

LONG-TERM BENEFITS OF REMANUFACTURED ELECTRIC VEHICLE BATTERY: A CASE STUDY OF THAILAND

Anatawat Chayutthanabun and Thanwadee Chinda*

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Abstract

Battery electric vehicles (BEVs) are a potential solution to mitigate the environmental impacts for the automotive industry. However, the high BEV demand results in high electric vehicle battery (EVB) production and retired EVBs. This study utilizes the system dynamic modelling approach to explore the growth of the BEV market based on key factors, namely the loan payment, fast charging station, driving range, available models, subsidy, tax reduction, and parking privilege. Benefits and costs of the remanufactured EVBs are then calculated to examine the feasibility of the EVB remanufacturing project. The simulation results reveal that providing parking privileges to the BEV users raises the BEV demand by 20.5%. The EVB remanufacturing project is feasible in seven years with the minimum acceptable internal rate return (IRR) of 18.49%. The sensitivity analysis results show that the IRR values increase to almost 65% at the end of year 25 when the selling prices of the remanufactured EVBs are as new and the remanufacturing costs are reduced by half. The simulation results offer insights to the Thai automotive industry and government to make strategies to promote the sustainable practices of the BEV and EVB industries.

Keywords: Benefit; Cost; Electric Vehicle Battery; Remanufacturing; System Dynamics Modelling

*School of Management Technology, Sirindhorn International Institute of Technology, Thammasat University, Pathumthani, Thailand.
E-mail: d6422300027@g.siiit.tu.ac.th; thanwadee@siiit.tu.ac.th*

* Corresponding author

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Introduction

The global battery electric vehicle (BEV) market grows by half annually with 4.3 million vehicles sold in 2022. It is expected that in 2025, the BEV market will constitute half of the total vehicle market (BOI, 2023). In Thailand, several government supporting policies, such as subsidy and tax reduction, have been initiated, resulting in a triple BEV sale in the past years (MICE, 2023). The growth of the BEV market makes it a major natural resource consumer and the largest contributor to electronic waste in the world. About 26 million retired electric vehicle batteries (REVBs) in the USA are expected in 2030 (Ai *et al.*, 2019). In Thailand, it is expected that the electric vehicle battery (EVB) waste will reach four million tons in 2040 (BOI, 2023). Fallah and Fitzpatrick (2024) mentioned that the global EVB waste will be extensive in the next two decades. The REVBs cause various environmental problems, as most of them are disposed of in landfills, causing soil and water contamination from toxic leachates (Fallah and Fitzpatrick, 2024). Governments worldwide push towards sustainable EVB management. For example, the European Union proposed measures to hold BEV suppliers accountable for ensuring the sustainability of EVBs and minimizing the environmental impacts (Tankou *et al.*, 2023). This initiative promotes responsible recycling practices and waste reduction in the EVB life cycle. China implemented a tax exemption program to promote the reusing, recycling, and refurbishing of EVBs

to expand the EVB lifespan and minimize the environmental footprint (Interesse, 2023). The USA established regulations and incentives to promote the reuse of EVBs (Tankou *et al.*, 2023).

The automotive industry is working on developing more environmentally friendly innovations that can enhance the sustainability of EVBs throughout their life cycles. For example, Nissan Motor Corporation (2023) improved the state of health (SOH) efficiency of EVBs through the remanufacturing process to prolong battery utilization. The SOH is the health status of the battery, indicating its remaining capacity compared to its original capacity (Nissan Motor Corporation, 2023). The SOH of EVBs of over 80% is possible for the remanufacturing process, while the SOHs of 60-80% and less than 60% are suitable for the repurposing and recycling processes, respectively (Nissan Motor Corporation, 2023). The remanufacturing process enhances the environmental benefits through the battery life extension and decreased material requirement and waste generation. It assists in ensuring a steady source for the growing BEV market.

In Thailand, the remanufacturing concept of REVBs should be encouraged to accommodate the growth of the BEV market and achieve sustainable development. However, it is necessary to examine the EVB remanufacturing process to ensure its economic possibility. Moreover, several factors influencing the BEV market may be dynamic and have interrelationships with each other. For

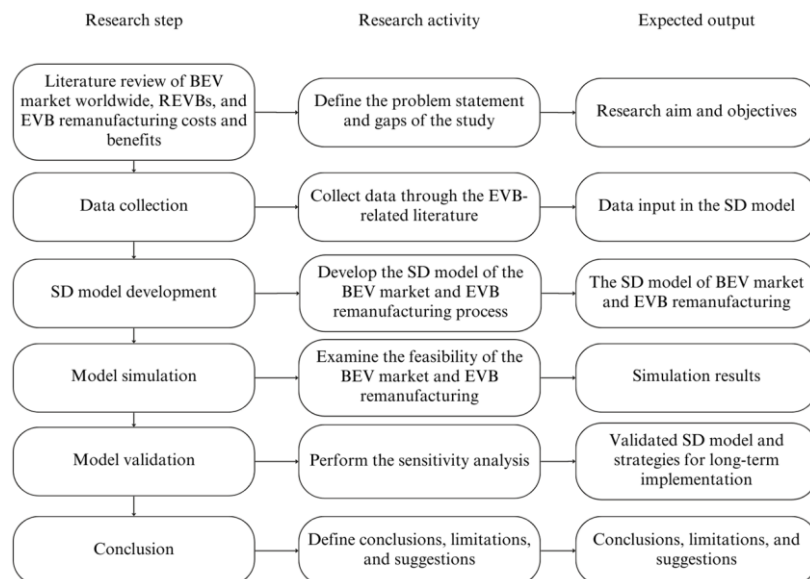


Figure 1. Research flow of the study

example, government policies, such as tax reductions and purchase rebates, increase the willingness to purchase EVs, leading to higher BEV demand. The high demand for BEVs forces more EVB production and utilization and results in more REVBs. This requires the remanufacturing process to reduce the requirement of virgin materials and long-term environmental impacts.

To strategically plan for the EVB remanufacturing from the BEV market, this study utilizes a system dynamics (SD) modelling approach to examine the BEV market, benefits and costs of the EVB remanufacturing project, and its feasibility in the long-term using the net cash flow (NCF) and internal rate of return (IRR). It is expected that the study results will assist the decision makers in planning for the EVB remanufacturing to achieve a long-term sustainable development plan. The research flow is shown in Figure 1.

Key Factors Influencing the Growth of the Thai BEV Market

The Thai BEV market has been steadily growing as a result of the government supporting policies and market demand for sustainable transportation solutions. The market has been expanded dramatically since 2021, reaching almost 80,000 vehicles in 2023 (BOI, 2023). Currently, there are 23 models of BEVs under 18 brands in Thailand (BOI, 2023). The Thai government has supported the BEV market by launching the “Electric Vehicle Promotion Plan” to promote BEV manufacturing, assembling, and adoption (MICE, 2023). Several policies, such as tax incentives, subsidies, and infrastructure development, have been implemented to encourage both customers and manufacturers to participate in the BEV market. Several collaborations between the government, private sector, and academia have been made to advance the BEV market. Many challenges, such as the charging infrastructure development, battery technology, customer awareness, and investment cost, are pinpointed (Ramoni and Zhang, 2012).

Several studies have been conducted to examine key factors influencing the BEV market. For example, Manutworakit and Choocharukul (2022) examined Thai BEV’s customer behaviours and preferences and identified key factors influencing the BEV market, namely pricing, range limitation, charging infrastructure, and perceived environmental benefits. Khaleghiyaraziz (2021) mentioned that incentives, such as tax reduction, purchase rebates, and parking fee exemptions, have high influence on the EV customer purchasing decision in Thailand. Town *et al.* (2022) stated that BEV technologies, such as fast charging stations

and battery capacities, attract at least 20% more of BEV customers.

In this study, the Scopus database is utilized to extract key factors affecting the BEV purchasing decisions in Thailand. Keywords, including “electric vehicle”, “market”, “sales”, “factor”, “adoption”, and “Thailand” are input into the database with the limitations of English journals published in the last 10 years. A total of 5000 journals are extracted and screened to list key factors influencing the BEV market. This list of key factors is further examined to achieve seven key factors with high frequencies of appearance as shown below.

- **Loan payment:** The ability to pay a loan reflects the BEV affordability and grows the BEV market. Proper loan payment with an appropriate payment period may raise the BEV purchasing by an additional 12.8% (Manutworakit and Choocharukul, 2022).
- **Fast charging technology:** A better fast charging technology improves charging time and may attract more BEV customers. Hanni *et al.* (2024) mentioned that customers are attracted to improvements in fast charging technology, driving range, and available models. The advancement of fast charging technology and driving range extension reduces the waiting time and frequencies of the charging and attracts more BEV customers.
- **Driving range:** Extended driving ranges reduce the need for frequent charging, thus enhancing the customer satisfaction and BEV adoption (Hanni *et al.*, 2024).
- **Available model:** Various BEV models stimulate the market and attract new and existing BEV customers. Launching new BEV models not only signifies the industry’s commitment, but also provides customers with various choices in terms of designs, performances, and features and may result in more BEV customers (Manutworakit and Choocharukul, 2022).
- **Subsidy:** Government supporting policies for BEVs, such as subsidy and tax reduction, may reduce the production cost and BEV prices and raise the BEV demand. Li *et al.* (2020) stated that subsidies make BEVs more economically viable, thus stimulating the BEV market.
- **Tax reduction:** Tax incentives play a crucial role in reducing the overall cost of BEVs, contributing to increased EV sales (Li *et al.*, 2020).
- **Parking privilege:** The parking privilege for EV users may attract new customers as

it offers the convenient parking in major areas. Access to parking privileges creates a favourable environment for BEV users and attracts more BEV customers (Hanni *et al.*, 2024).

Remanufacturing Process of REVBs

The growth of the BEV market resulted in a 9% increase in EVB production in 2023 with an investment of \$2.46 billion (BOI, 2023). It is expected that the production capacity of EVB in Thailand will increase to 270,000 batteries per year in 2030 (MICE, 2023). This, though, raises the demand for virgin materials used in the EVB production and results in the country being a major contributor to the material consumption and electronic waste disposal (Ai *et al.*, 2019). The landfill for electronic waste in Thailand has nearly reached its maximum capacity i.e., 95% of the space was occupied in 2023 (Kunacheva *et al.*, 2009). The adoption of BEVs leads to the new dynamics of Thailand's electronic waste challenges. When EVBs reach the end of their useful lives, their disposal becomes an environmental concern. EVBs contain valuable materials that can be recovered and reused, such as lithium, cobalt, nickel, and aluminium. Proper management of EVBs contributes to less battery disposal and better resource management. Several end-of-life management strategies, such as recycling, repurposing, and remanufacturing, have been introduced in recent studies. For example, Ai *et al.* (2019) examined current EVB recycling technologies and concluded that the cathode materials can be recovered via the hydrometallurgical process, and other materials can be recovered via a direct recycling process. Bobba *et al.* (2018) utilized the life cycle assessment method to examine the environmental benefits of the repurposed batteries and their adoptions in the industrial development zone in Europe. They concluded that user behaviour, battery lifetime, and battery degradation are the main factors for the adoption of repurposed batteries. Ramoni and Zhang (2012) studied various remanufacturing processes of REVBs to maximize their SOHs and concluded that a freshly exposed cathode surface enables the fast ions movement. This makes the remanufactured EVBs as efficient as new EVBs.

In this study, the remanufacturing option is considered for the end-of-life EVB management as it offers significant benefits without incurring high costs. Dong *et al.* (2023) stated that the EVB remanufacturing cost is 15% lower than that of the original EVBs, while the performance remains almost the same. By using the remanufactured EVBs, the valuable materials, such as lithium and cobalt, are conserved, thus reducing the demand for

new materials and contributing to the environmental preservation. The establishment of remanufacturing plants also generates job opportunities and supports the expansion of the BEV industry (MICE, 2023).

The remanufacturing process is a practical option of the end-of-life EVB management. It is designed to revive and enhance the performance of REVBs. Various studies have examined the remanufacturing process across different industries. For instance, Bensmain *et al.* (2019) optimized the remanufacturing practices for the components used in the construction machineries. They suggested that the production and the remanufacturing plans and the quality of spare parts used in the remanufacturing process should be optimized to minimize the total costs. Huster *et al.* (2022) developed a simulation model to determine the possibility of using the remanufactured EVBs as spare parts. The results address various aspects to achieve the sustainable remanufacturing practices, such as economic viability, environmental impacts, technological advancement, customer perceptions, and supply chain management.

Benefits and Costs of the Remanufactured EVBs

The remanufactured EVBs reduce the demand for new materials, thus lowering the global impacts. They are sold at a price close to their original prices. Despite this benefit, they incur the remanufacturing cost. The initial investment of \$57 million encompasses the establishment of the remanufacturing plants and dedicated storage facilities (EA, 2023). Other costs, such as buyback, electricity, material, labour, overhead, storage, material handling, and landfill costs are crucial in the remanufacturing process. It is expected that the average cost for EVB remanufacturing is about \$8,628 per battery (EA, 2023). The landfill charge constitutes an integral aspect of the total EVB remanufacturing cost. The charge rate in Thailand is currently \$62.18 per battery of the electronic waste (Kunacheva *et al.*, 2009). The charge increases to \$248.72 per battery when REVBs are exported to neighbouring countries for the disposal (Ai *et al.*, 2019).

Research Methodology

SD Modelling Approach

SD modelling is an approach for modelling the comprehensive system, utilizing feedback loops and interrelationships between key variables (Chinda, 2022). It is widely applied in the automotive-related studies to predict future scenarios and support decision-making processes. For instance, Chayutthanabun and Chinda (2018) examined long-term trends of lightweight hybrid

Cotisel *et al.*, 2017). The high remanufacturing cost reduces the number of remanufactured EVBs, representing a negative causal link.

Causal loops involve reinforcing and balancing loops (Tomoaia-Cotisel *et al.*, 2017). The reinforcing loops create the exponential growth or decline. For example, with various government supporting policies, the BEV demand increases. It boosts the EVB production and increases the REVBs and remanufactured EVBs. These represent the positive causal links between the BEV demand, EVB production, REVBs, and remanufactured EVBs. The uses of remanufactured EVBs attract green customers, resulting in more BEV sales in the market. This shows a positive causal link between the remanufactured EVBs and BEV demand and closes a reinforcing loop between the BEV demand, EVB production, REVBs, remanufactured EVBs, and green customers (EA, 2023).

The balancing loops, on the other hand, maintain the system stability. For instance, with the current limited remanufacturing technology, the remanufactured EVBs may have low driving ranges and battery capacities, while the remanufacturing cost is extensive (BOI, 2023). The high remanufacturing cost may influence the manufacturer's decision to remanufacture REVBs and, instead, transfer them to landfills. These represent the negative causal links between the remanufacturing cost, the remanufactured EVBs, and landfill disposal. The more REVBs disposed of in landfills, the greater the landfill cost and environmental problems (Ai *et al.*, 2019). This pushes the company to improve the remanufacturing technology to enhance the number of remanufactured EVBs, thus lowering the remanufacturing cost and reducing the demand for landfill spaces. A reinforcing loop between the

In an SD model, causal loop diagrams are developed to depict causal relationships of key factors in the system. A causal loop diagram consists of causal links and causal loops (Tomoaia-Cotisel *et al.*, 2017). A causal link between the two factors can be positive or negative, indicating the direction and strength of the influence. A positive causal link from factors A to B can be explained that when factor A increases, factor B increases, and vice versa (Tomoaia-Cotisel *et al.*, 2017). For example, an increase in the BEV demand increases the BEV production, representing a positive causal link. A negative causal link, in contrast, depicts an opposite effect between the two factors (Tomoaia-

Figure 2. Causal loop diagram of BEVs, REVBs, and remanufactured EVBs

remanufacturing technology, remanufacturing cost, landfill space, and landfill cost is then achieved.

The causal loop diagram of the EVB remanufacturing process in this study is shown in Figure 2.

Data Collection

Secondary data are used as input in the developed SD model. They are retrieved from international journals, company and government reports, company websites, and statistical data. Both quantitative and qualitative data are used, where

qualitative data are converted to quantitative ones before inputting into the SD model. Examples of data include the number of BEVs and EVBs in Thailand, fast charging stations, government supporting policies, remanufacturing costs, and battery selling prices. For instance, the current fast charging stations in Thailand are 3,884 stations with an increasing rate of 6% annually (EVAT, 2023). Government policies to support the remanufactured EVBs include the tax reduction of 40% and the subsidy for domestic BEV production of up to \$2,760 per vehicle (with the vehicle prices of less

Table 1. Data used in the SD model development

Data	Information	Detail
BEV market	BEV customer	Average BEV selling price: \$56,789 per vehicle
	EVB	- Average EVB selling price: \$12,067 per battery - EVB capacity: 11-114 kWh (average at 75 kWh) - EVB capacity increasing rate: 3% annually - Lifespan: 10 years
	REVB	- Percentage of REVBs to be remanufactured: 72% on average (based on SOH $\geq$ 80%) - Buyback price: 40% of the initial price (based on SOH $\geq$ 80%) - Remanufactured EVB selling price: \$5,696 per battery
Factor affecting BEV demand	Loan payment	- Average income: \$8,856 per person per year - Income increasing rate: 5% annually - Average electricity expense: \$564 per vehicle per year - Maximum loan period: 6 years - Average interest rate of vehicle loan payment: 4.75% annually - Increased customers from the loan payment factor: 12.8% of the BEV demand
	Fast charging station	- Number of fast charging stations: 3,884 stations - Fast charging station increasing rate: 6% annually - Dedicated fast charging station: 7.5% of total BEVs - Increased customers from the fast-charging station factor: 12.43% of the BEV demand
	Driving range	- Minimum driving range: 20% of average driving range per charge - Average driving range: 350 km per charge - Improvement in driving range: 20 km per model on average - Average Thai BEV user's driving range: 25,000 km annually - Increased customers from the driving range factor: 10.3% of the BEV demand
	Available model	- BEV brands in Thailand: 18 brands - New brand increasing rate: 11.1% annually - Average BEV models per brand: 3 models - Increased customers from the available model factor: 10% of the BEV demand
	Subsidy	- BEVs with at least 50 kWh and price below \$56,789: 46.3% of total BEV models - Increasing rate of BEVs with at least 50 kWh and price below \$56,789: 3% annually - Campaign duration: 4 years - Increased customers from the subsidy factor: 80.6% of the BEV demand
	Tax reduction	- BEV tax reduction: 40% of custom duty tax per vehicle - Campaign duration: 2 years - Increased customers from the tax reduction factor: 18.5% of the BEV demand
	Parking privilege	- BEV parking spaces: 28,595 parking spaces - BEV parking space increasing rate: 3% annually - Designated parking spaces for BEV users: 30% of total parking spaces - Increased customers from the parking privilege factor: 20.5% of the BEV demand
Cost	Remanufacturing process	- Investment cost: \$57 million - Remanufacturing cost: \$8,628 per battery
	Landfill	- Local charge: \$62.18 per battery - Maximum capacity: 245,098 Batteries - Landfill charge in neighbouring countries: \$248.72 per battery

Note: Reference includes Kunacheva *et al.* (2009); Murnane and Ghazel (2017); Ai *et al.* (2019); Manutworakit and Choocharukul (2022); Town *et al.* (2022); Dong *et al.* (2023); EVAT (2023); EA (2023); MICE (2023); Nissan Motor Corporation (2023); SCB (2023); Statista Research Department (2023); BOI (2023); Hanni *et al.* (2024).

than \$57,000) (EA, 2023). According to EA (2023), the average cost of an EVB remanufacturing is \$8,628. EVAT (2023) stated that the remanufactured EVBs can be sold at \$12,067 per battery, which is about 85% of the new EVB price. Table 1 summarizes the data used in the SD model development.

The SD Model of BEV Market and EVB Remanufacturing

The SD model of the EVB remanufacturing process comprises three sub-models: REVBs, remanufactured EVBs, and IRR sub-models.

REVBs Sub-model

The REVBs sub-model is explained in Figure 3. It depends on seven key factors influencing the BEV demand (Table 1) and loyal customers who repurchase BEVs every 10 years (which is an average lifespan of EVs) (Murnane and Ghazel, 2017). With a good and reliable BEV market, loyal customers will repurchase BEVs every 10 years when the EVB life span expires. The REVBs are bought back to the remanufacturing companies for the remanufacturing process. The remanufactured EVBs, once used as a second life, cannot be remanufactured and are disposed of in landfills; see Equations 1-3.

$$R = \text{History}(EVD, Y - 10) \quad (1)$$

$$REVB = R - \text{History}(RMEVB, Y - 10) \quad (2)$$

$$LFR = \text{History}(RMEVB, Y - 10) \quad (3)$$

Where

R = Repurchased BEVs (vehicles)

EVD = BEV demand (vehicles)

Y = Year

$REVB$ = Retired EVBs (batteries)

$RMEVB$ = Remanufactured EVBs (batteries)

LFR = Landfilled second-life EVBs (batteries)

About 12.8% of customers may purchase the new BEVs when they have the ability to pay loans and related BEV expenses, see Equations 4 and 5. The average interest rate for vehicle loans is 4.75% per year, with a maximum loan period of six years (SCB, 2023). SCB (2023) mentioned that at least half of the customer's income should be provided for the vehicle's loan payment.

$$LP = \text{If}[[S \times (1 + SR)^{y-1}] / 2 \geq (ALP + EVE)] \text{ Then } 0.128 \text{ Else } 0 \quad (4)$$

$$ALP = (EVP / I) \times (1 + LI)^{y-1} \quad (5)$$

Where

LP = Increasing rate of BEV customers from the loan payment factor (%)

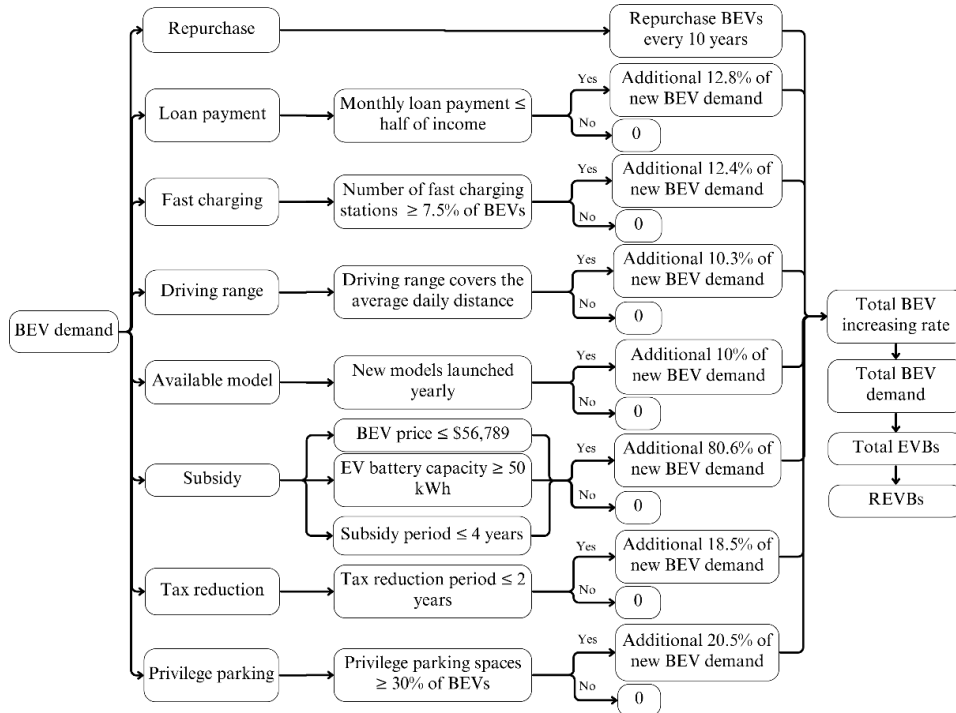


Figure 3. Flow of the REVBs

S	= Annual income (\$)	customers may purchase BEVs when they perceive various brands in the market; see Equations 10 and 11.
SR	= Annual income increasing rate (%)	
ALP	= Annual loan payment (\$)	
EVE	= Annual BEV expenses (\$)	
EVP	= BEV price (\$)	$AM = \text{If } (EB = 1) \text{ Then } 0.1 \text{ Else } 0 \quad (10)$
I	= Loan duration (year)	$EB = \text{If } EVD \geq [\text{History}(EVD, Y - 1) \times 1.5] \text{ Then } 1 \text{ Else } 0 \quad (11)$
LI	= Annual loan interest rate (%)	

Hanni *et al.* (2024) stated that the number of fast charging stations should be at least 7.5% of total BEVs to attract 12.43% more new BEV customers; see Equations 6-8. Based on Statista Research Department (2023), the number of fast charging stations increases by an average 6% per year.

$$CS = \text{If } [(EVD \times 0.075) \leq (ACS \times 1.06^{Y-1})] \text{ Then } 0.1243 \text{ Else } 0 \quad (6)$$

$$TCS(t) = TCS(t - dt) + (ACS \times dt) \quad (7)$$

$$ACS = TCS \times 1.06^{Y-1} \quad (8)$$

Where

CS	= Increasing rate of BEV customers from the fast charging station factor (%)
TCS	= Total fast charging stations (stations)
ACS	= Annual fast charging stations (stations)

The growth of the BEV market motivates manufacturers to enhance their production quality, particularly in driving ranges, to attract more BEV customers. Currently, the minimum and maximum driving range for BEVs are 84 km and 491 km with an average improvement of 3% annually (EVAT, 2023). Approximately 10.3% more customers may purchase BEVs if the minimum driving ranges (i.e., 20% of average driving range) can accommodate their daily travel distances, which is 68.5 km per day on average; see Equation 9 (EVAT, 2023; Hanni *et al.*, 2024).

$$DR = \text{If } \text{History}(ADR, Y - 1) \geq 491 \text{ Then } 0 \text{ Else If } [(IDR + (IMDR \times Y) \times 0.2) \geq 68.5] \text{ Then } 0.103 \text{ Else } 0 \quad (9)$$

Where

DR	= Increasing rate of BEV customers from the driving range factor (%)
IDR	= Initial driving range per battery (km)
$IMDR$	= Improved driving range (km)

The rapid BEV sales welcome new brands in the market. According to EVAT (2023), a new brand is introduced when the BEV demand is increased by half. It is expected that 10% more

Where

AM	= Increasing rate of BEV customers from the available model factor (%)
EB	= BEV brand (brands)

The Thai government supports the BEV market through the subsidy and tax reduction campaigns. It is stated that the subsidy of \$2,760 can potentially attract new BEV customers up to 80.6% (see Equation 12) (EVAT, 2023). This subsidy program lasts for four years and is applicable for BEVs with the battery capacities of at least 50 kWh and a price of up to \$56,789. EVAT (2023) reported that about 46.3% of BEVs have both the battery capacities of at least 50 kWh and prices up to \$56,789. This increases by 3% annually (see Equation 13).

$$SS = \text{If } Y \leq 4 \text{ Then } (PEP \times 0.806) \text{ Else } 0 \quad (12)$$

$$PEP = \text{If } \text{History}(PEP, Y - 1) \leq 1 \text{ Then } [0.463 + (0.03 \times Y)] \text{ Else } 1 \quad (13)$$

Where

SS	= Increasing rate of BEV customers from the subsidy factor (%)
PEP	= Percentage of BEVs with at least 50-kWh capacities and prices less than \$56,789 (%)

Leenabanchong (2021) reported that the Thai government promotes the BEV market by offering the tax reduction of 40% for two years. This could attract up to 18.5% more BEV customers; see Equation 14.

$$TR = \text{If } Y \leq 2 \text{ Then } 0.185 \text{ Else } 0 \quad (14)$$

Where

TR	= Increasing rate of BEV customers from the tax reduction (%)
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Thananusak *et al.* (2021) stated that reserved parking spaces for BEV users in prime locations,

such as shopping malls, hospitals, and gas stations, increase by 3% annually to attract more BEV users. They commented that the privilege parking spaces for BEVs should be at least 30% of the total BEVs to attract 20.5% more BEV customers; see Equation 15.

$$PP = \begin{cases} If [(PS \times 1.03^{y-1}) \geq (EVD \times 0.3)] Then 0.205 Else 0 \end{cases} \quad (15)$$

Where

PP = Increasing rate of BEV customers from the parking privilege factor (%)
 PS = Parking spaces (vehicles)

The total BEV increasing rate is achieved by summing the seven increasing rates from the seven key factors; see Equation 16. The BEV demand each year is then calculated; see Equations 17 and 18. It is used to calculate the number of EVBs, REVBs, and remanufactured EVBs.

$$IN = LP + CS + DR + AM + SS + TR + PP \quad (16)$$

$$EVD(t) = EVD(t - dt) + INEV \times dt \quad (17)$$

$$INEV = [EVD \times (1 + IN)] + R \quad (18)$$

Where

IN = Increasing rate of BEVs (%)

Remanufactured EVBs Sub-model

The calculation flow of remanufactured EVBs is in Figure 4. The REVBs after a 10-year lifespan are examined with the SOHs to determine the possibility to be remanufactured. According to

Phophongviwat *et al.* (2023), 72% of REVBs with the SOHs of at least 80% are designated for the remanufacturing process; see Equation 19. Subsequently, the REVBs that have lower SOH than 80% are disposed of in landfills. Total REVBs disposed of in landfills are calculated using Equation 20.

$$RMEVB = REVB \times 0.72 \quad (19)$$

$$LFEVB = (REVB \times 0.28) + LFR \quad (20)$$

Where

$RMEVB$ = Remanufactured EVBs (batteries)
 $LFEVB$ = REVBs disposed of in landfills (batteries)

The space in local landfills is limited. The REVBs that are not remanufactured are sent to neighbouring countries for disposal when the local landfill's capacity is reached, accounting for 245,098 batteries; see Equations 21 and 22 (Kunacheva *et al.*, 2009).

$$ALEVB(t) = ALEVB(t - dt) + (LFEVB \times dt) \quad (21)$$

$$ELEVB = \begin{cases} If ALEVB > MLC Then ALEVB - MLC Else 0 \end{cases} \quad (22)$$

Where

$ALEVB$ = Local landfilled REVBs (batteries)
 $ELEVB$ = Exported REVBs for the disposal (batteries)
 MLC = Maximum landfill capacity (batteries)

IRR Sub-model

Benefits of the EVB remanufacturing project are achieved from selling the remanufactured EVBs at a price of \$12,067 per battery; see Equation 23 (EVAT, 2023). Costs, on the other hand, include the facility investment, remanufacturing, and landfill costs. The investment cost (INC) of the remanufacturing facility is \$57 million (EA, 2023). The remanufacturing cost averages \$8,628 per battery (EA, 2023). The local and export landfill charges are \$62.18 and \$248.72, respectively, per battery; see Equation 24 (Kunacheva *et al.*, 2009). The NCF is calculated by subtracting benefits and costs each year (see Equation 25). The IRR is achieved in Equation 26. It is noted that the EVB remanufacturing project in this study is simulated for 25 years to follow the Thailand national EV goal in 2040 (EVAT, 2023).

$$TB = RMEVB \times 12067 \quad (23)$$

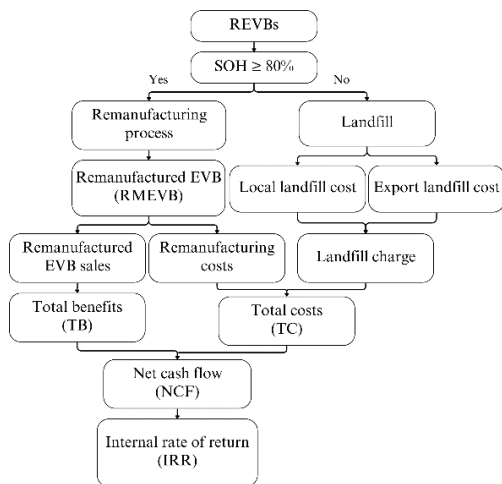


Figure 4. Flow of the remanufactured EVBs

$$TC = (RMEVB \times 8628) + (LFEVB \times 62.17) + (ELEVB \times 248.72) \quad (24)$$

$$NCF = TB - TC \quad (25)$$

$$IRR = (\sum_{y=1}^{25} NCF/NCF)^{1/25} - 1 \quad (26)$$

Results

Simulation Results

The SD model of EVB remanufacturing process is simulated to examine the feasibility of the remanufactured EVBs project. Table 2 shows the long-term trend of BEV demand, building up to 700,000 vehicles in 20 years and resulting in 1.6 million vehicles in 25 years. This is consistent with the Thailand National EV Goal (EVAT, 2023) in that the number of BEV demand is expected to be 800,000 vehicles in the next 20 years (i.e., year 2040) (EVAT, 2023).

Figure 5 reveals that providing parking privileges to BEV users can significantly boost the BEV demand. Offering parking privileges ensures that BEV users have access to designated parking spaces that are located in major areas in the cities. In addition, the ability to charge the vehicles while parking attracts customers who require large driving ranges (Hanni *et al.*, 2024). The increase in BEV demand results in an increase in the REVVs, reaching 600,000 batteries in 25 years; see Figure 6.

Table 3 shows the NCF of the EVB remanufacturing project. The investment at the beginning incurs the negative cash flow of \$57 million. After the REVVs are remanufactured, they are sold to achieve the benefits. The results show that the NCF becomes positive in year 1 when the benefit is higher than the remanufacturing cost.

Figure 7 reveals the IRR values of the EVB remanufacturing project. It reaches the minimum acceptable value (i.e. 14-18% for the automotive-related projects) at the end of year 7 (Hazen and Magni, 2021). The maximum IRR value of 41% is achieved at the end of year 25.

Model Validation

Model validation is an important step to provide accurate insights and enhance the model's predictive capability for future system behaviours. It helps address model limitations, making it a more reliable tool for scenario testing and assessing the impact of various interventions (Chayutthanabun and Chinda, 2018). Also, it assists policymakers in making better decisions in complex systems. Validation is performed by calibrating the model parameters using historical data and sensitivity analysis to understand parameters' impacts on the systems (Chayutthanabun and Chinda, 2018). In this

Table 2. The long-term trend of BEV demand

Year	BEV demand (vehicles)
1	30,510
2	40,988
3	55,561
4	75,990
5	84,626
6	94,244
7	104,955
8	116,883
9	130,167
10	144,961
11	170,713
12	201,040
13	236,755
14	278,814
15	328,345
16	386,676
17	455,369
18	536,265
19	631,533
20	743,724
21	875,847
22	1,031,441
23	1,214,677
24	1,430,464
25	1,684,586

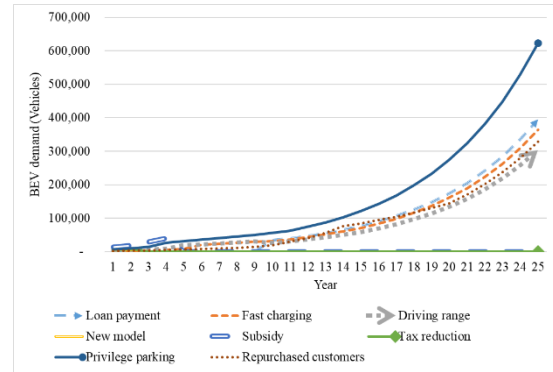


Figure 5. Graphical results of BEV demand

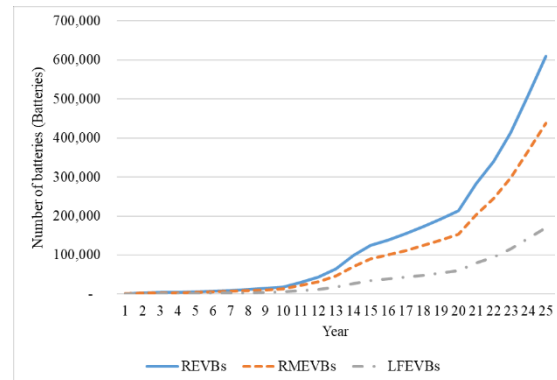
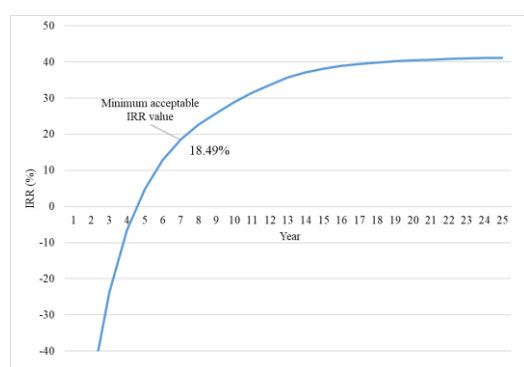
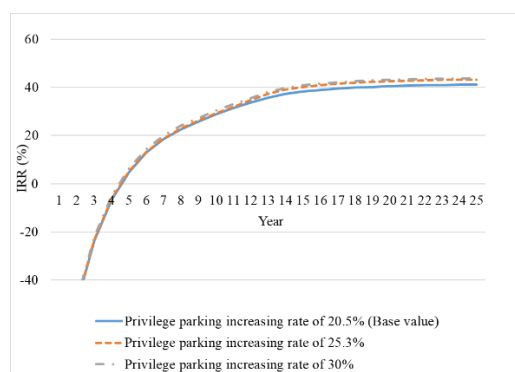


Figure 6. Graphical results of REVVs, RMEVBs, and LFEVBs

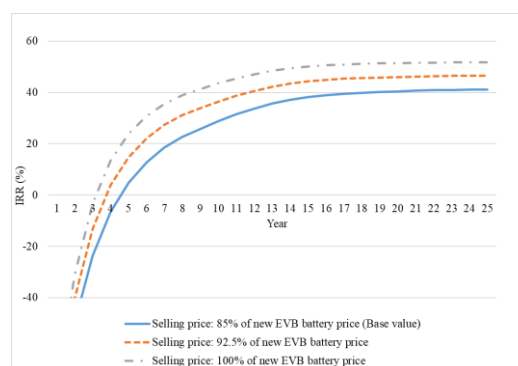
Table 3. NCF of the EVB remanufacturing project

Year	Total benefit	Total cost	NCF
0	0	57,142,857	-57,142,857
1	13,475,460	9,662,059	3,813,401
2	26,950,920	19,324,119	7,626,802
3	33,675,618	24,145,804	9,529,814
4	42,094,523	30,182,255	11,912,268
5	52,624,670	37,732,491	14,892,179
6	65,787,353	47,170,286	18,617,067
7	82,234,192	58,962,857	23,271,334
8	102,799,256	73,708,244	29,091,012
9	128,525,134	92,153,994	36,371,141
10	160,662,934	115,197,164	45,465,770
11	265,078,202	190,064,107	75,014,095
12	356,110,975	255,335,648	100,775,327
13	482,727,476	346,121,130	136,606,346
14	660,220,835	473,385,901	186,834,934
15	735,254,908	527,186,191	208,068,717
16	818,816,576	587,100,864	231,715,712
17	911,875,098	653,824,890	258,050,208
18	1,015,509,728	728,132,107	287,377,621
19	1,130,922,397	810,884,313	320,038,084
20	1,259,451,701	903,041,296	356,410,405
21	1,483,193,343	1,063,466,616	419,726,727
22	1,746,682,640	1,252,391,460	494,291,180
23	2,056,980,786	1,474,878,785	582,102,001
24	2,422,403,469	1,736,891,035	685,512,434
25	2,852,743,377	2,045,449,679	807,293,699

**Figure 7. IRR values of the EVB remanufacturing project****Figure 8. The IRR values of the EVB remanufacturing project when the privilege parking increasing rate is changed**

study, the sensitivity analysis is performed to validate the developed SD model by differing key values related to the BEV market (Chinda, 2022). They include the privilege parking, the selling price of the remanufactured EVB, and the remanufacturing cost. Based on Figure 5, the privilege parking factor has the highest impact on the BEV demand. Hanni *et al.* (2024) mentioned that privilege parking for BEVs attracts EV customers who are concerned about the parking convenience and the ability to charge while shopping. The BEV sales may increase by 30% when the privilege parking is available (Hanni *et al.*, 2024). The sensitivity analysis is then performed with three parking privilege increasing rates, from 20.5% to 30%. The results in Figure 8 show that despite the differences in increasing rates, the model's behaviour remains the same, thus validating the developed SD model for real-world applications (Chinda, 2022). The results also show that the higher the privilege parking increasing rate, the higher the IRR value of EVB remanufacturing project (i.e., achieving IRR value of 43.17% when the privilege parking increasing rate is 30%).

Currently, the remanufactured EVBs are sold at 85% of the new EVB price. With a better remanufacturing technology, the remanufactured EVBs may be sold at higher prices. The sensitivity analysis is performed by varying the selling prices of the remanufactured EVBs from 85% to 100% of the new battery price; see Figure 9 (Ramoni and Zhang, 2012). The simulation results confirm that with higher selling prices, the IRR values increase and reach 51.76% when the remanufactured EVBs are sold as new. Ramoni and Zhang (2012) stated that with the advancement of the remanufacturing process, the remanufactured EVBs have at least the same quality as the new ones and may be sold at the same price. Moreover, the manufacturers may offer customers extended warranties and maintenance

**Figure 9. The IRR values of the EVB remanufacturing project when the remanufactured EVB price is changed**

packages to attract more customers to use the remanufactured EVBs.

The remanufacturing cost depends on the number of REVBs, the remanufacturing cost, and the landfill charge. Huster *et al.* (2022) state that the remanufacturing cost ranges from \$4,314-\$8,628 per battery. The results in Figure 10 reveal that the lower the remanufacturing costs, the higher the IRR values of the project. When the remanufacturing cost is high, the customers tend to purchase the new batteries over the remanufactured ones. The results show that when the remanufacturing cost is half (i.e., \$4,314), the IRR value increases by 60% (from 41.10% to 64.56%).

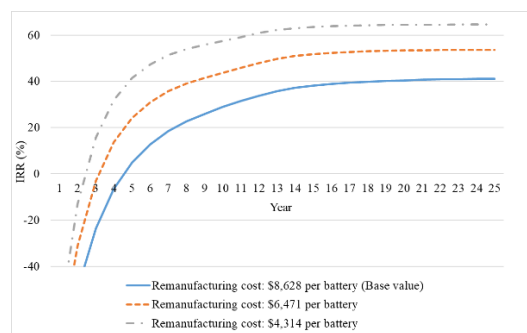


Figure 10. The IRR values of the EVB remanufacturing project when the remanufacturing cost is changed

Conclusions

With the growing demand of BEVs, it is expected that REVBs will be extensive. The EVB remanufacturing is encouraged to reduce the material's demand and electronic waste. The SD model of remanufactured EVBs is developed in this study to examine the feasibility of the EVB remanufacturing project. The BEV demand depends on the loan payment, fast charging stations, driving range, available model, subsidy, tax reduction, and parking privilege factors. The simulation results reveal that the BEV demand reaches 1.6 million and the number of REVBs increase to 600,000 batteries in the next 25 years. The results show that the privilege parking factor has the most impact on the BEV market as it represents 31% of the total BEV demand.

The growth of BEV demand results in more REVBs that need to be remanufactured. The benefits of selling remanufactured EVBs and costs related to remanufacturing process and landfilling are used to calculate the NCF and IRR values. The results reveal the IRR value of 16%, which is the

minimum acceptable value, is reached in seven years, and the IRR value of 41% over 25 years.

The sensitivity analysis is performed to validate the developed SD model and suggest strategies to enhance the EVB remanufacturing project. The results reveal that by offering more parking privileges to BEV users, the IRR value of the remanufacturing project slightly changed. Contrary, an increase in the remanufactured EVB's selling price raises the IRR values from 41% to 52%. Moreover, reducing the remanufacturing cost by half can increase the IRR to 64%. Successful implementation of these strategies, particularly in the early stages, relies heavily on government support to facilitate the BEV market and readiness for the adoption of the remanufactured EVBs.

The findings from this study aid the government and automotive industry in making decisions related to the EVB remanufacturing. The data used in this study are from developed and developing countries and may not fully represent the characteristics of the Thai BEV market. Future research may explore customer preferences and behaviours on the uses of remanufactured EVBs compared with the new ones. This may help the government and automotive industry to plan for future implementation effectively.

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