Global NEST Journal, **28** (8), 08297
Available online: 22/10/2026

# Feasibility Study of Conversion of Conventional to Modified Electric Buses in Thailand

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**Abstract**

This study evaluates the feasibility of converting conventional diesel buses (CBs) operated by the Bangkok Mass Transit Authority (BMTA) into modified electric buses (MEBs) using a system dynamic modeling framework. The model integrates costs, such as investment and operating costs, and benefits, such as fuel and maintenance savings, job creation, green image benefits, and environmental impacts. Three scenarios are compared over 25 years, including the continued operation of CBs, the adoption of imported electric buses, and the conversion of existing buses to MEBs. Simulation results show that the MEB conversion achieves a positive net present value and an internal rate of return, reaching about 43% at the end of the project, and outperforms the other two scenarios. From an environmental perspective, replacing CBs with MEBs reduces $CO_{2eq}$ emissions and roadside particulate matter, while increasing one-time upstream metal depletion and human toxicity associated with battery production. The sensitivity analysis shows that MEB conversion can be an economically attractive and environmentally beneficial pathway for accelerating bus electrification in Thailand. This study provides supportive policies that further enhance the return, including local manufacturing, cleaner power generation, and battery recycling.

**Keywords**: Case study; conventional bus; feasibility study; internal rate of return; modified electric bus; system dynamics modeling.

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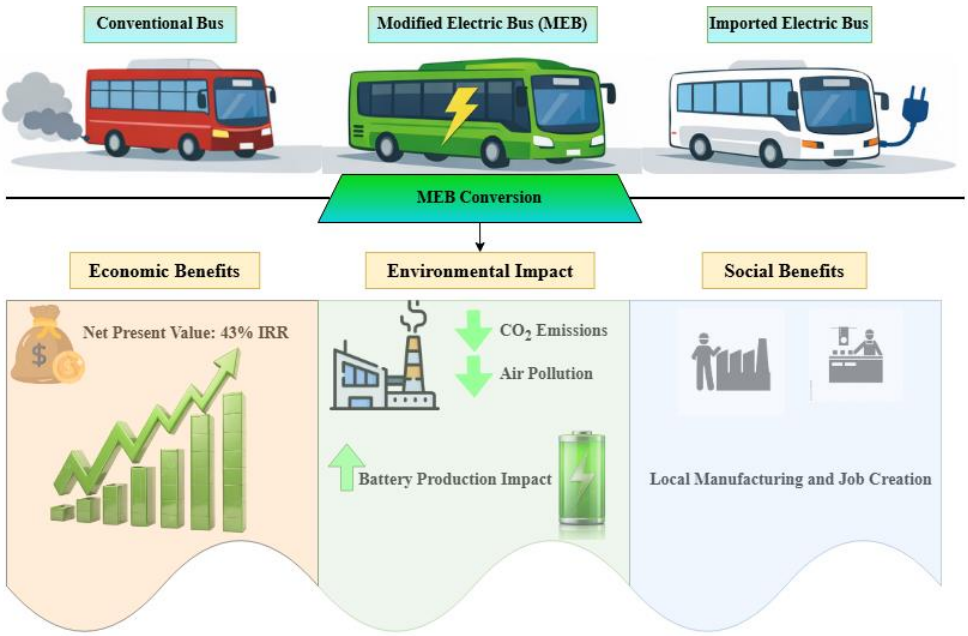
**Received**: 22/12/2025,

**Accepted**: 21/10/2026,

**Available online**: 22/10/2026

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**Graphical abstract**




## 1. Introduction

Urban air pollution and greenhouse gas (GHG) emissions continue to pose major challenges worldwide, particularly in rapidly developing countries such as Thailand. Road transportation is a main contributor to carbon dioxide ($CO_{2eq}$) and particulate matter (PM) emissions, impacting public health and accelerating climate change (Miraftabzadeh *et al.*, 2024). In Bangkok, buses rely heavily on diesel, which worsens air quality. The transition to low-carbon public transportation has become a government policy priority, which aligns with global commitments to climate mitigation and sustainable urban development.

The automotive industry in Thailand is rapidly developing environmentally friendly technologies to reduce GHG emissions. Many companies are accelerating the shift from internal combustion engines (ICEs) to electric vehicles (EVs), with global EV sales reaching 6.6 million units in 2021 (IEA, 2020). As the largest automobile assembler in Southeast Asia, Thailand has strong industrial capabilities. However, domestic EV adoption remains limited, mainly due to higher EV prices driven by import tariffs and materials. Reducing EV costs requires establishing domestic production and assembly capacity to achieve economies of scale. In response, the Thai government has introduced multiple policies to promote EV adoption, including incentives for environmental performance, infrastructure development, human resource development, safety standards, investment promotion, tax reductions, and domestic market stimulation (BOI, 2022).

In the public transportation sector, the Bangkok Mass Transit Authority (BMTA) announced a plan to replace 2,511 conventional buses (CBs) with modified electric buses (MEBs) as part of its modernization strategy (BMTA, 2017). However, Thai manufacturers currently face significant challenges in executing large-scale bus conversions. Converting CBs into MEBs requires advanced technical expertise and specialized components, many of which must be imported, particularly batteries. This reliance on foreign parts increases conversion costs and limits opportunities for domestic value creation (BOI, 2022). Addressing these constraints, including local production capabilities, technology partnerships, and targeted policy incentives, is essential for promoting Thailand's national EV goals.

Despite growing government policy interest, there remains a limited understanding of the economic feasibility of converting CBs to MEBs under Thailand's industrial and market conditions. Moreover, existing electric bus feasibility studies have primarily examined the purchase and operation of newly manufactured electric buses, using static total cost of ownership, life-cycle cost, or life-cycle assessment approaches. Limited attention has been given to the conversion of existing diesel buses, particularly in developing countries, where vehicle reuse, domestic manufacturing capacity, dependence on imported components, and gradual bus replacement strongly influence project feasibility. Moreover, previous SD-based EV studies have focused on market adoption and vehicle sales rather than the integrated financial, industrial, and environmental perspective of bus conversion. To address this gap, this study develops a system dynamics (SD) modeling approach:

1. To assess the economic feasibility of converting BMTA's existing CBs into MEBs under production-capacity limitations.
2. To compare the results with continued conventional bus operation and imported electric buses.
3. To examine the dynamic interrelationships between costs, technology learning, environmental impacts,

and social benefits over time, while the sustainability assessment incorporates economic (NPV, IRR), environmental (CO2eq, PM, toxicity, resource depletion), and social (employment, green image) dimensions.

4. To recommend the suggestion that incorporates battery replacement, component localization, and economies of scale over 25 years using sensitivity analysis.
5. To access broader environmental and socioeconomic implications of MEB conversion.

The results of this study aim to provide policymakers and industry stakeholders with evidence-based insights to guide Thailand's transition toward low-carbon public transportation. Accordingly, the study provides a retrofit feasibility framework rather than assuming the purchase of entirely new electric buses. It represents the temporal interactions among conversion capacity, battery replacement, component costs, energy savings, and policy interventions using system dynamics. It provides replicated frameworks for developing-country transport authorities considering bus electrification under limited capital budgets and reliance on imported vehicle components. By assessing multiple sustainability dimensions within a dynamic modeling framework, this research contributes to a more comprehensive understanding of electric bus conversion as a pathway for achieving long-term environmental and economic benefits.

## 2. Literature Review

### 2.1. *BMTA, Conventional, and Electric Bus Characteristics*

BMTA operates bus services primarily within Bangkok. In 2023, the BMTA operated 7,478 buses, all of which were CBs (BMTA, 2023). Key components of CBs include the combustion engine, exhaust emission system, cooling system, chassis, and fuel tank (Role, 2019). These systems contribute significantly to urban air pollution by emitting particulate matter (PM), nitrogen oxides ($NO_x$), and other harmful pollutants.

The shift toward MEBs, which relies on electric motors rather than combustion engines, presents an opportunity to eliminate tailpipe emissions and reduce operational fuel costs. MEBs in Thailand use lithium-ion battery chemistries, specifically nickel–manganese–cobalt (NMC), which offer high energy density and long cycle life. Removing the combustion engine also reduces maintenance requirements and extends the bus's lifespan. Using MEBs offers several benefits. For example, Peters *et al.* (2020) stated that using EVs reduces CO2 emissions and fuel consumption, thereby enhancing the country's green image. Malmgren (2016) stated that EVs generate jobs in automotive manufacturing. However, converting old CBs to MEBs incurs costs, including replacing the transmission and battery systems and modifying the engine system. In this study, five benefits of MEBs are listed: energy cost savings, maintenance cost savings, a green image, job opportunities, and salvage value. In contrast, eight costs are considered: battery system, motor system, in-vehicle air-conditioning, onboard charger, DC/DC converter, suspension, body, and miscellaneous.

**Table 1.** Similarities and differences of parts used in CBs and MEBs.

| Part and component | | Similarities and differences between CBs and MEBs | | |
|---|---|---|---|---|
| Part | Component | Identical | Resemble | Dissimilar |
| Body unit | Body | X | | |
| | Mirror | X | | |
| | Interior & Exterior | X | | |
| | Safety | X | | |
| | Body electronic component | X | | |
| Engine unit | Engine | | X | |
| | Emission system | | | X |
| | Engine electronic component | | | X |
| | Engine cooling system | | | X |
| Transmission unit | Transmission shaft | | | X |
| | Clutch | | | X |
| | Powertrain control unit | | | X |
| Chassis unit | Chassis | X | | |
| | Suspension | X | | |
| | Steering system | | X | |
| | Brake system | | X | |
| | Exhaust system | | | X |
| | Fuel tank | | | X |
| | Wheel and tires | X | | |
| | Bumpers | | X | |
| | Lubricant | X | | |

***Note:*** *The information is retrieved from the Thailand Automotive Institute (2021).*

The similarities and differences in the parts used in CBs and MEBs are summarized in **Table 1**. Many structural elements of CBs and MEBs, such as the chassis, body structure, and suspension systems, are identical and remain unchanged

during conversion. In addition, Conversion requires removing the engine, transmission shafts, and cooling systems and replacing them with electrical subsystems. The conversion process is highly dependent on manufacturer-specific designs, making standardization across different bus models and production facilities challenging.

Technical specifications for MEB components were obtained from interviews with three companies directly involved in electric bus conversion projects in Thailand. The primary systems include:

- Li-ion battery: Maximum capacity of 193.536 – 207 kWh (576 – 651.2 V, 300 – 360 Ah).
- Electric traction motor: Operational speed of 3000-3400 RPM, max/continuous torque of 3,000-3,600/1,000-2,800 Nm, max/continuous power of 240-380/120-270 kW, and operating battery voltage of 300 – 750 VDC.
- In-vehicle air conditioning: 400-720 VDC and 60,000 – 125,000 BTU.
- On board charger: 2xAC Type-2 (IEC 62196), max power of 36-40 kW, input of 3Ph-380V/50Hz, and output of 55A/680VDC maximum.
- DC/DC converter: 650VDC/24VDC 90 A.

These specifications inform the cost structure, energy consumption estimates, and the model's overall system behavior.

### 2.2. *Economic Evaluation*

The evaluation of conversion feasibility includes economic, environmental, and social aspects. Based on interviews and previous studies, the model included five key benefits and eight cost components.

Benefits are as follows:

- Energy cost savings: Lower electricity prices compared to diesel fuel cost (Pamidimukkala *et al.*, 2023).
- Maintenance cost savings: Electric motor with fewer mechanical components (Pamidimukkala *et al.*, 2023).
- Potential customer: Enhanced public perception and alignment with environmental policies (Lashari *et al.*, 2021).
- Job creation: Increased employment in MEB conversion and retrofitting industries (Malmgren, 2016).
- Salvage value: Value recovery of retired components and end-of-life battery reuse.

These benefits encompass both direct financial gains and strategic value associated with MEB adoption. Energy and maintenance cost savings directly improve operational efficiency. Job creation is estimated based solely on employment generated within Thailand's bus industry, which accounts for approximately 0.7% of the country's GDP (Statista, 2024). This represents the microeconomic contribution to the industry. The salvage value further supports economic efficiency and resource sustainability by recovering residual value at the end of their service life. Potential customer growth generates indirect benefits that extend beyond improvements in public perception. MEB adoption can strengthen corporate environmental, social, and governance (ESG) performance by demonstrating a commitment to low-carbon operations, regulatory compliance, and stakeholder expectations. Moreover, sustainability-oriented investments may enhance organizational adaptability, attract green financing, and improve long-term competitiveness (Li *et al.*, 2025).

Costs are as follows:

- Battery system cost
- Traction motor cost
- In-vehicle air conditioning cost
- Onboard charger cost
- DC/DC converter cost
- Suspension modifications cost
- Body refurbishment cost
- Miscellaneous conversion components and labor cost

These cost components represent the investment required to convert CBs into MEBs and directly affect the industry's financial burden. Among them, the battery system is the most expensive due to its high-cost materials and cannot be localized in Thailand. Other components, such as the motor, power electronics, and onboard systems, reflect the shift from a traditional mechanical setup to an electrical system in MEBs.

These cost-benefit categories form the basis for the techno-economic assessment in this study. The economic feasibility of converting CBs to MEBs is assessed through financial assessments, including net present value (NPV) and internal rate of return (IRR). The NPV is calculated as the discounted sum of net cash flows (benefits minus costs) over the project lifetime. A positive NPV indicates financial viability, while a negative NPV shows a loss in investment. The IRR is the discount rate at which NPV equals zero. It represents the project's expected rate of return in percentage (Gallant, 2022). For government projects in Thailand, a minimum IRR of 12% is required (Cerbo, 2023). These indicators allow comparisons between CBs and MEBs, as well as across different policy and market scenarios.

### 2.3. *Environmental Evaluation*

The environmental feasibility of CBs into MEBs is assessed using a well-to-wheel (WTW) framework. This boundary includes emissions and environmental burdens associated with electricity generation, battery production, and component manufacturing, as well as avoided emissions from diesel combustion. The WTW scope is designed to evaluate the conversion pathway, as it captures the upstream impacts of electrification while excluding end-of-life processes that vary widely by technology and region (Laurence & Bai, 2025). Environmental indicators were selected based on their relevance to transport electrification, availability in the literature, and applicability to Thailand's context. Four key environmental indicators were included:

- Carbon dioxide emission (CO2eq): The CO2eq measures total greenhouse-gas emissions associated with vehicle operation and electricity generation. This reflects the climate mitigation benefits of replacing diesel buses with MEBs (Leichter *et al.*, 2022).

- Particulate matter formation (PM): CBs are significant contributors to PM in urban areas. MEBs eliminate tailpipe PM emissions and improve roadside air quality (Leichter *et al.*, 2022).
- Human toxicity (HT): HT is calculated from toxic pollutants emitted mainly during battery manufacturing. This indicator captures the upstream impacts of battery production (Popien *et al.*, 2023).
- Metal depletion (MD): MD refers to the consumption of valuable metals such as lithium, cobalt, and nickel used in battery systems. This is essential for understanding resource sustainability and supply-chain implications (Leichter *et al.*, 2022).

These indicators were extracted from environmental LCA studies on electric buses and EV batteries (Peters *et al.*, 2020). The environmental evaluation was conducted in three steps:

- Quantification of CBs' environmental impact: The emissions from CBs were examined using literature-based emission factors for $CO_2$, PM, and toxic pollutants per kilometer of operation. Annual emissions were calculated based on BMTA's average mileage.
- Quantification of MEB environmental impact: Upstream emissions for the electric bus pathway were retrieved from battery production (NMC) and charging electricity consumption. These factors reflect Thailand's grid mix and specific interview data.
- Comparison of CB and MEB environmental performance: Environmental benefits were calculated from the difference between CB and MEB emissions. This approach captures avoided diesel combustion emissions, reduced PM, $CO_{2eq}$ emissions, and trade-offs from battery and component manufacturing.

## 3. Methodology

### 3.1. *Data Collection*

Both secondary and primary data sources were used to develop the system dynamics (SD) model. Secondary data were obtained from national and international journal articles, government publications, and company reports. These data include the number of BMTA buses, historical fuel and electricity prices, labor statistics, and employment rate. Primary data were collected through interviews with experts from three large-scale bus manufacturing companies in Thailand with direct experience in CB conversion. The first interviewee was an executive from a major bus manufacturer located in Chonburi Province. The second interviewee was a project manager at a bus manufacturing facility in Suphanburi Province. The third interviewee was the vice chairman of a bus manufacturer headquartered in Bangkok. Each interviewee possessed more than ten years of experience in bus manufacturing, providing credible insights into component costs, technical specifications, feasibility constraints, and practical considerations for bus conversion. **Table 2** summarizes the primary and secondary data inputs used for SD model development.

**Table 2.** Primary and secondary data were used to develop the SD model.

| Type | Data | Detail |
|---|---|---|
| Secondary | BMTA bus | • Number of old buses: 2511 units<br>• Bus driving distance: 242 km/day on average<br>• Round per year: 3285 rounds per MEB<br>• MEB lifespan: 25 years<br>• Ticket cost: 17 Baht/customer<br>• Battery capacity: 207 kWh |
| | Economy of scale | • Production cost reduction by 10-70% |
| | Imported electric bus | • 12.48 million Baht/unit on average<br>• Price's annual increasing rate: 0.75% |
| | Energy consumption | • Fuel price: 7 Baht/km on average<br>• Electricity price: 3.5 Baht/km on average |
| | GDP | • Increasing rate from MEB production: 14.2%<br>• Inflation rate: 2% per year |
| | Import part/component | • Cost increasing rate: 0.7% per year on average |
| | Customer | • Green customer: 6 customers per round |
| | Environmental-related cost | • CO2eq emissions from material extraction: 15 kg of CO2eq/kg of NMC battery<br>• CO2eq emissions from diesel combustion: 2.7 kg CO2eq/L<br>• CO2eq emissions from electricity generation: 0.4 kg CO2eq/kWh.<br>• PMs from diesel combustion: 0.0013 kg PM/L<br>• PMs from electricity generation: 0.006 kg PM/kWh<br>• PMs: $0.4/kg PM<br>• Human toxicity: 20 kg 1,4-DCBeq/kWh<br>• Metal depletion: 1.9 kg Feeq/kWh<br>• Diesel density: 0.85 kg/L<br>• Fuel depletion: 1.1 kg of oileq/km |

| | | |
|---|---|---|
| Primary | Battery system cost | • Minimum: 2.8 million Baht<br>• Maximum: 4.1 million Baht<br>• Average: 3.4 million Baht<br>• Units required per MEB: 1 |
| | Motor system cost | • Minimum: 0.3 million Baht<br>• Maximum: 0.9 million Baht<br>• Average: 0.6 million Baht<br>• Units required per MEB: 1 |
| | In-vehicle air conditioning cost | • Minimum: 0.2 million Baht<br>• Maximum: 0.4 million Baht<br>• Average: 0.3 million Baht<br>• Units required per MEB: 1 |
| | On board charger cost | • Minimum: 0.3 million Baht<br>• Maximum: 0.5 million Baht<br>• Average: 0.4 million Baht<br>• Units required per MEB: 1 |
| | DC/DC converter cost | • Minimum: 0.02 million Baht<br>• Maximum: 0.05 million Baht<br>• Average: 0.03 million Baht<br>• Units required per MEB: 1 |
| | Suspension cost | • Minimum: 0.5 million Baht<br>• Maximum: 1.06 million Baht<br>• Average: 0.8 million Baht<br>• Units required per MEB: 1 |
| | Body cost | • Minimum: 1.7 million Baht<br>• Maximum: 2.3 million Baht<br>• Average: 1.9 million Baht<br>• Units required per MEB: 1 |
| | Miscellaneous cost | • Minimum: 0.2 million Baht<br>• Maximum: 0.4 million Baht<br>• Average: 0.3 million Baht<br>• Units required per MEB: 1 |
| | Total cost | • Minimum: 6 million Baht per MEB<br>• Maximum: 9.7 million Baht per MEB<br>• Average: 7.9 million Baht per MEB |
| | MEB | • Production capacity: 192 units/year<br>• Maximum old CBs to be modified: 2511 units |
| | Battery lifespan | 10 Years |

*Note: References include BMTA (2023), Chayutthanabun et al. (2024), Laoonual (2022), IEA (2020), Juan and Constanza (2012), Husan (1997), Sereewatthanawut et al. (2025), Van Oers et al. (2022), and interviews.*

### 3.2. *System Dynamics Modeling*

System dynamics (SD) modeling is employed to evaluate the long-term feasibility of converting conventional buses into modified electric buses (MEBs). SD is well-suited for analyzing complex systems with interdependent variables, feedback loops, and time delays. It enables researchers to simulate dynamic behavior over time and test alternative policy scenarios (Soewin & Chinda, 2022).

SD has been widely applied in transportation and sustainability research. For instance, Sea-lim *et al.* (2018) applied SD to evaluate the feasibility of reverse logistics for steel waste in the construction industry. They found that achieving a 12% internal rate of return would require 8 years. Chayutthanabun and Chinda (2021) used SD to project long-term lightweight EV sales in Thailand and demonstrated that market penetration strongly depends on vehicle price ranges. These examples illustrate the relevance of SD for assessing technological transitions and investment performance.

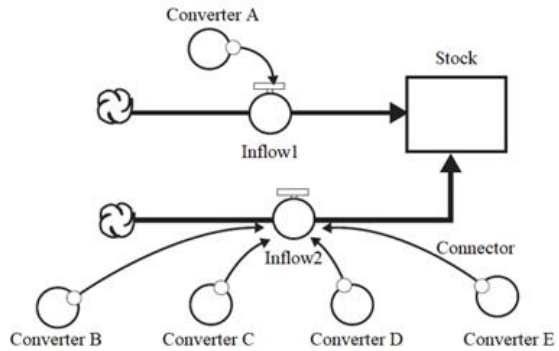



**Figure 1.** An example of an SD model.

In this study, the SD model of the MEBs is developed using iThink software version 9.1. It consists of four major components: stocks, flows, converters, and connectors

(Chinda, 2022). Equations are written using dialogue boxes accessible from the stock and flow diagrams. The graphical depictions of the SD model and the ability to quickly adjust and run it in the software have proven to be an excellent medium for model enhancement. An example of the SD model is in **Figure 1**.

Various methods can be used to validate SD models, including structural validation, historical fit tests, extreme-value tests, and sensitivity analysis. Model validation was performed through four complementary procedures. Structural verification was performed by comparing the model equations, causal relationships, and system-boundary assumptions with information obtained from manufacturer interviews, BMTA operational data, and relevant published studies. This process was used to confirm that the model structure adequately represented the conversion of CBs into MEBs. Second, consistency tests were performed for all stocks, flows, and converters using Ithink software version 9.1. These tests ensured that the variables and equations were expressed in consistent units and that the mathematical relationships within the model were correctly formulated. Third, an extreme-condition test was conducted by assigning boundary values to key production-cost parameters, including scenarios with cost reductions of up to 70%. The sensitivity analysis was performed by varying key input parameters, including battery costs, electricity prices, and component costs, and comparing the resulting model behavior with the baseline scenario. This analysis was used to examine the robustness of the results and determine whether the direction and pattern of the outputs remained consistent under different assumptions. Model behavior can be considered robust when changes in input parameters produce reasonable, logically explainable changes in model outputs (Ajayi & Chinda, 2022). Sensitivity analysis provides several advantages. It enables the development of alternative scenarios by adjusting parameters and observing the resulting system behavior. It also accommodates variations in parameters that may be difficult to assess with conventional statistical methods, including changes in individual variables or in combinations of variables. Furthermore, it supports policy formulation by identifying the variables that most strongly influence model outcomes (Nguyen & Chinda, 2018). The results of structural verification, dimensional-consistency testing, extreme-condition testing, and sensitivity analysis indicate that the model exhibits internally consistent and logically reasonable behavior. The validated model can therefore be used to examine alternative conversion scenarios, assess long-term economic feasibility, and evaluate policy options for converting conventional buses into modified electric buses.

### 3.3. *Well-to-Wheel Boundary*

The environmental assessment in this study utilizes a well-to-wheel (WTW) boundary to quantify the environmental impacts of CBs and MEBs. The WTW approach captures emissions and resource use up to the vehicle operation stage, providing a basis for comparing diesel and electric pathways in Thailand's context (Das *et al.*, 2023). The WTW boundary used in this study includes the following components:

- Electricity Generation and Supply: This includes emissions from fuel extraction, processing, and combustion used to produce grid electricity in Thailand. The model also considers the national electricity mix, including natural gas, coal, hydropower, solar, and other sources (Waite *et al.*, 2024).
- Battery Production: Battery manufacturing contributes to the environmental footprint of MEBs due to raw material extraction. The WTW boundary includes mining and processing of lithium, nickel, cobalt, and other minerals, as well as the production of cathode, anode, electrolyte, and casing materials (Llamas-Orozco *et al.*, 2023). Emission factors are retrieved from life-cycle studies of NMC batteries. These processes contribute to metal depletion, human toxicity, and $CO_{2eq}$ emissions (Llamas-Orozco *et al.*, 2023).
- Avoided Diesel Emissions: For tailpipe emissions, WTW calculates emissions from the diesel. These emissions serve as the baseline for the environmental benefits of MEB conversion.

The WTW perspective is applied because it captures both upstream and operational impacts, providing insight into the environmental impacts of the CB conversion, which are crucial for policy decisions in Thailand's transition from traditional to electrified public transport. As a limitation of this study, the WTW boundary excludes end-of-life processes and the recycling of batteries and components.

## 4. SD Model Development

The SD model for the MEB conversion project consists of four sub-models: MEBs, cost, benefit, and IRR. The cost sub-model has eight sections, each representing a significant component of the BMTA bus conversion. On the other hand, five benefits are considered in the benefit sub-model.

### 4.1. *MEBs Sub-model*

Based on the interviews, the maximum production capacity of MEBs is 64 units per year. This results in 192 MEBs/year, based on the involvement of three companies in the BMTA bus conversion project (Laoonual, 2022). With a maximum of 2,511 old CBs to be modified, the number of MEBs is calculated (see **Equations 1 and 2**).

$$MEB(t) = MEB(t - dt) + (INMEB \times dt) \quad (1)$$

$$INMEB = IF\left(MEB < 2511\right)THEN \left(MIN\left(192, 2511 - MEB\right)\right)ELSE\,0 \quad (2)$$

Where MEB = Accumulated MEBs (units/year)

INMEB = Number of produced MEBs (units/year)

### 4.2. *Cost Sub-model*

Costs of MEBs are calculated based on data in **Table 2** and the number of MEBs per year. The costs are expected to increase by 2% per year, in line with Thailand's average

inflation rate (Statista, 2024). For example, the motor system cost is calculated by multiplying the unit cost of 0.73 million Baht by the number of MEBs produced per year and the average inflation rate, see **Equation 3**.

$$MSC = 1.02^{YR-1} \times MSU \times INMEB \quad (3)$$

Where MSC = Motor system cost (Baht/year), YR = Count year (years), MSU = Unit cost of a motor system (Baht/unit)

The cost calculation for other components, except the battery system, is similar to **Equation 3**. Based on the interviews, the battery system has an average lifespan of 10 years, while the MEB has a lifespan of about 25 years. The battery system is therefore replaced every 10 years. This results in the battery system cost as in **Equation 4.**

$$BSC = (1.02^{YR-1} \times BSU \times \left( INMEB + DELAY\left( INMEB, 10 + DELAY\left( INMEB, 20 \right) \right) \right) \quad (4)$$

Where, BSC = Battery system cost (Baht/year), BSU = Unit cost of a battery system (Baht/unit)

The costs of all components are then summed to obtain the total cost of MEBs each year (see **Equation 5**).

$$COST = BSC + MSC + ACC + OBC + DCC + SPC + BDC + MNC \quad (5)$$

Where COST = Total cost (Baht/year), ACC = In-vehicle air conditioning cost (Baht/year), OBC = Onboard charger cost (Baht/year), DCC = DC/DC converter cost (Baht/year), SPC = Suspension cost (Baht/year), BDC = Body cost (Baht/year), MNC = Miscellaneous cost (Baht/year)

### 4.3. *Benefit Sub-model*

Five benefits, including saving energy costs, maintenance costs, green image perception, job opportunities, and salvage value, are considered in the SD model.

#### *4.3.1. Saving in Energy Cost*

MEBs utilize electricity, which is cheaper than fuel used in CBs (i.e., the average electricity cost is 3.5 Baht/km, while the average fuel cost is 11 Baht/km) (BMTA, 2017). The BMTA routes are about 242 km/day, resulting in energy cost savings per **Equation 6.**

$$SEN = \left( FC - EC \right) \times 242 \times WD \times MEB \quad (6)$$

Where SEN = Saving in energy cost (Baht/year), FC = Fuel cost of CBs (Baht/km), EC = Electricity cost of MEBs (Baht/km), WD = Working days (days/year)

#### *4.3.2. Saving in Maintenance Cost*

According to OTP (2023), the average maintenance cost of an MEB **i**s 0.22 million Baht/year, which is almost three times lower than that of a CB. The savings in maintenance costs are calculated by multiplying the savings by the total number of MEBs produced; see **Equation 7**.

$$SMT = \left( MTCB - MTMEB \right) \times MEB \quad (7)$$

Where SMT = Saving in maintenance cost (Baht/year), MTCB = Maintenance cost of a CB (Baht/year), MTMEB = Maintenance cost of an MEB (Baht/year)

#### *4.3.3. Potential Customers*

Converting CBs to MEBs encourages potential consumers to use public transport. According to BMTA (2023), the average passenger capacity per bus is about 44 customers/trip, while the maximum passenger capacity is 50 customers/trip. On average, the bus operates 9 daily trips at a fare of 17 Baht/trip. It is expected that the MEBs will enhance their green image and attract more potential customers, resulting in the maximum number of customers per trip; see **Equation 8**.

$$GI = \left( MCAP - ACAP \right) \times 9 \times WD \times TK \times MEB \quad (8)$$

Where GI = Benefit from green image perception (Baht/year), MCAP = Maximum passenger capacity (persons/bus), ACAP = Average passenger capacity (persons/bus), TK = Average ticket price (Baht/trip)

#### *4.3.4. Job Opportunity*

The conversion of CBs to MEBs creates 14.2% more job opportunities in the bus industry (IEA, 2020). This brings a higher industry's GDP, which is currently 185 billion Baht (NESDC, 2021). According to Sanchez and Liborio (2012), a 1% increase in GDP may raise the employment rate by 1%. The benefit from the job opportunity is then calculated in **Equation 9**.

$$JOB = GDP \times INEM \times RB \quad (9)$$

Where JOB = Benefit from job opportunity (Baht/year), GDP = GDP of the automotive industry (Baht/year), INEM = Increase in employment rate (%), RB = Ratio of GDP of BMTA to the automotive industries

#### *4.3.5. Salvage Value*

The most expensive component of MEBs is the battery system. With battery system and MEB lifespans of 10 and 25 years, battery systems used for less than 10 years have a salvage value. Based on the interviews, the battery's value decreases by 10% each year. To explain, using the battery for one year leaves its salvage value at 90% of its price. The salvage value is calculated based on the batteries' remaining lives; see **Equations 10 and 11.**

The total benefit of MEBs is obtained by summing the five benefits; see **Equation 12.**

$$PSV_t = 1 - \left( \left( DR - t \right) / BL \right) \quad (10)$$

$$SV = BSC \times \sum_{t=0}^{n} (TBS_t \times PSV_t) \quad (11)$$

$$BENEFIT = SEN + SMT + GI + JOB + SV \quad (12)$$

Where $PSV_t$ = Proportion of remaining salvage value on period t (%), DR = Project duration (years), t = Period (years), BL = Battery's lifespan (years), SV = Salvage value (Baht/year), TBS = Total battery systems (units/year), BENEFIT = total benefit of MEBs (Baht/year)

### 4.4. *IRR Sub-model*

The total benefit and cost of MEBs are used to calculate the net cash flow each year (see **Equation 13**). The NPV is then calculated based on the net cash flows over the 25 years following the MEB lifespan, and the IRR is calculated to determine the project's rate of return.

$$NCF = BENEFIT - COST \quad (13)$$

Where NCF = Net cash flow (Baht/year)

The NCF will use a 8% discount rate to calculate the present value of the MEB conversions. Since the appropriate discount rate varies with the local economy, it is selected using several benchmarks for Thailand's public investment. For example, the Bank of Thailand's average long-term lending rate for infrastructure-related financing has ranged from 6% to 9% (Bank of Thailand, 2024). The Office of the National Economic and Social Development Council (NESDC) applies a social discount rate of approximately 8% to evaluate long-term public investment projects, reflecting the opportunity cost of capital in the national economy (Zhuang *et al.*, 2007). Previous studies on the feasibility of electric buses in Asia have applied discount rates ranging from 7% to 10% (Al-Ogaili *et al.*, 2021).

## 5. Economic Results

### 5.1. *Simulation Results*

The SD model for the MEB conversion project is simulated over 25 years, which corresponds to the lifespan of MEBs. With an average of 192 MEBs produced yearly, it takes 14 years to convert all 2511 MEBs in this project. **Table 3** shows the MEB costs over 25 years. Other cost components, except the battery system, become zero after 14 years. All 2511 MEBs have been converted, and no further production is considered. The battery system, however, incurs the replacement cost of the batteries every 10 years of their lifespan.

Based on **Table 3**, the BSC has the highest cost, accounting for almost half of the total cost each year. The body and suspension parts are also crucial, taking about 25% and 13% of the total cost, respectively. Most interviewees agree that though the old bodies and suspensions of BMTA buses may be used in the MEBs, they require high adjustment costs.

**Table 4** shows the total benefit of the MEBs. The total benefit is zero in the project's first year, as no MEBs have been used in transportation yet. The results show that the benefit from job opportunities accounts for the largest share, i.e., more than 65% of the total benefit. This benefit, however, only lasts for 14 years, as no further MEB production is planned. On the other hand, the savings in energy and maintenance costs rank second and third in the total benefit, respectively.

Benefits and costs are summed to obtain NCFs, which are discounted at 8% to yield an IRR of about 43% at the end of year 25 (see **Figure 2**). It takes 6 years to achieve the World Bank's minimum acceptable IRR of 12% (Cerbo, 2023).

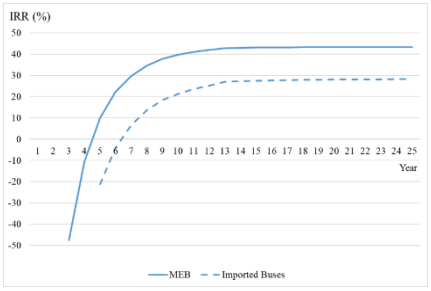



**Figure 2.** IRR values of the MEB project.

The IRR value of the MEB project is compared with that of the imported electric buses (see **Figure** 2). With an average price of about 12 million Baht/bus, 192 buses purchased each year, and a total of 2,511 buses purchased over the next 25 years, the NPV of the imported electric buses is 10,708 million Baht, with an IRR of about 28% at the end of year 25. The MEB project has an IRR that is almost twice as high. These confirm the feasibility of the MEB project in the next 25 years.

### 5.2. *Policy Analysis*

The developed SD model must be validated to ensure its reliability and practical applicability. Three common validation approaches in SD modeling are structural validation, behavioral validation, and policy implication testing (Nguyen & Chinda, 2018). Structural validation was conducted using iThink version 9.1 by checking the stock-and-flow relationships, equations, units, parameter values, and model boundaries. The model structure was compared with manufacturer interviews, BMTA operating data, and published studies to ensure that it reflected the actual MEB conversion process. For example, the accumulated number of MEBs was modeled as a stock with an annual production inflow of 192 buses/year and a maximum limit of 2,511 buses. Thus, the model stopped production once all available buses had been converted. The model was further assessed through extreme condition testing and sensitivity analysis. Extreme condition testing examined whether the model exhibited logical behavior under extreme-condition assumptions, while sensitivity analysis evaluated the validity of the results as key parameters were varied.

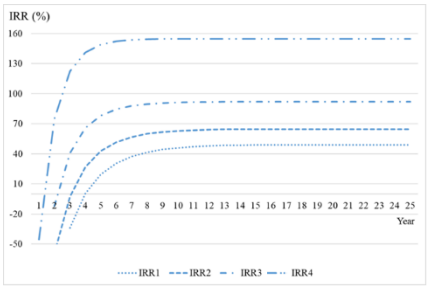



**Figure 3.** Extreme case testing results from economies of scale. Note: IRR1 = IRR value when production cost is reduced by 10% through economies of scale. IRR2 = IRR value when production cost is reduced by 30% through economies of scale. IRR3 = IRR value when production cost is reduced by 50% through economies of scale. IRR4 = IRR value when production cost is reduced by 70% through economies of scale

**Table 3.** Total cost of the project (Baht).

| Year | Battery system | Motor system | In-vehicle air conditioning | On board charger | DC/DC converter | Suspension | Body | Miscellaneous | Total |
|---|---|---|---|---|---|---|---|---|---|
| 2021 | 680,014,840 | 143,193,900 | 74,617,978 | 83,978,150 | 4,092,468 | 207,835,592 | 410,044,504 | 55,538,070 | 1,659,315,502 |
| 2022 | 693,615,137 | 146,057,778 | 76,110,337 | 85,657,713 | 4,174,318 | 211,992,304 | 418,245,394 | 56,648,831 | 1,692,501,812 |
| 2023 | 707,487,440 | 148,978,933 | 77,632,544 | 87,370,868 | 4,257,804 | 216,232,150 | 426,610,302 | 57,781,808 | 1,726,351,849 |
| 2024 | 721,637,189 | 151,958,512 | 79,185,195 | 89,118,285 | 4,342,960 | 220,556,793 | 435,142,508 | 58,937,444 | 1,760,878,886 |
| 2025 | 736,069,932 | 154,997,682 | 80,768,899 | 90,900,651 | 4,429,820 | 224,967,928 | 443,845,359 | 60,116,193 | 1,796,096,464 |
| 2026 | 750,791,331 | 158,097,636 | 82,384,277 | 92,718,664 | 4,518,416 | 229,467,287 | 452,722,266 | 61,318,517 | 1,832,018,394 |
| 2027 | 765,807,158 | 161,259,588 | 84,031,962 | 94,573,037 | 4,608,784 | 234,056,633 | 461,776,711 | 62,544,887 | 1,868,658,760 |
| 2028 | 781,123,301 | 164,484,780 | 85,712,601 | 96,464,498 | 4,700,960 | 238,737,765 | 471,012,245 | 63,795,785 | 1,906,031,935 |
| 2029 | 796,745,767 | 167,774,476 | 87,426,853 | 98,393,788 | 4,794,979 | 243,512,521 | 480,432,490 | 65,071,700 | 1,944,152,574 |
| 2030 | 812,680,682 | 171,129,965 | 89,175,391 | 100,361,663 | 4,890,879 | 248,382,771 | 490,041,140 | 66,373,134 | 1,983,035,625 |
| 2031 | 1,657,869,069 | 174,552,564 | 90,958,898 | 102,368,897 | 4,988,696 | 253,350,427 | 499,841,963 | 67,700,597 | 2,851,631,111 |
| 2032 | 1,691,026,450 | 178,043,616 | 92,778,076 | 104,416,275 | 5,088,470 | 258,417,435 | 509,838,802 | 69,054,609 | 2,908,663,733 |
| 2033 | 1,724,846,979 | 181,604,488 | 94,633,638 | 106,504,600 | 5,190,240 | 263,585,784 | 520,035,578 | 70,435,701 | 2,966,837,008 |
| 2034 | 948,396,565 | 14,471,608 | 7,541,118 | 8,487,085 | 413,597 | 21,004,492 | 41,440,335 | 5,612,845 | 1,047,367,645 |
| 2035 | 897,265,657 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 897,265,657 |
| 2036 | 915,210,970 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 915,210,970 |
| 2037 | 933,515,190 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 933,515,190 |
| 2038 | 952,185,494 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 952,185,494 |
| 2039 | 971,229,203 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 971,229,203 |
| 2040 | 990,653,787 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 990,653,787 |
| 2041 | 2,020,933,728 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2,020,933,728 |
| 2042 | 2,061,352,401 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2,061,352,401 |
| 2043 | 2,102,579,451 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2,102,579,451 |
| 2044 | 1,156,090,169 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1,156,090,169 |
| 2045 | 1,093,761,828 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1,093,761,828 |

**Table 4.** Total benefit of the project (Baht).

| Year | Saving on energy costs | Saving on maintenance costs | Green image | Job opportunity | Salvage value | Total |
|---|---|---|---|---|---|---|
| 2021 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2022 | 120,581,050 | 78,910,080 | 64,333,440 | 516,352,317 | 0 | 780,176,887 |
| 2023 | 241,162,099 | 157,820,160 | 128,666,880 | 1,032,704,635 | 0 | 1,560,353,774 |
| 2024 | 361,743,149 | 236,730,240 | 193,000,320 | 1,549,056,952 | 0 | 2,340,530,661 |
| 2025 | 482,324,198 | 315,640,320 | 257,333,760 | 2,065,409,270 | 0 | 3,120,707,548 |
| 2026 | 602,905,248 | 394,550,400 | 321,667,200 | 2,581,761,587 | 0 | 3,900,884,435 |
| 2027 | 723,486,298 | 473,460,480 | 386,000,640 | 3,098,113,904 | 0 | 4,681,061,322 |
| 2028 | 844,067,347 | 552,370,560 | 450,334,080 | 3,614,466,222 | 0 | 5,461,238,209 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 2029 | 964,648,397 | 631,280,640 | 514,667,520 | 4,130,818,539 | 0 | 6,241,415,096 |
| 2030 | 1,085,229,446 | 710,190,720 | 579,000,960 | 4,647,170,857 | 0 | 7,021,591,983 |
| 2031 | 1,205,810,496 | 789,100,800 | 643,334,400 | 5,163,523,174 | 0 | 7,801,768,870 |
| 2032 | 1,326,391,546 | 868,010,880 | 707,667,840 | 5,679,875,491 | 0 | 8,581,945,757 |
| 2033 | 1,446,972,595 | 946,920,960 | 772,001,280 | 6,196,227,809 | 0 | 9,362,122,644 |
| 2034 | 1,567,553,645 | 1,025,831,040 | 836,334,720 | 6,712,580,126 | 0 | 10,142,299,531 |
| 2035 | 1,576,974,039 | 1,031,995,890 | 841,360,770 | 0 | 0 | 3,450,330,699 |
| 2036 | 1,576,974,039 | 1,031,995,890 | 841,360,770 | 0 | 0 | 3,450,330,699 |
| 2037 | 1,576,974,039 | 1,031,995,890 | 841,360,770 | 0 | 0 | 3,450,330,699 |
| 2038 | 1,576,974,039 | 1,031,995,890 | 841,360,770 | 0 | 0 | 3,450,330,699 |
| 2039 | 1,576,974,039 | 1,031,995,890 | 841,360,770 | 0 | 0 | 3,450,330,699 |
| 2040 | 1,576,974,039 | 1,031,995,890 | 841,360,770 | 0 | 0 | 3,450,330,699 |
| 2041 | 1,576,974,039 | 1,031,995,890 | 841,360,770 | 0 | 0 | 3,450,330,699 |
| 2042 | 1,576,974,039 | 1,031,995,890 | 841,360,770 | 0 | 0 | 3,450,330,699 |
| 2043 | 1,576,974,039 | 1,031,995,890 | 841,360,770 | 0 | 0 | 3,450,330,699 |
| 2044 | 1,576,974,039 | 1,031,995,890 | 841,360,770 | 0 | 0 | 3,450,330,699 |
| 2045 | 1,576,974,039 | 1,031,995,890 | 841,360,770 | 0 | 6,825,746,054 | 10,276,076,754 |

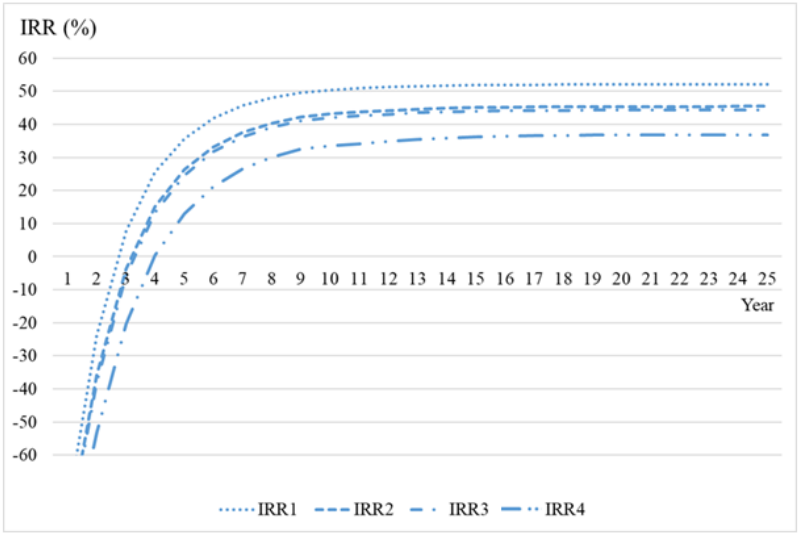



**Figure 4.** IRR values with various battery system costs. Note: IRR1 = IRR value when the battery system cost is 2.86 million Baht per unit. IRR2 = IRR value when the battery system cost is 3.38 million Baht per unit. IRR3 = IRR value when the battery system cost is 3.74 million Baht per unit. IRR4 = IRR value when the battery system cost is 4.17 million Baht per unit

*5.2.1. Extreme Condition Testing*

An extreme-condition test was conducted to examine whether the SD model produced logically consistent economic behavior under varying reductions in MEB manufacturing costs. Economies of scale can reduce unit production costs as output expands, because fixed costs, expenses, and production resources are spread across a larger number of vehicles. Husan (1997) reported that automotive manufacturing costs may decline by up to 70% under large-scale production conditions. Based on OTP (2023) and BMTA (2023), large-scale bus production was assumed to occur when annual production reaches approximately 2,023 buses. Accordingly, the test assumed that this production level would be achieved from the fifth year onward, with reference to the growth of EV production and sales in Thailand (EVAT, 2024). Production cost reductions were then progressively applied, with the 70% reduction representing an extremely upper condition rather than an expected market outcome.

The simulation results shown in **Figure 3** indicate that the model responds consistently to this extreme assumption. As manufacturing costs decline, project costs decrease, resulting in a higher IRR. With a maximum cost reduction of 70%, the IRR is approximately 154%. It demonstrates that the model produces a logically consistent response under an extreme cost-reduction scenario and confirms the SD model's strong validity. The test also indicates that policies supporting domestic manufacturing, workforce development, standardized conversion processes, and supply-chain coordination could improve the economic feasibility of MEB conversion. However, the actual cost reduction achievable in practice would depend on production volume, component localization, battery prices, supplier competition, and long-term market demand.

*5.2.2. Policy Analysis on the Battery System Price*

The battery system contributes most of the MEB's total cost (see **Table 3**). Based on the interviews, the cost ranges from about 3 to 4 million Baht per unit. The policy analysis is complete, and the simulation results (see **Figure 4**) confirm high IRRs when the battery system cost is low. A 10% increase in IRR is achieved as the battery system price decreases from its highest to its lowest level. The government should help connect manufacturers and suppliers to secure great deals and negotiate discounts with foreign suppliers on key MEB components. In the long term, the government should support local battery production through, for example, R&D investment, production incentives, and tax reductions to lower production costs.

*5.2.3. Policy Analysis on Job Opportunity*

The MEB production creates job opportunities in the market. Based on **Table 4**, this job opportunity factor contributes the highest benefit to the project. According to Furhmann (2022), the increase in GDP is directly proportional to the employment rate; i.e., a 1% increase in GDP may increase the employment rate by 0.5-2%. Policy analysis is performed by varying the GDP growth rate while holding the employment rate at 0.5%, 1%, 1.5%, and 2%, respectively. The simulation results (see **Figure 5**) show that IRR values increase with higher employment rates. It is suggested that the automotive industry continue developing the skills and technologies needed to manufacture MEBs, thereby creating more long-term job opportunities.

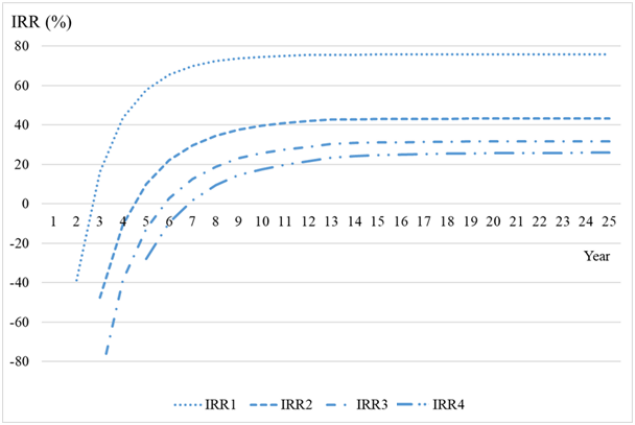



**Figure 5.** IRR values with various employment rates. Note: IRR1 = IRR value when an increase in GDP by 1% increases the employment rate by 0.5%. IRR2 = IRR value when an increase in GDP by 1% increases the employment rate by 1%. IRR3 = IRR value when an increase in GDP by 1% increases the employment rate by 1.5%. IRR4 = IRR value when an increase in GDP by 1% increases the employment rate by 2%

*5.2.4. Summary of Policy Analyses*

The analysis reveals the importance of economies of scale in achieving higher IRRs. Higher production volumes can reduce unit costs through bulk procurement, improved production efficiency, standardized conversion procedures, and better utilization of equipment and skilled labor. However, the estimated 154% IRR under the 70% cost-reduction scenario should be interpreted as an extreme case scenario. In practice, the achievable cost reduction will depend on the degree of component localization, battery prices, supplier competition, production continuity, and long-term demand for converted buses. Therefore, policy support should focus not only on increasing production volume but also on reducing structural production costs and improving the reliability of the domestic supply chain.

Government intervention is important for high-cost and import-dependent components, especially battery systems. In the short term, reductions in import duties and 8% tax incentives could lower acquisition costs for manufacturers. In the long term, research and development support should encourage local assembly, testing, and production of battery packs, battery management systems, chargers, and vehicle control systems. Full localization of battery cell production may not be immediately feasible due to high capital requirements and limited domestic access to precious metals such as lithium and cobalt. A strategy would prioritize activities in which Thailand can develop competitive capabilities, such as battery pack assembly, thermal management, software integration, diagnostics, remanufacturing, and second-life battery applications.

Workforce development is necessary because MEB production requires skills that differ from those used in CB manufacturing. Training programs should cover safety, battery diagnostics, power electronics, software-based vehicle control, thermal management, and fire risk prevention. Universities and institutions could collaborate with manufacturers to develop specialized curricula, certification programs, and work-integrated learning. These programs would reduce skill shortages and improve production quality, while reskilling existing workers could reduce employment disruption during the transition.

Policy implementation should be prioritized according to the stage of industry development. In the initial stage, the government should establish technical standards, vehicle registration procedures, safety certification requirements, and pilot conversion programs. These actions would reduce regulatory uncertainty on energy consumption, battery degradation, maintenance requirements, and vehicle reliability. Demand-perspective policies, including public procurement commitments and long-term service contracts, could provide manufacturers with predictable production volumes. This demand certainty is essential for achieving economies of scale because manufacturers are unlikely to invest in production capacity, workforce development, or local supply chains without a stable market. In the longer term, support should shift toward local innovation, export capability, and integration with regional EV supply chains.

The government's support is crucial to long-term MEB production. The support may be in various areas.

- Upskilling and reskilling workers for the MEB production.
- Adding EV production and new production technology to the university courses.
- Providing import duty privileges and tax exemption for local manufacturers.
- Reducing electricity charging costs to encourage the use of EVs and EBs.
- Streamlining legal procedures, such as importing spare parts and registering MEBs, to reduce barriers and build confidence in the market.
- Supporting the battery system production to reduce the overall production cost.
- Initiating the MEB center to promote the MEB production. The center should be equipped with the necessary resources, tools, and budget to test and certify production standards.
- Finding international partners to transfer production technologies to Thai manufacturers.

The proposed MEB center could play a central role in coordinating these activities. Rather than serving only as a testing facility, the center could function as a national platform for technical certification, safety assessment, performance monitoring, workforce training, battery diagnostics, and data collection. It could also maintain standardized testing protocols for driving range, electricity consumption, thermal safety, braking performance, and battery degradation, similar to the National Science and Technology Development Agency (NSTDA). This would improve consistency across manufacturers and reduce the technical and safety risks associated with converting different bus models.

As Thailand has a multi-agency coordination culture, effective implementation requires coordination among multiple government agencies and industry stakeholders. The Board of Investment could provide investment incentives and support technology. The Ministry of Transport could create demand through bus conversion targets, public procurement, and integration of MEBs into urban, intercity, and airport routes. The Ministry of Higher Education, Science, Research, and Innovation could support applied research, testing facilities, and human-capital development. The Ministry of Energy and electricity authorities could develop charging tariffs, grid upgrade plans, and renewable energy integration. BMTA, as the central operator, should provide operational data, evaluate pilot projects, and ensure that MEBs are compatible with route, depot, and maintenance conditions. Such cross-departmental collaboration reflects the concept of institutional synergy, where policy effectiveness depends on the alignment of roles, objectives, and execution across agencies rather than on isolated institutions or governments (Yan, 2024). Without alignment among these institutions, policy implementation may face delays, increased administrative complexity, and higher transaction costs for manufacturers (Li, 2026). This coordination is required to reduce barriers, improve policy efficiency, and accelerate the deployment of MEBs in Thailand.

The effectiveness of this institutional coordination should be evaluated using measurable indicators rather than only policy adoption. The indicators may include the proportion of locally produced components, average conversion cost per bus, annual production volume, battery cost per kWh, vehicle availability, electricity consumption per kilometer, maintenance cost per kilometer, number of certified technicians, and reduction in imported-component expenditure. Environmental indicators, such as lifecycle $CO_{2eq}$ emissions, upstream PM emissions, and renewable electricity use, should also be monitored. These indicators would allow policymakers to assess whether incentives are generating real improvements in productivity and sustainability.

The transition from conventional manufacturing to electric mobility requires adopting advanced technologies, including battery systems, power electronics, and digitally integrated control systems. This shift encourages firms to move beyond traditional assembly toward higher-value activities such as system integration, design, and innovation. The integration of digital and low-carbon technologies is a key driver of high-quality industrial development in traditional sectors. Policies that promote localization, R&D investment, and workforce development not only improve project feasibility but also support the long-term transformation of Thailand's automotive industry into a more knowledge-based and sustainable development.

*5.2.5. Case Studies*

The developed SD model is tested across three MEB manufacturers to examine changes in IRR values and the

model's reliability. All of them collaborate with government agencies to improve the MEB production skills and enhance production capacities (MHESI, 2020). Company#1 has more than 50 years of experience in bus and truck production. It strives to use local parts to reduce the overall production cost. Currently, about 60% of the MEB parts are manufactured locally, including the on-board charger and vehicle control unit. In contrast, Company#2 and Company#3 use local parts by about 40%.

The production costs for the three manufacturers are as follows.

- Battery system costs are 4.1 million Baht for Company#1, 3.3 million Baht for Company#2, and 2.8 million Baht for Company#3.
- Motor system costs are 0.9 million Baht for Company#1, 0.3 million Baht for Company#2, and 0.56 million Baht for Company#3.
- In-vehicle air conditioning costs are 0.3 million Baht for Company#1, 0.2 million Baht for Company#2, and 0.4 million Baht for Company#3.
- On-board charger costs are 0.35 million Baht for Company#1, 0.5 million Baht for Company#2, and 0.4 million Baht for Company#3.
- DC/DC converter costs are 0.02 million Baht for Company#1, 0.05 million Baht for Company#2, and 0.02 million Baht for Company#3.
- Suspension costs are 0.9 million Baht for Company#1, 0.6 million Baht for Company#2, and 1.05 million Baht for Company#3.
- Body costs are 2.1 million Baht for Company#1, 1.8 million Baht for Company#2, and 2.4 million Baht for Company#3.
- Miscellaneous costs are 0.5 million Baht for Company#1, 0.25 million Baht for Company#2, and 0.5 million Baht for Company#3.
- Total costs are 9.17 million Baht for Company#1, 7 million Baht for Company#2, and 8.13 million Baht for Company#3.

The simulation results (see **Figure 6**) reveal the IRR values for the three companies. Company #1, with the highest production cost, achieves the lowest IRR. Although 60% of parts are locally made, the major cost of MEB production comes from the imported battery system, which is 23% and 46% higher than those of Company#2 and Company#3, respectively. Company #2, with the lowest production cost, may expect an IRR of almost 60% over the next 25 years. This is because the company has international partners who provide skills training and offer lower prices on imported parts. Company #3 may expect an IRR of almost 50% over the next 25 years. This company incurs high costs for body parts due to the use of aluminum to reduce body weight. The company claims that with lighter weight, the MEBs consume less electricity and require less maintenance.

The results indicate strong potential for Thai manufacturers to enter the MEB market and compete with those of other Asian countries. The Vingroup company in Vietnam launched 3,000 electric buses, while the Malaysian government launched 2,000 electric buses, and Laos is expected to have 2,500 electric buses by 2040 (Staff, 2021).

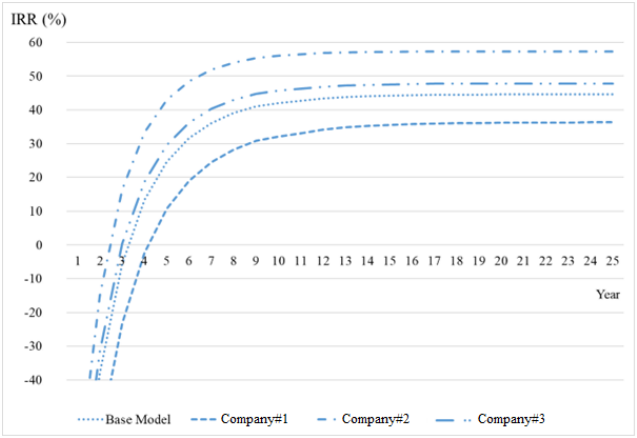



**Figure 6**. IRR values of the three case studies.

## 6. Environmental Results

According to **Table 2**, the environmental performance of CBs and MEBs is calculated on a per-day operational basis. The results cover four indicators: carbon dioxide emission ($CO_{2eq}$), particulate matter (PM), human toxicity (HT), and metal depletion (MD). Over its service life, each BMTA bus is assumed to operate an average of 242 km/day. The electricity used for a 12 m MEB is 1.3 kWh/km.

### 6.1. *$CO_{2eq}$ Emission*

The environmental impact of $CO_{2eq}$ emissions for the CBs and MEBs is 836.6 kg $CO_{2eq}$/day and 125.5 kg $CO_{2eq}$/day, respectively. It is calculated from the following.

- CBs: Each bus operates on average 242 km/day, and the $CO_{2eq}$ is emitted by fuel combustion of 2.7 kg $CO_{2eq}$/L:
  $$CO_{2eq} = 242 x 2.7 x 1.29 = 842.9\, kg\, CO_{2eq} / day$$
- MEBs: Similar to CBs; the $CO_{2eq}$ is emitted by electricity generation for batteries of 0.4 kg $CO_{2eq}$/kWh with electricity consumption of 1.3 kWh/km for MEBs:
  $$CO_{2eq} = 242 x 0.4 x 1.3 = 125.8\, kg\, CO_{2eq} / day$$

The results show that MEBs reduce daily CO2eq emissions by more than 700 kg CO2eq compared with CBs. This demonstrates the strong potential of MEB deployment as an effective strategy to reduce $CO_{2eq}$ emissions from public transportation.

### 6.2. *Particulate Matter (PM)*

The environmental impact of PM uses the same daily mileage of 242 km/day per bus, together with emission factors from **Table 2** for diesel combustion and electricity generation. It is calculated from the following.

- CBs: Each bus operates on average 242 km/day and consumes 1.3 L/km. With a particulate-matter emission factor of 0.0013 kg PM/L, the daily PM emissions from one CB are:
  $$PM_{CB} = 242 x 0.0013 x 1.3 = 0.4\, kg\, PM / day$$
- MEBs: PM emissions calculated from electricity generation. Using an electricity consumption of 1.3

kWh/km and a PM emission factor of 0.006 kg PM/kWh, the daily PM emissions associated with the electricity used by one MEB are:

$$PM_{MEB} = 242 x 0.006 x 1.3 = 1.9 kg\ PM / day$$

The results show that MEB has higher total PM emissions due to Thailand's current electricity generation mix. However, the emission locations differ. PMs from CBs are emitted at street level along bus routes in densely populated urban areas, while PMs from MEBs are emitted from power plants located away from the city center. From a public health perspective, MEB conversion eliminates tailpipe PM emissions along bus routes and reduces direct roadside emissions. However, under the electricity generation in Thailand, PM emissions may increase.

### 6.3. *Human Toxicity (HT)*

Within the WTW boundary, HT from NMC battery production contributes to upstream NMC battery production.

- Battery production: According to **Table 2**, the human toxicity is calculated from kWh of the battery at 20 kg 1,4-DCB-eq/kWh with a battery capacity of 207 kWh. The HT is calculated:
  $$HT = 20 x 207 = 4{,}140 kg\ 1{,}4 - DCB_{eq} / battery.$$
- Battery replacement: Because the battery lifespan is assumed to be 10 years, while the project duration is 25 years, each bus requires the initial battery and two replacement batteries over the assessment period. The total HT (THT) impact is:
  $$THT = 4{,}140 x 3 = 12{,}420 kg\ 1{,}4 - DCB_{eq} / battery.$$

Although each battery production impact occurs as an upstream event rather than as a continuous operational emission, the cumulative effect reflects the environmental concerns associated with battery material extraction and manufacturing. This finding emphasizes the importance of mining and refining processes, especially for cobalt and nickel, improved battery durability, and effective end-of-life management.

### 6.4. *Metal Depletion (MD)*

MD consumes precious metals, particularly Nickel, Cobalt, Manganese, and Copper, in NMC batteries.

- Battery production: Similar to HT, MD is also considered a one-time impact on battery production for MEBs. The MD calculated from **Table 2** indicates that 1 kg of NMC battery is equivalent to 2 kg of Feeq, with an NMC battery energy density of 5 kg/kWh (200 Wh/kg). The MD for 3 batteries is calculated:
  $$MD = 2 x 5 x 207 x 3 = 6{,}210 kg\ Fe_{eq} / battery$$

Therefore, each 207 kWh NMC battery is associated with approximately 2,070 kg Fe-eq of metal depletion. Although converting CBs to MEBs can reduce CO2eq emissions and eliminate tailpipe pollution along bus routes, battery production increases upstream resource demand. Previous studies show that well-designed regulations, such as air quality standards, vehicle emission limits, and controls on industrial pollution, can encourage companies to adopt cleaner technologies and improve resource efficiency (Zhang *et al.*, 2025). In Thailand, this issue is particularly relevant for the recurring PM2.5 pollution in Bangkok, where road transport is a major contributor to urban air pollution. The national ambient air quality standard for PM2.5 is set at 50 µg/m³ (24-hour average), while the World Health Organization recommends a much stricter guideline of 15 µg/m³ (ThaiHealth, 2026). PM2.5 levels in Bangkok frequently exceed both thresholds during winter pollution episodes. Existing measures, including the adoption of Euro 5 vehicle emission standards, aim to reduce emissions from the transport sector. Enforcing these policies would not only help address roadside air pollution directly but also encourage MEB manufacturers to improve their upstream supply chains, thereby reducing impacts such as metal depletion and human toxicity.

Environmental regulations can support economic growth while reducing environmental impacts. This occurs as investment shifts toward cleaner and more efficient technologies (Ma *et al.*, 2025). This suggests that stricter environmental policies should not be seen as a barrier to MEB adoption but a driver that can improve both environmental outcomes and long-term economic performance.

## 7. Discussions

### 7.1. *MEB Conversion Results*

The simulation results indicate that the MEB conversion project can generate a positive economic return over the 25 years. Under the assumptions adopted in the current model, the project reaches an IRR of approximately 12% in Year 6 and approximately 43% by the end of the period. However, this result is achieved under these model assumptions, particularly the socioeconomic benefits, additional ridership from potential customers, battery replacement, annual distance traveled, and the difference between diesel and electricity costs. The current results show that battery systems account for half of the conversion cost, while body refurbishment and suspension modification account for approximately 25% and 13%, respectively.

The economic attractiveness of conversion stems from avoiding the purchase of an entirely new electric bus. The average conversion cost estimated across the three participating manufacturers is THB 7.9 million per bus, compared with an average imported electric bus price of THB 12.48 million per bus. Conversion can reduce the initial capital requirement by retaining usable vehicle components, particularly the chassis, body parts, suspension, steering, and interior systems.

A second economic benefit is the difference between diesel and electricity operating costs. The current model uses an average diesel-bus energy cost of approximately THB 11/km and an MEB electricity cost of approximately THB 3.5/km. At the assumed daily distance of 242 km, this difference creates substantial cumulative savings over 25 years. These results are consistent with the general TCO mechanism observed in other electric-bus studies. Although electric buses require a greater initial investment than CBs, their higher drivetrain efficiency and lower energy consumption can offset part of the capital cost

difference over the life of the bus. In Indonesia, electric buses were estimated to be four to five times more energy-efficient than the Euro III-equivalent diesel buses operating on the evaluated routes (Triatmojo *et al.*, 2024).

Maintenance savings provide another recurring benefit. Electric powertrains have fewer moving components than diesel engines and do not require engine oil changes, exhaust system servicing, fuel system maintenance, or many engine-related repairs. In the model, the average annual maintenance cost of an MEB is THB 0.22 million, approximately one-third of that of a CB. In Chile, it is reported that operators have achieved lower electric bus maintenance costs than for diesel buses. However, actual savings depend on contractual arrangements, vehicle maturity, spare-part availability, technician training, and battery maintenance contracts (World Bank, 2020).

Battery replacement partially offsets the energy and maintenance savings. A battery lifetime of ten years implies that buses require at least one replacement over a 25-year duration. The economic result is sensitive not only to the initial battery price but also to degradation, warranty conditions, replacement timing, residual value, and possible second-life use. The sensitivity analysis supports this interpretation. By reducing the battery-system price from the upper estimate of approximately THB 4.17 million to the lower estimate of approximately THB 2.86 million, the IRR increases by approximately 10%. This result demonstrates that battery procurement and warranty design are central to project feasibility. Long-term supply agreements, minimum-capacity warranties, replacement-price guarantees, and clear responsibility for premature battery degradation could reduce this risk.

The three manufacturers raise additional concerns about component prices. The estimated conversion costs are approximately THB 9.17 million, THB 7.00 million, and THB 8.13 million per bus for Companies 1, 2, and 3, respectively. The company with the lowest conversion cost achieves an estimated 25-year IRR of nearly 60%, while the company with an expensive battery cost has the lowest return. The results suggest that international partnerships, technical training, bulk purchasing, and access to lower-cost imported components can influence economic performance. At the same time, the higher IRRs in these cases should be treated as best-case scenarios rather than guaranteed investment returns, because they remain dependent on assumptions concerning energy savings, employment effects, ridership, and operating life. The economic results suggest that conversion may provide a lower-capital pathway to MEBs, particularly when bus transit is available, and annual utilization is high. However, the estimated return depends on diesel and electricity prices, battery costs, maintenance performance, conversion quality, utilization, and financing terms.

From an environmental perspective, our findings also align with previous studies that report climate benefits from bus electrification, along with trade-offs in certain environmental impacts. Several LCAs indicate that MEBs reduce GHG emissions and urban air pollutants compared with diesel buses. However, battery production and upstream electricity generation can increase some other impacts, such as resource depletion and human toxicity. In this study, replacing CBs with MEBs lowers $CO_{2eq}$ emissions and roadside PM, while increasing metal depletion and human toxicity due to the use of NMC batteries. In addition, this study does not quantify population-weighted exposure or health impacts. Consequently, it cannot be concluded that total PM-related health damages decrease. The environmental results show clear benefits of MEB conversion. However, focusing only on reduced tailpipe emissions may overlook upstream impacts such as HT and MD, as well as electricity generation that relies in part on fossil fuels. This can lead to greenwashing, where environmental benefits are presented more positively than they are (Zhong *et al.*, 2025; Hu *et al.*, 2026). To avoid this, transparent and comprehensive reporting that includes full life-cycle impacts is essential for MEB industries. Thailand is gradually increasing the share of renewable energy, particularly solar and hydropower, to 51% of the total generation mix as part of its long-term energy transition toward 2037 (PCMO, 2024). This shift is expected to improve MEBs' environmental performance over time, as cleaner electricity will further reduce indirect emissions. Therefore, aligning MEB development with the expansion of renewable energy will be important to ensure that the environmental benefits are both real and sustainable in the long run.

The socioeconomic impacts of adopting MEBs are consistent with findings that this industry can support long-term economic growth and create new jobs. The results show that expanding MEB production, charging infrastructure, and related supply chains can boost national economies and generate employment across manufacturing, services, and energy sectors. Therefore, the job creation estimates in this study should be viewed as possibilities, especially given Thailand's goal of becoming a major EV production hub in Southeast Asia. By combining economic modeling, environmental indicators, and an understanding of Thailand's industrial capabilities, this study contributes to existing research on bus electrification. It demonstrates that converting conventional buses to MEBs can be a practical and scalable solution for emerging economies.

### 7.2. *Comparison with Electric Bus Studies in Developing Countries and Economies*

The findings are consistent with international studies showing that electric buses have higher or comparable initial costs but can become competitive when lifecycle energy and maintenance costs are considered. Nevertheless, international studies show that economic and environmental results vary with local operating conditions. The World Bank's analysis of clean buses in five Latin American cities emphasizes that the total cost of ownership (TCO) should include vehicle acquisition, charging infrastructure, operation, maintenance, labor, battery, taxes, and end-of-life costs. Its results indicate that the competitiveness of electric buses varies with vehicle prices, financing costs, maintenance expenditures, energy prices, and charging configurations (World Bank, 2019).

The BMTA conversion model differs from most international studies by evaluating the reuse of existing buses rather than the purchase of new electric buses. In Latin America, electric buses commonly have higher acquisition costs than diesel buses, even though competitive tenders and green financing, such as tax exemption, can reduce the difference. The World Bank (2019) reported that, before taxes, prices for the same electric bus model were 42% higher in Buenos Aires and 50% higher in Montevideo. In comparison, the Thailand conversion pathway seeks to reduce capital cost by retaining serviceable vehicle components and conducting part of the conversion domestically.

In Indonesia, it is particularly relevant because Jakarta and Bangkok share comparable tropical climates, congested urban traffic, high demand for air conditioning, and large public bus fleets. The study found that annual distance, contract duration, diesel and electricity prices, and taxation strongly affect electric-bus competitiveness (Triatmojo *et al.*, 2023). It shows that 13% increase in annual activity reduced costs per km by 9%, while extending the operation contract to 15 years could close the cost gap with CB.

In Vietnam, it shows a similar dependence of environmental performance on the electricity supply. Nguyen *et al.* (2022) found that electricity consumed during operation could present about 72% of lifecycle GHG emissions under the Vietnamese electricity mix. This result is directly relevant to Thailand. Although the present MEB model estimates a reduction of more than 700 kg $CO_{2eq}$ per bus per operating day relative to the diesel baseline, the magnitude of that benefit depends on the assumed grid-emission factor. It will change as Thailand's generation mix evolves.

In China, it demonstrates that electric buses can produce lifecycle benefits while remaining sensitive to grid composition and real-world energy consumption. Gao *et al.* (2017) evaluated electric buses under actual operating conditions in China and found petroleum utilization reductions of approximately 85% lead to lifecycle $CO_{2eq}$ reductions of 19–35% relative to diesel buses. This is important because an electric bus has no tailpipe emissions, but its upstream impacts depend on the fuels and technologies used to generate the electricity for charging.

The comparison between these countries suggests that high, long-term utilization is necessary to offset higher capital costs through lower operating costs. Environmental performance depends strongly on electricity generation and energy consumption. This study contributes by showing that conversion reduces the initial cost barrier through component reuse. Nevertheless, the same conditions as in previous studies are required, such as high annual distance, long operating life, predictable routes, reliable charging, and favorable electricity prices.

## 8. Conclusions

This study evaluates the feasibility of converting conventional buses (CBs) into modified electric buses (MEBs) in Thailand using a system dynamics (SD) modeling approach. The findings show that MEB conversion is a highly cost-effective strategy for decarbonizing public transport. From an economic perspective, the project achieves the minimum acceptable IRR of 12% within 6 years and reaches 43% by the end of the project. This return is significantly higher than that of imported electric buses. From an environmental perspective, the results show benefits from MEB conversion. It reduces emissions by more than 700 kg of $CO_{2eq}$ every day and eliminates tailpipe PM emissions along roadsides. Although upstream impacts such as metal depletion and human toxicity arise from NMC battery production. Battery recycling could potentially reduce these upstream burdens, but this mitigation option was outside the present system boundary and was not quantified.

The policy analysis is performed to validate the developed SD model and suggest various policies. The results show that promoting local MEB production to achieve economies of scale yields higher IRR values. Economies of scale reduce production costs, lower defect rates through accumulated work experience, and increase job creation in the domestic market. To support this industrial expansion, a human resource development roadmap is strongly recommended. Close collaboration among government agencies, technical universities, and manufacturers is essential for designing new curricula, specialized training courses, and long-term reskilling and upskilling programs that prepare the workforce for electric powertrain technologies. In addition, supporting the production of local battery systems is recommended. This can be advanced by reducing import duties and excise taxes on battery components during the initial phase, while establishing incentives that encourage technology transfer and domestic battery manufacturing in the longer term. Although battery systems are currently imported, localizing production would reduce parts lead times, minimize costs, strengthen supply chain resilience, and create new employment opportunities.

The three case studies tested with the SD model further confirm that increasing the share of locally produced parts significantly reduces conversion costs and improves IRR outcomes, reinforcing the importance of material localization as a strategic direction. The Thai government can use the results of this study as a guideline for decision-making on the MEB project. Future studies are recommended to explore other criteria related to the MEB project, such as investment in charging infrastructure, training programs for manufacturers, tax policies, and green campaigns. The sensitivity analysis provides a useful framework for future studies to assess the feasibility of other policy measures. Researchers can use this framework to analyze the impacts of various policies and select suitable options for implementation.

This study is limited to the specific context of Thailand, a developing country in Asia. Therefore, the results should not be directly generalized to countries with different transport systems, energy prices, industrial capacities, or regulatory conditions. Nevertheless, the findings may provide useful insights for neighboring countries with similar economic and public transport characteristics,

particularly regarding policies that support local production, workforce development, and investment in research and development in the MEB industry. The model was developed using both secondary and primary data. Secondary data were obtained from national and international literature, while primary technical and cost data were collected only from three Thai manufacturers involved in the MEB conversion project. Because the number of participating manufacturers was limited and some data was confidential, the current parameters may not fully represent the wider industry. The model also relies on several fixed assumptions and average operational values. Therefore, it should be adjusted and recalibrated as more detailed manufacturer-, route-level-, battery-performance-, and long-term operational data become available.

Despite these limitations, this study provides a foundation for further research and policy development on MEB conversion for developing countries with similar transport and industrial conditions. Future studies should examine how different value chains influence the long-term economic and environmental sustainability of MEB production. As Thailand seeks to strengthen its position as a regional EV manufacturing hub, greater attention should be given to upstream activities, including raw material extraction, battery cell production, component manufacturing, and assembly, as these factors directly affect cost, domestic value creation, and supply chain resilience. Examining the complete value chain, from material extraction and component production to battery reuse, recycling, and end-of-life recovery, would help identify strategic areas where policy support, local investment, and technological development could generate both economic and environmental benefits. Future research should also consider the broader global implications of transport electrification, particularly the growing interdependence among energy systems, critical-mineral markets, international investment, and financial stability. These linkages are especially important for developing countries such as Thailand, which may benefit from new industrial opportunities while remaining exposed to imported technologies, commodity-price fluctuations, and global capital movements. The findings and policy recommendations of this study therefore provide an initial framework for policymakers and researchers to design strategies that support the expansion, localization, and long-term sustainability of the MEB industry.

**Acknowledgments**

This study is financially supported by the National Science and Technology Development Agency (NSTDA). The authors thank the companies involved in the interviews and data collection.

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