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Modeling an Investment Framework for BMTA Electric Bus Fleet Development

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Abstract: In Thailand, diesel buses are notorious for their poor energy efficiency and contribution to air pollution. To combat these issues, battery electric buses (BEBs) have emerged as a promising alternative. However, their high initial costs have posed challenges for fleet management, especially for agencies such as the Bangkok Mass Transit Authority (BMTA). This study aims to revolutionize BEB fleet management by developing an energy model tailored to the BMTA's needs. The methodology consists of two crucial steps: analyzing BMTA bus routes and designing fleet management and charging systems. Through this process, the study seeks to determine the maximum number of BEBs that can be operated on each route with the fewest chargers possible. The results reveal exciting possibilities. Within the city bus landscape, two out of five BMTA bus routes show potential for transitioning to BEBs, provided they meet a maximum energy requirement of 200 kWh every two rounds. This analysis identifies routes ripe for BEB adoption while considering the limitations of battery size. In the next step, the study unveils a game-changing strategy: a maximum of 13 BEBs can operate on two routes with just four chargers requiring 150 kW each. This means fewer chargers and more efficient operations. Plus, the charging profile peaks at 600 kW from 4:00 to 8:00 p.m., showing when and where the fleet needs power the most. However, the real eye-opener? Significant energy savings of THB 10.44 million per year compared to diesel buses, with an initial investment cost savings of over 37%. These findings underscore the potential for BEB fleet management to revolutionize public transportation and save money in the long run. However, there is more work to be done. The study highlights the need for real-time passenger considerations, the development of post-service charging strategies, and a deeper dive into total lifetime costs. These areas of improvement promise even greater strides in the future of sustainable urban transportation.

Keywords: battery electric bus (BEB); charging design; electric bus fleet; energy model; feasible routes; fleet management; investment decisions

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1. Introduction

1.1. Significance of Approaching Electric Vehicles

The transportation sector is a significant contributor to environmental issues, primarily due to combustion, which leads to greenhouse gas (GHG) emissions [1]. Electric vehicles (EVs) have emerged as a promising solution to mitigate these environmental challenges. EVs come in various forms, including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs) [2]. The adoption of EVs not only positively impacts the environment but also enhances energy efficiency [3]. However, integrating EVs into grid energy management systems requires careful energy modeling and design [4], particularly regarding charging management systems [5].

1.2. The State of Fleet Buses in Thailand

In Thailand, the transportation sector, particularly internal combustion engine (ICE) vehicles, is a major source of GHG emissions, with the energy sector accounting for 74.35% and transportation 25% [6]. Thailand's Nationally Determined Contribution Roadmap for Mitigation 2021–2030 (NDC Roadmap 2021–2030) aims to reduce GHG emissions to approximately 41 MtCO2eq by 2030 [6]. Transforming the public transportation system is crucial to achieving this goal, with battery electric buses (BEBs) playing a significant role in making public transportation environmentally friendly. However, despite their environmental benefits, BEBs often face investor reluctance due to perceived financial feasibility challenges. The Bangkok Mass Transit Authority (BMTA), responsible for operating Bangkok's buses, is one such operator. In a bustling metropolis such as Bangkok, with over 800,000 daily commuters utilizing the BMTA, the financial viability of a BEB fleet hinges on effective management and design [7]. The BMTA plans to replace and enhance its fleet with 2511 BEBs in the future, necessitating optimized fleet operations and significant energy consumption [7].

1.3. Electric Battery Buses in Public Transportation

The literature review explores the performance boundaries of electric buses (BEBs) in public transportation, comparing both numerical models and practical implementations [8]. It highlights the suitability of BEBs with lithium-ion batteries exceeding 324 kWh or achieving 250 km per cycle due to their stability and energy capacity [8]. Factors influencing BEB energy consumption and State of Charge (SOC) reduction, such as passenger load, environmental temperature, and average speed, are analyzed [8]. Despite their environmental benefits and energy efficiency, BEBs face challenges such as limited range, extended recharging times, battery-related risks, costs, and necessary system investments [8]. Technical challenges persist from 2010 to 2023, including fleet over-sizing, available SOC, and impacts on the grid [8].

Challenges in implementing BEBs include traction battery sizing, charging power systems, and fleet scheduling, all tied to investment costs [8]. Higher battery capacities exceeding 324 kWh require significant charger power, increasing investment costs [8]. Recommendations suggest optimizing battery size around 80–100 kWh and exploring alternative system parameters for enhanced performance [8]. Battery degradation studies reveal insights into SOC decreases and energy consumption reduction strategies [9].

In China, a slight decrease in private charging stations is attributed to profitability issues during peak-hour periods [10]. Battery capacity requirements vary based on operating routes, with higher capacities necessitating cost comparisons with charging infrastructure and bus schemes [11]. Introducing charging agency models requires careful consideration of initial investments and bus scheduling [11].

1.4. Review of Literature on Fleet Design and Optimization

Numerous studies have attempted to develop energy models for managing and designing BEB fleets, focusing on optimizing battery size, charger capacity, and operating schedules while minimizing investment and operating costs [12]. Notable models include flow-based models for optimizing oil and gas station locations [13–16] and network equilibrium models for EV charging station location optimization [17,18]. Some studies integrate business and policy recommendation models [19,20]. One study developed an electric bus fleet management and design model that used bus route characteristics, electric bus specifications, charging time, driving characteristics, energy consumption, and simulation data as input. It employed Mixed-Integer Non-Linear Programming (MILP) and the Grouping Genetic Algorithm (GGA) for calculations. Although showing promise, the complexity and lack of flexibility were limitations [21]. Many studies, while complex, may not offer the most practical solutions, particularly in terms of finances and the economy.

1.5. Objectives of the Study

Furthermore, various studies have aimed to enhance the performance of battery electric buses (BEBs) and assess this in terms of total cost of ownership (TCO) compared to internal combustion engine (ICE) buses and non-strategic BEB management. Results indicated that optimizing the battery size and charging infrastructure could improve the TCO of a BEB fleet by over 13% [22]. Another study demonstrated that energy management strategies could reduce the TCO by 15 to 25% [23]. Additionally, optimizing fleet operations by implementing overnight charging to avoid daytime operation issues was found to be beneficial [24].

While numerous studies have focused on optimizing charging schedules to minimize operational costs and TCO, these objectives were often presented separately and not simulated in real-service scenarios. This lack of real-service simulation may affect actual investment costs, operational expenses, and operating conditions.

An essential aspect of managing BEB fleets and chargers is infrastructure, including charging systems, investment decisions, and charging management, as these factors impact operating costs and influence future schedules and routes. The aim of this study is to apply a simple energy model for BEB management and design, transformed into an investment model. The investment model comprises two steps, firstly route analysis, and secondly fleet management and charging design. Using the Bangkok Mass Transit Authority (BMTA) service as a case study to simulate real-world conditions, the investment and operating energy cost savings will validate the model. Additionally, simple financial modeling will be applied to further illustrate the case study.

2. Materials and Methods

Addressing the key challenge in BEB operation, particularly the limitations of operational range and charging time compared to traditional combustion buses, the investment model development flow was initiated. This flow consisted of (1) data collection as input parameters, (2) BMTA route analysis, (3) BEB and charger design, and (4) investment modeling and economic feasibility. Each process yielded essential outputs, including initial input data, possible routes for the sample fleet, the number of BEBs and chargers, charging profiles, and investment and operating cost comparisons for steps (1), (2), (3), and (4), respectively.

This section is divided into three subsections that describe the data collection, BMTA route analysis, and fleet management and charging design. Each subsection expands upon more details.

(1) Data collection

The data collection process focused on the scope of the BMTA's services, specifically within BMTA Bus Operation Division 1 Zone 1: Bangkhen Depot. This area operates five routes with conventional buses: routes 107, 129, A1, 95, and 543. The characteristics of each bus route were gathered using global positioning system (GPS) data and a questionnaire directed at operators.

The collected data included:

- Number of service rounds per day
- Service distance per round
- Service time per round
- Average speed
- Average acceleration
- Idle time
- Number of bus stops
- BEB specifications for simulation

Most of the electric vehicles (EVs) in this area were battery electric buses (BEBs). According to BMTA specifications, these BEBs should be 12-m buses with a battery capacity ranging from 100 kWh to 300 kWh, a seat capacity of 30 seats, a maximum capacity of 50 passengers, and a curb weight limited to 16,000 kg.

A power diagram of a BEB was designed, with 650 VDC for the main battery load and 24 VDC for auxiliary components. The traction motor and air conditioning system were considered the main loads for the battery.

Velocity profiles were collected through GPS tracking, operating in real-time with 10 values per second. These parameters provided sufficient data for the development of the investment model.

(2) BMTA route analysis

The objective of this step was to identify potential routes suitable for converting conventional buses to battery electric buses (BEBs). The criteria for calculation included battery sizing, BEB specifications, and BMTA route characteristics. The calculation flow is illustrated in Figure 1, with the following assumptions:

1. The model started with battery size case 1, considering a number of rounds per charge of 1, and contributed to the energy consumption per round.
2. "The route is possible to change to BEB" refers to the possibility of transforming the route for use by an electric vehicle (EV).
3. The limitation of a BEB's battery capacity was determined by the energy required to operate the BEB under the constraint of the number of rounds per charge.

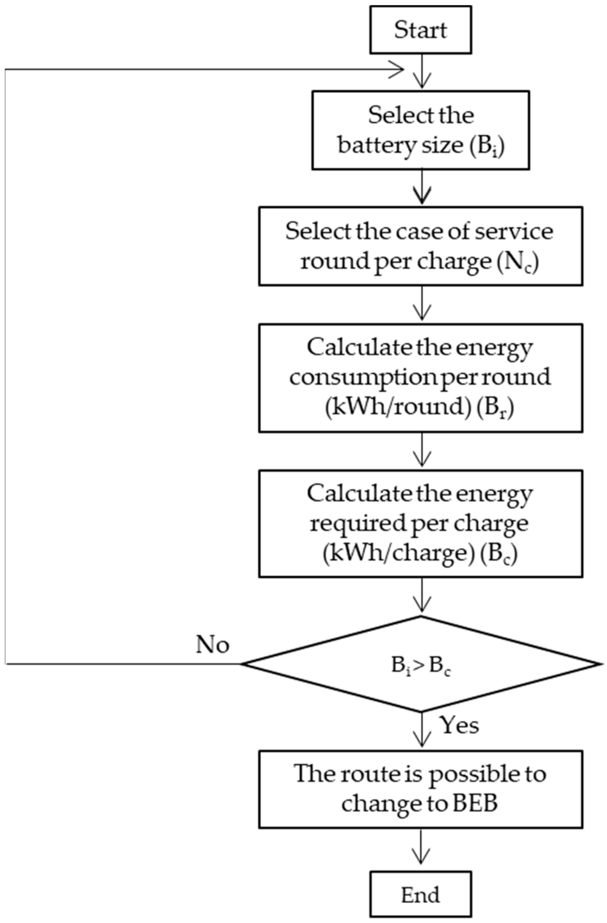

Figure 1. The BMTA route analysis flowchart.

The objective was to filter the possible BEB conversion routes, which could involve a large amount of data, to streamline the model's focus.

(3) Assumption of this work

This work makes the following assumptions regarding city bus public transportation in Bangkok, Thailand:

Charging Plan: Charging is planned for the daytime using quick DC charging, and there are no charging limitations.
BEB Energy Consumption: The energy consumption of battery electric buses (BEBs) is assumed to be 1.23 kWh/km [18], considering the use of a regenerative braking system. This average applies to all bus routes.
Traction Battery Capacity: Two capacities are considered for the traction battery: 150 kWh and 200 kWh, representing the possible installed capacities in the BEBs. This parameter is denoted as "Bi".
Service Trips: Service trips are divided into two cases: 5 rounds per charge or 2 rounds per charge. This parameter is denoted as "Nc".
Sample Fleet Routes: The service routes 107, 129, A1, 95, and 543 represent the sampling fleet.

The sensitivity parameters are the BEB battery capacity and the routes. The step begins with route selection. For each route, the following parameters are defined: the number of service rounds ("Nc"), energy consumption ("Br"), and the energy required for each charge ("Bc"). The constraint "Bi > Bc" indicates the possibility of switching to a BEB, shown in terms of the feasible routes. If this condition is not met, it is not recommended to switch to a BEB due to the limitation of battery size.

(4) Fleet management and charging design

The results for the possible EV route from the previous step were used in this step as the input data. As the outcomes of the previous step were routes, which usually involve large amounts of data, they were filtered to minimize the input data. The possible routes were input into the fleet management and charging design steps by using the route characteristics and operating requirements. The output of the step was illustrated in the form of an operation timetable, the maximum number of BEBs in the sample route, and the number of chargers required. The step was processed as shown in Figure 2, and the below-listed assumptions were made.

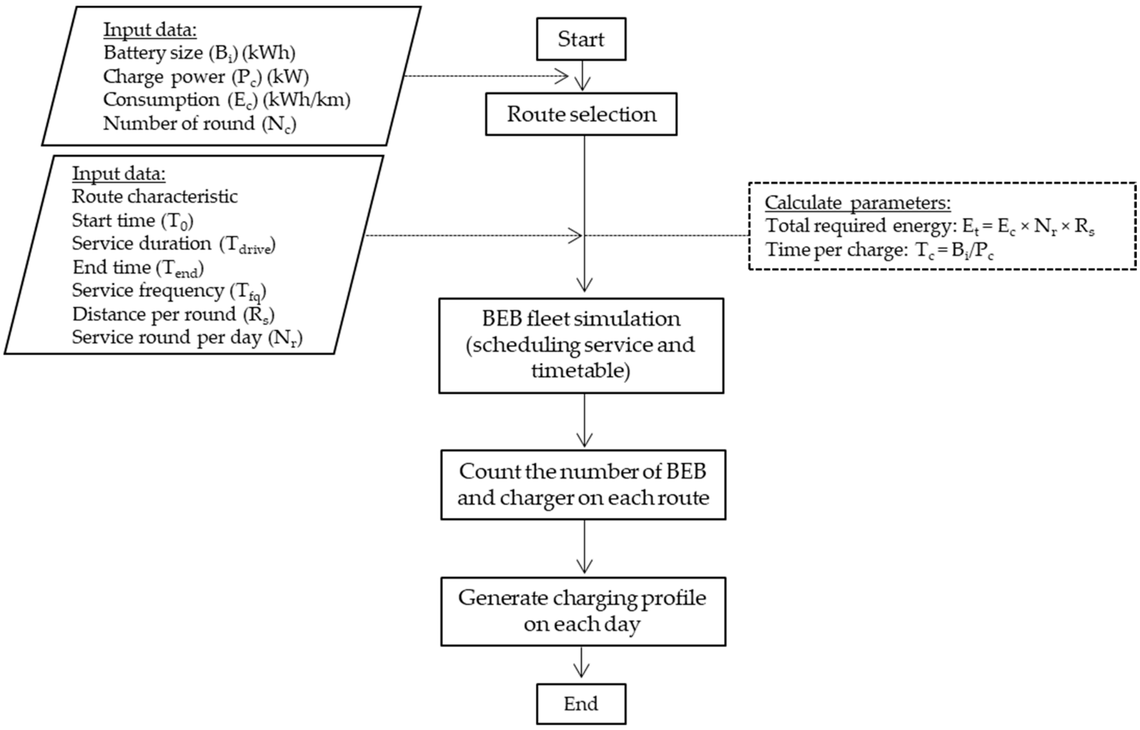

Figure 2. The fleet management and charging design flowchart.

The model assumptions

- The BEBs started with a full battery charge each day.
- The BEBs were operated on every day.
- The service time in each service round (T_{drive}) needed to be more than the running frequency (T_{fq}); if this requirement was not met, it is not a calculation.
- All the chargers were installed at the original station (Bangkhen Depot).

The sensitivity parameters of this step were the charging capacity (power of the chargers) and the traction battery capacity. The fixed parameters were the energy consumption of the BEBs and the average speed for each route. The variable parameters were the starting time (T_0), vehicle range per round (S_r), running frequency (T_{fq}), ending time on each day (T_{end}), and number of service rounds per day. The definitions of the step parameters are shown in Table 1.

Table 1. Parameter definition.

Parameters	Unit	Description	Parameter Type
B_c	kWh/charge	Energy consumption per charging cycle	Calculation
B_i	kWh	Installed battery capacity	Input
B_r	kWh/round	Energy consumption per cycle	Calculation
E_c	kWh/km	Energy consumption	Input
E_t	kWh/day	Daily total energy requirement	Calculation
N_c	-	Number of rounds per charge cycle	Input
N_r	Round/day	Daily number of rounds	Input
R_s	km/round	Distance covered per cycle	Calculation
T_0	-	Start of operation Time	Input
T_c	hours	Charging duration	Calculation
T_{drive}	hours	Driving duration	Input
T_{end}	-	End of operation time	Input
T_{fq}	hours	Service frequency	Input

Variable parameters were also explored, such as the total required energy (E_t), and time per charge, as shown in Equations (1) and (2).

$$\text{Total required energy: } E_t = E_c \times N_r \times R_s \quad (1)$$

$$\text{Time per charge: } T_c = B_i / P_c \quad (2)$$

The number of BEBs and chargers, operating timetable, and charging profile were defined by hand, starting from T_0 and running until T_{end}. The results demonstrated the energy cost savings of the BEBs compared to those of diesel engine buses. These were used to compare the investment models with a simple financial analysis. The model was started with the route and service characteristics as the input data and attempted to generate a timetable for the BEBs. The BEB timetable was related to the number of BEBs and the number of chargers required.

3. Results and Discussion

The results of the BMTA route data collection and analysis revealed the operations of five routes originating from the Bangkhen Depot. On average, five rounds were conducted per day for routes 107, 129, 95, and 543, while an average of seven rounds per day were conducted for route A1. Routes 107, 129, 95, and 543 were characterized by longer distances and lower frequencies, whereas route A1 was shorter with a higher frequency.

Based on BTMA route characteristics, an estimated energy consumption of approximately 1.23 kWh/km was determined for all BEBs equipped with a regenerative braking system [25]. The results, presented in Tables 2 and 3, consider different charging strategies, including overnight charging and daytime charging with two charges per day.

Table 2. Analysis of the BMTA routes considering the overnight charging strategy.

Route	B_r (km/Round)	N_c (Rounds/Charge)	B_c (km/Charge)	E_c (kWh/km)	E_t (kWh/Day)
543	80	5	400	1.23	492
107	76	5	380	1.23	467
129	102	5	510	1.23	627
A1	62	7	434	1.23	534
95	104	5	520	1.23	640

Table 3. Analysis of the BMTA routes considering the daytime charging strategy.

Route	B_r (km/Round)	N_c (Rounds/Charge)	B_c (km/Charge)	E_c (kWh/km)	E_t (kWh/Day)
543	80	2	160	1.23	197
107	76	2	152	1.23	187
129	102	2	204	1.23	251
A1	62	2	186	1.23	229
95	104	2	208	1.23	256

The analysis showed the feasibility of using BEBs on each route originating from the Bangkhen Depot. While a BEB battery capacity of 150 kWh may not be sufficient, switching operations to BEBs with a 200 kWh battery capacity is feasible, albeit limited to two rounds per charge. This recommendation applies to routes 543 and 107, as they require less than 200 kWh for every two rounds. These routes were further analyzed and designed in the subsequent step. The 200 kWh capacity falls within the range identified in a previous study [11].

The results from the BMTA route analysis step showed the possibility of operating with BEBs on routes 543 and 107, which began at the Bangkhen Depot. These routes were confirmed to be limited to two rounds, as they illustrated the lowest service distance per round. For route 543, it would be possible to switch to BEBs with two rounds per charge beginning at 5:00 a.m. and ending at 11:00 p.m. while taking 3 h per loop. Route 107 started at 4:30 a.m. and ended at 9:45 p.m. while taking 2 h and 40 min per loop. The time schedules on routes 543 and 107 are shown in Table 4.

Table 4. BEB schedule.

Route	T_0	T_{drive} (min)	T_{end}	R_s (km/Round)	N_r (Round/Day)	Daily Range (km/Day)
543	5.00 a.m.	180	11.00 p.m.	80	5	400
107	4.30 a.m.	100	09.45 p.m.	76	5	380

The parameters in Table 4 were used as input data for the fleet management and design models. The model's results are illustrated in Tables 5 and 6 for routes 543 and 107, respectively. The "Go" symbol indicates that the BEB is in operation, while the "C" symbol, highlighted in yellow, indicates that the BEB is charging. The number of vehicles required for 6 and 7 BEBs for routes 543 and 107, respectively, are shown. Cells with no vehicles needed are shaded in grey. The service characteristics were expanded into the total energy required for the system when routes 543 and 107 were operated with BEBs. The traction batteries of the BEBs on these routes had a capacity of 200 kWh, the power of the chargers was 150 kW (using fast DC charging, which was completed within 90 min for the 200 kWh battery capacity), and the bus timetable involved a departure frequency of 1 h.

Table 5. Timetable for running and charging BEBs on route 543.

Time	No. of Vehicles										No. Chargers
	1	2	3	4	5	6	7	8	9	10	
5:00 A.M.	Go										0
6:00 A.M.		Go									0
7:00 A.M.			Go								0
8:00 A.M.				Go							0
9:00 A.M.					Go						0
10:00 A.M.	Go					Go					0
11:00 A.M.		Go									0
12:00 P.M.			Go								0
1:00 P.M.				Go							0
2:00 P.M.					Go						0
3:00 P.M.	C					Go					1
4:00 P.M.	C	C									2
5:00 P.M.	Go	C	C								2
6:00 P.M.		Go	C	C							2
7:00 P.M.			Go	C	C						2
8:00 P.M.				Go	C	C					2
9:00 P.M.					Go	C					1
10:00 P.M.	Go					Go					0
11:00 P.M.		C									1
N_r	4	3	3	3	3	3					2 (Max)

After applying these conditions and constraints, it was found that six BEBs and seven BEBs were required for routes 543 and 107, respectively, thus comprising a BEB fleet. The fleet was required to have 150 kW of charging power with four available slots, which could be either four plugs in a charging system or four chargers. The charging profile peaked at 600 kW in the period of 4:00–8:00 p.m., as shown in Figure 3. The sharing of charger resources was proved by these results. Fleet management and design can be optimized with this model. The first BEB started charging at 2:00 p.m. and finished at 11.00 p.m. every day. For routes 543 and 107, most of the BEBs could be charged once daily, with one BEB being charged twice. At the end of each day, ten BEBs required overnight charging for either route 543 or route 107, while two BEBs already had fully charged batteries.

Table 6. Timetable for running and charging BEBs on route 107.

Time	No. of Vehicles										No. Chargers
	1	2	3	4	5	6	7	8	9	10	
4:00 A.M.	Go										0
5:00 A.M.		Go									0
6:00 A.M.			Go								0
7:00 A.M.				Go							0
8:00 A.M.					Go						0
9:00 A.M.	Go					Go					0
10:00 A.M.		Go					Go				0
11:00 A.M.			Go								0
12:00 P.M.				Go							0
1:00 P.M.					Go						0
2:00 P.M.	C					Go					1
3:00 P.M.	C	C					Go				2
4:00 P.M.	Go	C	C								2
5:00 P.M.		Go	C	C							2
6:00 P.M.			Go	C	C						2
7:00 P.M.				Go	C	C					2
8:00 P.M.					Go	C	C				2
9:00 P.M.	Go					Go	C				1
10:00 P.M.		C					C				2
N_r	4	3	3	3	3	3	3				2 (Max)

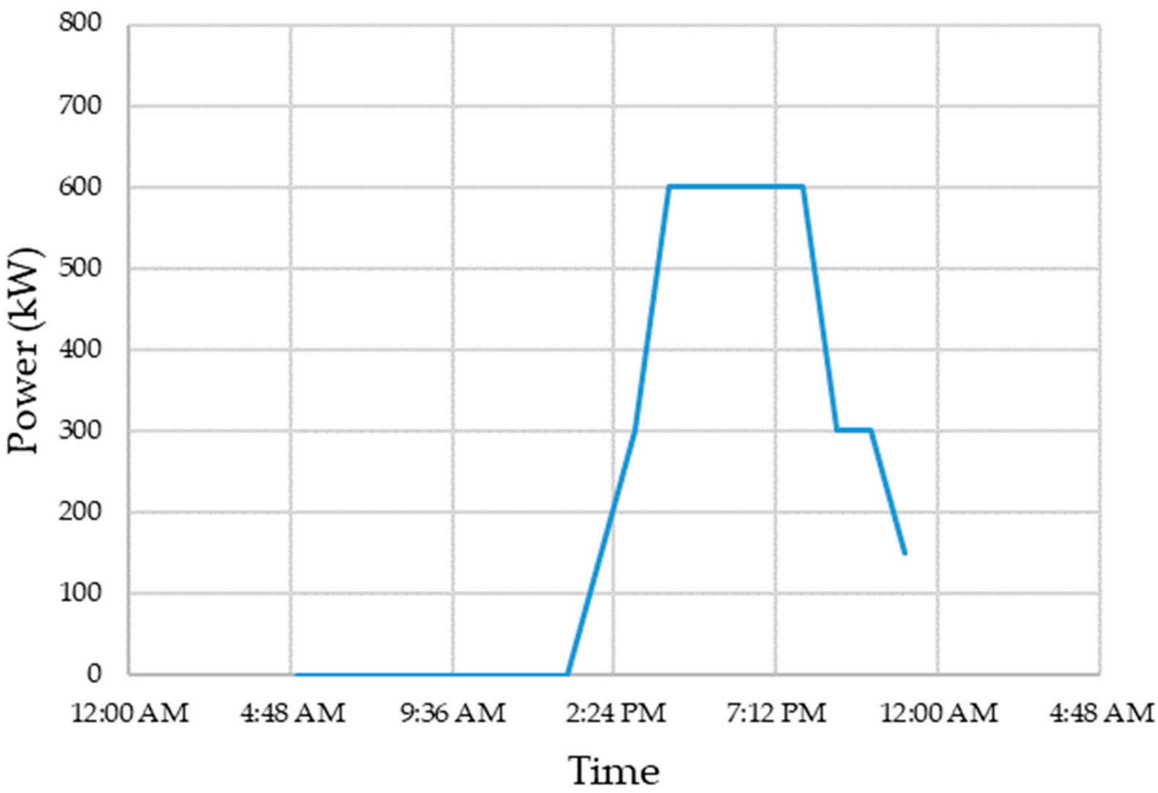

Figure 3. Charging profile.

Thirteen BEBs, the timetables, and four chargers were used for the model validation. The model needed to save costs. The daily charging energy at the terminal, the total charging energy at the end of each day, the total vehicle range per year, and the average total vehicle range per year are illustrated in Tables 7 and 8. The average total vehicle ranges per year were 146,000 km/year and 138,720 km/year for routes 543 and 107, respectively.

The fleet's energy management and design still involved a traction battery capacity of 200 kWh and a charging power of 150 kW. On route 543, five BEBs were charged one time per day, and one BEB was charged at the end of the day. On route 107, five BEBs were charged once per day, and two BEBs were charged again at the end of the day. At the end of each day, it was necessary to charge five BEBs each for route 543 and route 107. These show the differences in the charging required at different times, which affected the charging cost. The characteristics of operating a diesel bus were assumed and used for comparison.

Table 7. Annual charging cycle and energy consumption.

Route	Daily Charging Cycle	Charging Cycle at the End of the Day	Charged Energy per Cycle	Charged Energy at the End of the Day	Daily Range (km/Day)	Yearly Range (km/Year)
543	3	1	200 kWh	200 kWh	400	146,000
107	3	1	200 kWh	200 kWh	380	138,700

Table 8. Total annual charging energy and vehicle range.

Route	BEBs	Chargers	Total Daily Charged Energy	Total Charged Energy at the End of the Day	Total Distance (km/Day)	Total Distance (km/Year)
543	6	2	1400 kWh	1000 kWh	2400	876,000
107	7	2	1600 kWh	1000 kWh	2660	970,900

Finally, the energy cost savings when using the BEB fleet design and management were validated, as shown in Tables 9 and 10. Route A1 was assumed to use seven BEBs in the fleet with a total charging energy of 400 kWh per vehicle per day, and this was used for the verification and confirmation of the model. Routes 543 and 107 were also assessed in terms of energy savings, but route A1 did not provide savings. Route A1 is not recommended for BEB operation. The amount of energy saved on routes 543 and 107 was better than that saved with diesel buses. A total of 10.44 million baht per year were saved. These results require further study in terms of the economic scale and total ecosystem cost. The initial cost, which was the price of either the diesel bus or electric bus, the fuel cost, which was the price of either diesel oil or electricity, and other investment costs, such as that of the charging infrastructure, were used as sensitivity parameters for the calculation of the economic model.

Table 9. Financial model for the diesel fleet simulation.

Vehicle Type	Diesel Bus		
Route	543	107	A1 (Reference)
Daily range (km/day)	400	380	434
Fuel consumption (km/L) [22]	3.07	3.07	3.07
Fuel cost (THB/L)	30.00	30.00	30.00
Number of vehicles (buses)	6	7	7
Total fuel cost (THB/day)	23,529	26,078	29,784
Total fuel cost (THB/year)	8,588,235	9,518,627	10,871,275

Table 10. Financial model for the BEB fleet simulation.

Vehicle Type	BEB		
Route	543	107	A1 (Reference)
Number of vehicles (BEBs)	6	7	7
Daily charged energy (kWh/day)	1400	1600	2800
Electricity price (peak hour) (THB/kWh)	5.00	5.00	5.00
Charged energy at the end of day (kWh/day)	1000	1000	1000
Electricity price (off-peak hour) (THB/kWh)	3.00	3.00	3.00
Total energy cost (THB/day)	10,000	11,000	14,800
Total energy cost (THB/year)	3,650,000	4,015,000	6,205,000
Energy saving (THB/year)	4,938,235	5,503,627	4,666,275

Another method to optimize the model results was to consider the investment cost. The two scenarios for investment costs were compared. The first scenario, known as business as usual (BAU), assumed the BMTA fleet operated normally on routes 543 and 107 with 5 buses and 15 buses, respectively, and chargers (150 kW) were prepared for the operation of all buses. In the second scenario, the optimization of bus and charging resource sharing was considered. The investment costs for each scenario are shown in Table 11. The cost of a BEB was THB 7,000,000, while the cost of a charger was THB 1,500,000.

Table 11. The investment cost in each scenario.

Scenarios	Number of BEBs		Number of Chargers	Total Investment Cost (Million THB)
	543	107		
BAU	5	15	10	155
This study	6	7	4	97

In the BAU case, there were a total of 20 buses and 10 chargers (sufficient for the operation of 20 buses). The investment cost in the BAU case was more than 37% higher than that in the optimization scenario. The cost savings in the optimization scenario resulted from optimizing the number of BEBs and sharing charging system resources between different routes. This analysis focused solely on investment costs. For a more comprehensive understanding of investment decisions, the total lifetime cost of the product may be considered.

4. Conclusions

The route analysis model demonstrated that buses on BMTA routes 543 and 107 could transition to battery electric buses (BEBs) equipped with a 200 kWh battery capacity. A daytime charging strategy was simulated, allowing BEBs to operate for at least two rounds per charge.

The analysis indicated that routes 543 and 107 would require a minimum of six and seven battery electric buses (BEBs), respectively, to replace conventional buses from the Bangkhen Depot. Optimal investment calls for a 150 kW charger with four plugs to support this fleet. A peak demand of 600 kW was calculated daily from 4:00 to 8:00 p.m., highlighting the impact of the optimized design on investment decisions. This underscores the potential of the fleet management and design model.

Key parameters influencing fleet management and design optimization included BEB energy consumption (E_c, kWh/km), traction battery capacity (Bat_size, kWh), charging capacity (P_c, kW), and number of rounds per day (N_r, rounds per day). These parameters had variable effects on the number of BEBs (nBEB, vehicles), BEB timetables, and the required number of chargers (nCh, chargers).

A comparison of the model's outcomes for managing and designing BEB fleets on routes 543 and 107 with diesel buses validated its efficacy. The model is recommended for assessing cost savings compared to conventional systems. A basic financial analysis demonstrated annual energy cost savings of THB 10.44 million when employing a BEB fleet instead of diesel buses, with these BMTA routes benefiting from energy cost savings through BEB operation. However, these findings solely pertain to model validation and do not constitute a conclusive assessment or financial modeling of project feasibility. The optimization of BEB numbers and charging resource sharing resulted in over 37% savings in investment costs compared to the original scenario.

The study highlights the effectiveness and simplicity of the energy model for managing and optimizing BEB fleets. Most findings are valuable for investment decisions. While charging resource sharing was implemented, the models lacked consideration for post-service charging strategies, and peak charging times affected operational costs. BEB operation and charging system rescheduling were not addressed, nor was the total lifetime cost of BEB fleets. These factors should be accounted for to enhance decision-making efficacy.

It is important to note that the results of this study may not cover the full spectrum of electric bus varieties available worldwide. Factors such as bus size (including buses larger than 18 m), passenger capacity (ranging from 75 to 150 passengers), battery size (exceeding 330 kWh), charging power (over 150 kW), and energy consumption linked to air-conditioning load were not explicitly addressed. This study is based on assumptions specific to the electric bus landscape in Thailand, considering factors such as manufacturers, operators, laws, and regulations. Limitations include the real-time variability in passenger usage and demand on each route.

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