On Feasibility of Ultracapacitor Full Electric Transit Bus for Jakarta, Indonesia

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***Abstract*—Electric vehicles (EVs) and its technology, including the EVs storage system are getting the attention in the last decade. So far, batteries have been the most common storage type for EVs. However, several storage technology alternatives are being considered recently, including ultracapacitors (UCs). One prominent characteristic of UC is its high power density –can be up to hundreds times of Li-ion power density– enabling it to be charged or discharged with high power. On the other hand, UC has lower energy density, causing EVs with UCs as sole energy will not have long range. Thus, in electric cars, UCs are more common to be hybridized with batteries as complementary storage. However, as opposed to private cars, transit vehicles such as buses or trams have specific routes and stops with predefined distance. This particular characteristic of transit vehicles is potential to be fulfilled by UCs only, as the UC energy capacity is sufficient for a single route, and afterward it can be fully charged in a few minutes. This paper will present a feasibility study of a UC pure electric transit bus specific to Jakarta, Indonesia. Comparison of battery and UC system for the bus will be presented from both technical and economic aspects.**

Keywords—batteries, ultracapacitors, electric vehicle, electric bus, life cycle cost.

I. INTRODUCTION

Global warming crisis related to fossil fuel consumption has led the world in recent years towards alternative energy. Electric vehicles (EVs) and its technology are getting a steady position in the world's market today. Different types of EVs can be loosely categorised into hybrid electric vehicles (HEVs) –which combines electric propulsion and internal combustion (IC) engine– and another type which utilises only electric propulsion system. References name the latter type in various ways such as full EV, full EV, or sometimes battery EV (BEV), specifically when the only electric source or energy storage is battery [1][2].

It is unquestionable that nowadays the most common energy storage for EVs is batteries. Among other types of storage, batteries have a high power-to-weight ratio as well as high energy density. On the other hand, there are some downsides of batteries owing to its electrochemical related storage mechanism. One of them is thermal vulnerability of batteries, because of which thermal runaway could occur, leading to fire [3]. Some of the documented BEV fire accidents including fire in the parked vehicle, fire while being charged, as well as while being driven [4]. Another limitation of using battery is that although its energy density is high, usually its power density is not. It is common that EV battery system is being oversized in terms of energy to meet power requirements of the EV [5], otherwise the battery should have high discharge and charge C rate [6]. This drives the growing research of using alternative energy storage such as ultracapacitors (UCs).

UCs characteristics are complementary to that of batteries, such as high power density and faster charge duration. Unlike batteries, energy storage mechanism of UCs does not involve chemical reaction. Therefore, its cycle life is theoretically unlimited and the thermal risk is much lower. However, an inherently lower energy density than batteries is the reason why UCs are rarely used as a sole energy source for EVs, as its low energy density will affect the vehicle range. Instead, it is common that UCs are hybridised with batteries to get an advantageous characteristic combination of both storages [7]–[9].

Despite the downside of UCs affecting vehicle range, transit vehicles such as buses and trams can potentially be powered by UCs only. This is because generally, transit vehicles have specific routes and stops with predefined distance, from which the UCs can be sized accordingly. Some full UC bus fleets are already in operation in different parts of the world including China, Israel, Italy, Hong Kong, and few other countries, as summarised in [10].

In Indonesia, research and interests in the topic of EVs has been improving in the last ten years [11], [12]. One most recent and notable milestone is the signing of the presidential regulation of BEV program acceleration in 2019. The state-owned utility company (PLN) has also installed a number of charging stations with the charging power level of 25-kW, 50-kW, 125-kW and 150-kW [10], [13]. Also in the same year, a main bus operator in Jakarta, PT. Transjakarta, trialled few electric buses and planned to launch the service in 2020 [14].

A preliminary study on the feasibility of UCs full electric bus for the Transjakarta route has been published in [10]. The route data was averaged from all Transjakarta operating routes. The bus energy consumption was approximated from existing UC bus with similar route distance. The study shows that full electric bus powered by UCs only has the potential to serve the Transjakarta route, considering the capacity of the planned charging stations.

The objective of this paper is to explore further this feasibility in more details, including from the economical aspect, specifically for Jakarta, Indonesia. It is also expected that results in this paper will contribute to the few existing publications particularly related to UC-powered full electric bus.

From the economical point of view, many papers analysing economic feasibility of UC system conclude similar result. In reference [8], which compared costs of battery-only, UC-only, and hybrid system electric city bus, although the initial cost is the highest among all, the total energy storage cost per 100 km and per 500,000 km is the lowest for the UC-only system. However, typical drive cycle was used in this paper.

In reference [15], a particular route of 4.23 km in Kharkiv, Ukraine, was chosen to compare battery-powered and UC-powered electric bus. The reference proposed higher technical and economic indexes to the UC system, in particular due to its longer service time compared to battery. The route used for the analysis is also a short distance route, making it even more prospective.

Hence, in this paper a driving cycle specific to the route for planned Transjakarta electric buses is considered. The route is built in the simulation to calculate the bus energy consumption. Sizing of both battery-only system and UC-only system is performed for comparing the two storage systems. Life cycle cost comparison will also be presented. Costs will also be shown in Indonesian currency to give a better understanding.

The paper is organised as follows. Materials and method in Section 2 includes the Transjakarta drive cycle used in this study is and its parameters for simulation as well as sizing of the battery and UC system. The results and discussion including the economic aspect is given in Section 3, and finally this paper is concluded in Section 4.

II. Materials and Methods

First, a specific driving cycle is built in ADVISOR (Advanced Vehicle Simulator). ADVISOR is a MATLAB/Simulink-based vehicle simulator developed by National Renewable Energy Laboratory. Information on how ADVISOR works, input and output parameters, as well as other details can be found in its documentation website [16].

Next, based on ADVISOR simulation, the energy requirement based on the driving cycle is used to size the battery only system, and UC only system, which will be compared. Finally, these two systems will be compared economically.

A. *Transjakarta Drive Cycle*

The selected route used in this paper is Blok M – Kota route which is planned to be served by the electric bus. Information about the route is shown in Fig. 1 [17]. The total distance and travelling time are approximately 13.9 km and 49 minutes, respectively. The drive cycle is built according to ADVISOR drive cycle input format consisting of two columns: time and speed. To get the data of these two columns, we match the time needed to get from one stop to another based on Trafi, real-time tracker application of city buses [18]. The resulting drive cycle can be seen in Fig. 2.

Fig. 1. The Blok M – Kota route and its information [17].

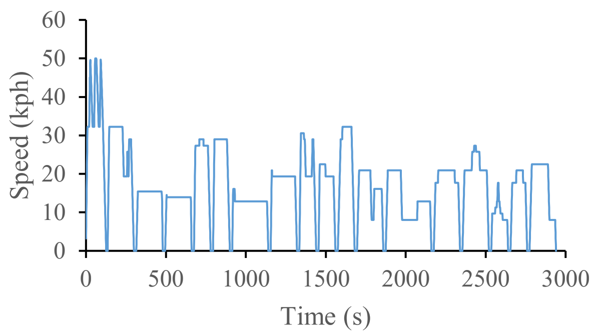

Fig. 2. The Blok M – Kota route drive cycle.

Two manufacturers of the Transjakarta electric buses are BYD and PT Mobil Anak Bangsa (MAB) and the specifications of the selected buses from both manufacturers are similar [10], [14]. For this study, the energy consumption was generated from ADVISOR using the available specifications from MAB MD12E and BYD K9. Other required specifications for the ADVISOR input are taken from the default ADVISOR data of RTS-06 40-foot transit bus. The bus dimension and parameters are shown in Fig. 3 and Table 1.

Specifications of the bus permanent magnet synchronous motor (PMSM) is based on a Siemens PEM motor 1DB2022 and are shown in Table 2.

In ADVISOR, the "motor/controller" block translates the required torque and speed to required electric power and converts the actual input power into output torque and speed. ADVISOR default setting of efficiency of each part is used, with the motor efficiency map adjusted to the data. The resulting required power based on a single drive cycle is shown in Fig. 4. Based on the graph, total required energy for a single drive cycle is 14.385 kWh with a total route length of 13.894 km, resulting an energy consumption of 1.035 kWh/km. Peak power requested is 251.853 kW.

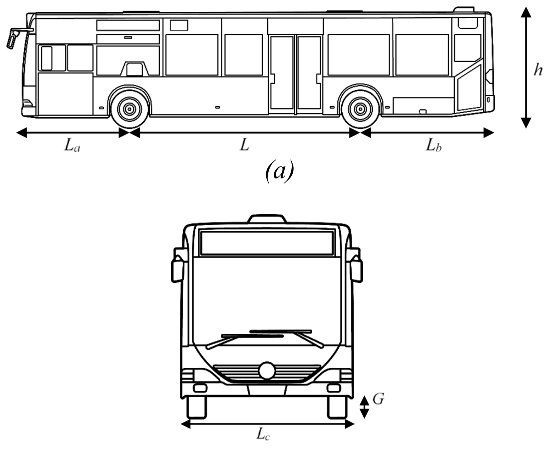

Fig. 3. Bus dimension: (a) Side view; (b) Front view [19].

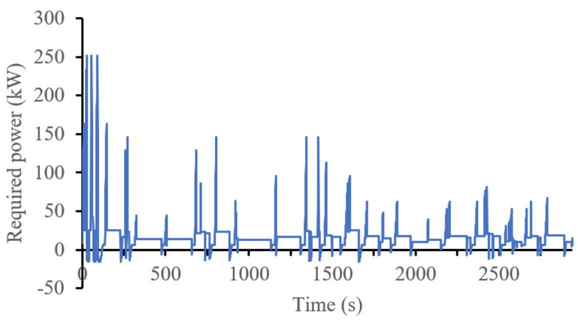

Fig. 4. Required power based on the driving cycle and vehicle specification.

B. Battery and Ultracapacitor Sizing

In this section, batteries and UCs are sized based on the required power shown in the previous section. Power balance calculation is also emphasized here to spot the difference between batteries and UCs.

The configuration considered for this study is shown in Fig. 5, in which a storage system (either battery or UC system) is connected to the electric motor directly or via a converter (can be either AC/DC or DC/DC converter).

The battery and UC modules used for this study are shown in Table 3. From the specifications shown in the table, there are few notable differences between the two storages which consequently will affect the sizing process and result.

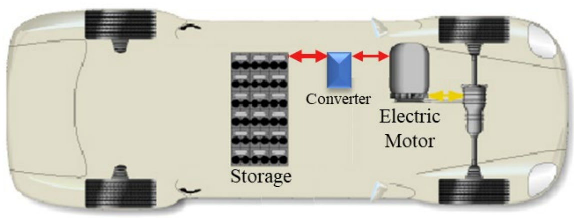

Fig. 5. Electric bus power system configuration. Figure is modified from ADVISOR input page.

TABLE I. BUS PARAMETER

Parameters	Notation	Value	Unit
Height	h	3.72	m
Frontal area	A	7.89	m^2
Distance between front and rear axle	L	6.1	m
Ground clearance	G	0.25	m
Width	L_c	2.5	m
Total mass	m	16,000	kg
Drag coefficient	C_D	0.79	-
Rolling coefficient	C_r	0.00938	-
Air density	ρ_u	1.23	kg/m^3
Gravitational acceleration	g	9.81	m/s^2
Wheel diameter	D	1.006	m

TABLE II. MOTOR SPECIFICATION

Parameters	Value
Rated voltage	650 V
Rated power	200 kW @1500 rpm
Rated torque	2,000 Nm @320 A
Max. torque	3,800 Nm @600 A
Max. speed	3,500 rpm
Weight	480 kg
Dimension	620 mm x 510 mm x 500 mm

TABLE III. BATTERY AND UC SPECIFICATION

Parameters	BYD B-Plus 2.5	Maxwell BMOD0165P048C01
Voltage	51.2 V	48 V
Capacity	50 Ah	165 F
Energy	2.45 kWh	0.053 kWh
Maximum power	2.56 kW	91.2 kW
Weight	34 kg	14.2 kg

First, the energy and the maximum power capability of the storages. While the single cell parameters information is not available, it is apparent that the battery module has much higher available energy than the UC module. On the other hand, the UC module has much higher peak power compared to that of the battery module.

III. RESULTS AND DISCUSSION

A. Ultracapacitor System

1) Sizing based on voltage, energy, and peak power requirement

For UC module, based on the motor working voltage there should be 14 UC modules in series. Hence, the total available energy for the 14-module UC series string the total energy is 742 Wh.

For the UC energy calculation, the UC working voltage range should be considered, which are 650 V of maximum voltage and 325 V of minimum voltage in this study. The UC module capacity is calculated as below.

$$E_{UC} = \tfrac{1}{2} C \left(V^2_{min} - V^2_{max}\right) \quad (1)$$

where E_{UC} is the UC useable energy (in Joule; converted from 14.385 kWh), C is UC capacitance, and V_{max} and V_{min} are UC maximum and minimum working voltage, respectively. Selected V_{max} is 650 V while V_{min} is 325 V. The calculation yields total capacitance of 325.15 F which is fulfilled by 28 paralleled strings, resulting in total energy of 20.78 kWh. The parameters for this configuration is shown in Table 4.

The peak power capability of the 14S28P UC module is 14 × 28 × 91.2 kW = 35,750 kW, more than enough to cover the peak power requirement of 251.85 kW.

2) Charging scenario

Based on the calculation in the previous section, the UC module could fulfil the energy and peak power requirement of a single drive. Hence, a scenario of charging the bus for each single drive cycle is considered. In this study, we assume that the UC system could be charged using any of the 25-kW, 50-kW, or 125-kW available charger stations. The UC system is capable to be charged based on those three different charge rates and the charging duration is presented in Table 5.

TABLE IV. BATTERY AND UC SPECIFICATION

Parameters	UC system 14S8P configuration	Battery system 13S8P configuration
Voltage	672 V	656.6 V
Capacity	330 F	400 Ah
Energy	20.78 kWh	254.68 kWh
Maximum power	35,750 kW	266.24 kW

TABLE V. UC SYSTEM AND BATTERY SYSTEM CHARGING DURATION

Parameters	Charging duration	
	UC system	*Battery system*
25 kW	50 minutes	10 hours 7 minutes
50 kW	25 minutes	5 hours 4 minutes
125 kW	10 minutes	2 hours 22 minutes

From the table, fully charging the UC system takes only 10 minutes. Hence, using the charger with the highest rate make it possible to charge the bus UC system after each drive cycle is completed, given that this charger is available at the start and end terminal of the route. This would enable the bus to continuously operate the whole day. The estimation of the bus operation related to economical aspect is presented in Section 4.

B. Battery System

1) Sizing based on voltage, energy, and peak power requirement

To fulfil the motor working voltage, the batteries as well as the UCs need to be connected in series, and this calculation dictates the number of series-connected modules. With a working voltage of 650 V, there should be 13 battery modules in series. Hence, the total available energy for the 13-module battery series string is 31.85 kWh.

The energy balance calculation will determine the required number of paralleled strings. In Section II we have seen the required energy for a single drive cycle is 14.38 kWh which can be fulfilled by the 13-module series string. The string maximum power is 13 × 2.56 kW = 33.28 kW, lower than the required peak power of 251.85 kW.

Hence, for a single drive cycle, the battery sized based on the energy balance cannot satisfy the peak power requirement. Adjusting the size based on peak power requirement yielding battery configuration of 8 paralleled strings. The parameters for this configuration is shown in Table 4.

With this amount of energy, the battery could cover around 15 times the single drive cycles, approximately 208.41 km. However, this range capability trades off with the charge duration, again due to the peak power capability, especially during charging.

2) Charging scenario

In this study, we assume that the bus could be charged using any of the 25-kW, 50-kW, or 125-kW available charger stations. The battery charging duration is presented in Table 5.

Fully charging the battery systems will take 607 minutes (10 hours 7 minutes) using the 25-kW charger or 304 minutes (5 hours 4 minutes) using the 50-kW charger or 2 hours 22 minutes using the 125-kW charger. As opposed to the UC system, this means the bus would not be able to operate continuously during the day as it needs at least 2 hours break to charge. The estimation of the bus operation related to economical aspect is presented in Section 4.

C. Economic Aspect Comparison

In this section the economic feasibility analysis will be discussed. The total cost of battery system and UC system for the electric bus over particular years is calculated. For the analysis, the considered daily distance covered by the electric bus is the same, which is 208.5 km. All the cost values are obtained from the available price online or based on scientific papers. As this study is intended specifically for Jakarta, Indonesia, the costs are shown in Indonesian Rupiah (notated "Rp."). The exchange rate used for the analysis is based on the rate on 8 June 2020 in which 1 USD equals to Rp. 14,706.

The system considered for the cost analysis in this study is the energy storage system, i.e. the battery system and the UC system. The costs are analysed based on the total of initial cost, operational and maintenance cost, plus replacement cost [20], [21] as shown in (2).

$$Total\ cost = Cost_{init} + \sum_{i=1}^{n}\left(Cost_{O\&M} + Cost_{rep}\right) \qquad (2)$$

where $Cost_{init}$ is initial cost, $Cost_{O\&M}$ is operational and maintenance (O&M) cost, $Cost_{rep}$ is replacement cost, with i is the index for the *i*th year up to the *n*th year.

Initial cost is the cost to be paid for system acquisition. The obtained cost data are $1,294 (Rp. 19,029,564) per BYD battery module and $725 (Rp. 10,661,850) per Maxwell module.

Fixed O&M cost data are obtained from [22] which are $10/kW per year for Li-ion system –reduced to $8/kW per year by 2025– and $1/kW per year for UC system.

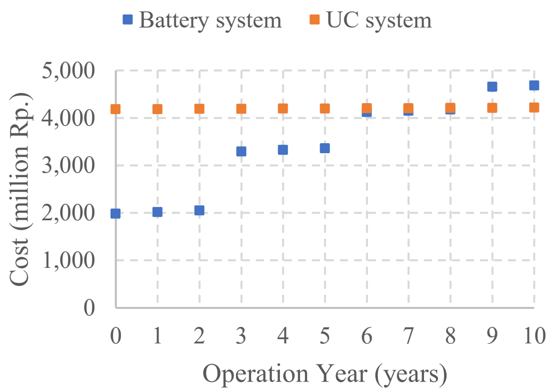

Fig. 6. Cost comparison of battery and UC system for 10-year operation.

As for the replacement cost, life expectancy of 3.3 years for Li-ion system and 10 years for UC system is assumed [9]. Assuming a 10-year life expectancy of the electric bus, the battery system would need to be replaced three times. For the replacement cost, an average decrease of battery cost of 20% and inflation rate of 6% are considered. The cost comparison for 10-year operation is illustrated in Fig. 6.

It can be seen that the total cost for the given battery system is higher than the UC system due to replacement cost. As the UC bus will allow an even longer bus service (e.g. 24-hour bus service; as some Transjakarta route is serving [10]) which might be impossible for the battery bus, the profit obtained from the UC bus service will also be higher compared to that of the battery bus. Hence, it can be concluded that the use of UC full electric transit bus in Jakarta, Indonesia, is economically feasible.

IV. Conclusions

This paper studies the feasibility of a UC-powered full electric bus for Jakarta, Indonesia, using a specific route of Transjakarta buses. Technical and economical aspects are compared between the UC system and the more common storage system, i.e. battery powered electric bus. The readily available charging stations are also considered. Making use of the ultra-fast charging station of 125-kW and/or 150-kW charging power, the UC bus can be fully charged in 10 minutes. This becomes an advantage over the battery bus, as the UC bus can operate 24 hours with 10-minute charging break at the end of each drive cycle.

From the economic aspect, with inherently longer service time than battery, UC system will have lower total life cycle cost. Based on the results of this study, it is concluded that UC full electric transit bus in Jakarta, Indonesia, is both technically and economically feasible. The similar feasibility study could be performed for other locations with different routes, road types, traffic, altitude, and transit vehicle type.

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