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Bus-to-Grid Integration of Battery Electric Buses Charging by a Photovoltaic-Grid Network

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ABSTRACT

To mitigate greenhouse gas emissions from the transportation and electricity sectors, a large-scale adoption of battery electric buses (BEBs) and photovoltaic solar energy is planned in the upcoming decades. Nevertheless, the integration of these technologies may result in a mismatch between electricity demand and supply. This paper addresses these challenges by proposing a generic framework of different technologies that involves calculating the energy consumption of battery electric buses, sizing the photovoltaic charging system, and scheduling bus-to-grid integration. The energy consumption of a large-scale BEB network is calculated by applying well-to-wheel (WTW) assessment and combining the Geographical Information System combined with the longitudinal dynamic model. Particle swarm optimization is also applied to size the charging system. A voltage profile based on a typical residential or commercial load profile is required in scheduling the energy storage of BEBs, support load power balancing, and regulate the voltage and frequency of the power grid. Real-world data on the Rapid Penang bus network of Malaysia, Space Shuttle Radar Topography Mission, and Malaysia Representative Network are used to validate the proposed framework. This framework provides the necessary groundwork for a further examination of charging infrastructure requirements, photovoltaic charging sizes, battery sizes, and bus-to-grid technology scheduling.

Keywords: battery electric bus, photovoltaic-grid charging, geographical information system, energy demand, particle swarm optimization

1. INTRODUCTION

The electricity and transportation sectors are major contributors to greenhouse gas (GHG) emissions [1]. Therefore, over the past decade, the mitigation of GHG emissions from these sectors has received much attention from the academia and the manufacturing sector with an aim to reduce reduction global GHG emissions. Transportation electrification can increase the electricity demand, significantly alter its spatial-temporal patterns, and affect the electricity supply of existing infrastructure [2,3]. However, the expansive electrification of transportation is hindered by several factors. Addressing these barriers may require an upgrading of the electricity supply infrastructure and a modernized expansion of electrical grids. New development opportunities also emerge from the growing interdependency between the transportation sector and stationary electric power generation, the latter of which is increasingly based on renewable energy sources. Such opportunities are particularly relevant nowadays with the upcoming introduction of battery electric buses (BEBs), which can offer several benefits such as the prospective diffusion of bus-to-grid integration (BGI) technologies that can support load balancing, buck-up electricity power, regulate voltage and frequency, reduce peak loads, minimize the uncertainty in grid load forecasts, and promote the adoption of renewable energy [4].

The energy demand of each bus route has to be determined over an entire day under different traffic conditions to plan the BEB network and to determine the optimum battery capacity. Previous studies have proposed numerous approaches for estimating the energy consumption of BEBs, which can be classified into simulation models and actual measurements [5].

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The adoption of photovoltaic BEBs (PV-BEBs) has expanded to significantly reduce the cost of PV modules, support the rapid growth of BEBs, increase the efficiency of PV charging systems, and mitigate their impacts on the power grid. BEB charging stations that consume the energy produced by PV panels at daytime can be classified into PV-standalone, PV-grid, on-board PV, and mobile PV technologies. All related features of PV charging, including power converter topologies, charging mechanisms, and control for both PV-grid and PV-standalone, have been summarized in [6]. These authors have investigated how a PV mounted onboard a BEB affects the stored energy consumption of buses and the lifespan of vehicle batteries. In [7], the authors showed that OBPV can reduce battery size based on the simulation results reported on a single clear day [8]. By suggesting 20-foot container, authors in [9] built a mobile PV charging system comprising PV panels, MPPT controllers, a back-up generator, and battery packs.

Previous studies that integrate BEB energy storage into PV-grid charging have largely ignored the modelling of large-scale networks in developing solutions to the challenges being faced by large-scale bus networks. To fill such gap, this paper presents a novel framework for establishing a PV-BEB model that can support the electrification of global bus networks. This framework is based on the Geographical Information System (GIS) model, which calculates the elevation values over the topographic surface of bus routes. The longitudinal dynamics model (LDM) is also developed to estimate the BEB energy consumption of bus networks. To size a PV charging system, a particle swarm optimization (PSO) algorithm based on hourly solar radiation data has been introduced. The generic distribution network of a specific region is required in scheduling the energy storage of BEB. As shown in Figure 1, these models comprises three stages as follows:

a) **Estimation of BEBs energy demand:** The energy demands of BEBs for large-scale networks are accurately estimated via a well-to-wheel (WTW) assessment.

b) **PV-Grid:** The PV-grid charging stations are sized by using the PSO algorithm to fully charge the battery.

c) **BGI technology:** A massive stored energy in BEBs is modelled and supplied to the power grid.

The proposed framework can be applied straightforward to different large-scale bus networks and can handle the problems encountered in practice. The contributions of this study are summarized as follows:

a) This study formulates builds on a current bus network to formulate a comprehensive generic framework for calculating the energy demand of BEBs.
b) This study plans the integration of BEBs into PV-grid charging and the replacement of diesel buses with BEBs in transportation networks.
c) A case study is performed by using a real dataset of the entire bus network of Penang Island in Malaysia.

This paper is organized as follows. Section 2 discusses the WTW assessment for determining the energy demand of BEBs. Section 3 presents the PSO algorithm for sizing PV-Grid-BEB charging components. Section 4 introduces the BGI technology. Section 5 describes the application of the framework in a case study of Penang Island in Malaysia. Section 6 outlines the environmental aspects of this study. Section 7 concludes the paper and provides suggestions for future work.

2. WTW ASSESSMENT

This section estimates the energy consumption of BEBs based on an WTW assessment. WTW analysis is an assessment method used to compute the energy flowing from the well (or where the energy is generated) to the bus battery (WTB) and from the battery to the wheels (BTW).

2.1 WTB Assessment

The omission of efficiency variation under varying conditions may lead to increased electricity losses and operation costs. Power losses are particularly problematic for high-duty cycles, such as grid-to bus-integration (GBI) functions. Likewise, when charging electric buses, power losses occur in the power grids and charging stations supplying the buses. Therefore, WTB assessment is required to evaluate the energy losses during the charging of buses. To achieve WTB assessment, power flow analysis, which yielded the power losses is essentiality require. The lines and transformers in BEB charging stations are considered in the assessment. The BEB charging stations have an alternating current, and the voltage is adjusted to the required level by using a DC/DC converter.

The energy losses in the power supply network can be computed by using the following equations:

$$E_{HV} = \sum_{i=1}^{N} \int_{t_i}^{t_i+t_c} V_{HV}(t)\, I_{HV}(t)\ dt, \tag{1}$$

where E_{HV} is the input energy supply for a BEB charging in the high voltage (HV) side, $V_{HV}(t)\ and\ I_{HV}(t)$ are the voltage and current for a BEB charging in the HV side, t_i and t_c are the starting time and charging duration, respectively, and N is the number of roundtrips.

$$E_{LV} = \sum_{i=1}^{N} \int_{t_i}^{t_i+t_c} V_{LV}(t)\, I_{LV}(t)\ dt, \qquad (2)$$

where E_{LV} is the output energy supply for a BEB charging in the low voltage (LV) side, whereas $V_{LV}(t)$ and $I_{LV}(t)$ are the voltage and current for a BEB charging in the LV side, respectively.

$$E_{AC_{in}} = \sum_{i=1}^{N} \int_{t_i}^{t_i+t_c} V_{AC}(t)\, I_{AC}(t)\ dt, \qquad (3)$$

where $E_{AC_{in}}$ is the input energy of the AC/DC converter for a BEB charger, whereas $V_{AC}(t)$ and $I_{AC}(t)$ are the voltage and current in the input of the AC/DC converter for a BEB charger.

$$E_{DC_{out}} = \sum_{i=1}^{N} \int_{t_i}^{t_i+t_c} V_{DC}(t)\, I_{DC}(t)\ dt, \qquad (4)$$

where $E_{DC_{out}}$ is the output energy of the AC/DC converter for a BEB charger, whereas $V_{DC}(t)$ and $I_{DC}(t)$ are the voltage and current in the output of the AC/DC converter for a BEB charger.

$$\eta_{HV-LV} = \frac{E_{HV} - E_{LV}}{E_{HV}} \qquad (5)$$

$$\eta_{AC_{in}-DC_{out}} = \frac{E_{AC_{in}} - E_{DC_{out}}}{E_{AC_{in}}} \qquad (6)$$

2.2 BTW Assessment

The energy consumption of electric buses should be estimated based on mission-related kinematic factors (e.g., bus routes characteristics, stops/km, travel time, and driving aggressiveness) and bus-related factors (e.g., moto drive efficiency, auxiliary power consumption, ambient temperature, and payload).

2.2.1 Data

High-accuracy spatial and temporal data, including Space Shuttle Radar Topography Mission (SRTM) and GPS tracking bus data, are required in the assessment as will be discussed in the following sections.

2.2.1.1 Geospatial Data

RTM is an international project spearheaded by the US National Geospatial-Intelligence Agency (NGA) and NASA. SRTM data are used to generate a digital elevation model with a resolution of 1 arc-second for global coverage by approximately 30 meters and 3 arc-seconds for global coverage by around 90 meters.

2.2.1.2. Temporal Data

The acceleration and deceleration of driving mode can be formulated by using a GPS tracking system. The current position of a bus is determined by installing a GPS device on the bus, and the coordinates of this bus are sent by either the GPRS service provided by GSM networks or satellite systems. The information collected by the GPS device is sent to a centralized control unit or directly to bus stops that use RF receivers.

2.2.2 LDM

An LDM is developed to determine the energy consumption of BEBs in a large-scale bus network based on the collected data described in the previous section. The total required mechanical energy (E) at the wheels can be expressed as follows as a function of the kinematic parameters that describe bus movement:

$$E = \frac{\eta}{3600}\Bigg[(MgC_r\ cos\phi) + (Mgsin\phi) + \left(\frac{1}{2}pAC_d(v-w)^2\right) + \left(\left(\ M + m_f\right)\frac{dv}{dt}\right)\Bigg] d, \qquad (7)$$

where η is the overall powertrain efficiency between the battery and wheels, M is the total mass in kg, C_r is the coefficient of rolling resistance, ϕ is the angle of inclination in rad, g is the acceleration due to gravity 9.81 $m/(s^2)$, A refers to the bus frontal cross-sectional area in m^2, C_d is the aerodynamic drag coefficient, v is the bus driving velocity in m/s, and w is the wind speed in the bus driving direction in m/s.

3. SIZING PV-GRID-BEB CHARGING COMPONENTS

The PSO technique has been identified as an effective sizing tool given its many advantages, including its robustness, easy implementation, and global convergence capability. This study then employs the PSO algorithm to determine the optimum size of PV-Grid-BEB charging components. This algorithm is further described as follows:

Number of particles (k): At this stage, the candidate solutions of multiple particles within the feasible solution space associated with the position of particle $\lambda_s(n)$ are randomly generated. The outcome of this stage is the structure of each particle, which comprises multiple parameters of the PV-Grid-BEB charging configuration.

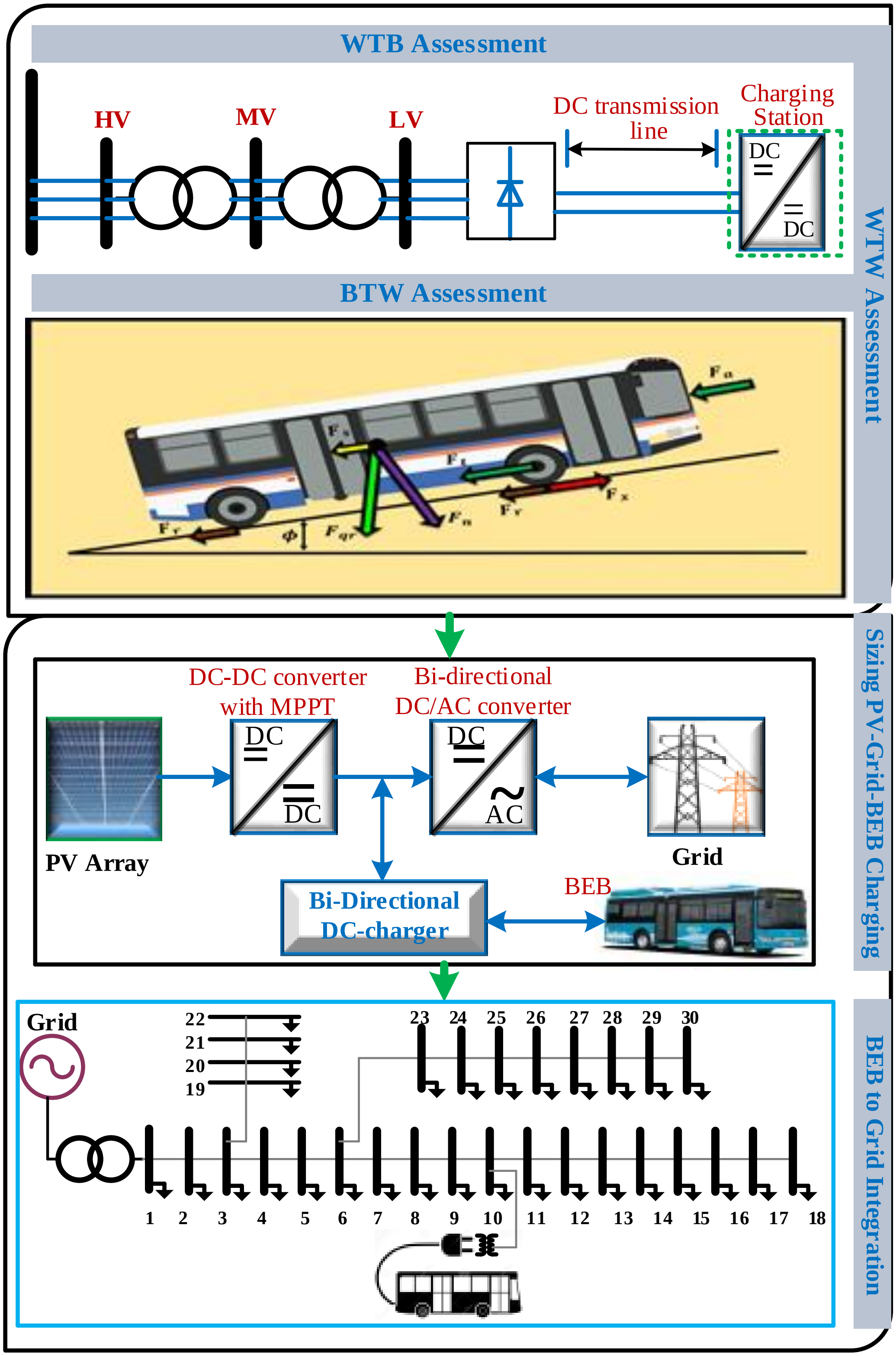


Fig. 1 Three-stage block diagram of the proposed framework.

Fitness value: The current objective function is evaluated in the optimization problem.

Comparison of particles: The fitness value in the current iteration is compared with the prior best. The group best (gbest) and individual best (pbest) are also updated at this stage.

Velocity evaluation: The magnitude and direction of each particle, denoted by $u_s(n)$, are evaluated at this stage. The position and velocities of the particles are then updated by applying the following equations:

$$\lambda_s(n+1) = \lambda_s(n) + u_s(n+1) \tag{8}$$

$$u_s(n+1) = \omega.\, u_s(n) + \alpha_1.rand_1.\left(pbest_s - \lambda_s(n)\right) + \alpha_2.rand_2.\left(gbest_s - \lambda_s(n)\right), \tag{9}$$

where α₁ and α₂ are the values of acceleration parameters, whereas rand1 and rand2 are uniform random numbers ranging from 0 to 1.

Repeated procedures: To meet the termination criteria, stages (b) to (d) should be repeated.

4. BGI TECHNOLOGY

The BGI requirements are satisfied in the following stages:

4.1 Newton–Raphson flow analysis

In an electrical grid, Newton–Raphson flow analysis is applied at different load levels to compute the voltage at each node, the total power generation, and the losses until convergence. In this context, models of the trial networks can be developed by using a power flow software.

4.2 Bi-directional chargers

At this stage, the battery capacities and discharging requirements are determined based on real-world bus route calculations. During the BGI operation mode, the converter operates as a boost converter to elevate the battery voltage to an adequate DC-bus voltage in order to guarantee the successful operation of the bidirectional AC–DC power converter.

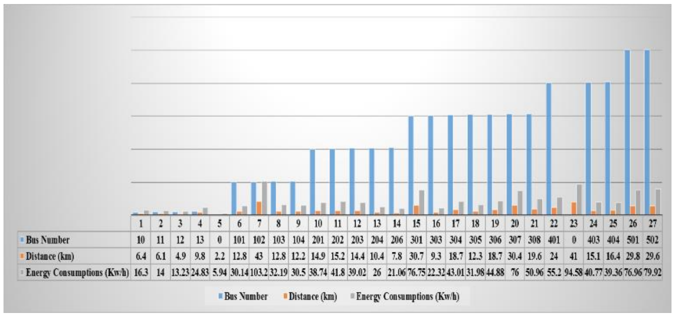
4.3 Scheduling

In BGI technologies, the scheduling strategy of a BEB energy storage can enhance the efficiency and reliability of electric grids. Therefore, the operation of this scheduling can support load balancing power and regulate the voltage and frequency of the power grids. The scheduling time is determined based on the representative profile voltage of an electrical grid.

5. APPLICATION OF THE FRAMEWORK IN A CASE STUDY OF PENANG ISLAND, MALAYSIA

Rapid Penang is a public transportation network operating across Penang Island, Malaysia. Rapid Penang has a daily ridership of 94,185 passengers, and its longest line is the 102 bus route that traverses 43 km from Lapangan Terbang to Hub Teluk with 111 bus stops. Meanwhile, the shortest line of Rapid Penang is the JF bus route, which traverses from Juru Feeder to Penang Bridge. The exterior and interior aspects of the chosen BEB, including a bus weight of 12000 kg, average bus capacity of 60 passengers, frontal bus area of 7.5 m^2, bus drag coefficient of 0.6, and rolling resistance of 0.01, are considered in the development of the BEB energy consumption model. In the case study, the GIS technique is applied to obtain the gradient data of Rapid Penang bus routes (every 30 meters). The estimated BEB energy consumption values in Figure 2 are obtained by using equation (7) and the collected data. This figure also shows the estimated BEB energy consumption values of Area One bus routes in Penang Island.

Figure 3 presents the voltage profile based on a typical commercial load profile in Penang Island before the installation of a charging station. This profile is recorded within a 24 h period at 1 h intervals. According to the voltage profile in Figure 4, the estimated demand of BEBs as shown in Figure 2 has been scheduled with a 50 kW charging standard. The voltage profile in Figure 5 is measured based on two partitions, with the first partition (PV-grid-BEB) supporting the grid from 7 AM to 7 PM and the second partition (BGI) supporting the grid form 12 AM to 2 AM.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
▪ Bus Number	10	11	12	13	0	101	102	103	104	201	202	203	204	206	301	303	304	305	306	307	308	401	0	403	404	501	502
▪ Distance (km)	6.4	6.1	4.9	9.8	2.2	12.8	43	12.8	12.2	14.9	15.2	14.4	10.4	7.8	30.7	9.3	18.7	12.3	18.7	30.4	19.6	24	41	15.1	16.4	29.8	29.6
▪ Energy Consumptions (Kw/h)	16.3	14	13.23	24.83	5.94	30.14	103.2	32.19	30.5	38.74	41.8	39.02	26	21.06	76.75	22.32	43.01	31.98	44.88	76	50.96	55.2	94.58	40.77	39.36	76.96	79.92

Fig. 2 Estimated BEB energy consumption values in Penang Island, Malaysia.

6. THE ENVIRONMENTAL ASPECTS OF THIS STUDY.

With the shift on renewable energy resources for electricity generation, the interdependency opportunities and increase of new technologies between electric power generation and BEBs are evolving that includes PV-BEB integration systems. This new growth of PV-BEB integration system became the introduction of increasing BEBs technologies to be considered a promising option for GHG issues, while also providing a reliable and cost-effective option for cities.

7. CONCLUSIONS

The electrification of buses by using the PV-grid-BEB charging system and BGI technology is explained in this paper. BEB charging by using the PV system is highly recommended by bus manufacturers because of its potential in reducing global warming and GHG emissions.

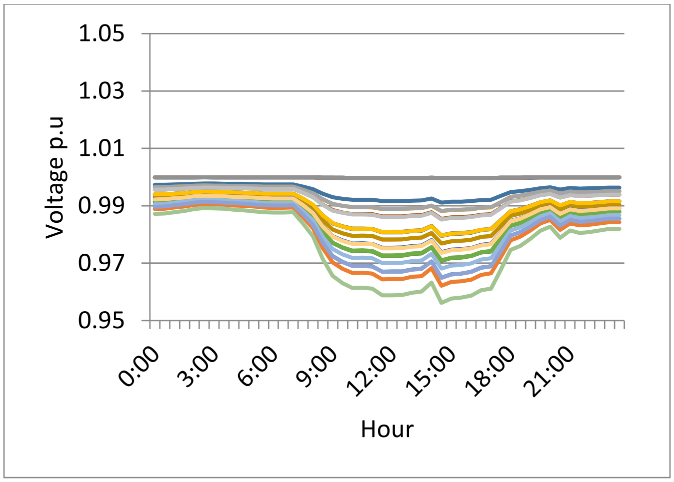


Fig. 3 Voltage profile based on a typical commercial load profile in Penang Island (without connecting BEB charging).

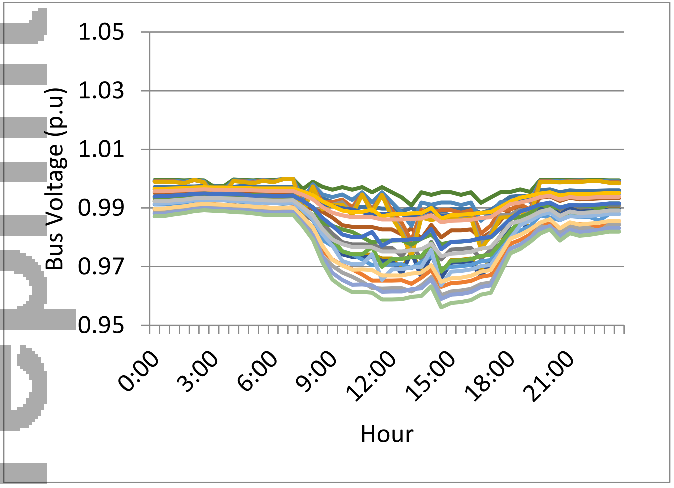


Fig. 4 Voltage profile based on a commercial load profile in Penang Island (with connecting BEB charging).

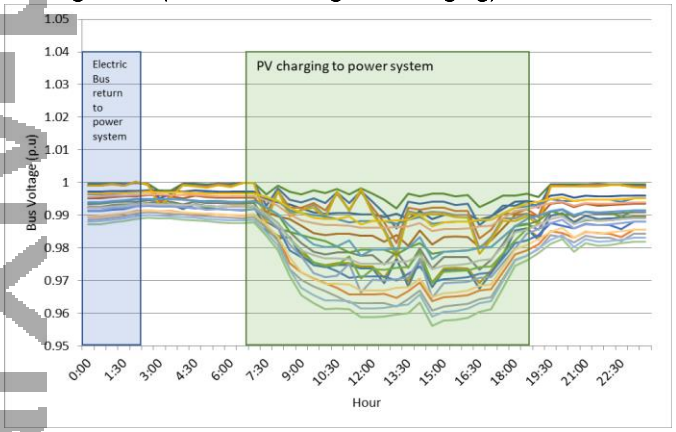


Fig. 5 Voltage profile of a commercial load profile in Penang Island measured by PV-grid-BEB and BGI.

This paper also explains in detail the WTW assessment for estimating the energy consumption of BEBs. A PSO algorithm is also designed to accomplish an optimal sizing of PV-grid-BEB charging components. This study also highlights significant enhancements in a power grid by considering the adaptability of BGI technologies. To evaluate the proposed framework, a case study of Penang Island, Malaysia is conducted by using real-world data.

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