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Optimization Model for Electric Bus Systems Integrated with Solar Energy: a preliminary Study

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The electric bus is introduced to fulfil the travel demand without compromising the carbon mitigation target, but the presence of an electric bus may lead to higher carbon emissions as it increases the power load at the power plant. Renewable energy systems, such as solar systems, are introduced to mitigate the high energy demand during peak hours. A mathematical model is developed to minimize the total cost of the electric bus system integrated with the solar system. The results show that integrating solar systems into the electric bus system can help reduce the total cost as it avoids high dependence on the energy from the grid during peak hours. The results shows that solar system can lead to 4 % of total cost reduction.

1. Introduction

Electric bus is introduced to mitigate the carbon emission without compromising the increasing travel demand of growing population. Electric bus can help to reduce the carbon emission by using electric from greener source. However, the electric bus has a limited energy storage and required charging process during the service period (Perumal et al. 2021). The charging process for electric bus is longer when compared with conventional internal combustion engine bus. The electric bus charging profile required proper scheduling and optimization to ensure the travel demand of the service route is fulfil and does not lead to a high load on the grid then lead to a higher cost. Solar power systems can be introduced into the electric bus system to further mitigate the carbon emission (Lim et al. 2023). There is higher solar irradiation in Equatorial region and it does help further benefit the implementation of solar system The previous study (Lim et al. 2022 and Pranav Gairola et al. 2023) did not integrate the renewable energy system with the electric bus system. In this paper, a solar power system is selected and integrated with the electric bus system. The objective of the paper is to design a mathematical model to optimise the total cost of an electric bus system integrated with a solar power system. In this study, the impact of solar system on the electric bus system will be evaluated and the potential of integrating the solar system with electric bus system will be determined.

2. Case Study

2.1 Description

The Johor Bahru (PAJ) bus system is used as the case study in this paper. The case study uses the service schedules of the four routes with a total of 10 electric buses that were chosen to be included in the model for the Johor Bahru area. The bus timetable and routes can be viewed by visiting the following website: https://paj.com.my/bmj-route-schedules-mbjb. The bus info and route info is shown in Figure 1. The service route and map application have also been used to compute the distance between each stop. All buses are only permitted to charge at the depot and at bus stops along their route of service. The model's input data is tabulated in Table 1. Total capital expenses are converted into yearly costs using the amortisation factor. With the assumption that the battery and charger have a 6-year lifespan each and an interest rate of 3 %, the amortisation factor is calculated using the amortisation equation. Tenaga Nasional Berhad's (TNB) commercial power tariff serves as the basis for this tariff. Table 2 shows the power of each type charger and their respective unit cost.

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In this study, there are 2 scenarios conducted, Scenario 1 and Scenario 2. In Scenario 1, solar power system is allowed to be integrated in the electric bus system but not applicable in Scenario 2.

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

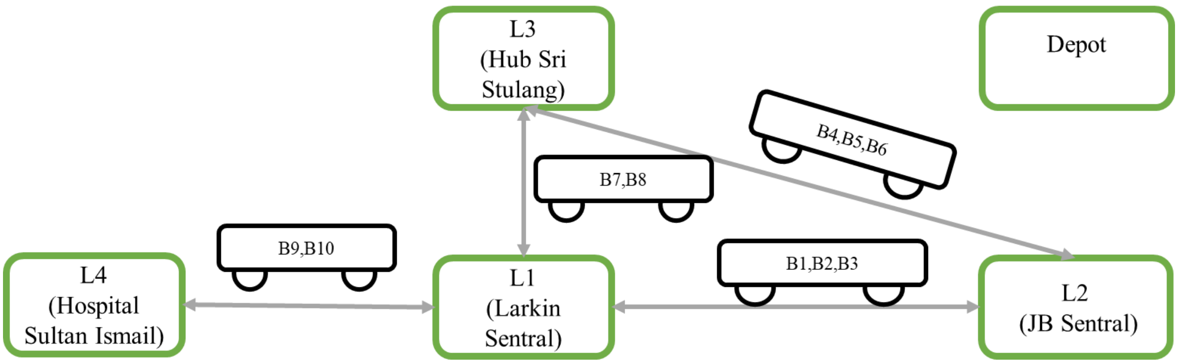

Figure 1: Bus and Route Information.

A number of assumptions have been established: (1) The depth of discharge is a measure of bus battery capacity. (2) The energy consumption of the bus is constant. (3) The bus will spend the night parked at the bus depot. (4) The deterioration of the battery and charger is neglected. (5) The solar maximum installation area for each location is fixed at 100 m^2. The assumptions are selected to clarify the scope of the study. Battery capacity degradation and charger degradation are neglected as they show minimal impact on the result as the study is not carried out on a macro level. The study area is at Johor Bahru as the bus data is obtained from the PAJ as well as the solar irradiation data is based on the Johor Bahru.

2.2 Mathematical Modelling

A mathematical model is developed to minimize the total cost ($TCost$) of the electric bus system. The model is further developed from the previous model which published in. There are four indices applied in this model which are time (T), bus (B), location (L) and charger type (CT). The model is applied on a daily basis and the time interval is 5 min which is 288 intervals per day. A time interval of 5 min is selected as it can represent the timetable of the bus service and any time interval lower than 5 minutes will lead a huge load for the model There are 10 buses included in the bus index and 5 locations included in the location index. There are 5 types of chargers included in the charger index. Eq(1) is the objective function of the model. The total cost includes the charger cost, grid cost, solar system cost, battery cost of electric bus and battery cost of solar system. The total cost is calculated based on a yearly basis. The cost for charger, battery and solar panel are amortized at a yearly basis. The grid cost is then multiplied with 365 days for a yearly basis. Charger cost is determined by multiplying charger quantity ($Charger_{L,CT}^{QTY}$) with charger unit price ($Charger_{CT}^{UP}$) and charger amortization factor (AR^{C}). Grid cost is determined by multiplying the amount of energy usage from grid ($Energy_{L,T}^{Grid}$) with the tariff rate ($Energy_{T}^{Tariff}$) and 365 d. Solar power system cost is determined by multiplying the solar panel area ($Solar_{L}^{Area}$) with the solar panel unit price ($Solar^{UP}$) and the solar amortization factor (R^{B}). The battery cost for electric bus is determined by multiplying the electric bus battery capacity ($Battery_{B}^{Cap}$) with battery unit price ($Battery^{UPBus}$) amortization factor of battery. The battery for solar system is determined by multiplying the solar system battery capacity ($Battery_{L}^{BS}$) with battery unit price ($Battery^{UPSolar}$) and amortization factor of battery (R^{B}).

$$\begin{aligned} TCost = & \sum_{L,CT} Charger_{L,CT}^{QTY} \times Charger_{CT}^{UP} \times AR^{C} \\ & + \sum_{L,T} Energy_{L,T}^{Grid} \times Energy_{T}^{Tariff} \times 365 \\ & + \sum_{L} Solar_{L}^{Area} \times Solar^{UP} \times AR^{S} \\ & + \sum_{B} Battery_{B}^{Cap} \times Battery^{UPBus} \times AR^{B} \\ & + \sum_{L} Battery_{L}^{BS} \times Battery^{UPSolar} \times AR^{B} \end{aligned} \quad (1)$$

Eq(2) is to determine the state of charges of electric bus ($SOC_{B,T}$) by adding one the energy charged into the electric bus ($SOC_{B,T}$) and deduct with the travel demand ($Energy_{B,T}^{TD}$). Eq(3) is to determine the $Energy_{B,T}^{Bus}$ by summing up the energy charged into bus for each location ($Energy_{B,L,T}^{Char}$).

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

$$Energy_{B,T}^{Bus} = \sum_{L} Energy_{B,L,T}^{Char} \quad (3)$$

Eq(4) is to determine the $Energy_{B,L,T}^{Char}$by summing up the $Energy_{L,T}^{Grid}$ and the energy to the electric bus from solar system ($Energy_{L,T}^{SolarBus}$). Eq(5) is to determine the technology of charger for charging the energy into the electric bus. Eq(6) and Eq(7) are used to ensure each electric bus can only be charged by one type of charger at one single electric bus station at each time slot given. Eq(8) is to ensure the $Charger_{L,CT}^{QTY}$ at each location is higher than the charger quantity on usage ($Bin_{B,L,T,CT}^{Char}$). Eq(9) is to ensure the electric bus can only be charged at the bus stop where they are parked during the service period.

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

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

$$Energy_{B,L,T,CT}^{CharCT} \le Bin_{B,L,T,CT}^{Char} \times DN \quad (6)$$

$$\sum_{CT} Bin_{B,L,T,CT}^{Char} \le 1 \quad (7)$$

$$\sum_{B} Bin_{B,L,T,CT}^{Char} \le Charger_{L,CT}^{QTY} \quad (8)$$

$$\sum_{CT} Bin_{B,L,T,CT}^{Char} \le BusLocation_{T,B,L} \times DN \quad (9)$$

Eq(10) is to ensure the $SOC_{B,T}$ is lower than $Battery_{B}^{Cap}$. Eqs(11~13) are to determine $Battery_{B}^{Cap}$ and ensure they are higher than minimum battery capacity and lower than maximum battery capacity. Eq(14) to Eq(16) are used to ensure the electric bus are not undergoing charging process and discharging process simultaneously.

$$SOC_{B,T} \le Battery_{B}^{Cap} \quad (10)$$

$$Battery_{B}^{Cap} = Battery_{B}^{Pack} \times Battery^{PackSize} \quad (11)$$

$$Battery_{B}^{Cap} \le Battery^{Max} \quad (12)$$

$$Battery_{B}^{Cap} \le Battery^{Min} \quad (13)$$

$$Energy_{B,T}^{Bus} \le Bin_{B,T}^{Char} \times DN \quad (14)$$

$$Energy_{B,T}^{TD} \leq Bin_{B,T}^{Tra} \times DN \quad (15)$$

$$Bin_{B,T}^{Char} + Bin_{B,T}^{Tra} \leq 1 \quad (16)$$

Eq(17) is to determine the $Energy_{L,T}^{SolarBus}$ by summing up the direct energy usage from solar system ($Energy_{L,T}^{SolarBusD}$) and the energy discharged from the solar battery ($Energy_{L,T}^{BatOut}$). Eq(18) is to determine the energy produced from the solar panel while Eq(19) is to determine the energy distribution of the solar system. Eq(20) is to ensure the solar area installed is below the solar maximum area.

$$Energy_{L,T}^{SolarBus} = Energy_{L,T}^{SolarBusD} + Energy_{L,T}^{BatOut} \quad (17)$$

$$Energy_{L,T}^{Solar} = Solar_{T,L}^{Irr} \times Solar_{L}^{Area} \times Solar^{Eff} \quad (18)$$

$$Energy_{L,T}^{Solar} = Energy_{L,T}^{SolarBusD} + Energy_{L,T}^{Sales} + Energy_{L,T}^{BatIn} \quad (19)$$

$$Solar_{L}^{Area} \leq Solar_{L}^{MaxArea} \quad (20)$$

Eq(21) is to determine the SOC of solar battery system ($Solar_{L,T}^{Bat}$) by summing up the energy charged into the solar battery from solar system ($Energy_{L,T}^{BatIn}$) and $Energy_{L,T}^{BatOut}$. Eq(22) is to ensure the $Solar_{L,T}^{Bat}$ is below the $Battery_{L}^{SMax}$. Eq(23) and Eq(24) is to ensure the $Energy_{L,T}^{BatIn}$ and $Energy_{L,T}^{BatOut}$ is lower than the $Solar_{L,T}^{Bat}$.

$$Solar_{L,T++1}^{Bat} = Solar_{L,T}^{Bat} + Energy_{L,T}^{BatIn} + Energy_{L,T}^{BatOut} \quad (21)$$

$$Solar_{L,T}^{Bat} \leq Battery_{L}^{SMax} \quad (22)$$

$$Energy_{L,T}^{BatIn} \leq Battery_{L}^{SMax} \quad (23)$$

$$Energy_{L,T}^{BatOut} \leq Battery_{L}^{SMax} \quad (24)$$

3. Results and Discussion

The model was solved using GAMS 34.2 with CPLEX solver 12.6 on a PC with 16 GB of RAM and a 2.5 GHz processor. The results from both of the scenarios show that the energy demand of all electric buses can be fulfilled with or without the solar power energy system. Figure 2 and Figure 3 shows the energy charged and SOC of bus 1 in Scenario 1 and Scenario 2. The absence of a negative value of SOC for every electric bus in both scenarios indicated that the model has the ability to fulfil the energy demand of the electric bus. The impact of solar system has minimal effect on the charging profile.

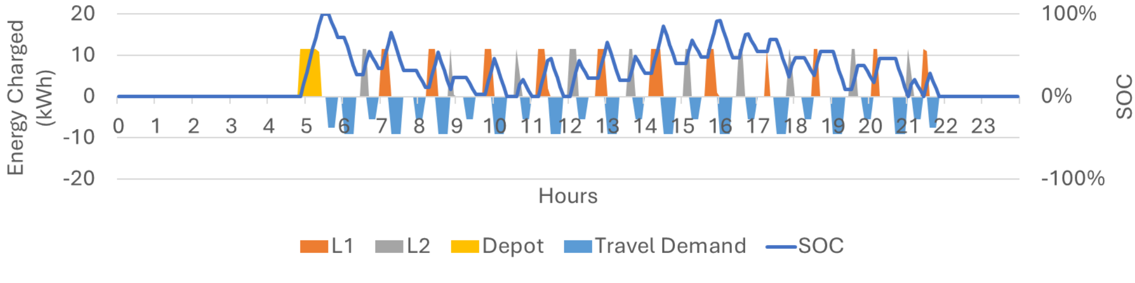

Figure 2: Energy Charger and State of Charge of B1 in Scenario 1.

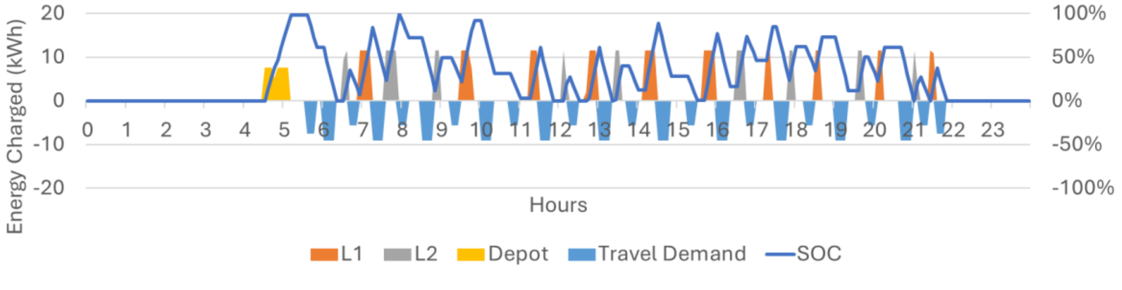

Figure 3: Energy Charger and State of Charge of B1 in Scenario 2.

Figures 4 and 5 show the charger placement and technology for Scenario 1 and Scenario 2. There will be 5 chargers total installed in each location. There will be one charger installed in each location. This charger placement can help ensure the electric bus has enough to charge whenever it is parked at the bus stop. Four out of five chargers are Level 3 chargers, which are more cost-effective. Since it can fulfil most of the demand for the electric bus, there is no necessity to install a Level 4 charger, which is not cost-effective. The charger placement in both scenarios is identical. These results show that the solar system has the minimum effect on the charger placement.

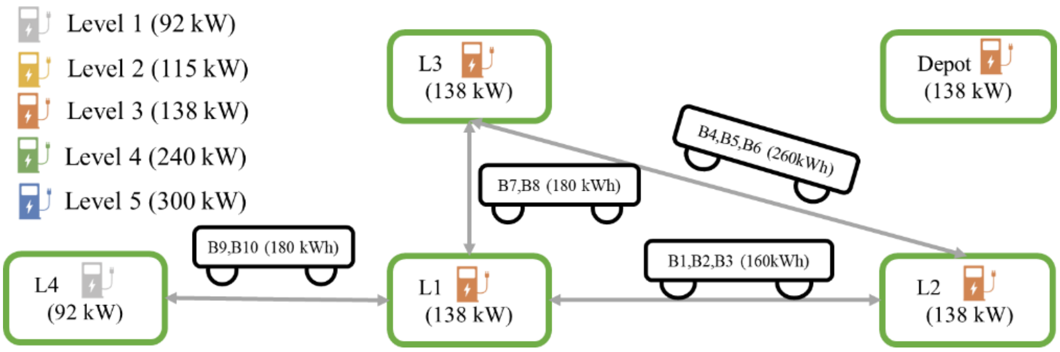

Figure 4: Charger Placement of Scenario 1

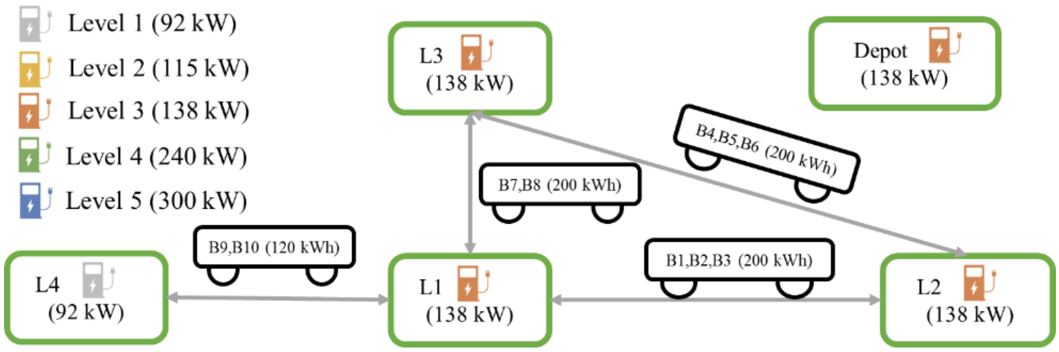

Figure 5: Charger Placement of Scenario 2

Figure 6 shows the energy distribution for both scenarios. There are four types of energy sources for the electric bus to fulfil their travel demand. The blue colour bar represents the energy usage from the grid during peak hours, while the orange colour bar represents the energy usage from the grid during off-peak hours. The yellow colour is the energy directly transferred from the solar system to the electric bus, while the green colour is the energy from the battery of the solar system. In Scenario 1, around 7 % of energy is provided by the solar system. Compared to Scenario 1, Scenario 2 has higher energy charges during peak hours. Models prefer to apply solar systems to charge the electric bus instead of charging during peak hours. Charging during peak hours will lead to a higher cost compared to the solar system.

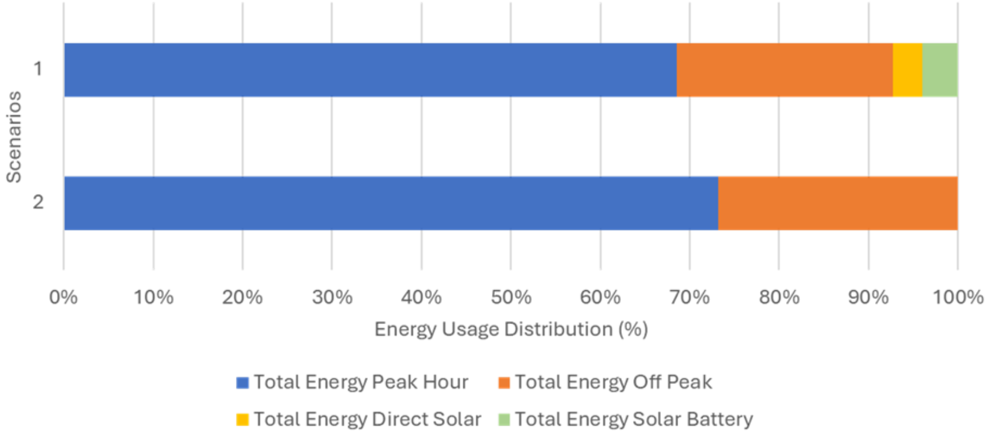

Figure 6: Energy Distribution for Scenarios 1 and 2

Table 3: Result of Sensitivity Analysis

		Scenario 1	Scenario 2
Charger Cost	USD/year	17,331	17,331
Grid Cost	USD/year	138,408	148,782
Battery Cost	USD/year	15,488	16,779
Solar Panel Cost	USD/year	4,414	0
Total Solar Area	m^2	400 m^2	-
Solar Battery Cost	USD/year	400	0
Total Solar Battery	kWh	18.576	-
Total Cost	USD/year	176,040.5	182891.5

Table 3 shows the results for each scenario. Scenario 1 has lower expenses compared to Scenario 2. The cost of the charger is identical in both scenarios. Scenario 1 has a lower grid cost and battery cost compared to Scenario 2. Scenario 1 has a total of 4.7 kUSD for the solar panel and solar battery. The high grid cost in Scenario 2 leads to a higher cost compared to Scenario 1. Scenario 1 has a lower cost than Scenario 2. The total cost of scenario 2 is 4% higher than scenario 1. The results prove that the installation of solar power systems can help reduce the total cost of electric bus systems. All four bus stations are equipped with the maximum number of solar panels. There are no solar panels installed at the bus depot. There is a low amount of solar battery installed at the bus stations. However, the battery is not favorable to the model, regardless of whether it is an electric bus or a solar system, due to its high unit cost. The model prefers to charge during peak hours and shift the cost to the grid instead of having a high cost in the battery system. The solar system can help reduce 4% of the total cost of installing an electric bus system.

4. Conclusions

The model developed has indicated that the solar system can be integrated into the electric bus system, and all the energy demands for the electric bus will be fulfilled. The result also shows that the model able to identify the multiple variables in an electric bus system, including charging profile, charger placement, and battery capacity for both the electric bus and the solar system. Due to the smaller scale of case study, the impact of solar system on charging profile and charger placement is minimal. The results also show that the solar system can help reduce the total cost with proper optimization by shifting the dependence on peak energy from the grid. Current model is the integration of two model which are validated via LCOE.

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