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Strategic Charging and Sizing of Electric Bus Batteries under Solar Availability

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The increasing integration of renewable energy (RE) into power systems introduces variability and instability, necessitating effective energy storage solutions such as batteries. Electric buses, which rely on batteries, often face range limitation, prompting the use of larger battery capacities to ensure reliable operation. However, larger batteries increase upfront costs, raising concerns about economic feasibility. To address this issue, this study explores a strategy in which buses are pre-charged during daytime solar peaks to support evening and nighttime operations, thereby aligning energy consumption with RE availability. A cost-optimisation model is developed to evaluate the economic impact of different battery sizes and charging strategies, assessing whether a fixed battery range is sufficient or if dynamic sizing offers greater benefits. The analysis also investigates if the higher cost associated with batteries can be offset through savings on electricity tariffs and grid-related services. Results suggest that with strategic planning, larger batteries can enhance both operational flexibility and economic viability.

1. Introduction

The transition to electric buses is essential for alleviating traffic congestion and reducing urban pollution. However, since electricity in Malaysia is still mainly generated from fossil fuels, the environmental benefits of electric buses remain limited. As an initiative towards decarbonisation, renewable energy—particularly solar—is gaining attraction. Yet, due to its intermittent nature, energy storage is crucial to ensure a stable and reliable power supply. Electric buses typically rely on large batteries to mitigate range limitations, enhancing operational reliability but also increasing costs. One effective strategy is to store surplus solar energy generated during the day for use in the evening or at night. This approach can help avoid peak electricity tariffs and reduce maximum power demand.

Liu et al. (2024) proposed a mixed-integer linear programming model that integrates solar PV with battery storage, accounting for real-world variables such as route variability and flexible charging schedules. Their case study in Beijing demonstrated cost savings and improved solar utilisation, though it did not consider battery capacity constraints or charger availability. Meanwhile, Gairola and Nezamuddin (2023) developed a model aimed at minimising annual costs by assigning route-specific battery sizes and shifting charging to off-peak periods, although it lacked integration with renewable sources.

Building on previous research (Lim et al., 2024), this study extends the optimisation model to compare the costs of using maximum battery capacity versus an optimally sized battery, highlighting the trade-off between operational flexibility and overall cost.

2. Methodology

This study presents an optimised mathematical framework aimed at minimizing the total cost ($TCost$) of operating an electric bus system. Building on previous research, the model is structured using four key indices: time (T), bus unit (B), location (L), and charger category (CT). It operates with a 5-min resolution, resulting in 288 intervals per day, sufficient to meet the scheduling requirements of public bus operations. A shorter time interval was avoided to prevent excessive computational load. The system considers 10 buses, five different

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locations, and five charger types. The main objective, defined in Eq(1), is to minimise the total annual expenditure by factoring in various system components.

The total cost comprises several elements: charger investment, grid electricity usage, solar panel setup, and battery systems for both the buses and the solar infrastructure. Capital expenditure such as chargers, batteries, and solar panels is annualized using amortisation. Grid electricity cost and maximum power cost is extrapolated across the year by multiplying daily consumption with 365 and multiplying monthly power demand with 12.

The charger cost is calculated by multiplying the quantity ($Charger_{L,CT}^{QTY}$) by the unit price ($Charger_{CT}^{UP}$)) and its amortisation rate (AR^{C}). Grid energy expenses are derived from the amount consumed ($Energy_{L,T}^{Grid}$), the time-dependent tariff ($Energy_{T}^{Tariff}$), and the number of days in a year. The solar system cost is estimated by combining the panel area ($Solar_{L}^{Area}$), unit price ($Solar^{UP}$), and its respective amortisation factor (AR^{S}). Battery costs for buses and solar storage are similarly calculated using their capacity ($Battery_{B}^{Cap}$), corresponding unit prices ($Battery^{UPBus}$), and amortisation rates (AR^{B}). Additionally, profits from any electricity sold back to the grid (XX) are deducted from the total expenditure. To account for demand-based charges, the model also includes a term representing the cost incurred by peak power demand, calculated by multiplying the maximum power usage with the applicable peak tariff ($Energy^{PowerCost}$).

$$\begin{aligned}
TC \sum_{L,CT} Cost = \ & harger_{L,CT}^{QTY} \times Charger_{CT}^{UP} \times AR^{C} \\
& + \sum_{L,T} Energy_{L,T}^{Grid} \times Energy_{T}^{Tariff} \times 365 \\
& + \sum_{L} Solar_{L}^{Area} \times Solar^{UP} \times AR^{S} \\
& + \sum_{B} Battery_{B}^{Cap} \times Battery^{UPBus} \times AR^{B} \\
& + \sum_{L} Battery_{L}^{BS} \times Battery^{UPSolar} \times AR^{B} \\
& - \sum_{L,T} Energy_{L,T}^{Sales} \times Energy_{T}^{Tariff} \times 365 \\
& + \sum_{L,T} Power_{L}^{Grid} \times Energy^{PowerCost} \times 12
\end{aligned} \tag{1}$$

Eq(2) defines the state of charge (SOC) for each electric bus over time ($SOC_{B,T}$). It is computed by adding the amount of energy the bus receives from charging ($Energy_{B,L,T}^{Char}$) and subtracting the energy consumed to meet its travel demand ($Energy_{B,T}^{TD}$). This dynamic balance tracks how much energy remains in the battery at each time interval. Meanwhile, Eq(3) calculates the total charging energy supplied to a bus ($Energy_{B,L,T}^{Char}$) by summing the energy received across all locations (XX) during each time step.

$$SOC_{B,T++1} = SOC_{B,T} + Energy_{B,T}^{Bus} - Energy_{B,T}^{TD} \tag{2}$$

$$Energy_{B,T}^{Bus} = \sum_{L} Energy_{B,L,T}^{Char} \tag{3}$$

Eq(4) calculates $Energy_{B,L,T}^{Char}$ and time by combining grid-supplied energy ($Energy_{L,T}^{Grid}$) with energy drawn from the solar system ($Energy_{L,T}^{SolarBus}$). Eq(5) identifies the charger type used for delivering this energy. Eq(6) and Eq(7) restrict each bus to charging from only one charger type at a single station per time step. Eq(8) ensures that the number of chargers in use ($Bin_{B,L,T,CT}^{Char}$) never exceeds the available quantity at any location. Eq(9) limits charging to the locations where buses are actually stationed during operation.

$$\sum_{B} Energy_{B,L,T}^{Char} = Energy_{L,T}^{Grid} + Energy_{L,T}^{SolarBus} \tag{4}$$

$$\sum_{B} Energy_{B,L,T,CT}^{CharCT} = Energy_{B,L,T}^{Char} + Energy_{B,L,T}^{Ex} \tag{5}$$

$$Energy_{B,L,T,CT}^{CharCT} \leq Bin_{B,L,T,CT}^{Char} \times DN \tag{6}$$

$$\sum_{CT} Bin_{B,L,T,CT}^{Char} \leq 1 \tag{7}$$

$$\sum_{B} Bin_{B,L,T,CT}^{Char} \leq Charger_{L,CT}^{QTY} \tag{8}$$

$$\sum_{CT} Bin_{B,L,T,CT}^{Char} \leq BusLocation_{T,B,L} \times DN \tag{9}$$

Eq(10) ensures that the $SOC_{B,T}$ does not exceed the bus battery's maximum capacity ($Battery_B^{Cap}$). Eq(11) to Eq(13) define the $Battery_B^{Cap}$ for each bus, keeping it within specified minimum and maximum limits. Eq(14) to Eq(16) prevent the buses from charging and discharging at the same time, maintaining realistic energy flow constraints.

$$SOC_{B,T} \leq Battery_B^{Cap} \quad (10)$$
$$Battery_B^{Cap} = Battery_B^{Pack} \times Battery^{PackSize} \quad (11)$$
$$Battery_B^{Cap} \leq Battery^{Max} \quad (12)$$
$$Battery_B^{Cap} \leq Battery^{Min} \quad (13)$$
$$Energy_{B,T}^{Bus} \leq Bin_{B,T}^{Char} \times DN \quad (14)$$
$$Energy_{B,T}^{TD} \leq Bin_{B,T}^{Tra} \times DN \quad (15)$$
$$Bin_{B,T}^{Char} + Bin_{B,T}^{Tra} \leq 1 \quad (16)$$

Eq(17) calculates the energy supplied to buses from the solar system ($Energy_{L,T}^{SolarBus}$) by adding direct solar usage ($Energy_{L,T}^{SolarBusD}$) and energy discharged from the solar battery ($Energy_{L,T}^{BatOut}$). Eq(18) determines the total energy generated by the solar panels, while Eq(19) handles how this energy is allocated. Eq(20) sets an upper limit on the installed solar panel area, ensuring it does not exceed the maximum allowable size ($Solar_L^{MaxArea}$).

$$Energy_{L,T}^{SolarBus} = Energy_{L,T}^{SolarBusD} + Energy_{L,T}^{BatOut} \quad (17)$$
$$Energy_{L,T}^{Solar} = Solar_{T,L}^{Irr} \times Solar_L^{Area} \times Solar^{Eff} \quad (18)$$
$$Energy_{L,T}^{Solar} = Energy_{L,T}^{SolarBusD} + Energy_{L,T}^{Sales} + Energy_{L,T}^{BatIn} \quad (19)$$
$$Solar_L^{Area} \leq Solar_L^{MaxArea} \quad (20)$$

Eq(21) tracks the state of charge of the solar battery system ($Solar_{L,T}^{Bat}$) by adding energy stored from solar generation ($Energy_{L,T}^{BatIn}$) and subtracting discharged energy ($Energy_{L,T}^{BatOut}$). Eq(22) ensures the battery's charge level stays below its maximum capacity ($Solar_{L,T}^{Bat}$). Eq(23) and Eq(24) restrict the charging and discharging rates so they do not exceed the battery's current state of charge.

$$Solar_{L,T++1}^{Bat} = Solar_{L,T}^{Bat} + Energy_{L,T}^{BatIn} + Energy_{L,T}^{BatOut} \quad (21)$$
$$Solar_{L,T}^{Bat} \leq Battery_L^{SMax} \quad (22)$$
$$Energy_{L,T}^{BatIn} \leq Battery_L^{SMax} \quad (23)$$
$$Energy_{L,T}^{BatOut} \leq Battery_L^{SMax} \quad (24)$$

Eq (25) estimates the grid's peak power demand ($Power_L^{Grid}$) by converting 5-min power values (XX) into energy using a scaling factor of 1/12. A binary indicator ($Peak_T$) flags peak periods, ensuring only energy consumed during these hours contributes to the peak demand calculation.

$$Energy_{L,T}^{Grid} \times Peak_T \leq Power_L^{Grid} * 0.083 \quad (25)$$

3. Case Study

This study uses the Perbadanan Pengangkutan Awam (PAJ), Johor Bahru bus route as a case study, focusing on four routes operated by a total of 10 electric buses. Bus schedules and route details are publicly available at https://paj.com.my/bmj-route-schedules-mbjb. Distances between stops were determined using the official service route and mapping application. Buses are permitted to charge only at depots or designated stops along their service routes. The input data for the model are summarised in Table 1. Capital expenditures are annualised using an amortisation factor, calculated based on a 6-year lifespan for both batteries and chargers and an interest rate of 3 %. The tariff structure is based on Tenaga Nasional Berhad's (TNB) commercial electricity rates. Table 2 presents the specifications and unit costs of each charger type. Two scenarios are analysed: Scenario 1 allows battery capacity to be optimised, whereas Scenario 2 will fixes all battery capacity of electric bus at 400 kWh.

4. Result and Discussions

Figures 1 and 2 illustrate the system's energy flow. The blue area represents energy purchased at the appropriate tariff, while the blue line indicates energy drawn from the grid. The grey line shows solar energy generated and exported to the grid, the green line represents solar energy stored in the batteries, and the yellow line indicates solar energy directly transferred to the buses. Both figures display a similar trend, with reduced reliance on grid energy during peak hours. In Figure 1, grid energy usage remains relatively constant from 12:00 a.m. to around 5:30 a.m. At 5:30 a.m., buses begin departing for their respective routes and gain access to external chargers, as depot charging capacity is limited. Starting 8:00 a.m., energy drawn from the grid declines sharply and remains low until around 8:00 p.m. After 8:00 p.m., fewer buses require charging as most have completed their daily routes. Once peak hours end around 10:00 p.m., grid energy usage rises again as buses return to depots and begin charging. Regarding the solar energy, the amount exported to the grid (grey line) gradually increases from 8:00 a.m., peaks around 1:00 p.m., and decreases gradually until 8:00 p.m. Solar energy stored batteries (green line) fluctuate around 20 kWh between 9:00 a.m. and 7:00 p.m. Direct solar energy supplied to buses (yellow line) remains limited due to the short duration buses spend at stops and their typically low battery levels during these hours.

Table 1: Input Parameter of Model

Description	Unit	Value	Reference
Interest Rate	%	3	Assumption
Energy Consumption per km	kWh/km	2.486	Saadon Al-Ogaili et al. (2020)
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)
Solar Panel Efficiency	%	22	Assumption
Solar Panel CAPEX	USD/m^2	164.18	Supplier
Solar Panel Lifetime	years	20	Assumption

Table 2: Case Study Information

Case Study	Charger Power (kW)	Cost (USD)	Source
Electric Charger (LVL 1)	92.16	21120	Sung et al. (2022)
Electric Charger (LVL 2)	115.2	26400	Sung et al. (2022)
Electric Charger (LVL 3)	138.24	31680	Sung et al. (2022)
Electric Charger (LVL 4)	240	76800	Website
Electric Charger (LVL 5)	300	155078	Website

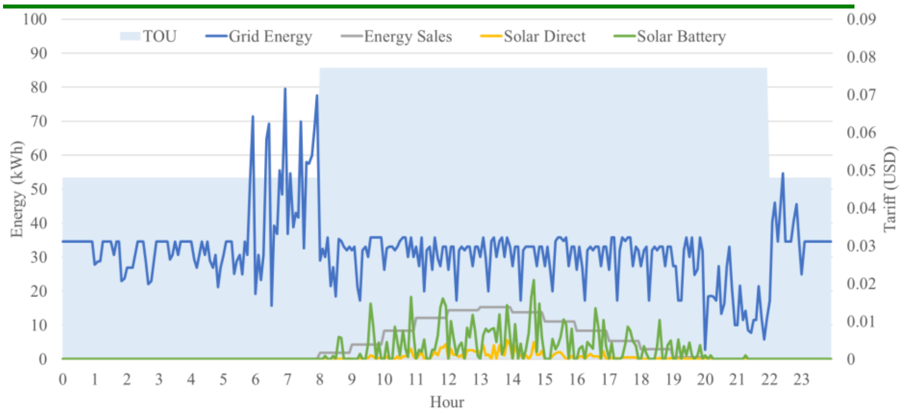

Figure 1: Energy flow diagram for Scenario A

Figure 2 presents the hourly energy flow and tariff rate within the system across a 24-hour period for Scenario B. Energy drawn from the grid remains relatively constant from midnight until approximately 5:30 a.m. Both figures show constant energy drawn from grid during midnight however Scenario B has higher constant value as the bus depot has higher number of charger and the electric bus has higher battery capacity. After this point, there is a noticeable drop in grid energy usage, reaching its lowest point around 8:00 a.m., and staying low throughout the day until about 8:00 p.m. This pattern aligns with bus operations, as they begin departing for routes and rely more on external chargers, reducing dependence on depot-based grid supply. After 8:00 p.m., grid energy consumption begins to rise again as buses return to the depot and start recharging. Energy sales back to the grid start to increase around 8:00 a.m., peak near 1:00 p.m., and then gradually decrease until 8:00 p.m., reflecting typical solar generation patterns. Solar energy stored in the battery fluctuates between 10 to 25 kWh from around 9:00 a.m. to 7:00 p.m., indicating intermittent storage activity based on generation and demand. Direct solar energy usage by buses remains low throughout the day, suggesting limited charging opportunities during brief stops and lower onboard battery levels.

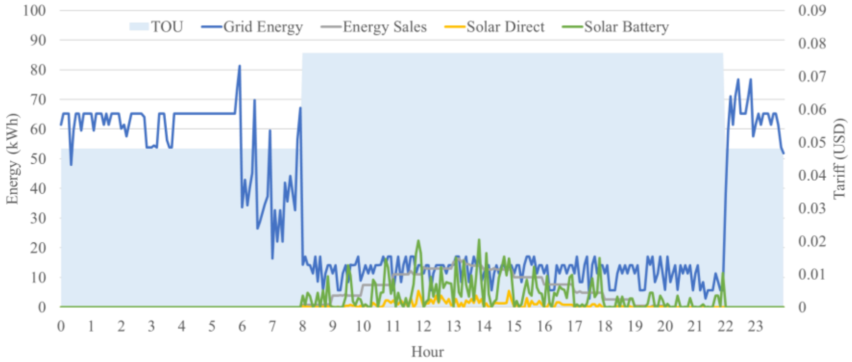

Figure 2: Energy flow diagram for Scenario B

Scenario A shows a sharp increase in grid energy usage between 5:30 a.m. and 8:00 a.m. as buses have greater access to chargers at bus stations. In contrast, Scenario B shows a decrease during this period due to limited station chargers, with more located at the depot. Daytime grid usage in Scenario A fluctuates around 25–35 kWh, while Scenario B remains lower, under 20 kWh. Solar energy sales are more stable in Scenario A, whereas Scenario B shows greater fluctuation due to higher bus battery capacity allowing more solar capture. Direct solar usage is slightly higher in Scenario B but remains low due to limited charging time.
Table 3 compares the total and average battery capacities of all buses in Scenario A and Scenario B. Scenario A has a total battery capacity of 3,220 kWh, with an average of 201.25 kWh per bus, while Scenario B has a significantly higher total of 6,400 kWh and a fixed average of 400 kWh per bus. The variance in Scenario A is 132.36, indicating varying battery sizes tailored to individual route requirements. In contrast, Scenario B has a variance of 0, meaning all buses are equipped with standardised 400 kWh batteries.

Table 3: Battery Result

Case Study	Scenario A	Scenario B
Total	3220	6400
Average	201.25	400
Variance	132.3568	0

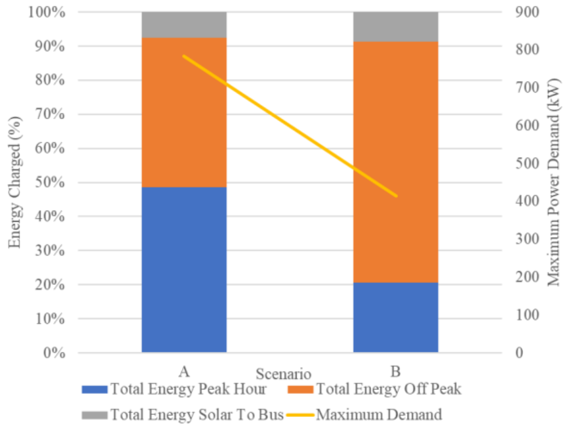

Figure 3: Power source contribution chart

Figure 3 compares the power source contribution chart and maximum demand between Scenario A and Scenario B. In Scenario A, 49 % of the total energy is charged during peak hours, significantly higher than Scenario B, which only uses 21 % during the same period. Off-peak charging is lower in Scenario A at 44 %, while Scenario B achieves 71 %, indicating better load shifting. Energy directly supplied from solar to the bus is 8 % in Scenario A and slightly higher in Scenario B at 9 %. The higher peak hour usage in Scenario A can be attributed to its lower battery capacity, which limits the ability to store energy during off-peak periods. This constraint results in a greater dependency on peak-hour charging. Additionally, the limited battery storage also reduces the amount of solar energy that can be captured and used later. A notable outcome is the significant drop in maximum power demand, from 49,621.47 kW in Scenario A to 23,516.07 kW in Scenario B—an overall reduction of approximately 47 %. This demonstrates the effectiveness of Scenario B in managing demand, likely due to better battery utilisation, energy scheduling, and more efficient use of off-peak and solar energy sources.

Table 4: Cost Breakdown and Comparison of Electric Bus Charging Scenarios

Case Study (USD)	Scenario A	Scenario B
Charger Cost	44,285	45,185
Grid Cost	211,669	180,470
Battery Cost	69,265	137,670
Solar Panel Cost	19,864	19,864
Solar Battery Cost	2,302	2,870
Solar Sales	33,132	30,188
Maximum Power Cost	49,621	23,516
Total Cost	363,875	379,388
Percentage of Total Cost Increment compared to Scenario 1 (%)	-	4 %

Table 4 compares the costs between Scenario A and Scenario B, highlighting important trade-offs in system design. Scenario B shows a 4 % increase in total cost (RM 379,388 vs RM 363,875), mainly due to its higher battery cost (RM 137,670 vs RM 69,265) from using larger, standardised batteries. Although more expensive, this allows for greater flexibility and better use of off-peak charging. Scenario B also reduces grid cost (RM 180,470 vs RM 211,669) and cuts maximum power cost by 47 % (RM 23,516 vs RM 49,621), thanks to improved load management. While solar energy sales are slightly lower (RM 30,188 vs RM 33,132), this suggests more solar power is used directly for charging. Other cost differences are minor, with solar panel costs being equal. Overall, the small increase in cost brings significant benefits, such as better route planning, reduced range anxiety, and improved energy efficiency, making Scenario B a more practical and future-ready option.

5. Conclusions

This paper examined the impact of large battery systems on the overall operational cost of electric bus fleets, particularly in relation to solar energy integration. The findings show that using larger batteries can significantly reduce grid costs and maximum power demand charges by enabling more off-peak charging and better energy management. These reductions contribute to overall cost savings and enhance system efficiency. Additionally, storing solar energy for direct bus use can help reduce energy export to the grid, though this is limited by the overlap between bus operation hours and solar generation periods. Future research could explore how battery systems can further support cost reduction and system resilience, especially in scenarios where solar export is restricted due to energy security concerns.

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