatial model.

\[ F_i = M \sin \phi \]

\( F_i \) is the grade force, which originates from the road slope:

\[ F_i = M g \sin \phi \]

This is the aerodynamic drag force:
\[ F_a = \frac{1}{2} \rho C_d A (v - w)^2 \]  

(A.4)

is the density of air in \( k_g/m^3 \), the value of the density of air (\( \rho \)) changes with variations in temperature and humidity; \( C_d \) is the drag coefficient of the bus frontal cross-sectional area in \( m^2 \); and \( w \) is the wind speed in the bus driving direction in \( m/s \). \( F_t \) is the transient force required to accelerate or decelerate the BEB:

\[ F_t = (M + m_f) \frac{dv}{dt} \]  

(A.5)

\( m_f \) is the fictive mass of rolling inertia in \( k_g \).

\[ F_t = C_d M g \cos \phi + M g \sin \phi + \frac{1}{2} \rho C_d A (v - w)^2 + (M + m_f) \frac{dv}{dt} \]  

(A.6)

Appendix B

Table B.1.

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<th>Nominal capacity</th>
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<tr>
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Appendix C

Table C.1.

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Appendix D

References


