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Impact of Battery Price on Electric Bus Charging Scheduling and System

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The electric bus can replace the continuously increasing number of diesel buses in the public transport sector as a result of strong travel demand, making it a promising alternative for reducing carbon emissions. The constraint in implementing the electric bus is the limited energy storage and high capital cost of batteries. A mathematical model is developed to minimize the total cost of electric buses, including capital costs and operation costs, by optimizing the bus charging schedule. A scenario analysis is carried out to determine the impact of battery costs on bus charging schedules. The results show that battery cost will have a huge impact on the charging pattern of electric buses and charger layout. In normal conditions, the model will prefer low battery capacity and charging during peak hours. When the battery price goes down from BAU to 10%, the battery capacity increases from 3,200 to 3,600 kWh, reducing the number of chargers built in a bus stop. This model can be a reference for transit planners.

1. Introduction

As pandemic restrictions were eased and passenger and cargo traffic picked up after a historic fall in 2020, global CO_2 emissions from the transport sector recovered in 2021, rising by 8 % to over 7.7 Gt CO_2 (IEA, 2022). In 2021, road transportation will emit a total of 5.86 Gt CO_2. Due to their extensive use as public transportation, diesel buses are a substantial contributor to greenhouse gas emissions in urban areas. Public transport that is powered by electricity appears to provide hope for reducing air pollution and carbon emissions. There are several constraints in implementing the electric bus, such as low energy storage compared to diesel buses, a long charging time, and a high capital cost. The electric bus's limited battery capacity limits its range and restricts its ability to provide bus service.. Lim et al. (2023) has listed multiple electric bus scheduling problem and one of them is the charging infrastructure and electric buses optimization problem. Previous study is focusing on finding optimal number of chargers for a single route but it does not able to optimize the battery capacity of electric buses for multiple routes. This study is the extension of the previous study with additional optimization for multiple routes and battery capacity. This objective of the study is to determine the optimum system cost for electric bus system and focus on discussing the battery price impact on the implementation system including charger layout and battery capacity via mathematical modelling. The electric cost at the bus stop based on the tariff of the commercial area which can be categorized as peak hour and non-peak hour. The model is then used to carried out sensitivity analysis under different cost of battery. The model can help transport planners and local authorities to implement electric buses in the transport system. This paper will consist of 5 parts where introduction, case study, methodology, result and discussion and conclusion.

2. Case Study

2.1 Description

In this paper, the bus system in Johor Bahru (PAJ) is taken as the case study. There are 8 routes around the Johor Bahru area selected to be included in this model, and the service timetable of each different route is used for the case study. The bus schedule and the routes can be referred to on the website (https://paj.com.my/bmj-route-schedules-mbjb). The route information is listed in Figure 1. All the buses are only allowed to charge at

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bus stops along their service route and at the depot. Table 1 is the input data for the model. The amortization factor is used to convert total capital costs into annual costs. The amortization factor is determined by using the amortization equation with the assumption that battery lifetime is 6 years and charger lifetime is 10 years with an interest rate of 3%. The tariff is based on the commercial electricity tariff by Tenaga Nasional Berhad (TNB). The bus travels based on the existing bus service schedule table. The distance between each stop has also been calculated based on the service route and map application. The scenario analysis is carried out based on the battery unit price, as shown in Table 2. Table 2 shows the price of the battery for different battery capacities in different scenario analyses. There are 5 scenarios in this study. A is the market price for battery while case B is -20 %, case C is -10 %, case D is +10 % and case E is +20 %.

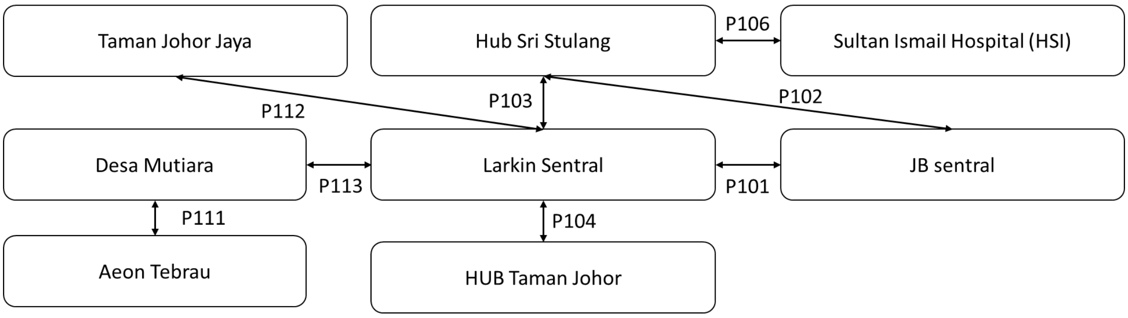

Figure 1: Route System

Table 1: Input Parameter of Model

Description	Unit	Value	Reference
Interest Rate	%	3	-
Energy Consumption per km	kWh/km	2.486	Saadon Al-Ogaili et al. (2020)
Normal Charger	USD	21120	Sung et al. (2022)
Normal Charger Rate	kW	92.16	Sung et al. (2022)
Normal Charger Lifetime	years	10	Online Suppliers
Fast Charger	USD	31,680	Sung et al. (2022)
Fast Charger Rate	kW	138.24	Sung et al. (2022)
Fast Charger Lifetime	years	10	Suppliers[B]
Charger Amortization Factor	%	0.117	-
Battery Amortization Factor	%	0.142	-
Battery Cost	USD/kWh	137	Global EV Outlook 2021
Battery Lifetime	years	8	McGrath et al. (2022)
Off-Peak Tariff	USD/kWh	0.056	Tenaga Nasional Berhad (TNB)
Peak Tariff	USD/kWh	0.0913	Tenaga Nasional Berhad (TNB)

Table 2: Case Study Information

Case Study	A	B	C	D	E
Percentage Change	0%	-20%	-10%	+10%	+20%
200 kWh Battery	13,610	10,888	12,249	14,971	16,332
300 kWh Battery	27,310	21,848	24,579	30,041	32,772
400 kWh Battery	41,010	32,808	36,909	45,111	49,212

2.2 Mathematical Modelling

A mathematical model is developed to minimize the total cost of the electric bus system, which includes only the operation fee, charger cost, and operation cost. The mathematical model has to ensure all the electric buses fulfill their energy demands. The model is further developed based on the previous model (Lim et al, 2022). There are 4 sets in this modelling which are time (T), bus (B), location (L) and battery type (BT). The model is run using a daily schedule and a 24-h period. There are 288 5-minute segments that make up each of the periods. For the Bus set, there will be 16 buses included in this model. There are 8 routes included in the model.

There will be 9 locations in this model where the buses can stop by based on their route service. There will be 3 different battery capacity can be chosen by the electric buses.
There are several assumptions are made: (1) The bus battery capacity is depth of discharge. (2) The energy consumption of electric buses is. (3) The bus will be parked at the bus depot for overnight. (4) The battery and charger degradation is neglected.
Eq (1) is the objective function of this mathematical model. The objective function of the model is to minimize the total cost ($Tcost$) which consist of charger cost ($Cost^{CC}$), operation cost ($Cost^{Ope}$) and battery cost ($Cost^{Batt}$). $Cost^{CC}$ and $Cost^{Batt}$is amortized as the model is running a basis of 365 days. Eq (2) is to determine $Cost^{CC}$ by summing up the normal charger and fast charger amortized cost. The amortized normal charger cost is obtained by multiplying the normal charger quantity ($Chgr_L^N$) with the normal charger cost ($Cost^{NC}$) and normal charger amortization factor (AF^{NC}). AF^{NC} is obtained based on the interest rate and charger lifetime. The amortized fast charger cost is obtained by multiplying the fast charger quantity ($Chgr_L^F$) with the fast charger cost ($Cost^{FC}$) and fast charger amortization factor (AF^{FC}). AF^{FC} is obtained based on the interest rate and charger lifetime. Eq (3) is to determine the $Cost^{Ope}$ by first multiplying the energy charged into the bus ($E_{B,T}^{Bus}$) with time-based tariff (Ele_T^{Tariff}) and 365 days then sum up the cost to the index of bus and time period. Eq (4) is to determine $Cost^{Bat}$ by multiplying battery type of each bus ($Batt_{B,BT}^{Type}$) with battery unit price ($Batt_{BT}^{UP}$) and battery amortize factor (AF^{Batt}). $Batt_{B,BT}^{Type}$ is a binary number with either 1 or 0.

$$\min TCost = Cost^{CC} + Cost^{Ope} + Cost^{Batt} \quad (1)$$

$$Cost^{CC} = Chgr_L^N \times Cost^{NC} \times AF^{NC} + Chgr_L^F \times Cost^{FC} \times AF^{FC} \quad (2)$$

$$Cost^{Ope} = E_{B,T}^{Bus} \times Ele_T^{Tariff} \times 365 \quad (3)$$

$$Cost^{Bat} = \sum_{B,BT} Batt_{B,BT}^{Type} \times Batt_{BT}^{UP} \times AF^{Batt} \quad (4)$$

Eq (5) is to determine the state of charge for each bus ($E_{B,T}^{SOC}$) by summing up the previous $E_{B,T}^{SOC}$ with the $E_{B,T}^{Bus}$ and travel demand ($E_{B,T}^{TD}$). Travel demand is the input parameter for the model. Eq (6) is to determine $E_{B,T}^{Bus}$ by sum up energy from a fast charger ($E_{B,L,T}^{FC}$) and energy from a normal charger ($E_{B,L,T}^{NC}$). Eq (7) is to ensure the electric buses only allowed to get the energy from where they are located. The $Loc_{B,L,T}$ is the location constraint which is one of the input parameters in this model. DN is the dummy number which has a large value. Eq (8) until Eq (11) is to determine the $Chgr_L^F$ and $Chgr_L^N$. $BN_{B,L,T}^{NC}$ and $BN_{B,L,T}^{FC}$ is the quantity of normal charger and fast charger in used at specific location, time and bus. This is to ensure the charger in used is always lower or equal to the charger quantity installed.

$$E_{B,T+1}^{SOC} = E_{B,T}^{SOC} + E_{B,T}^{Bus} - E_{B,T}^{TD} \quad (5)$$

$$E_{B,T}^{Bus} = E_{B,L,T}^{FC} + E_{B,L,T}^{NC} \quad (6)$$

$$E_{B,L,T}^{FC} + E_{B,L,T}^{NC} \leq Loc_{B,L,T} \times DN \quad (7)$$

$$E_{B,L,T}^{FC} \leq BN_{B,L,T}^{FC} \times DN \quad (8)$$

$$E_{B,L,T}^{NC} \leq BN_{B,L,T}^{NC} \times DN \quad (9)$$

$$BN_{B,L,T}^{FC} \leq Chgr_L^F \quad (10)$$

$$BN_{B,L,T}^{NC} \leq Chgr_L^N \quad (11)$$

Eq (12) until Eq (14) is to determine the battery capacity of each bus ($Batt_B^{Max}$). Eq (12) is to ensure that the $E_{B,T}^{SOC}$ is always less than $Batt_B^{Max}$. $Batt_{BT}^{Cap}$ is the battery capacity for each battery type. Eq (14) is to ensure each electric bus only have battery installed. There are several constraints in the model including limited charging rate, charging and discharging simultaneously is forbidden as well as normal charging and fast charging simultaneously is forbidden.

$$E_{B,T}^{SOC} \leq Batt_{B}^{Max} \tag{12}$$

$$Batt_{B,BT}^{Type} \times Batt_{BT}^{Cap} = Batt_{B}^{Max} \tag{13}$$

$$\sum_{BT} Batt_{B,BT}^{Type} \leq 1 \tag{14}$$

3. Results and Discussion

The results from all case studies indicated that the model has the ability to fulfill the energy demand of all electric buses on each route to complete their service demand. Table 3 shows the optimal results for each scenario. All electric buses in cases A, D, and E selected minimum battery storage. There are two electric buses in case B and C, which selected a 400 kWh battery due to the lower battery unit price. Figure 2 shows the total cost pattern for different case studies. The shifting has made the cost slightly lower and increased off-peak hour electricity usage. From Case A to Case C, the gap between the cost difference is small, but the gap between Case C and B for the cost difference is larger. The reason will be further explained in the next part of this section. The battery unit cost is still high as compared to other aspects such as peak hour tariffs and charger costs. Normal condition results stated that all electric buses prefer to have a minimum battery storage level rather than charging in peak hours and installing more charger poles.

Table 3: Result of Sensitivity Analysis

Description		B (-20 %)	C (-10 %)	A (BAU)	D (10 %)	E (20 %)
Total Cost	USD/year	330,669	334,552	337,664	340,767	343,869
Annualized Charger Total Cost	USD/year	28,473	28,473	30,949	30,949	30,949
Annualized Operation Cost	USD/year	271,134	271,134	275,694	275,694	275,694
Annualized Battery Total Cost	USD/year	31,062	34,945	31,021	34,123	37,226
Normal Charger Quantity	Unit	4	4	2	5	2
Fast Charger Quantity	Unit	5	5	7	5	7
200 kWh Battery	Unit	14	14	16	16	16
300 kWh Battery	Unit	0	0	0	0	0
400 kWh Battery	Unit	2	2	0	0	0
Off-Peak Hour Electricity Usage	kWh/d	4,620	4,620	4,266	4,266	4,266
Peak Hour Electricity Usage	kWh/d	5,302	5,302	5,656	5,656	5,656

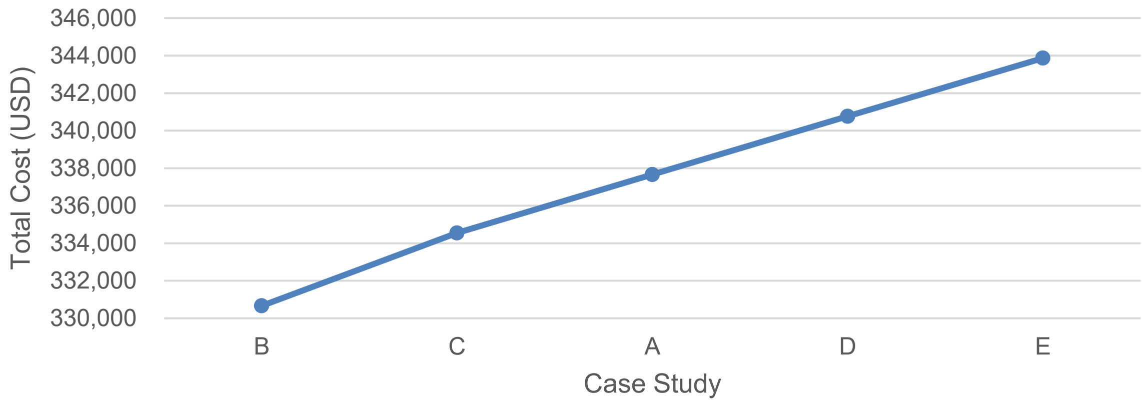

Figure 2 Total Cost Pattern for Different Case Studies

Figure 3 stated that energy demand by each bus in a single day. Every electric bus has different travel demand as they are under service of different bus routes. Bus B7 and B8 has a lower travel demand as their route service has fewer trips required than other trips.

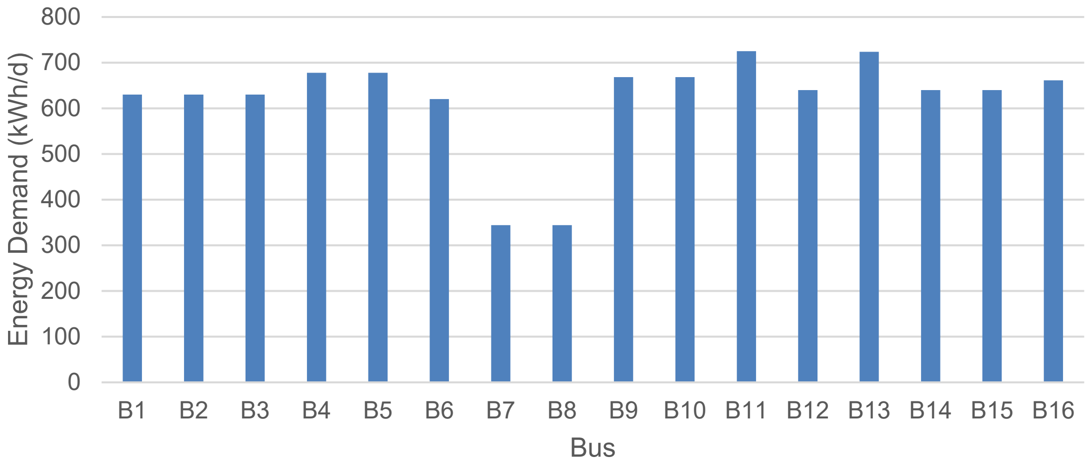

Figure 3: Energy Demand of each Electric Buses per day

Figure 4 illustrates the energy charged into the electric bus throughout 24 h. The charging pattern of the electric buses is affected by two main factors, which are peak hour tariffs and service schedules. There will be two main time periods: peak hour and off-peak hour. Different tariffs for peak hours and off-peak hours had some impact on the charging pattern. The model tends to avoid overcharging during peak hours and charges to store the energy in the electric bus battery. However, battery storage in electric buses is limited. Electric buses still have to charge during their service period and peak tariff period. The peak period is from 08:00 until 22:00. The remaining time period is off-peak. The bus service period generally starts at 8:00 and ends at 21:00.

Starting at 05:40, the bus will depart from the depot for each bus station. After they reach the bus stop, some of the buses will have the opportunity to charge first as their service trip does not start sharply at 6:00. Those buses will continue charging their batteries to their desired SOC before departing. Those buses will continue their charging session at their related service bus stop. There are limited charging spots at the bus depot. After the buses go to the bus stop that belongs to their service route, those buses will have access to the charging port. This is to explain the power peak at 06:00 and 07:00 time periods, as most of the buses will have access to the charger's plot and the tariff is still in the off-peak category. During the time periods from 08:00 until 19:00, the charging patterns are similar and do not have a significant difference between each scenario. However, as mentioned above, Case B and C have lower energy charges throughout the period compared to Cases A, ,D,E despite their charging patterns being similar in this period. After 19:00, most of the buses either have sufficient energy to complete their trips or have finished their own service trips. After finishing the service trips, they will depart back to the depot, but they do not have their charging session until 22:00, as the off-peak sessions begin at 22:00. After 22:00, the electric buses will start charging, and there are two main charging patterns. The energy charged into buses in scenarios B and C is slightly higher than in scenarios A, D, and E. This is due to the fact that the number of chargers in B and C is higher than in A, D, and E.

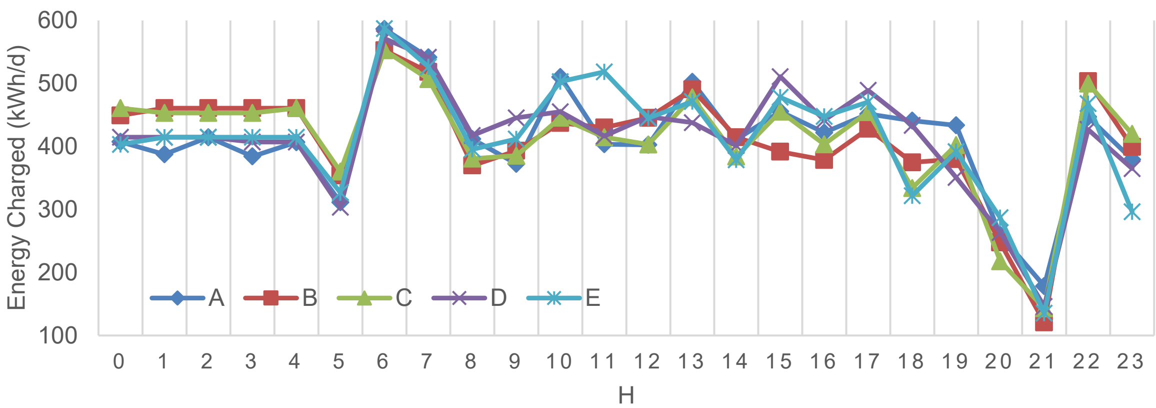

Figure 4: Energy Charged into the Buses

Table 4 shows that the charger quantity and type in each bus stops. L9 is the bus depot where the bus will be park at after their service period. There are chargers port installed at L1, L2 and L3 in every scenario as they are the bus stop where most of the bus will drop by. It will be more economic efficient when the chargers occupy time increases. In L4, there are no charger will be installed at case B and C. There are 2 buses in this case study will have larger battery storage then allow those buses need not to charge at L4 and have sufficient energy to fulfil their service trip. In Case B and C, there will be only 2 fast charger and 2 normal chargers installed with the power rate of 460 kW at the depot. In Case A, D and E, there will be a total of 415 kW Charger installed. Therefore, there will be more energy charged during peak hour in Case A,D as there is limited energy storage at electric buses then there will be not necessary to have higher power charger installed at the depot.

Table 4: Charger Quantity and Location

	B		C		A		D		E	
	NC	FC	NC	FC	NC	FC	NC	FC	NC	FC
L1	1	1	1	1	1	1	1	1	1	1
L2	0	1	0	1	0	1	0	1	0	1
L3	1	0	1	0	1	0	1	0	1	0
L4	0	0	0	0	0	1	0	1	0	1
L5	0	0	0	0	0	0	0	0	0	0
L6	0	0	0	0	0	0	0	0	0	0
L7	0	1	0	1	0	1	0	1	0	1
L8	0	0	0	0	0	0	0	0	0	0
L9	2	2	2	2	0	3	3	1	0	3

Overall results show that the variation in battery cost will not only affect the battery cost but also the charger layout. The increase in battery capacity may help reduce the number of chargers at certain bus stops. The results indicate that the battery capacity can be optimized together with the charger layout to increase savings.

4. Conclusions

The model developed has shown that the charging infrastructure and charging schedule can be optimized to reduce the total cost of electric buses for multiple routes and locations. The model can select charger quantity, battery capacity, and charger layout for the whole electric bus system, which consists of multiple routes and different locations. The model has been able to find the optimum point in between battery cost, charger cost, and operation cost. The scenario analysis shows that batteries are not favorable in every scenario, as most of the electric buses are equipped with smaller battery capacities and the battery price is costly.

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