ECONOMIC AND ENVIRONMENTAL VALUES OF ELECTRIC VEHICLE BATTERIES IN THAILAND UTILIZING SYSTEM DYNAMICS MODELING AND LIFE CYCLE ASSESSMENT APPROACHES

BY

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ABSTRACT

The rapid global expansion of battery electric vehicles (BEVs) has led to an increase in retired EV batteries (REVBs), posing significant environmental challenges worldwide. Thailand, influenced by government incentives and technological advancements in EV batteries (EVBs), has seen a rise in BEV adoption, resulting in higher number of REVBs. Effective end-of-life (EOL) management strategies, including remanufacturing, repurposing, and recycling, are essential to mitigate environmental impacts and promote a circular economy. This research examines the environmental impacts and feasibility of EOL management of REVBs utilizing life cycle assessment (LCA) and system dynamics (SD) modeling approaches. The LCA method is utilized to assess the key environmental impacts associated with EOL management of REVB, including CO_{2eq} emissions, human toxicity, terrestrial acidification, particulate matter formation, photochemical oxidant formation, water depletion, metal depletion, ozone depletion, and fossil fuel depletion. Normalized impact scores for different EOL management strategies are calculated in the LCA analysis and combined to achieve the final impact scores. The LCA results revealed that recycling process is the best EOL management process based on the environmental perspective. It gives the best final impact score of -279, presenting a significant reduction in the environmental impacts. The research also develops causal loop diagrams and an SD model to analyze the dynamic interactions among factors influencing EOL management. The benefits and costs, including environmental costs, are input in the SD model to select suitable EOL management strategies for implementation using the net present value (NPV) and internal rate of return (IRR). The simulation results revealed that the remanufacturing process is the most suitable EOL management process based on economic and environmental perspectives. It yields the highest IRR value of 45% in the next 30 years. Repurposing-only and remanufacturing plus repurposing strategies are also recommended for implementation as they yield the IRR values of 35 and 26% at the end of year 30. The sensitivity analysis was performed to validate the developed SD model and examine long-term strategies to enhance EOL management of REVBs in Thailand. The results suggest that the privilege parking, lithium reserve discovery rate, buyback cost, and human toxicity cost are major contributors to the feasibility of the EOL management project. The integration of these strategies promises an effective REVB management, reduces environmental footprints, and supports the sustainable growth of the Thai automotive sector in the long term.

Keywords: Battery electric vehicle, Benefit, Circular economy, Cost, Economic feasibility, Electric vehicle battery, End-of-life management, Environmental impact assessment, Landfilling, Life cycle assessment, Recycling, Remanufacturing, Repurposing, Retired electric vehicle battery, System dynamics modelling

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Symbols/Abbreviations	Terms
$	U.S. dollar
%	Percentage
ACS	Annual fast charging stations
ADR	Average driving range per battery
Ah	Ampere-hours
Al	Aluminum
ALEVB	Local landfilled retired electric vehicle battery
ALP	Annual loan payment
ALS	Annual salary in the automotive industry
AM	Increasing rate of battery electric vehicle customers from the available model factor
BEVs	Battery electric vehicles
BMS	Battery management system
BP	Battery price
C	Coal
CFCs	chlorofluorocarbons
CLD	Causal loop diagram
CMB	Cell monitor board
Co	Cobalt
CO_{2eq}	Carbon dioxide equivalent
CS	Increasing rate of battery electric vehicle customers from the fast-charging station factor
CTG	Cradle-to-grave
Cu	Copper

DB_{eq}	Dichlorobenzene equivalent
DR	Increasing rate of battery electric vehicle customers from the driving range factor
ELEVB	Exported retired electric vehicle battery for disposal
EOL	End-of-life
EOL1	Reference scenario (landfilling)
EOL2	Remanufacturing scenario
EOL3	Repurposing scenario
EOL4	Recycling scenario
ESB	Benefits from energy storage system
ESBC	Buyback cost of retired electric vehicle battery for repurposing
ESEC	Electricity cost for repurposing
ESEXC	Repurposing capacity expansion cost
ESIC	Inventory cost for repurposing
ESLC	Labor cost for repurposing
ESMC	Material cost for repurposing
ESOC	Overhead cost for repurposing
ESS	Energy storage system
EVBs	Electric vehicle batteries
EVC	Percentage of EVBs with at least 50-kWh capacities
EVD	Battery electric vehicle demand
EVE	Annual battery electric vehicle expenses
EVP	Battery electric vehicle price
Fe_{eq}	Iron equivalent
FRS	Time duration from the facilities to the storage
GHGs	Greenhouse gases

I	Loan duration
IMDR	Improved driving range
IN	Additional increasing rate of battery electric vehicle from key factors
IRR	Internal rate of return
kg	Kilograms
kWh	Kilowatt-hours
LCA	Life cycle assessment
LF	Landfilling
LFCO	CO_{2eq} emission of landfilling
LFFDC	Fossil depletion of landfilling
LFFRC	Un-recycled retired electric vehicle battery forwarded for landfilling
LFHTC	Human toxicity of landfilling
LFMDC	Metal depletion of landfilling
LFODC	Ozone depletion of landfilling
LFP	Lithium iron phosphate
LFPMC	PM formation of landfilling
LFPOC	Photochemical oxidant formation of landfilling
LFR	Landfilled remanufactured electric vehicle battery
LFTAC	Terrestrial acidification of landfilling
LFWDC	Water depletion of landfilling
Li	Lithium
LP	Increasing rate of battery electric vehicle customers from the loan payment factor
m^3	Cubic meters
MLC	Maximum landfill capacity
Mn	Manganese
MP	Material price

n	Project duration
NCF	Net cash flow
NEB	Benefits from new electric
NEBC	Buyback cost of retired electric vehicle battery for recycling
NEEC	Electricity cost for recycling
NEEXC	Recycling capacity expansion cost
NEIC	Inventory cost for recycling
NELC	Labor cost for recycling
NEMC	Benefits
NEMC	Material cost for recycling
NEOC	Overhead cost for recycling
NEVB	New electric vehicle battery
NG	Natural gas
Ni	Nickel
NMC	lithium nickel manganese cobalt oxide
NO_x	Nitrogen oxides
NPV	Net present value
PEP	Percentage of BEVs with the prices less than $56,789
PHEVs	Plug-in hybrid electric vehicles
PM	Particulate matter
PP	Increasing rate of battery electric vehicle customers from the parking privilege factor
PS	Parking spaces
R	Repurchased battery electric vehicle
RC	Recycling
RCC	Recycling capacity
RCCO	CO_{2eq} emission of recycling

RCCP	Recycling labor productivity per person per year
RCFDC	Fossil depletion of recycling
RCFRP	Un-repurposed retired electric vehicle battery forwarded for recycling
RCHTC	Human toxicity of recycling
RCLRC	Stocked retired electric vehicle battery to be recycled
RCMDC	Metal depletion of recycling
RCMHC	Material handling cost for recycling
DOS	Time duration from the drop-off to the storage
RCODC	Ozone depletion of recycling
RCPMC	PM formation of recycling
RCPOC	Photochemical oxidant formation of recycling
RCSC	Recycling storage capacity
RCTAC	Terrestrial acidification of recycling
RCWDC	Water depletion of recycling
RE	Renewable energy
REB	Benefits from remanufactured electric vehicle battery
REBC	Buyback cost of retired electric vehicle battery for remanufacturing
REEC	Electricity cost for remanufacturing
REEXC	Remanufacturing capacity expansion cost
REIC	Inventory cost for remanufacturing
RELC	Labor cost for remanufacturing
REMC	Material cost for remanufacturing
REOC	Overhead cost for remanufacturing

REVBs	Retired electric vehicle batteries
RM	Remanufacturing
RMC	Remanufacturing capacity
RMCO	CO_{2eq} emission of remanufacturing
RMCP	Remanufacturing labor productivity per person per year
RMEVB	Remanufactured electric vehicle battery
RMFDC	Fossil depletion of remanufacturing
RMHTC	Human toxicity of remanufacturing
RMLRC	Stocked retired electric vehicle battery to be remanufactured
RMMDC	Metal depletion of remanufacturing
RMMHC	Material handling cost for remanufacturing
RMODC	Ozone depletion of remanufacturing
RMPMC	PM formation of remanufacturing
RMPOC	Photochemical oxidant formation of remanufacturing
RMTAC	Terrestrial acidification of remanufacturing
RMWDC	Water depletion of remanufacturing
RP	Repurposing
RPC	Repurposing capacity
RPCO	CO_{2eq} emission of repurposing
RPCP	Repurposing labor productivity per person per year
RPFDC	Fossil depletion of repurposing
RPFRM	Un-remanufactured retired electric vehicle battery forwarded for repurposing
RPHTC	Human toxicity of repurposing

RPLRC	Stocked retired electric vehicle battery to be repurposed
RPMDC	Metal depletion of repurposing
RPMHC	Material handling cost for repurposing
RPODC	Ozone depletion of repurposing
RPPMC	PM formation of repurposing
RPPOC	Photochemical oxidant formation of repurposing
RPSC	Repurposing storage capacity
RPTAC	Terrestrial acidification of repurposing
RPWDC	Water depletion of repurposing
S	Annual income
SC	Storage capacity
SD	System dynamic
SEXC	Storage capacity expansion cost
SO_{2eq}	Sulfur oxide equivalent
SOHs	State of health
SREVB	Stocked retired electric vehicle battery
SRF	Time duration from the storage to the facilities
SS	Increasing rate of battery electric vehicle customers from the subsidy factor
STELLA	Structural Thinking Experimental Learning with Animation
TB	Total benefits
TBC	Total buyback cost of retired electric vehicle battery
TC	Total cost

TCOC	Total CO_{2eq} cost
TEC	Electricity cost
TFDC	Total fossil depletion cost
THTC	Total human toxicity cost
TIC	Total inventory cost
TLC	Total labor cost
TLFC	Total landfill cost
TMC	Total material cost
TMDC	Total metal depletion cost
TMHC	Benefits from energy storage system
TOC	Total overhead cost
TODC	Total ozone depletion cost
TPMC	Total PM formation cost
TPOC	Total photochemical oxidant formation cost
TR	Increasing rate of battery electric vehicle customers from the tax reduction
TTAC	Total terrestrial acidification cost
TWDC	Total water depletion cost
V	Voltages
	vehicle battery provided from recycled materials
VOCs	Volatile organic compounds
WTW	Well-to-wheel
Y	Year

CHAPTER 1
INTRODUCTION

This chapter explains the background of this research study. The characteristics of the battery electric vehicle (BEV) industry, electric vehicle batteries (EVBs), environmental-related problems, and end-of-life (EOL) management of the retired EVBs (REVBs) are presented in this chapter. The research problems, aim, and objectives are described at the end of the chapter.

1.1 Introduction

The global BEV market is experiencing remarkable growth with a half increase, reaching 4.3 million units in 2022, see Figure 1.1 (IEA, 2023). It was predicted that by 2025, BEVs will make up half of the total vehicles in the market (Bonafide Report, 2022). In Thailand, various government policies, such as subsidies and tax reduction have significantly raised BEV sales, resulting in a threefold increase in recent years (Sattayathamrongthian and Vanpetch, 2023). Moreover, the advancements in EVB technology, including extended driving ranges and lower prices, have made BEVs more appealing to customers (Wang, 2023). The development of EV infrastructure, such as the expansion of charging stations across Thailand, further supports the adoption of BEVs (Thananusak et al., 2020). These factors boost BEV sales and, in turn, increase retired EVBs (REVBs). Dewantoro et al. (2021) mentioned that a huge expansion of the BEV market makes it a major consumer of natural resources and major contributors of electronic waste on a global scale. By 2030, the United States will generate approximately 26 million REVBs, while Thailand's EVB waste is expected to reach 4 million tons by 2040 (Boonchunone et al., 2023). Harper (2019) added that the global EVB waste will be a critical issue in the next two decades and will significantly cause soil and water contamination due to toxic leachates.

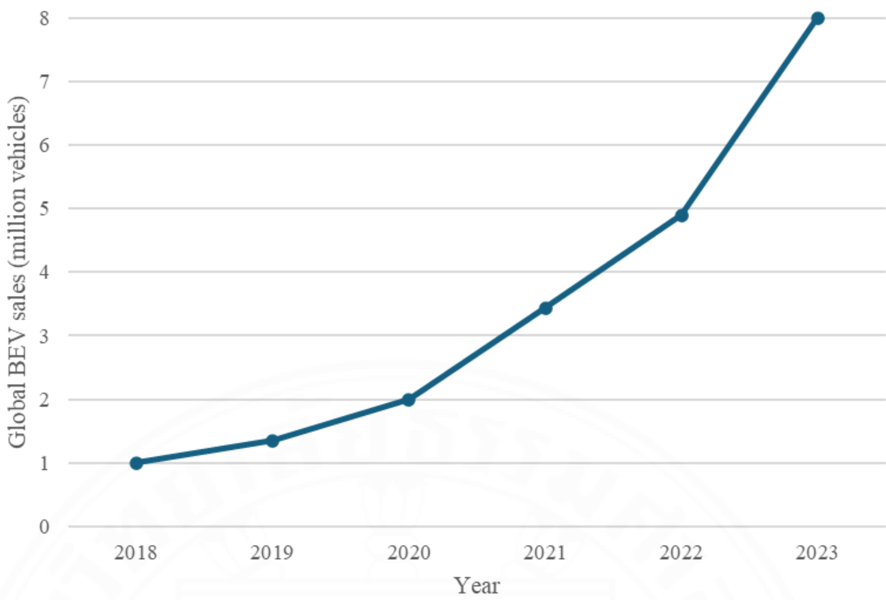


Figure 1.1 Global BEV sales (IEA, 2023)

Governments worldwide take steps to promote the sustainable management of EVBs. The European Union, for instance, has introduced measures to make BEV manufacturers responsible for ensuring the sustainability of their batteries and minimizing environmental impacts (Malinauskaite et al., 2021). This initiative promotes responsible recycling practices and waste minimization throughout the EVB lifecycle. China has implemented tax exemption programs to encourage the reuse, recycle, and refurbishment of EVBs, thereby extending their lifespans and reducing the environmental footprint (Wang and Yu, 2020). In the United States, regulations and incentives are in place to support the reuse of EVBs, while South Korea has established a comprehensive recycling program and collection centers to ensure proper disposal and support a circular economy (Park and Kim, 2021).

The circular economy emphasizes the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems (Serzhena, 2019). However, the production, use, and disposal of EVBs pose significant environmental and economic challenges. The extraction of raw materials, such as lithium, cobalt, and nickel, is resource-intensive and often associated with adverse environmental impacts (Baum et al., 2022). Furthermore, the disposal of REVBs contributes to waste and pollution, highlighting the need for sustainable management practices (Baum et al., 2022). The circular economy offers a framework to mitigate these issues by promoting the remanufacturing, repurposing, and recycling of EVBs. By extending the lifecycle of EVBs and recovering valuable materials, it not only reduces environmental footprints but also enhances resource efficiency and economic value (Bobba et al., 2020). This concept aligns with the goals of sustainable development by minimizing waste, reducing dependency on virgin resources, and fostering innovation in battery technology and management practices (Fan et al., 2020).

Sustainable EVB management urges the automotive industry to focus on end-of-life (EOL) management, specifically, the remanufacturing, repurposing, and recycling processes, to recover valuable materials from REVBs and mitigate hazardous waste (Bobba et al., 2020). Remanufacturing offers significant environmental benefits by extending battery life, reducing material needs, and decreasing EVB waste generation (Casals and Garca, 2016). However, remanufactured EVBs often come with shorter warranties and shorter lifespans compared to new batteries, raising concerns among users who prioritize long-term reliability (Olsson et al., 2018). Repurposing involves utilizing batteries with reduced efficiency in other applications, such as energy storage systems, thereby maximizing their utility and decreasing the EVB waste (Kotak et al., 2021). Recycling focuses on extracting and reusing valuable materials from REVBs, which conserves natural resources and reduces environmental impacts (Baum et al., 2022). These practices support a circular economy by keeping materials in use for longer periods and minimizing waste (see Table 1.1).

Table 1.1 EOL management of REVBs (Sato and Nakata, 2019)

EOL management	SOH	Final product
Remanufacturing	At least 80%	Remanufactured EVBs
Repurposing	Between 60-79%	Energy storage system
Recycling	below 60%	New EVBs

Many companies develop eco-friendly innovations to enhance the sustainability of EVBs throughout the lifecycle (Thirupathi et al., 2018). For example, Nissan Company has improved the state of health (SOHs) of EVBs through remanufacturing, thereby extending their useful lives (Sato and Nakata, 2019). The SOH is a metric that indicates the health status of a battery, comparing its current capacity to its original capacity (Casals and Garcia, 2016). EVBs with an SOH of at least 80% are suitable for remanufacturing. Those with SOHs between 60-79% are suitable for repurposing, and those below 60% are to be recycled (Catton et al., 2019). For instance, Repurpose Energy (2024) repurposed the REVBs to create low-cost second-life energy storage systems up to 1.2 MWh to be used for the solar rooftop at the Robert Mondavi Institute in Davis. Tesla Company (2023) recycled the REVBs to recover its valuable materials for new EVB production.

In Thailand, the remanufacturing, repurposing, and recycling of REVBs are encouraged to support the growth of BEV market and achieve the sustainable development (Noudeng et al., 2022). However, it is essential to assess the feasibility of the EOL management processes to ensure economic viability. Remanufacturing, for example, requires specialized skills and equipment, which entail high costs (Anthony and Cheung, 2017). Furthermore, the dynamic and interrelated factors involved in the EOL management processes must be considered. Increased demand for BEVs drives more EVB production, resulting in more REVBs that need efficient processes, e.g., remanufacturing, to reduce material requirements and long-term environmental impacts (Sato and Nakata, 2019). Limited capacity in remanufacturing plants could lead to storage challenges or increased landfill usage. Expanding plant and storage capacities can enhance production; however, it requires significant investment and strategic planning to avoid delays.

Establishing effective EOL management of REVBs in Thailand is crucial to support the country's sustainable development goals. Proper EOL management can reduce CO_2 equivalent (CO_{2eq}) emissions, decrease human toxicity, and mitigate terrestrial acidification (Misila et al., 2020). It also reduces particulate matter (PM) formation, metal depletion, ozone depletion, and fossil fuel depletion from material consumption (Wang et al., 2022). By integrating strategies for remanufacturing, repurposing, and recycling, the country can manage EVB waste effectively, thus mitigating the environmental impacts and supporting the circular economy within the automotive sector in the long term.

1.2 Problem statement

The rapid growth of the BEV market in Thailand has led to a significant increase in REVBs. This poses a substantial environmental challenge, as improper management of REVBs can lead to severe soil and water contamination due to toxic leachates and other impacts on a global scale, such as CO_{2eq} emissions and ozone depletion. The EOL management of REVBs through the remanufacturing, repurposing, and recycling processes is expected to extend the life cycle of EVBs and minimize the environmental impacts. Nevertheless, the feasibility study of those EOL management processes is necessary as each process has distinct environmental impacts and incurs different benefits and costs. Establishing an effective EOL management system for REVBs is crucial to support the country's sustainable development goals, reduce environmental impacts, and promote a circular economy within the automotive sector.

This research study, therefore, highlights the following issues.

- The EVB industry in Thailand faces a challenge in managing the REVBs to reduce the long-term environmental impacts.
- The EOL management for REVBs in Thailand is still in its early stages and remains unclear. An effective management system is required to achieve sustainable development in economic, environment, and social perspectives.
- The dynamic changes in the EVB industry urge the industry to develop long-term strategies to understand complex relationships of the EOL management processes and benefits and costs of implementation. The plans should be assessed with economic-related indicators to ensure feasibility in the long term.

1.3 Research aim and objectives

This research aims to examine EOL management processes of REVBs and suggests suitable strategies for long-term implementation. The system dynamic (SD) modelling and life cycle assessment (LCA) approaches are utilized to achieve the research aim. The research objectives are set to support the research aim.

- Identify the EOL management processes for REVBs and their environmental impacts.
- Assess the environmental impacts of the EOL management processes utilizing the LCA approach.
- Define benefits and costs of the EOL management processes from the economic and environmental perspectives.
- Develop causal loop diagrams to illustrate the causal relationships among benefits, costs, and other factors influencing the REVBs and EOL management processes.
- Develop an SD model to examine the feasibility of the EOL management strategies in the long-term using the net present value (NPV) and internal rate of return (IRR).
- Recommend long-term strategies to achieve sustainable development for the EVB industry.

1.4 Research flow

To strategically plan for the REVB's EOL management, it is necessary to understand complex relationships between key EOL management processes, their benefits and costs in the long term, and their ecological footprints. This study utilizes the LCA approach to explore the environmental impacts of EOL management. The SD modeling approach is then utilized to examine the benefits and costs of EOL management and its feasibility in the long term. The environmental impacts achieved from the LCA analysis are also converted into environmental benefits and costs (in economic values) and are included in the SD model for feasibility examination. The study results assist decision makers in planning for the REVB's EOL management to achieve long-term sustainability.

The flow of this study is in Figure 1.2. The initial step involves conducting a comprehensive review of BEVs and EVBs in Thailand and abroad to better understand the current statuses (see Chapters 1 and 2). The REVB's EOL management, considering the remanufacturing, repurposing, and recycling processes, was reviewed to achieve the research aim and objectives. The methodologies used in the analysis, i.e., the LCA and

SD modeling approaches are explained in Chapter 3. The LCA method is conducted in Chapter 4. In this chapter, the inventory data are collected to gain necessary information related to the EOL management processes. The LCA analysis results reveal the environmental impacts of the EOL management processes. The impacts are converted to the environmental benefits and costs to be used in the SD modeling in Chapter 5. Other benefits and costs related to EOL management strategies (i.e., remanufacturing, repurposing, and recycling) and their complex relationships achieved from the causal loop diagrams are also used as input in the SD model. The SD model was simulated to examine the feasibility of the EOL management processes in the long-term using the NPV and IRR values. The sensitivity analysis was then performed to validate the developed SD model and suggest suitable strategies for long-term implementation (see Chapter 6). The final chapter (Chapter 7) concludes the study results, contribution to the body of knowledge, and limitations and suggestions for further studies.

1.5 Thesis organization

This thesis consists of seven chapters as follows.

- Chapter 1 introduces the BEV and EVB markets, EOL management of REVBs, and environmental impacts associated with EOL management. This chapter also presents the problem statement, research aim and objectives, research flow, and thesis organization.
- Chapter 2 provides a comprehensive literature review. It includes the studies of the BEV and EVB industries in Thailand, EOL management of REVBs, environmental impacts of EOL management, and benefits and costs of EOL management.
- Chapter 3 outlines the research methodologies used in this study, including the LCA and SD modeling approaches.

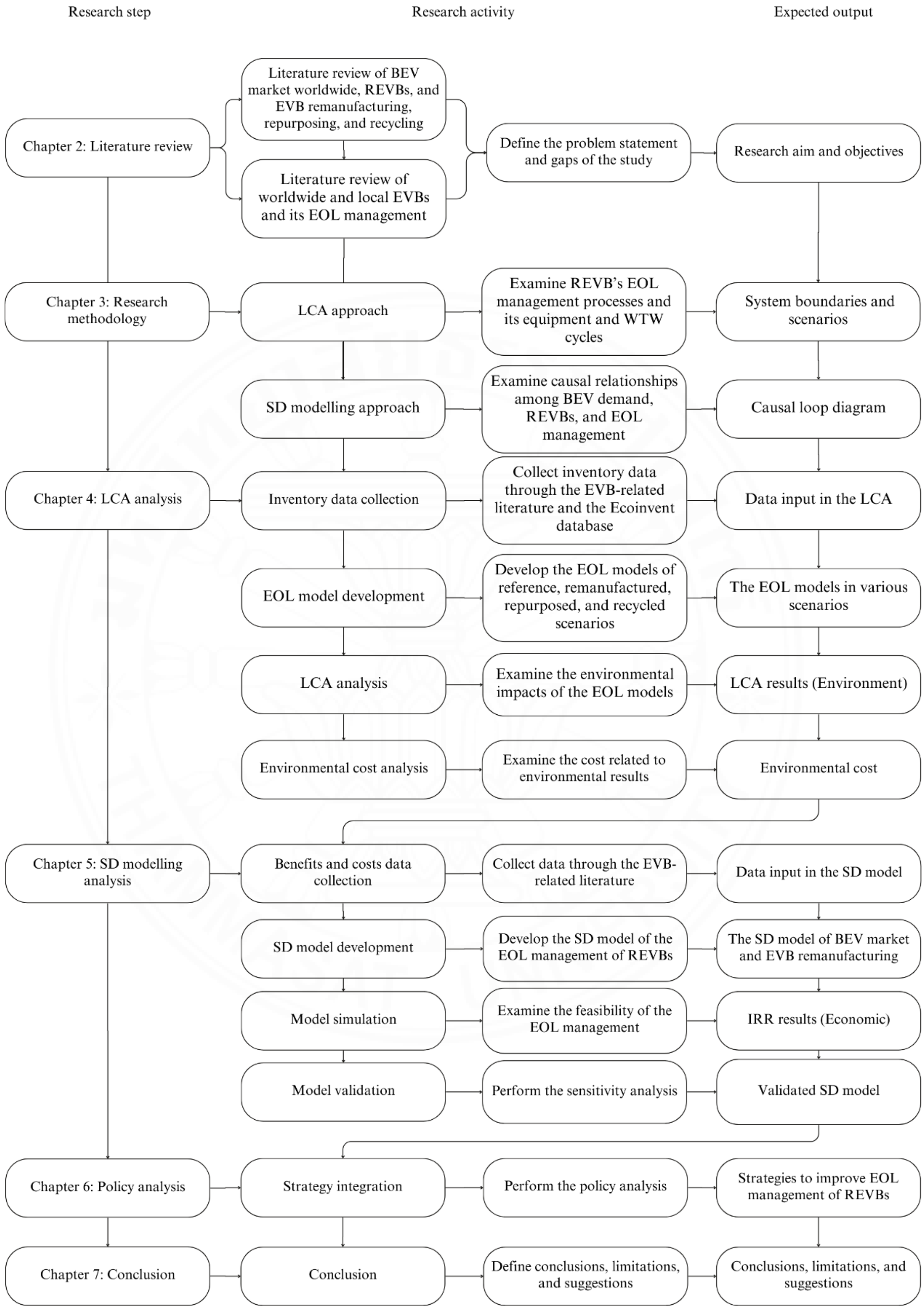


Figure 1.2 Research flow of the study

- Chapter 4 details the LCA analysis. The EOL management strategies are explored with their environmental impacts to achieve the final impact of the EOL management processes. The suitable EOL management practices for REVBs in Thailand from an environmental perspective are presented in this chapter.
- Chapter 5 presents the SD modeling analysis. Benefits and costs related to EOL management processes are explored and input into the SD model. The environmental impacts achieved from the LCA analysis are converted into economic values and used as input into the SD model. The complex relationships of the EOL management processes are examined using the causal loop diagrams and input into the model. The SD model was simulated, and the analysis results reveal the feasibility of EOL management practices and suggest suitable EOL strategies for long-term implementation.
- Chapter 6 performs the sensitivity analysis to validate the developed SD model and recommend strategies for policymakers to enhance the EOL management processes of REVBs in the long term.
- Chapter 7 concludes the study, details the contribution to the Thai government and related agencies, addresses limitations, and provides recommendations for future research.

CHAPTER 2
LITERATURE REVIEW

2.1 General overview

This chapter presents the characteristics of the Thai BEV market, EVB and REVB statuses, and EOL management. Key benefits and costs related to EVB production and its EOL management are explained. Environmental impacts of REVB's EOL management are discussed in this chapter.

2.2 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, and aiming to achieve 100,000 BEV sales by 2030 and 30% of the total automotive sales by 2040, see Figure 2.1 (Thananusak et al., 2020; Sattayathamrongthian and Vanpetch, 2023). These targets reflect the country's commitment to sustainable transportation solutions (Charoenpao and Chomchai, 2024). This rapid growth has been fueled by advancements in battery technology and charging infrastructure. Thai government provides several supports to advance battery technology and driving ranges, thus enhancing customers' confidence in the viability of BEVs for their daily transportation (Ajanapanya, 2024). Charging stations also highly increase, specifically in major locations and cities across Thailand, to support customer adoption (Sharma, 2024). Many of these stations are equipped with applications that assist customers in locating charging stations, checking their availability, and reserving a spot, thus enhancing convenience and improving the BEV customer experiences (Sharma, 2024).

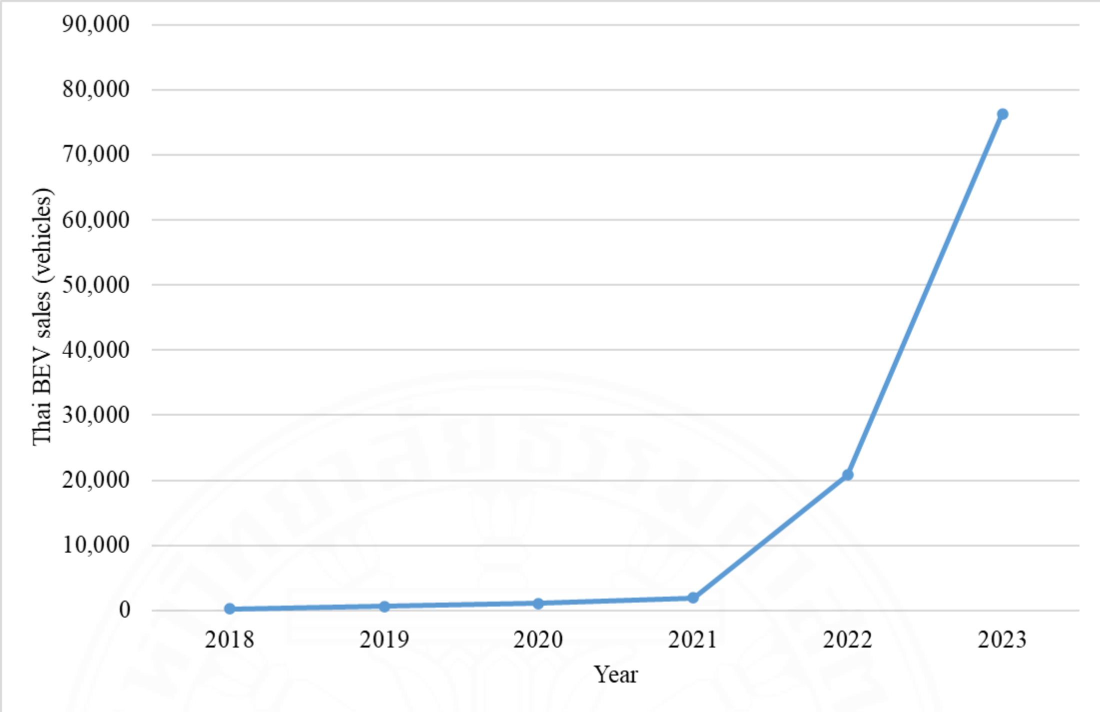


Figure 2.1 Thai BEV sales (Sattayathamrongthian and Vanpetch, 2023)

Currently, there are 23 models of BEVs under 18 brands in Thailand (see Figure 2.2) (Thananusak et al., 2020; EVAT, 2023). Among those, BYD, Neta, MG, Tesla, and GWM are the top five brands, representing 91% of the total EV sales in 2023 (Statista, 2024a). The Thai government supports the BEV market by launching the "Electric Vehicle Promotion Plan" (EV 3.5 Policy) to promote the BEV manufacturing, assembling, and adoption (SAIC Motor, 2019). The policy initiates various incentives to boost BEV adoption, such as purchase rebates, subsidies, and infrastructure development (PRD, 2023). For example, customers purchasing BEVs with battery capacities of at least 50 kWh receive a subsidy of up to $2,857 per vehicle. For BEVs with battery capacities under 50 kWh, the subsidy is up to $1,428 per vehicle (Charoenpao and Chomchai, 2024). Tax incentives include the zero import taxes for China-brand BEVs and 20% and 40% tax reduction for Asian and European BEVs, respectively (Sathitsuksomboon and Pornpipatkul, 2022). These initiatives triple the BEV sales in 2023 (Chutima and Tiewmapobsuk, 2021). The EV 3.5 Policy not only supports customers, but also encourages local manufacturers for in-house production, i.e., the manufacturers receive up to 8% deduction of excise tax for the EVB production

(EVAT, 2023; PRD, 2023). This boosts domestic production, encourages technology transfer, and enhances local expertise in BEV and EVB production.

2.3 Key factors influencing the growth of the Thai BEV market

Several collaborations between the government, private sector, and academic have been made to advance the BEV market. Many challenges, such as charging infrastructure development, battery technology, customer awareness, and investment cost, are pinpointed in the literature (Adamo and Rosa, 2019). For example, Thananusak et al. (2017) examined Thai BEV's customer behaviors and preferences and concluded key factors influencing the BEV market, namely pricing, range limitation, charging infrastructure, and perceived environmental benefits. Brinkmann and Bhatiasevi (2021) studied the BEV preferences in Europe and concluded that customer education, living zone, income, and BEV infrastructure positively influence BEV adoption. The BEV technologies, such as charging method, efficiency of power management, and BEV lifetime, are crucial to promote the BEV adoption (Li et al., 2017).

In Thailand, several studies are conducted to examine key factors influencing the BEV market. One of the primary drivers is the rapid advancement in BEV technology, leading to improved performance, reliability, and affordability (Forsythe et al., 2023). Technological progress has been a crucial factor in shaping customer perceptions and increasing the willingness to adopt the BEVs. The availability of various BEV models with different prices also plays a crucial role in boosting customer interest in BEVs (Li et al., 2017). Forsythe et al. (2023) commented that the technology advancements and government policies and incentives are crucial in nurturing the growth of the Thai BEV market. The policies, such as lowering import taxes, providing investment subsidies, and supporting the development of charging infrastructure, are initiated to boost the BEV adoption (Chutima and Tiewmapobsuk, 2021). In Thailand, government subsidies for BEVs were initially planned to last for approximately four years since 2020 (OTP, 2020). However, studies suggest that extending the subsidy period to ten years could significantly accelerate early BEV adoption, enabling the market to reach equilibrium more effectively by offsetting initial costs and achieving broader economic and environmental benefits (IEA, 2021). This extended duration would help ensure that the benefits derived from increased BEV adoption, such as reduced greenhouse gas emissions and fossil fuel dependency, outweigh the investment costs more rapidly (ADB, 2022). Thananusak et al. (2017) added that incentives, such as tax reduction, purchase rebates, and parking fee exemptions, also have high influence on the BEV purchasing decisions. Bjerkan et al. (2016) stated that BEV technologies, such as fast charging stations and battery capacities, influence at least 20% of BEV customers. Figenbaum (2020) stated that the BEV purchase intention is positively influenced by improved performance, available models, and affordable prices.

In this study, the Scopus database was utilized to extract key factors affecting the growth of the Thai BEV market. Keywords, including the “battery electric vehicle”, “market”, “sales”, “factor”, “adoption”, and “Thailand” are input in the database with the limitations of English journals published in the last 10 years. A list of journals was extracted and screened to conclude seven key factors influencing the BEV market that have high frequencies of appearances in the database. Details are as below.

- Loan payment: The ability to pay loan reflects the affordability of BEVs (Chen et al., 2021b). Hamza et al. (2021) mentioned that loan payment significantly impacts the BEV purchasing decisions. A proper loan payment with an appropriate payment period may raise the BEV purchase by 12.8%.
- Fast charging technology: A better fast charging technology improves charging time and attracts more BEV customers (Yang et al., 2020). Wu et al. (2019) mentioned that customers are attracted to improvements in fast charging technology, driving ranges, and available models. The advancement of fast charging technology and driving range extension reduce the waiting time and charging frequencies, thus attracting 12% more of BEV customers (Yang et al., 2020).
- Driving range: Extended driving ranges reduce the need for frequent charging, thus enhancing customer satisfaction and BEV adoption (Yang et al., 2020). With advancements in battery technology, the driving range of BEVs is expected to improve, diminishing the range anxieties and enhancing the vehicle compatibility. This could lead to 10 % more BEV sales.

- Available model: Various BEV models stimulate the market interest and attract new and existing BEV customers (Wang et al., 2023). 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 (Li et al., 2017).
- Subsidy: Government supporting policies for BEVs, such as subsidy and tax reduction, may lower the production cost, resulting in lower BEV prices and higher BEV demand (Li et al., 2020b). Li and Ren (2020) stated that subsidies make BEVs more economically viable and stimulate the BEV market. During the subsidy program, the BEV sales increased by 80% per year (EVAT, 2023).
- Tax reduction: Tax incentives play a crucial role in reducing the overall cost of BEVs, contributing to increased BEV sales (Yan, 2018). About 18% more customers may be interested in purchasing BEVs when the tax incentives are offered (Yan, 2018).
- Parking privilege: According to Lu et al. (2020), BEV parking privilege may attract BEV customers by offering convenient and allocated parking spaces. In Thailand, similar to many developing countries, consumers would prioritize convenience and are influenced by marketing strategies designed to enhance their social status (Nivornusit et al., 2024). For example, offering exclusive parking spaces for BEVs has been shown to attract customers by providing both practical benefits and a sense of prestige (Chunhavanich and Pichitlamken, 2021). This approach aligns with local culture in developing countries, where social status often plays a significant role in consumer decision-making (Kiatkawsin and Han, 2017). It is stated that 20% of customers consider reserved parking spaces as a criterion when deciding on the BEV purchasing (Lu et al., 2020).

2.4 EVB status in Thailand

The adoption of BEVs in Thailand raises the EVB demand. Currently, about 3.5 GWh of lithium-ion (Li-ion) EVBs are produced annually to serve BEV production;

see Figure 2.2 (Noudeng et al., 2022). EVAT (2023) stated that about 90% of EVBs are imported from China. To support the local EVB production, the Thai government initiates the Thai National Electric Vehicle Policy to offer $660 million subsidy to local manufacturers (EVAT, 2023). The manufacturers with the production capacities less than 8 GWh receive the subsidy of $14 per kWh, while those with the production capacities over 8 GWh receive $20 per kWh (EVAT, 2023). This policy aims to increase the local EVB production to 270,000 units in 2030 (i.e., about 46.8% increase per year, on average) (EA Report, 2022).

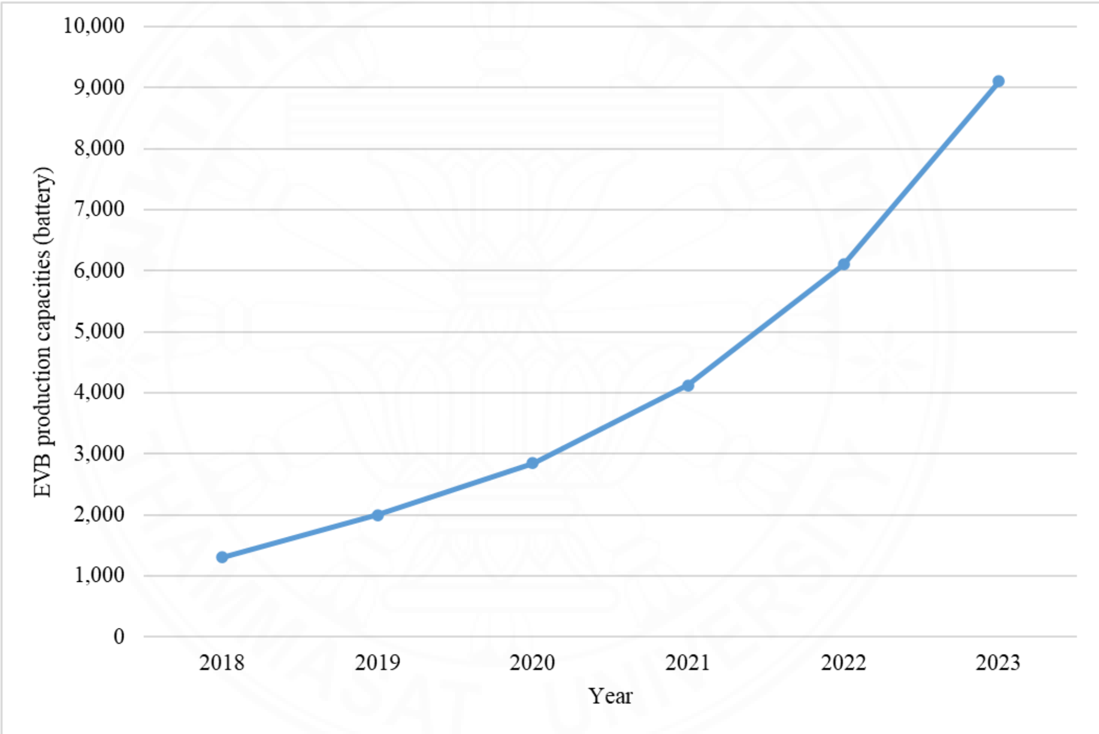


Figure 2.2 Thai EVB production capacity (EVAT, 2023)

As the number of EVBs increases, the volume of REVBs also increases. Figure 2.3 show the forecasted number of REVBs in Thailand. It is anticipated that Thailand will generate approximately 100,000 REVBs by 2030 (The Nation, 2023; Banpu Next, 2024). This prediction highlights the urgent need for the development of policies and infrastructure to facilitate the collection, recycling, and reuse of REVBs. Effective management of REVBs is essential to minimize environmental impacts and recover valuable materials. Conversely, improper management of REVBs could result in significant environmental degradation and destroy the ecosystem (Apisitniran and Tortermvasana, 2018).

2.5 Lithium-ion batteries

There are several types of EVBs in Thailand; however, the Li-ion battery is the most popular type, accounting for 96% of the BEV market (Thananusak et al., 2020). It is used in several BEV models, such as Tesla, BYD, and MG due to its advantages in energy density, efficiency, and maturity of technology (Pelegov and Pontes, 2018). It can also be classified according to three cell types: prismatic (such as MG ZS EV, BYD e6, and BMW i3 models), cylindrical (such as Tesla M3, Nissan Leaf, and Chevrolet Bolt models), and pouch cells (such as Hyundai Kona Electric, Kia Soul EV, and Jaguar I-PACE models) (Lobberding et al., 2020).

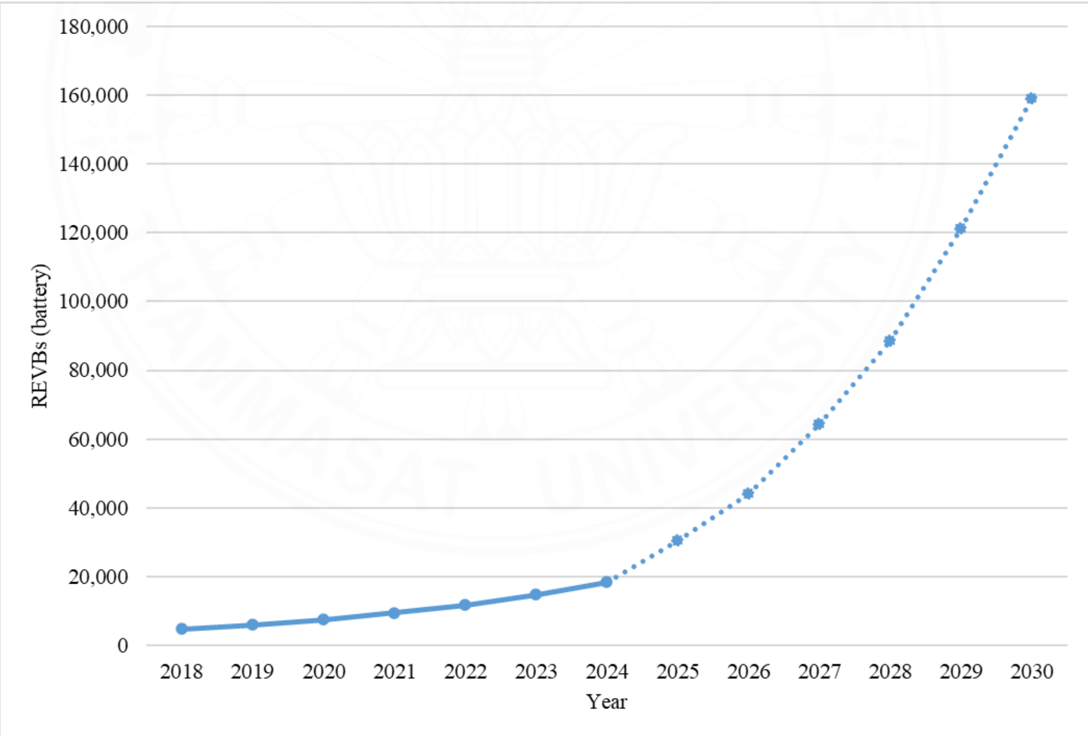
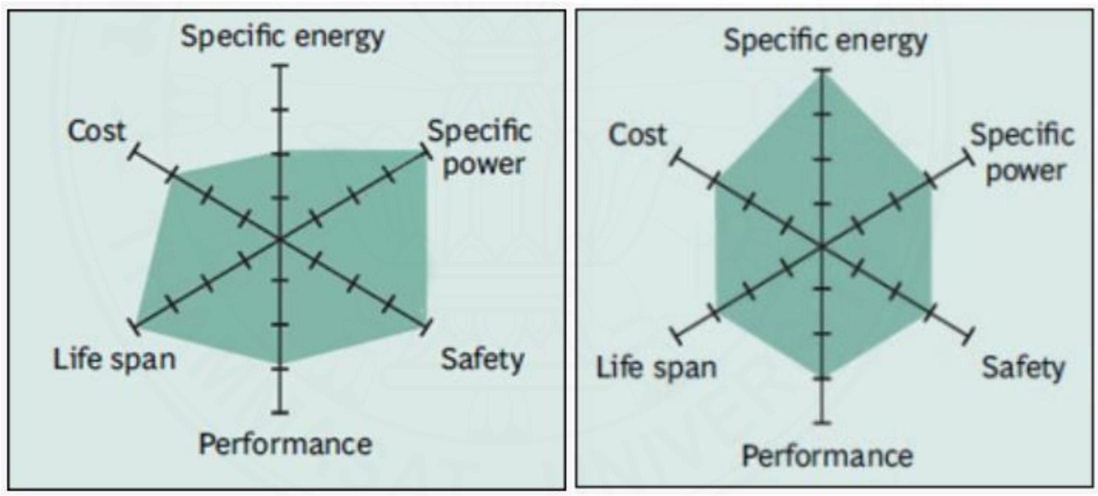


Figure 2.3 Estimated number of REVBs in Thailand (Forsythe et al., 2023)

In Thailand, the most used Li-ion batteries are classified into lithium iron phosphate (LFP) and lithium nickel manganese cobalt oxide (NMC) types (Arambarri et al., 2019). LFP batteries are tolerant to full charge conditions and have low stress when kept at high voltage for a prolonged time. This makes them superior in safety and thermal stability. Moreover, they are more cost-effective due to their long life and stability. However, they have low nominal voltage (i.e., 3.2 V/cell), resulting in low driving ranges (see Figure 2.4) (Suait et al., 2018).

Like LFP batteries, NMC batteries can be tailored to serve as energy cells for BEVs (Baczynska et al., 2018). They provide high energy density and are lightweight, thus contributing to long driving ranges and compact design. They can deliver high nominal voltage (i.e., 4.2V/cell) with more energy power than LFP batteries (Zhang et al., 2018). Nevertheless, they have poor thermal stability and are more expensive due to the limited cobalt supply (Hammond and Hazeldine, 2015). Moreover, their performance and service life are lessened in extreme weather conditions (see Figure 2.4).



LFP NMC

Figure 2.4 LFP and NMC batteries' specification

Li-ion batteries are separated into three cell types: prismatic, cylindrical, and pouch cells (Schroder et al., 2017). Prismatic batteries are in rectangular and hard shells. They have energy densities of 150 - 200 Wh per kg, life cycles of 1000 - 2000 cycles, and voltages of 3.2 - 4.2 V per cell, thus allowing optimal space utilization and enhancing the design flexibility and thermal management of BEVs (Lobberding et al., 2020; Sakti et al., 2015). Nevertheless, their compact designs make the manufacturing more complex and costly, and their robust casing adds the overall weight of the battery pack (Kerler et al., 2014). Cylindrical batteries are known for their high energy density, good mechanical stability, and ease of manufacture (Arora et al., 2016). Typically, cylindrical batteries offer energy densities comparable to prismatic batteries and exhibit excellent thermal management properties due to their uniform shape. This allows for effective heat dissipation (Butler et al., 2004). However, the cylindrical design may be challenged compared to prismatic batteries and may not be as conducive (Shen et al., 2023). Pouch cells have flat design encased in a lightweight foil pouch (Shen et al., 2023). This allows for excellent packaging efficiency and high energy density per unit volume, thus maximizing the space in the battery pack (Schroder et al., 2017). Pouch cells can conform to irregular shapes and are generally lighter than prismatic and cylindrical batteries (Schroder et al., 2017). However, their flexible structure makes them more susceptible to swelling and puncture, which can lead to safety concerns. Moreover, the flexible casing complicates thermal management and handling, thus making it less ideal for remanufacturing, repurposing, and recycling (Cha et al., 2017). Table 2.1 summarizes cell types of Li-ion batteries.

Table 2.1 Cell types of Li-ion batteries (Buchmann, 2024)

Battery type	Energy density	Life span	Voltage	EOL management
Prismatic	150-200 Wh/kg	10 years (1500 cycle-charges)	3.2-4.2 V/cell	Remanufacturing, repurposing, and recycling
Cylindrical	160-250 Wh/kg	8 years (1200 cycle-charges)	3.2-4.2 V/cell	Remanufacturing, repurposing, and recycling
Pouch	200-300 Wh/kg	6 years (1000 cycle-charges)	3.2-4.2 V/cell	Repurposing and recycling

2.6 EOL management of REVBs

The growth of BEV market in Thailand raises the demand of raw materials used in the EVB production. This makes the country a major contributor of the material consumption and electronic waste disposal in Asia (Noudeng et al., 2022). The landfill for electronic waste in Thailand nearly reaches its maximum capacity i.e., 95% of the space was occupied in 2023 (Mangmeechai, 2022). The adoption of BEVs leads to the new dynamics of Thailand's electronic waste challenges.

EVBs are critical components of BEVs; however, their production and disposal present significant environmental and economic challenges (Kunacheva et al., 2009). The extraction of raw materials, such as lithium, cobalt, and nickel, is resource intensive. Moreover, the disposal of REVBs contributes to waste and pollution, highlighting the need for sustainable management practices (Dutta et al., 2016). To properly manage the REVBs, the concept of a circular economy is introduced. It is a transformative approach to achieve sustainable development (Sahajwalla and Hossain, 2023). Unlike the traditional linear economic model of take, make, and dispose, the circular economy emphasizes keeping resources in-use as long as possible (Wang et al., 2022). It aims to extend the lifespan of EVBs, minimize electronic waste, and optimize resource utilization by reusing, repairing, refurbishing, and recycling existing materials (Rodrigo et al., 2021). It offers a framework to address the challenges, such as design for longevity, second-life application, and efficient recycling process (Hua et al., 2021). Designing EVBs with longer lifespans and easier recyclability can significantly reduce waste. Manufacturers are increasingly focusing on creating EVBs that can be easily disassembled and recycled at the end of their life. Developing and implementing efficient recycling processes to recover valuable materials from REVBs can reduce the demand for virgin materials (Fan et al., 2020).

The circular economy can enhance the sustainability of the BEV and EVB industries. It reduces the environmental footprint of battery production and disposal, conserves valuable resources, and promotes economic efficiency (Olsson et al., 2018). This approach not only aligns with the goals of sustainable development, but also supports the broader transition to a low-carbon economy. In this study, the three EOL management processes of REVBs follow the circular economy concept. Each process contributes to the sustainable management of REVBs and supports the broader goals of reducing environmental impacts and promoting resource efficiency. The three EOL management processes (i.e., remanufacturing, repurposing, and recycling) are examined in many studies. For example, Mahmood and Gutteridge (2016) commented that the remanufacturing approach is the best sustainable option for the second-life EVBs. Mohamad-Ali et al. (2017) studied various remanufacturing processes of REVBs to maximize their SOHs and concluded that freshly exposed cathode surface will enable fast ions movement, which will make the remanufactured EVBs as efficient as new EVBs. Zhang et al. (2014) evaluated different types of REVBs to maximize their energy storage performance. They concluded that nickel-cobalt-aluminum and nickel-manganese-cobalt cells are optimal types for the second life electricity grid performance. Alharbi et al. (2019) introduced the repurposing process to reduce EVB waste and conserve the original materials. Bobba et al. (2022) utilized the LCA method to examine the environmental benefits of the repurposed batteries and their adoptions in the industrial development zone in Europe. They concluded that the user behavior, battery lifetime, and battery degradation are the main factors for the adoption of repurposed batteries. Tripathy et al. (2017) developed a business model for EVB recycling to help organizations and policymakers prioritize recycling campaigns. Harper et al. (2018) commented that the EVB recycling provides valuable secondary sources of materials for future demand and implementation. Ji et al. (2021) examined current EVB recycling technologies of EVB recycling and concluded that the cathode materials can be recovered via the hydrometallurgical process, and other materials can be recovered via a direct recycling process.

2.6.1 Remanufacturing process of the REVBs

The remanufacturing process is one of the EOL management options for REVBs designed to restore and reuse EVBs. Various studies have explored the remanufacturing process across different industries. For example, Yuksek et al. (2021) evaluated the environmental impacts of remanufactured electronic products. It was concluded that the transportation sector generated the highest CO_{2eq} emissions from centralized remanufacturing operations. Kanazawa et al. (2016) optimized the remanufacturing practices for components used in the construction machinery and suggested that the production and remanufacturing plans should be optimized, and the quality of spare parts should be used to minimize total costs. Huster et al. (2023) developed a simulation model to assess the feasibility of using remanufactured EVBs as spare parts. Their findings addressed various aspects, such as economic viability, environmental impact, technological advancements, customer perception, and supply chain management, highlighting the potential for sustainable remanufacturing practices.

The remanufacturing process of REVBs in this study is in Figure 2.5. The initial step involves discharging the batteries and ensuring safe handling during the remanufacturing process. The SOHs are tested to evaluate the remaining battery capacities and performance (Casals et al., 2017). The cooling system, busbars, and cell monitor board (CMB) are disconnected, evaluated and replaced, if necessary (Kampker et al., 2020). The disassembly process proceeds with the removal of battery modules and cooling plates. These modules undergo testing to evaluate their capacities, voltages, and internal resistances (Kampker et al., 2020). Individual cells within the modules are disconnected and separated into blocks for capacity, voltage, and internal resistance testing (Long et al., 2016). The cells with SOHs of less than 80% are removed and transported to landfills (Marshall et al., 2020). To optimize the EVB's performance and lifespan, the battery cells of the remanufactured EVBs are tested to ensure that the SOHs of at least 95% (Casals et al., 2017). Electronic parts, such as circuit boards, connectors, and related components, are also checked if refurbishment and replacement are required (Casals and Garcia, 2016). Finally, the modules and parts are assembled back to achieve the remanufactured EVBs.

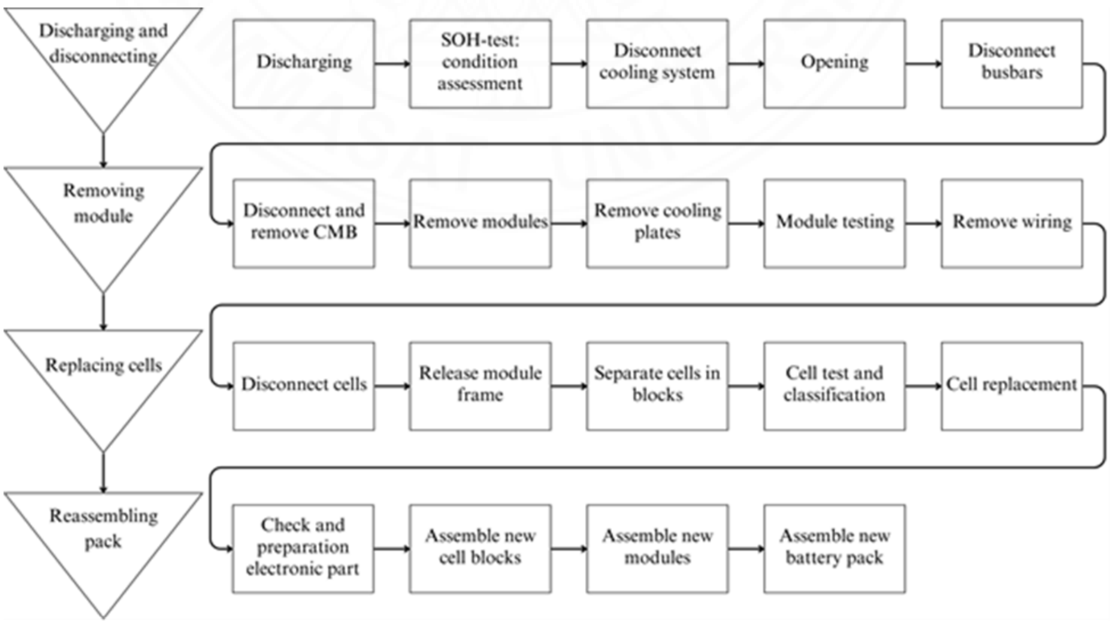


Figure 2.5 The remanufacturing process of REVBs

2.6.2 Repurposing process of the REVBs

The repurposing process for REVBs involves several steps to ensure the effectiveness and safety of the repurposed EVBs in the new applications, particularly the stationary energy storage systems (Hua et al., 2021). An initial assessment and implementation of safety measures are first conducted, where the REVBs are discharged to a safe voltage level to prevent any risks during handling (see Figure 2.6). The batteries are inspected for any visible damage before the SOH testing. The REVBs with the SOH between 60-79% are disassembled to remove the cooling system, bus bars, and CMB (Casals et al., 2017; Stewart et al., 2019). The battery modules are then separated, and individual cells are tested for their capacities, voltages, and internal resistances. Cells with suitable SOHs undergo the reconfiguration process by grouping cells with similar capacities and performance characteristics to ensure balanced and efficient operations in the new application (Kampker et al., 2020). Cells with SOH less than 60% are removed and sent for recycling or landfilling (Marshall et al., 2020). The reconfigured battery modules are integrated into a new BMS designed specifically for stationary energy storage applications and grid support services (Yang et al., 2022). This BMS ensures the optimal performance, safety, and longevity of the repurposed battery system (Richa et al., 2014). Once reconfiguration is complete, the repurposed battery modules undergo a series of rigorous tests, including capacity, cycle, and safety testing under various conditions to ensure the performance and safety standards (Zhang et al., 2020b). Several companies have successfully implemented repurposed REVBs in the stationary energy storage systems. For instance, Toyota Company used the repurposed EVBs from the Camry Hybrid model to store energy from solar panels and use in the buildings in a remote area (Toyota, 2020). Nissan Company repurposed the Nissan Leaf model batteries and used them in the factory’s automated guided vehicles at the Atago railroad crossing (Nissan, 2021).

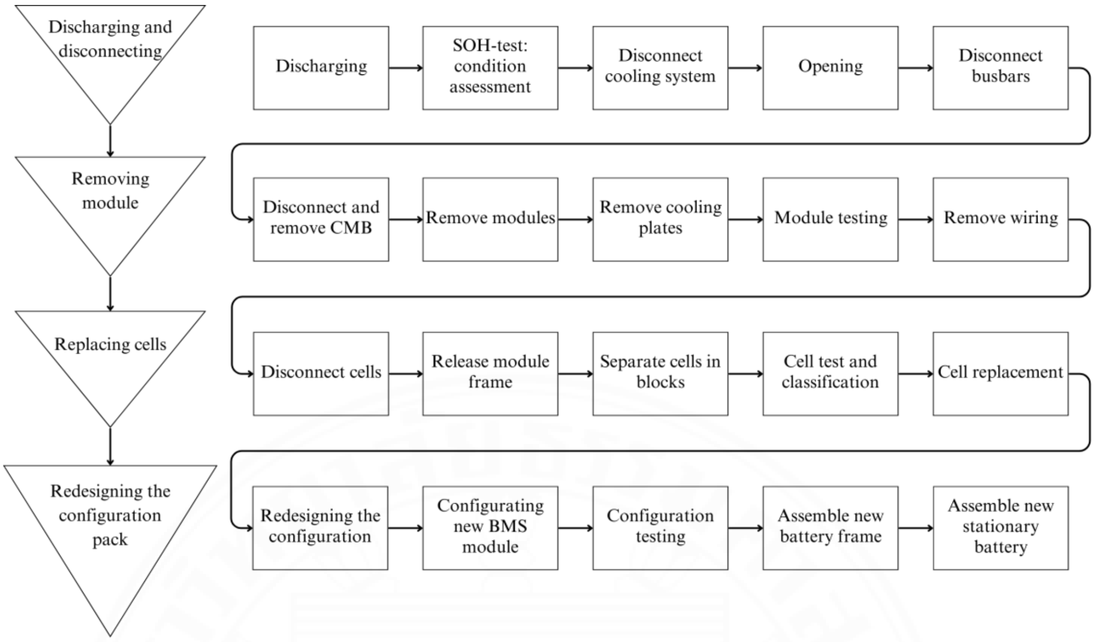


Figure 2.6 The repurposing process of REVBs

2.6.3 Recycling process of the REVBs

The recycling process of REVBs plays a crucial role in sustainable resource management by extracting valuable materials, such as lithium, cobalt, and nickel (Sato and Nakata, 2019). These materials are recovered using advanced methods, like the hydro-metallurgical and pyro-metallurgical processes (Mohanty et al., 2021). The hydro-metallurgical process involves leaching valuable metals from the battery materials using aqueous solutions and purification techniques, such as solvent extraction, ion exchange, and precipitation to separate the metals from impurities (Noudeng et al., 2022). Purified metals are recovered through the electro-winning or chemical precipitation processes (Nguyen et al., 2015). In contrast, the pyro-metallurgical process involves high-temperature treatments to smelt and separate metals from the REVBs (Cui and Zhang, 2008). The REVBs undergo pre-treatment by discharging, crushing, and smelting, where metals are separated based on their melting points and densities (Faris et al., 2017). The molten metals are refined to remove impurities and achieve high purity levels. The metals are solidified and processed into usable forms (Liu et al., 2018).

The recycling process of REVBs is in Figure 2.7. Upon arrival, the batteries undergo a series of diagnostic tests to determine their SOHs, capacity, voltage, and internal resistance (Fan et al., 2020). The batteries are then disassembled, with components being disconnected and evaluated. Components that are damaged or no longer functional are landfilled (Drallmeier et al., 2022). The battery modules are disassembled and individual cells within the modules are tested for their remaining capacities and performance. The REVBs that cannot be inspected for their SOH due to physical damage or technical error are removed from the recycling process and directed to landfilling facilities to ensure safe disposal (Kampker et al., 2020). The extraction process is performed with hydro-metallurgical and pyro-metallurgical methods to achieve valuable materials (Cui and Anderson, 2016). The recovered metals are purified and processed into raw materials used in the EVB production (Li et al., 2019).

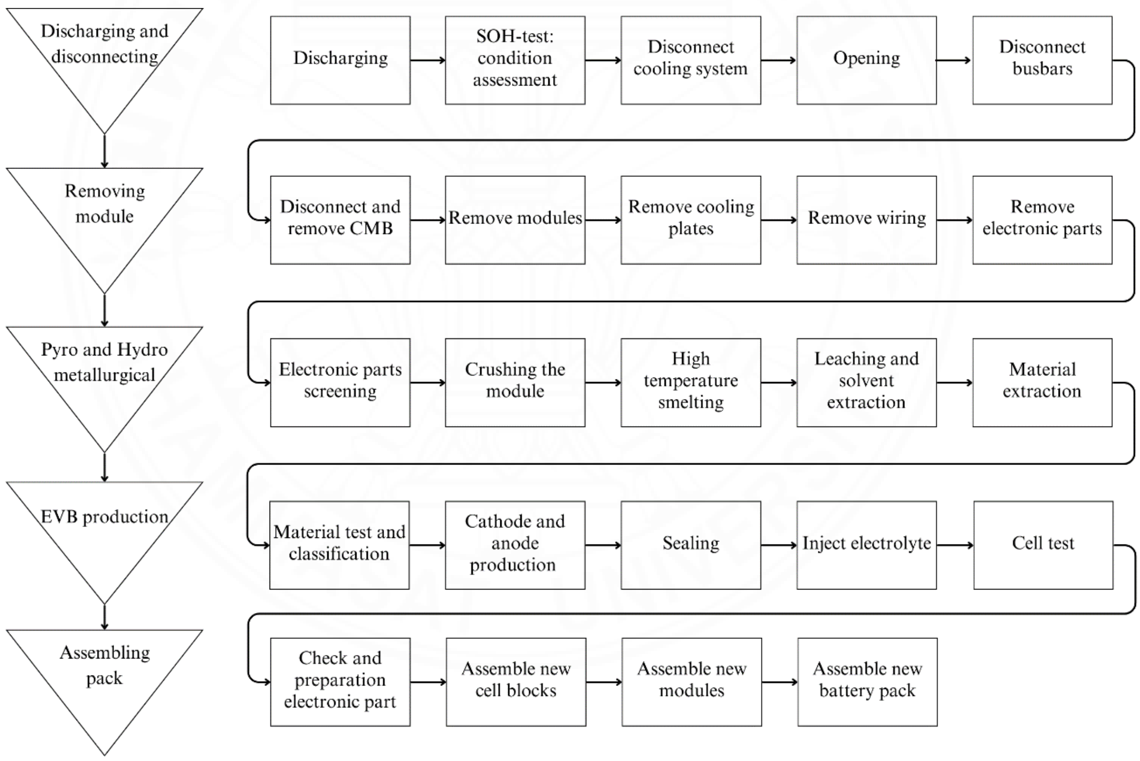


Figure 2.7 The recycling process of REVBs

Several companies attempt to recycle the REVBs to achieve sustainable management of EVBs. For example, Umicore Company utilized a closed-loop recycling process to recover and refine metals from the retired EVBs and used in the new EVB production, thus reducing the demand for virgin resources and the environmental impacts associated with the mining and extraction (Leisegang and

Treffer, 2016). This closed-loop system significantly reduces the demand for virgin resources, thereby minimizing the environmental impacts associated with mining and extraction activities (Clausen and Sörensen, 2022). American Battery Technology Company designed the battery recycling system that separates and recovers critical materials from REVBs and purifies the metal to higher quality specification than virgin mining operations (ABTC, 2024).

The environmental benefits of EVB recycling are substantial. Proper recycling processes mitigate the risks of hazardous substances, such as heavy metals and toxic electrolytes, contaminating soil and water (Li et al., 2019). This is crucial for preventing environmental degradation and protecting ecosystems. Additionally, recycling reduces the greenhouse gas emissions associated with the production of new materials, contributing to climate change mitigation efforts (Sahajwalla and Hossain, 2023). The extraction and refining processes of virgin materials are energy-intensive by recycling REVBs, the energy consumption and emissions associated with these processes are substantially decreased (Amato et al., 2019; Wang et al., 2022).

2.6.4 Landfilling process of the REVBs

REVBs that are not suitable for second-life uses are disposal in landfills. According to Sathitsuksomboon and Pornpapatkul (2018), the available landfill space for the EVB disposal in Thailand is 2566.5 m^2. This is equivalent to 245,098 batteries. Currently, 95% of the landfill space is utilized and the remaining space is expected to be filled by 2028 (Jutidamrongphan, 2018). The landfilling process of REVBs must conform to safe disposal to ensure health and safety (Tantisattayakul et al., 2018). The REVBs that are collected from recycling centers and automotive service centers undergo preparation steps before landfilling, such as draining remaining electricity and securing them for transportation and disposal. They are then transported to landfill sites and disposed of in designated areas following local regulations and environmental guidelines to prevent soil and water contamination (Shao and Li, 2019). The site may undergo closure and rehabilitation measures, such as covering the area with protective layers and implementing soil remediation strategies, to mitigate environmental risks (Lafebre et al., 1998). While landfilling is a conventional disposal method, it is considered the least environmentally preferable option due to potential hazards from battery components like heavy metals and electrolytes (Winslow et al., 2018). Promoting sustainable EOL management is crucial to minimizing environmental impacts and maximizing resource recovery from REVBs.

2.7 Environmental impacts of REVB's EOL management

Several EOL management strategies may be implemented to extend the life of EVBs. Different processes affect the environment differently (Li et al., 2020a). For instance, though the recycling process reduces the demand for the virgin materials used in the EVB production, the process consumes energy and produces CO_{2eq} emissions (Adamo and Rosa, 2019). To ensure sustainability of the EOL management process and achieve the circular economy, it is necessary to examine environmental impacts incurred in the EOL management process. In this study, the environmental impacts from raw material extraction to the EVB production, usage, EOL management (i.e., remanufacturing, repurposing, recycling, and landfilling) and second-life production are examined. The Scopus database was utilized to extract key environmental impacts that are frequently cited in EVB-related literature. Keywords, including the "electric vehicle battery", "environmental impact", "EOL management", and "life cycle assessment" are input in the database with the limitations of English journals published in the last 10 years. The extracted journals are extracted and screened to achieve key impacts utilized in this study.

- CO_{2eq} emission: The production and disposal of EVBs contribute significantly to CO_{2eq} emission, impacting global warming and climate change. The production and disposal of EVBs contribute significantly to CO_{2eq} emission, impacting global warming and climate change. The EVBs have a significant carbon footprint associated with their production and disposal (Egede et al., 2015). The EOL management through the remanufacturing, repurposing, and recycling processes can reduce the emissions and landfill consumption (Qiao et al., 2019). Niikuni et al. (2015) stated that the EVB production generates 3.7 tonnes of CO_{2eq} emissions. Using the recovered materials in EVB production helps reduce CO_{2eq} emissions by 40% (Sato and Nakata, 2019).

- Human toxicity: Human toxicity is a major concern in the lifecycle of EVBs due to the presence of hazardous chemicals and heavy metals (Shen et al., 2015). Improper handling and disposal of these batteries can lead to significant health risks for workers and surrounding communities (Noudeng et al., 2022). EVBs contain chemicals and metals that may be hazardous if not managed properly. The potential health risks for workers working in the battery recycling facilities should be examined to guide a safe recycling process. Wang (2021) mentioned that EVB recycling could lead to a reduction of 377.8 kg of human carcinogenic toxin from the recycled materials in the EVB production.
- Terrestrial acidification: The EVB recycling and disposal can lead to soil acidification and contamination, affecting ecosystems and agricultural productivity (Wang, 2022). The improper disposal of EVBs in a landfill could lower the soil pH by 0.5 to 1.5 units over 5-10 years (Noudeng et al., 2022). Xu et al. (2017) measured the concentration of aluminum in soils near the EVB recycling facilities and found that aluminum concentrations increased by half compared to control sites without EVB exposure. High aluminum levels can inhibit root growth and reduce the uptake of essential nutrients, leading to stunted plant growth and reduced crop yields. Effective waste management systems, such as safe disposal methods and containment measures, can prevent soil degradation and protect the ecosystem (Silva, 2012).
- Particulate matter (PM) formation: PM consists of tiny particles or droplets in the air that can be harmful to human health and the environment. These emissions arise primarily from the mechanical processing of EVBs and the combustion of fossil fuels. The recycling process can generate PM emissions, contributing to air pollution (Timmers and Achten, 2016). Implementing advanced recycling technologies can reduce PM emissions by up to 30% (Adamo and Rosa, 2019). These technologies include improved filtration systems and dust suppression techniques that capture PM before it is released into the atmosphere. Facilities using the state-of-

the-art air filtration systems can lower their PM emissions from 50 to 35 mg/m^3. Kelektsoglou et al. (2018) noted that repurposed EVBs could lower PM emissions by 4%. This reduction is due to the extended life of EVBs, thus delaying the need for recycling process that generates PM formation.

- Photochemical oxidant formation: Photochemical oxidants, such as ground-level ozone, are formed by reactions between sunlight and pollutants like nitrogen oxides (NO_x) and volatile organic compounds (VOCs). The EOL management of EVBs, specifically the recycling and repurposing, can contribute to the emissions of these pollutants. Implementing effective emission control technologies and using cleaner energy sources can help reduce photochemical oxidant formation (Kelektsoglou et al., 2018).
- Water depletion: The EVB production and recycling processes consume large amounts of water. Efficient EOL management can lower the water consumption by recycling and reusing water in the plants. Water used in cooling and processing can be reclaimed and treated to reduce overall consumption. According to Bortolini et al. (2018), implementing water-efficient technologies in recycling facilities can reduce water usage by up to 30%.
- Metal depletion: The materials used in the EVB production, such as lithium, cobalt, and nickel, are non-renewable and limited (Saleem et al., 2023). By using recycled metals, the demand for virgin materials decreases. Hossain (2023) added that effective recycling can cut the demand for new cobalt by up to 50%. The recycling process can recover up to 95% of the metals used in EVB production (Leon and Miller, 2020).
- Ozone depletion: The ozone depletion mostly arises from the chemicals leakage and materials used in metal extraction, EVB production, and recycling processes (Hantanasirisakul and Sawangphruk, 2023). The recovered materials from its EOL management can reduce the mining process and ozone depletion (Wang, 2022). Certain chemicals used in the manufacturing and recycling of EV batteries, such as halons and

chlorofluorocarbons (CFCs), can contribute to ozone depletion if released into the atmosphere (Arambarri et al., 2019).

- Fossil depletion: The production and recycling of EVBs consume significant amounts of fossil fuels, contributing to its depletion. The use phase of BEVs reduces fossil fuel consumption and greenhouse gas emissions. Nevertheless, the EVBs may consume fossil fuel during the EOL management processes (Adamo and Rosa, 2019). The EVB remanufacturing process can lower fossil fuels used in material extraction process by 20% (Arambarri et al., 2019). Messagie et al. (2010) suggest that using renewable energy sources in the recycling facilities can reduce fossil fuel consumption by 30%.

2.8 Benefits and costs of EOL management of REVBs

The EOL management of REVBs through remanufacturing, repurposing, and recycling extends the life of EVBs, reduces the environmental inspects, and enhances the circular economy of the BEV industry (Hua et al., 2021). However, to ensure the economic feasibility of the EOL management processes, it is crucial to examine the benefits and costs of the REVB's EOL management project.

Benefits of EOL management include the following.

- Remanufactured EVBs achieved from the remanufacturing process can be sold at a price of $11,373 per unit (Anthony and Cheung, 2017).
- Energy storage batteries achieved from the repurposing process can be sold at a price of $10,500 per unit (Foster et al., 2014)
- Recovered materials achieved from the recycling process can be used in the new EVB production that can be sold at a price of $13,380 per unit (BYD Report, 2024).

Costs of EOL management are as follows:

- The initial investment (EA Report, 2022):
  - The remanufacturing plant and storage costs $13 million.

  - The repurposing plant and storage costs $13 million.
  - The recycling plant and storage costs $19 million.
- The expansion cost (Chua et al., 2015):
  - The remanufacturing plant expansion costs $1.33 million per expansion.
  - The repurposing plant expansion costs $1.54 million per expansion.
  - The recycling plant expansion costs $2.06 million per expansion.
  - The storage expansion costs $0.59 million per expansion.
- The buyback cost (Arambarri et al., 2019):
  - The buyback cost for the remanufacturing process is $6,690 per battery.
  - The buyback cost for the repurposing process is $4,014 per battery.
  - The buyback cost for the recycling process is $2,007 per battery.
- The electricity cost (EA Report, 2022):
  - The electricity cost for the remanufacturing process is $72 per battery.
  - The electricity cost for the repurposing process is $161 per battery.
  - The electricity cost for the recycling process is $1,302 per battery.
- The material cost (Dura et al., 2013; Wood et al., 2015; Liu et al., 2023):
  - The material cost for the remanufacturing process is $2,085 per battery.
  - The material cost for the repurposing process is $4,170 per battery.
  - The material cost for the recycling process is $208 per battery.
- The labor cost is about $8,856 per year for the EOL management (Silalertruksa et al., 2012).
- The storage cost is about $161 per battery (Guerra and Daziano, 2020).
- The material handling cost (EA Report, 2022):
  - The material handling cost is $0.1 per battery from the drop-off to the storage.
  - The material handling cost is $0.15 per battery from the storage to the facility.
- The overhead cost is about 10% of the total production cost (Guerra and Daziano, 2020).
- The landfill cost (Siriruttanaruk and Sumrit, 2020):
  - The local landfill charge is $62 per ton of EVBs.

- The landfill charge in neighboring countries is $248 per ton of EVBs.

Apart from the above costs, the environmental cost plays a crucial role in EOL management. Carbon credit trading is an essential aspect, and the carbon credits achieved from the EOL management processes can be traded to offset the costs (Diabat et al., 2013). This encourages the adoption of greener technologies and practices. Costs associated with mitigating ozone depletion are also crucial (Mundy et al., 2018). Regulatory fees for ozone-depleting substances are established in Table 2.2. These costs are integrated into the benefit and cost analysis in this study to examine the feasibility of the EOL management strategies in environmental and economic perspectives (Adamo and Rosa, 2019).

Table 2.2 Environmental cost of the environmental impacts (Bailey et al., 2017; Mundy et al., 2018; Adamo and Rosa, 2019; Kaunda, 2020)

Environmental impact	Cost ($)	Unit
CO_{2eq} emission	0.0052	kg CO_{2eq}
Human toxicity	0.0169	kg 1,4-DB_{eq}
Terrestrial acidification	1.22	kg SO_{2eq}
Particulate matter formation	0.45	kg $PM10_{eq}$
Photochemical oxidant formation	3.57	kg VOC_{eq}
Water depletion	0.58	m^3_{eq}
Metal depletion	0.25	kg Fe_{eq}
Ozone depletion	24,387	kg CFC-11_{eq}
Fossil depletion	0.26	kg oil_{eq}

2.9 Scope of study

This study focuses on the EOL management of EVBs in Thailand, with an emphasis on analyzing their economic and environmental impacts using a system dynamics model and LCA approach. The scope of this research is outlined as follows:

- Technology (Lutsey and Nicholas, 2019; Preedakhorn et al., 2023; Statista, 2024):

  - The study specifically considers lithium-ion EVBs, which are currently the dominant battery technology in Thailand.
  - Advanced technologies, such as solid-state batteries and other emerging innovations, are excluded from this analysis as they currently have no practical applications and data in Thailand.
  - The data of EVBs are specifically retrieved from major BEV brands in Thailand, such as BYD (40% of total sales in 2023), Neta (17% of total sales in 2023), MG (16% of total sales in 2023), Tesla (11% of total sales in 2023), and GWM (9% of total sales in 2023).
- Functional unit (Pillot, 2019; Hao et al., 2017; EVAT, 2023):
  - The EVB capacity is 75 kWh per battery.
  - The EVB weight is 412 kg per battery.
  - The EVB valuable metals are nickel (15% of total weight), cobalt (5% of total weight), manganese (7% of total weight), lithium (7% of total weight), aluminum (15% of total weight), and steel (10% of total weight)
- Geographic (IEA, 2022; ETN, 2020):
  - The emission levels of this study in Thailand may be higher due to different country's energy mix, industrial practices, and regulations compared to developed country.
  - For developed countries, different sources of energy or materials may affect the environmental impact value of the same EOL management process. For example, cleaner energy and more efficient recycling technologies can result in lower emissions compared to countries with higher reliance on fossil fuels. Additionally, the local availability of materials for repurposing or remanufacturing can influence the environmental outcomes of these processes.
- Order of EOL management flow (Bobba et al., 2018):
  - The simulation model will sequentially prioritize utilizing the capacity of remanufacturing for REVBs, followed by repurposing, recycling, and landfilling, respectively.

- Currency (BOT, 2024):
    - All currency in this study uses US. Dollar as the base currency with exchange rate from Thai Baht at 35 Baht per US. Dollar.
- BEV-related national goals in Thailand (BOI, 2021; MHM, 2023):
    - In 2030, 30% of total vehicle production will be BEVs, emphasizing developing the local BEV supply chain including battery manufacturing.
    - In 2050, Thailand aims to achieve carbon neutrality in automotive sector.
    - In 2065, Thailand aims to achieve net-zero greenhouse gas emissions in automotive sector.
- Energy-related goals in Thailand (LSE, 2024; Challacoop and Cheuchart, 2022):
    - In 2037, Alternative Energy Development Plan (AEDP) aims for solar power to constitute 30% of the energy mix.
    - In 2040, Thailand aims to increase the share of renewable energy in electricity generation to 50%.

CHAPTER 3
RESEARCH METHODOLOGY

3.1 General overview

This chapter presents the life cycle assessment (LCA) approach used to examine the environmental impacts of the EOL management of REVBs. The complex relationships of benefits and costs of the EOL management strategies are explained using the causal loop diagrams. The feasibility of the EOL management strategies was examined using the system dynamics (SD) modeling approach.

3.2 LCA approach

3.2.1 LCA in the automotive industry

The LCA approach is a systematic methodology used to evaluate the environmental impacts associated with all stages of a product's life, i.e., from raw material extraction to production, usage, and disposal (Rebitzer et al., 2004). It provides a comprehensive view of the environmental aspects of a product system (Curran, 2000). Using the LCA method to assess the environmental impacts offers several advantages. It provides a comprehensive environmental impact assessment, detailing the effects from production to disposal and identifying stages that contribute most to the environmental degradation, thereby enabling targeted improvements (Silva and Amaral, 2009). It also highlights opportunities to enhance the environmental performance through improved recycling processes and the uses of less harmful materials (Janssen and Janssen, 2016). It supports policymakers and stakeholders to trade-off different EOL management strategies and develop regulations and incentives for sustainable practices (Tintelecan et al., 2020). Implementing LCA-driven strategies can lead to environmental benefits through more efficient resource usage and waste management and reduce the overall environmental footprint of REVBs.

The LCA method is used in various industries. For example, Chen et al. (2021a) developed a cradle-to-gate model to compare the environmental impacts of a baseline concrete building and a functionally equivalent timber building that uses crosslaminated timber as the primary material. The results reveal that timber has a lower overall environmental impact than concrete, due to low GHG emissions and energy consumption during production. Pittau et al. (2019) compared the environmental impacts of organic and conventional crop systems using the LCA method and found that organic farming reduces environmental impacts through less use of pesticide and good soil quality. Kalliala and Nousiainen (1999) explored the environmental impacts associated with fabric production (i.e., cotton and synthetic fiber) for hotel textile services. The results show that cotton has a higher environmental impact due to significant water and pesticide use during cultivation. In contrast, synthetic fiber has a lower water footprint but higher energy consumption and GHG emissions during production. Recycling synthetic fiber significantly reduces the environmental impact, making it a sustainable option when managed properly.

The LCA method is widely applied to evaluate environmental impacts in the automotive industry. For example, Hawkins et al. (2013) revealed that internal combustion engines (ICEs) vehicles contribute significantly to GHG emissions, terrestrial acidification, and fossil fuel depletion, especially during their use phase and EOL stages. This study highlights the environmental impacts posed by ICEs, with over 80% of their lifetime emissions occurring during the operational phase. On the other hand, Nordelof et al. (2014) found that BEVs produce approximately 25% fewer GHG emissions over their entire life cycle, despite higher impacts during the production phase due to battery manufacturing. Similarly, Dunn et al. (2015) emphasized that while BEVs involve higher resource demands for battery production, their environmental performance during the use phase significantly outweighs these initial impacts, leading to a net benefit over ICEs. The studies consistently show that BEVs offer environmental advantages over ICEs. For example, Ellingsen et al. (2016) concluded that BEVs may further reduce GHG emissions by about 35% by transition to renewable energy for the energy mix used for electricity generation. Moreover, BEVs generate lower levels of air pollutants such as particulate matter and nitrogen oxides, particularly in regions with cleaner energy grids (Holland et al., 2016).

In addition to automotive related studies, the LCA method has been extensively utilized within the BEV industry to assess specific processes and materials. This includes analyzing the environmental impacts of battery production and second-life applications. For instance, Tintelecan et al. (2020) explored the environmental impacts of BEV manufacturing and operation. The results show that material extraction and processing contribute most to the environmental impacts, particularly CO_2 emissions and human toxicity. Egede et al. (2015) studied the influences of energy mixes on the environmental impacts of BEVs using a case study in Europe. It was found that Brazil, which utilizes the hydropower energy, has the lowest environmental impacts compared with Germany and Spain. The results also pinpoint that the environmental impacts of BEVs are influenced by energy mixes, manufacturing processes, and EOL management. Messagie et al. (2010) assessed the environmental impacts of BEVs in Belgium considering the well-to-wheel (WTW) and cradle-to-grave (CTG) emissions. Hawkins et al. (2013) conducted an LCA of EVs and conventional vehicles and revealed that EVs have lower CO_{2eq} emissions over their entire lifecycle but higher impacts during the production phase, especially in battery manufacturing. The results emphasize the significance of electricity sources used for charging EVs, as cleaner energy sources substantially reduce the overall environmental impacts. Peters et al. (2017) examined the environmental impacts of li-ion batteries used in EVs and concluded that battery production is a significant contributor to the overall environmental impact, particularly resource depletion and CO_{2eq} emissions. Nordelof et al. (2014) analyzed the life cycle impacts of the plug-in hybrid EVs (PHEVs) and conventional vehicles. It was found that PHEVs offer substantial reductions in CO_{2eq} emissions and energy consumption during the use phase. However, the production phase, especially the battery manufacturing, poses significant environmental challenges in terms of resource depletion.

3.2.2 LCA analysis

The LCA method is utilized in this study to investigate the environmental impacts of the EOL management of REVBs, including remanufacturing, repurposing, recycling, and landfilling processes. A scenario-based LCA is conducted following the ISO 14040 and 14044 standards to evaluate the environmental impacts of REVBs (Adamo and Rosa, 2019). The approach comprises two cycles: the equipment and WTW cycles (Adamo and Rosa, 2019). The equipment cycle encompasses processes related to EVB manufacturing, including raw material extraction, manufacturing, and

EOL management processes (Singh, 1999). The WTW cycle encompasses the energy for EVB propulsion, covering processes from material extraction to energy conversion, distribution, and storage (Wirasingha et al., 2012).

To conduct the LCA analysis, three key pieces of information are considered: the system boundary, scenario, and functional unit (Messagie et al., 2014). The system boundary specifies the stages of the battery's life cycle considered in this study, including raw material extraction, EVB production, EOL management, and final disposal (Notter et al., 2010). There are four scenarios in this study: remanufacturing, repurposing, recycling, and landfilling. Figure 3.1 shows the system boundaries and scenarios of this study. The reference scenario represents the current EOL management of REVBs, i.e., landfilling (Pagell et al., 2007). In the remanufacturing scenario, the EOL stage is assessed with the remanufacturing process of the REVBs with the SOHs of at least 80% to achieve remanufactured EVBs used in new BEVs (Hua et al., 2021). The repurposing scenario focuses on the repurposing process of the REVBs with the SOHs between 60-79%, and the use of repurposed EVBs in the stationary storage systems. The recycling scenario examines the extraction process of the REVBs with the SOHs less than 60% to achieve valuable materials used in the new EVB production.

Functional units define units used for comparison across different scenarios or products (Sato and Nakata, 2019). In this study, the functional units, such as battery capacity (i.e., kWh), energy density (i.e., Wh per kg), and EVB weight (i.e., kg), are considered. The EVB capacity of 75 kWh that lasts for 160,000 km over a 10-year lifetime represents the average EVB capacity in Thailand, accounting for 80% of the total EVBs (Thananusak et al., 2020). The EVB production and EOL management are assumed to take place in Thailand. In the remanufacturing scenario, the EVB cells are remanufactured and used in BEVs for another 10 years (Kerdlap and Gheewala, 2016). In the repurposing scenario, the REVBs are reconfigured and used in stationary energy storage with the capacity of 75 kWh (Maharajan et al., 2019). In the recycling scenario, the recovered materials are extracted and used in the new EVB production with the capacity of 75 kWh and 10-year lifespan (Casals et al., 2017).

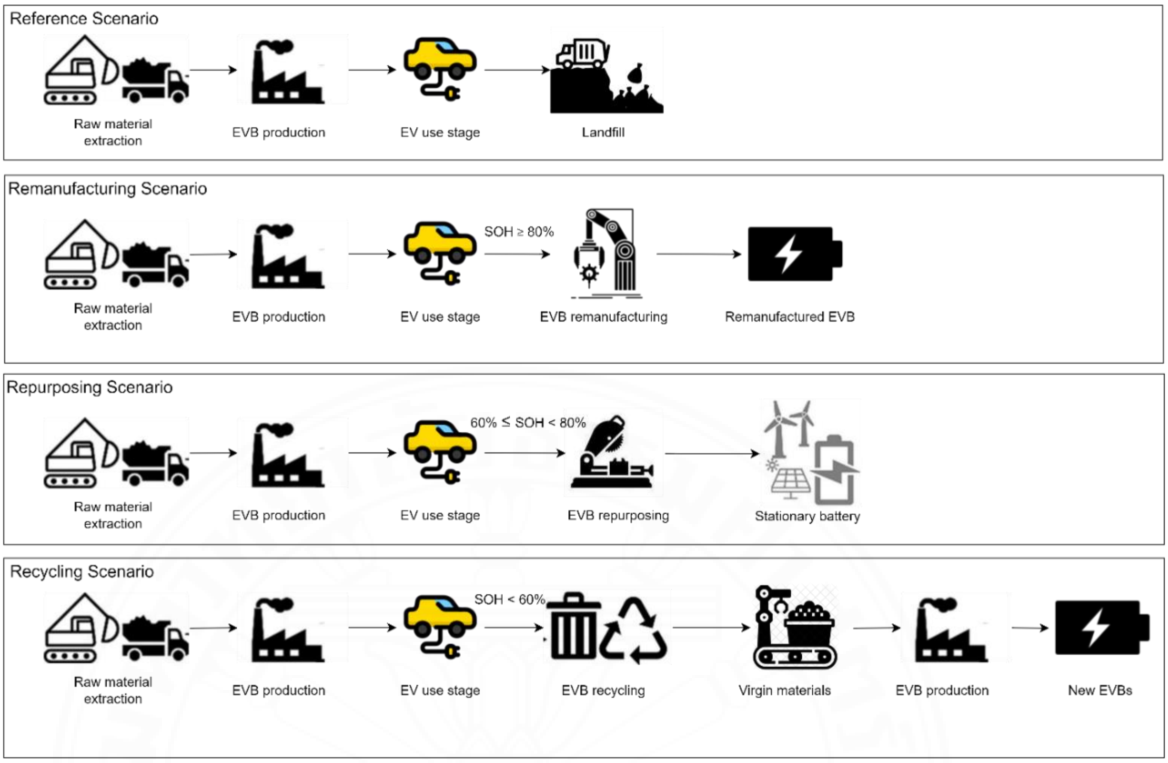


Figure 3.1 System boundaries and scenarios in this study

Various software programs are available for LCA analysis, such as SimaPro, GaBi, and EcoInvent (Sphera 2024; SimaPro, 2024). Nevertheless, SimaPro is a widely used platform as it offers comprehensive information on a wide range of materials and processes and supports various impact assessment methods, such as resource depletion, human toxicity, and emissions (Herrmann and Moltesen, 2015). Various studies have utilized the SimaPro program to evaluate the environmental impacts of EVBs. For instance, Koroma et al. (2022) used SimaPro to analyze the life cycle of EVBs across three scenarios: landfilling, refurbishing, and recycling. Zackrisson (2021) utilized SimaPro to examine the life cycle of EVBs, focusing on the toxicity impacts associated with chemical risks in battery disposal. In this study, the LCA analysis was performed using SimaPro software version 8.0. The users can input the inventory data into the program and analyze the impacts from the data collected, see Figure 3.2 (Iswara et al., 2020).

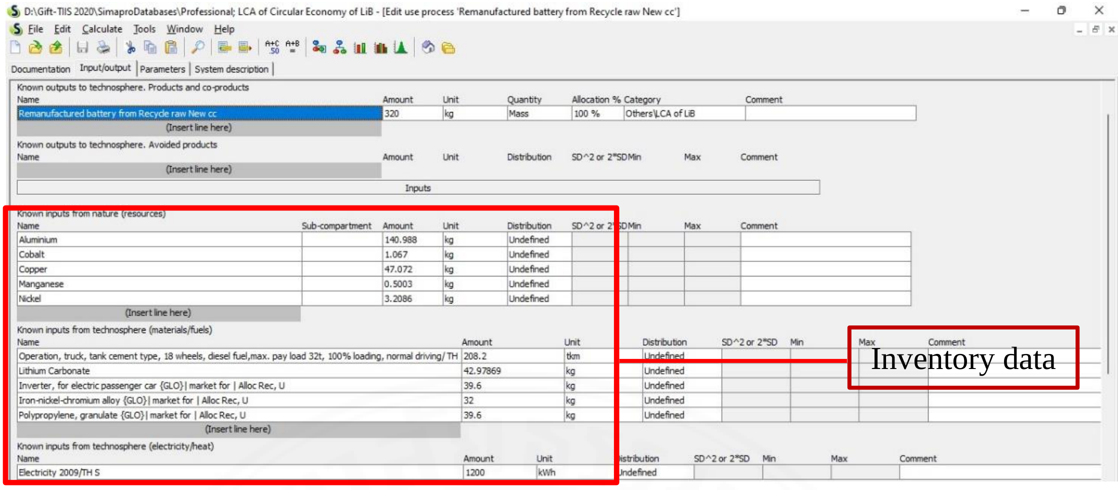


Figure 3.2 Interface of Sima Pro program

The LCA analysis involves three phases: 1) goal and scope definition, 2) inventory analysis, and 3) impact assessment (Pell et al., 2019). Goal and scope definition involves defining the purpose of the study, system boundaries, functional units (i.e., the measure of the function of the studied system), and specific environmental impacts to be assessed (Rebitzer and Buxmann, 2005). For this study, the goal is to assess the environmental impacts of different EOL management strategies for REVBs in Thailand. Inventory analysis involves compiling an inventory of relevant energy and material inputs and environmental impacts associated with each stage of the product's life cycle (Kofoworola and Gheewala, 2009). Data collection is a critical component of this phase and includes inputs, such as raw materials, energy consumption, and emissions to air, water, and soil (Zhang et al., 2020a). The inventory data was then analyzed in the impact assessment phase to assess the potential environmental impacts (Rethmeyer, 1993). It includes categorizing and quantifying emissions and resources used, and translating them into impacts on human health, ecosystems, and resource availability (Crenna et al., 2019). Common impact categories in LCA studies include CO_{2eq} emission, human toxicity, terrestrial acidification, PM formation, photochemical oxidant formation, water depletion, metal depletion, ozone depletion, fossil depletion.

To comprehensively evaluate and compare the environmental impacts of different EOL management scenarios, it is essential to normalize the impact scores. Normalization is a step in the impact assessment phase where the quantified impacts are compared against their reference values (i.e., the average global impacts per person per year). It converts impacts in different units into unitless scores, so that impacts can be calculated, and strategies can be compared for decision making. It is noted that a positive normalized score indicates a harmful impact to the environment, while negative normalized score saves the environment (Bulle et al., 2019). Marson et al. (2023) calculated the normalized score to packaging materials over their life cycle. The results reveal that plastic is the most environmentally friendly option compared with aluminum and glass packaging, despite its toxicity and acidification. Mahdavi et al. (2008) commented that organic farming has a lower normalized score than conventional farming as it does not use synthetic fertilizers and pesticides. Meier et al. (2015) evaluated the environmental impacts of different municipal solid waste management scenarios, and the normalized score shows that recycling is the best option compared with incineration and landfilling.

3.3 SD modelling approach

3.3.1 SD modelling in the automotive industry

SD modeling is an approach for modelling comprehensive systems utilizing feedback loops and interrelationships between key variables (Shobeirinejad et al., 2016). It shows the interrelationships of the system, making it useful for users to make accurate decisions (Shobeirinejad et al., 2016). By constructing a conceptual model that maps out the key variables and their interactions, SD modeling allows researchers to simulate how changes in one part of the system can affect other parts over (Darabi and Hosseinichimeh, 2020). This holistic view is crucial for analyzing systems, where multiple processes interact in non-linear ways.

Utilizing the SD modeling approach to examine the feasibility of the EOL management of REVBs in this study offers several advantages. It allows for a comprehensive analysis of the entire lifecycle of EVBs, including production, usage, and disposal stages. It helps identify key factors influencing the environmental and economic impacts of different EOL management strategies and provides a dynamic framework to evaluate complex relationships, such as market demand, policies, and technological advancements, thus enabling stakeholders to make suitable decisions.

SD modeling is utilized in various industries. For example, Schuh et al. (2015) applied SD modeling to optimize inventory levels, reduce lead times, improve production efficiency, and reduce the overall costs. Sanchez and Savachkin (2011) used SD modeling to address the spread of infectious diseases and revealed that efficient resource allocation can control disease outbreaks and improve public health outcomes. Ford (2008) explored the dynamics of energy consumption and production and concluded that the adoption of renewable energy can enhance energy sustainability. Abdalla and Qarmout (2023) applied SD modeling to simulate the adoption of solar power. It was found that strategic investments and policy incentives significantly accelerate the transition to renewable energy sources and reduce fossil fuel dependency.

The SD modelling approach is applied in automotive-related studies. For instance, Lindow et al. (2022) utilized an SD model to simulate the adoption rates of new automotive technologies in Europe. They concluded that the adoption rate depends on increased availability of telematics interfaces and vehicle data accessibility. Chinda and Chayutthanabun (2019) examined long-term trends of lightweight hybrid EVs in Thailand and concluded that the government supporting policies in tax reduction and subsidies are crucial to attract EV customers. Chinda (2022) utilized an SD model to examine long-term trend of EV sales in Thailand. The results reveal that implementing strategies and campaigns related to the five key factors (environment, economy, charging infrastructure, government support, and battery maintenance) could potentially increase EV sales in Thailand by almost ten times in the next 20 years. Jasinski et al. (2018) developed an innovative decision-making model for a sustainable automotive industry in the UK. They concluded that power consumption during mining has a major impact for sustainable development. Thirupathi et al. (2021) identified factors influencing resource consumption in the Indian automotive sector and the impacts of sustainable initiatives. It was concluded that improved machine efficiency and use of renewable energy reduce the carbon footprint in the system.

3.3.2 SD model components

The SD model of EOL management was developed using Structural Thinking Experimental Learning with Animation (STELLA) software (iThink version 9.1.3).

The model consists of four key components: stocks, flows, converters, and connectors (see Figure 3.3) (Subhani et al., 2018).

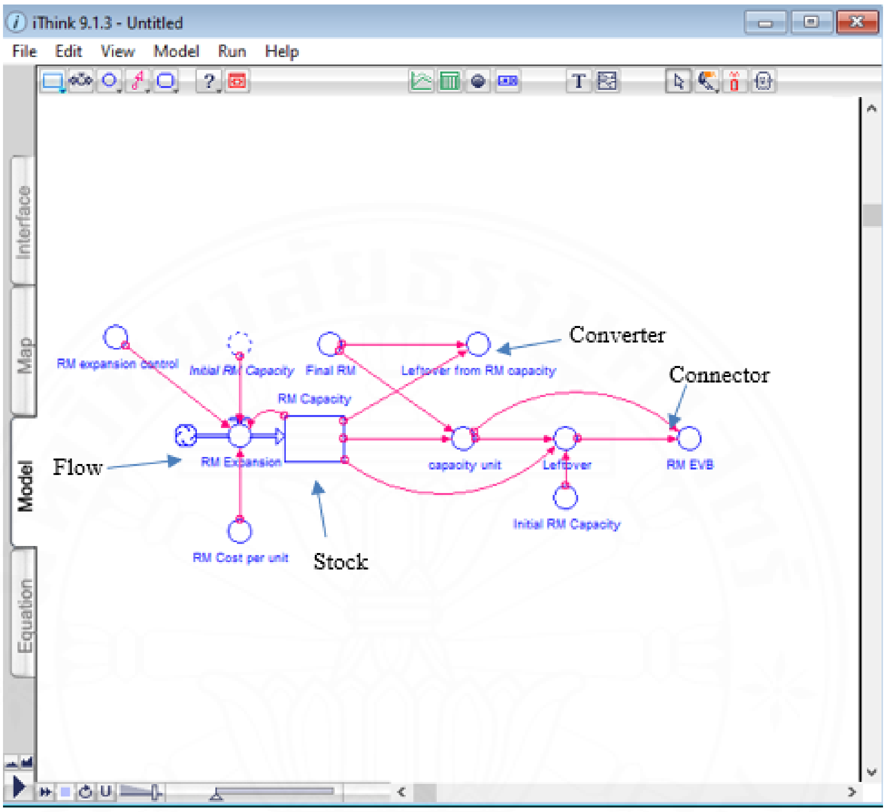


Figure 3.3 Interface of Ithink program

Stocks represent the accumulation of quantities or resources within the system, while flows represent inflow and outflow amounts of different stocks (Cui et al., 2021). The converters include variables or numerical quantities, such as BEV prices, remanufacturing capacities, and BEV demand increasing rates (Cui et al., 2021). Converters are connected through connectors in the SD model (Xiang et al., 2017). In Figure 3.3, the stock of "RM capacity" is increased through the "RM expansion" inflow. The increase of the inflow is from several converters, such as "Initial RM capacity", "RM cost per unit", and "RM expansion control" that are connected using the connectors.

3.3.3 Causal loop diagram

To understand the complex relationships of variables in the SD model, causal loop diagrams (CLDs) are developed in this study. It explains the relationships using causal links and causal loops (Mohamad-Ali et al., 2017). Causal links between two factors can be positive or negative, indicating the direction and nature of their influence. A positive causal link from factor A to factor B suggests that when factor A increases, factor B also increases, and vice versa (Xu et al., 2023). For example, an increase in number of BEVs leads to an increase in number of REVBs, representing a positive causal link, see Figure 3.4. Conversely, a negative causal link indicates an inverse relationship between the two factors. Low loan payment increases the purchasing capacity and number of BEVs (SCB, 2023).

CLDs can be either reinforcing or balancing (Chritamara et al., 2002). Reinforcing loops generate exponential growth or decline (Gu et al., 2018). For example, low loan payment increases the BEV adoption; this results in more REVBs (representing positive causal links). The increased REVBs dictate the expansion of remanufacturing capacity, representing a positive causal link (see Figure 3.4). As production capacity expands, the quantity of remanufactured EVBs increases, leading to economies of scale that reduce remanufactured EVB and BEV costs, and in turn, lower BEV prices (representing a negative causal link between the number of REVBs and BEV price) (Lee et al., 2021). Low BEV prices raise the affordability through lower loan payment and attract more BEV customers (SCB, 2023). These close a reinforcing loop between the loan payment, BEV demand, REVBs, remanufacturing capacity expansion, F

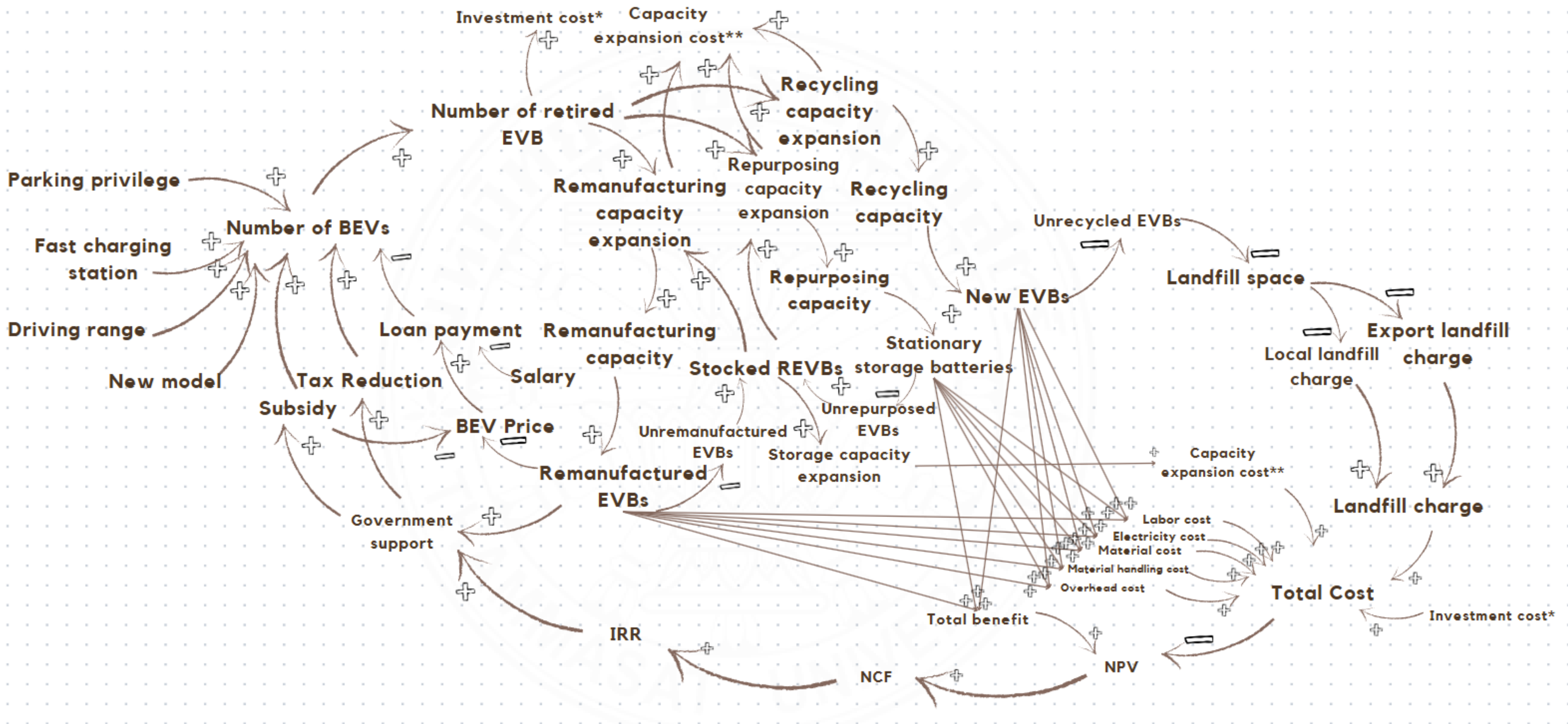


Figure 3.4 Causal loop diagram of REVB's EOL processes

On the other hand, balancing loops help maintain the system stability (Gu et al., 2018). For example, when the repurposing capacity is limited and the expansion is not possible, then, the stationary storage batteries produced from the repurposed EVBs reduce (i.e., positive causal links between the repurposing capacity, repurposing capacity expansion, and stationary storage batteries). These result in an accumulation of un-repurposed EVBs awaiting processing when the production capacity is available (i.e., a negative causal link between the stationary storage batteries and un-repurposed EVB and positive causal links between un-repurposed EVBs, stocked REVBs, and repurposing capacity expansion) (Qiao et al., 2019). A balancing loop is then achieved from the repurposing capacity, stationary storage batteries, un-repurposed EVBS, stocked REVBs, and repurposing capacity expansion (see Figure 3.4).

3.4 Measures of feasibility

The benefits and costs of the EOL management of REVBs are used to calculate the feasibility of the project using the net cash flow (NCF), net present value (NPV) and internal rate of return (IRR). The NCF refers to the difference between the cash inflows and outflows of a project over a specific period considering income (revenues) and expenses (costs, salaries, and materials) (Remer and Nieto, 1995). It reflects the actual cash position of a project and provides insights into liquidity, financial health, and ability to generate positive cash flow (Martin, 1997). The positive NCF indicates that the project generates more cash than its spending. Conversely, the negative NCF raises concerns about the project's liquidity and sustainability (Stoiljkovic, 2010). The NPV is a financial metric that calculates the present value of all future cash flows generated by a project that is discounted back to their current values. It helps determine the profitability and feasibility of an investment by considering the time value of money (Shou, 2022). A positive NPV indicates that the project is likely to be profitable. The IRR is the return that an investment is expected to generate over its lifespan (Dai et al., 2022). It is a financial metric used to evaluate the profitability and attractiveness of a project. It represents the discount rate at which the NPV of all future cash flows from a project equals zero (Chen et al., 2022b). A higher IRR indicates a more attractive investment opportunity, as it implies a higher rate of return on the initial investment. It provides a single percentage value that summarizes the expected return of a project, making it easy to compare and rank the projects.

Several studies utilize the NCF, NPC, and IRR values to make economic-related decisions. For example, Alawneh (2018) studied the impacts of NCFs on investors' decisions in the Amman Stock Exchange. The results showed that a positive NCF has a positive effect on investors' purchasing decisions. Ramezani et al. (2013) explored the relationships between NCFs and firm performance and concluded that companies with strong cash flow management tend to perform better in terms of profitability and growth. Yadav et al. (2020) used NPV to evaluate the viability of renewable energy projects and found that a positive NPV significantly influences the investment decisions in the energy sector. Sharma et al. (2017) analyzed the use of NPV in infrastructure projects and demonstrated that projects with positive NPVs attract more investors and funding. Liu et al. (2022) studied the use of IRR in evaluating real estate investments and found that projects with higher IRRs are more likely to attract investors. Khan et al. (2015) analyzed the impact of IRR on capital budgeting decisions in manufacturing firms and confirmed that higher IRR values lead to better financial performance and growth of the companies.

In this study, the developed SD model calculates IRRs for various EOL management strategies using NCFs and NPVs. Unlike static standard financial analysis, SD modeling allows for a dynamic approach, where values different scenarios change through time and affect the calculated IRRs (Fang et al., 2018). It provides a more responsive and realistic assessment of the IRR calculation under various conditions. The IRR values of the project can be different depending on the selected strategies. For instance, Liu et al. (2022) stated that real estate investments with the IRR values above 12% are considered attractive. Niresh and Velnampy (2014) suggested that a 14% IRR value ensures profitability and long-term success of manufacturing firms. In this study, an IRR value of at least 14% is considered feasible for the EOL management project.

CHAPTER 4
LIFE CYCLE ASSESSMENT RESULTS

4.1 General overview

This chapter presents the LCA analysis and results. The inventory data related to the EOL management processes are collected. The normalization of environmental impact was performed to confirm suitable EOL management scenarios with the lowest environmental impacts. Strategies to enhance EOL management in the long term are also presented in this chapter.

4.2 Inventory data collection

The first step in inventory analysis involves a meticulous collection of data regarding material consumption and production processes in the EVB life cycle (Sato and Nakata, 2019). It forms the fundamental basis for the subsequent impact assessment, ensuring a comprehensive understanding of the environmental impacts associated with EVBs (Sanfelix et al., 2016). Inventory data collection involves input and output related to the EOL management processes of REVBs (Sato and Nakata, 2019). It includes materials (e.g., lithium, cobalt, and nickel), energy (e.g., electricity consumption), emissions (e.g., CO_{2eq}, $PM10_{eq}$, and non-methane volatile organic compounds), and waste (e.g., natural gas and water) associated with the remanufacturing, repurposing, recycling, and landfilling processes. It was collected from secondary sources, such as scientific literature, technical databases, and company reports. Background data are obtained from the Ecoinvent database v3.6 in the SimaPro software version 8.0 (Tintelacan et al., 2020).

The material consumption data encompasses various aspects. For example, electricity consumption is examined in the raw material extraction and EOL management processes. It includes the energy required in raw material mining and extraction and EVB recycling and disposal processes. Data of raw materials used in the battery cells, such as copper (Cu), aluminum (Al), nickel (Ni), manganese (Mn), cobalt (Co), and lithium (Li), and reagents used in the EVB production and recycling processes are collected (Leon and Miller, 2020). A breakdown information for a single Li-ion battery cell by percentage of total cell weight includes Cu by 15%, Al by 5%, Ni by 45%, Mn by 15%, Co by 15%, and Li by 5% (Leon and Miller, 2020). These values may vary depending on the specific chemistry and the li-ion battery cells' design and manufacturer (Leon and Miller, 2020). Diesel fuel is used in the mining equipment for material extraction, while natural gas is consumed to generate electricity in the power plants. Thailand primarily generates electricity using natural gas (i.e., 65%), coal (i.e., 20%), and renewable energy (i.e., 15%) (Wilaipon et al., 2002). About 46 Nm^3 of air is utilized in the recycling process to extract valuable materials from the REVBs (Wilaipon et al., 2002).

4.2.1 The inventory data associated with the EVB production

An EVB comprises four major units: EVB cell, battery management system (BMS), cooling system, and battery pack (with battery frame) (Zhang et al., 2020b). The inventory data for the EVB cell production follows the Thai EVB specifications (see Table 4.1) (Lewchalermwong et al., 2018; Duangsrikaew et al., 2019; Zhang et al., 2020b). The production of EVB components has significant environmental impacts. For instance, the extraction and processing of raw materials for EVB cells generate GHG emissions and consume natural resources (Koiwanit and Hamontree, 2018). The manufacturing of electronic components for the BMS and cooling system involves hazardous chemicals and energy-intensive processes (Arambarri et al., 2019). The assembly and production of battery packs contribute to emissions and waste (Messagie et al., 2010). It was estimated that producing one unit of EVB generates between 60 to 80 kg of CO_{2eq} per kWh of battery capacity (Ellingsen et al., 2016).

The 75-kWh NMC cell, a main component in EOL management, is widely used due to its high energy density and stability (Accardo et al., 2021). Each cell weighs 70 g and contains a cathode made from nickel, manganese, and cobalt (NMC) and an anode with graphite as the active material (Kelly et al., 2019). The manufacturing process of EVB cells involves several stages: raw material extraction, electrode production, cell assembly, and formation (Leon and Miller, 2020). This process requires significant amounts of energy and generates emissions and waste (Manjong et al., 2021). For instance, the production of NMC cells involves extracting and refining metals like nickel and cobalt, which are energy-intensive (Jiao et al., 2020). It was estimated that the production of 1 kg of NMC material generates approximately 11.5 kg of CO_{2eq} emissions (Ahmed et al., 2017). The formation stage, where cells are charged and discharged multiple times to stabilize the performance, also consumes a considerable amount of electricity (Accardo et al., 2021).

Table 4.1 Inventory data associated with the EVB production

EVB unit	Detail	Value
Cell	Total weight	412 kg
	Nominal voltage (V)	3.7 V
	Nominal capacity (Ah)	4.3 Ah
	SOH	100%
	Energy density	264.2 Wh/kg
BMS	Weight	6 kg
Cooling system	Weight	6 kg
Battery pack	Weight	42 kg

Note: References include Lewchalermwong et al., 2018; Duangsrikaew et al., 2019; Zhang et al., 2020b; Rajchapanupat and Poramapojana, 2021

BMS is crucial for monitoring and managing the performance of EVB cells. It ensures the safety, efficiency, and longevity of EVBs by regulating temperature, voltage, and current (Omariba et al., 2018). Badrinarayanan et al. (2014) stated that a BMS of Thai EVBs weighs 6 kg. The BMS also includes software that provides diagnostics and communication with the vehicle's main control unit. The production of BMS involves the manufacturing of electronic components, such as microcontrollers, sensors, and communication modules (Sivaraman and Sharmeela, 2020). This process requires various metals, plastics, and electronic components, contributing to the environmental footprint. For example, the production of electronic components involves significant energy consumption and the use of hazardous substances like lead and brominated flame retardants (Marques et al., 2013). The environmental impacts of producing electronic components for a BMS include 200 kg of CO_{2eq} emissions and 300 kWh of electricity (Yung et al., 2018).

The cooling system is essential in maintaining the optimal operating temperature of EVBs, preventing overheating, and ensuring safety and performance (Falcone et al., 2022). For Thai EVBs, the cooling system weighs 6 kg and includes liquid or air-based cooling mechanisms, pumps, radiators, and control units (Rajchapanupat and Poramapojana, 2021). The manufacturing of cooling systems involves the production of mechanical and electronic components, assembly, and testing processes that consume electricity and materials, contributing to the overall environmental impacts (Schulze et al., 2018). For instance, the production of aluminum radiators involves mining, refining, and manufacturing processes that generate significant emissions (Brough and Jouhara, 2020). It was estimated that producing 1 kg of aluminum generates approximately 11.5 kg of CO_{2eq} emissions (Liu et al., 2018).

The battery pack provides structural support and protection of EVB cells, BMS, and cooling system. A typical battery pack weighs 42 kg and includes a frame, connectors, and safety features to ensure the integrity of the battery during operation and under severe conditions (Lewchalermwong et al., 2018; Skegro et al., 2023). The production of battery packs involves assembling cells, BMS, and cooling system into a single unit, testing, and quality control (Li et al., 2010). The processes require materials, such as metals, plastics, and composites, adding to the environmental footprint. The production of a battery pack frame typically involves the use of steel or aluminum, which requires significant energy for mining, refining, and manufacturing (Ramirez et al., 2020). The production of 1 kg of steel generates approximately 1.85 kg of CO_{2eq} emissions, while 1 kg of aluminum generates about 11.5 kg of CO_{2eq} emissions (World Steel Association, 2019; Liu et al., 2018).

4.2.2 The inventory data associated with the REVB's EOL management

The WTT stage of EVBs is set from 2023 to 2033, reflecting the current lifespan of 10 years (Tintelecan et al., 2020). After 10 years, four EOL management scenarios are considered: landfilling, remanufacturing, repurposing, and recycling, each with distinct processes and environmental impacts; see Table 4.2.

Table 4.2 EOL models

Data	Detail			
	Reference (EOL1)	Remanufacturing (EOL2)	Repurposing (EOL3)	Recycling (EOL4)
EOL product	Landfilled EVBs	Remanufactured EVBs	Stationary energy storage	Materials used in the new EVB production
EVB cell	100% landfilled	20% replaced	40% replaced	95% recycled
BMS	Landfilled	Direct reused	Landfilled	Recycled
Cooling system	Landfilled	Direct reused	Landfilled	Recycled
Battery pack	Landfilled	Direct reused	Landfilled	Recycled

Note: References include Maharajan et al., 2019; Kampker et al., 2020; Leon and Miller, 2020; Tintelecan et al., 2020

4.2.2.1 Reference scenario: Landfilling

The reference scenario (EOL1) occurs in 2034, where REVBs, after 10 years of usage, are disposed of in landfills. This scenario is considered the baseline for comparison with other EOL management strategies. In this scenario, all components of the EVBs, including cells, BMS, cooling system, and battery packs are disposed of in landfills. This scenario poses significant environmental concerns due to potential leakages of hazardous materials into soil and groundwater, contributing to environmental pollution and resource wastage (Arambarri et al., 2019).

4.2.2.2 Remanufacturing scenario

The remanufacturing scenario (EOL2) considers REVBs with SOH of at least 80%. In this scenario, 20% of the EVB cells are replaced, while the BMS, cooling system, and battery packs are directly reused. Remanufacturing involves refurbishing REVB cells to restore them to like-new conditions, extending their lifespan and reducing the need for new materials (Schulz et al., 2020). This process involves disassembling the battery, inspecting and replacing defective parts, reassembling, and testing (Olsson et al., 2018). The primary environmental benefits of remanufacturing are the significant reduction in raw material consumption and waste generation.

4.2.2.3 Repurposing scenario

The repurposing scenario (EOL3) is established for REVBs with SOHs between 60-79%. In this scenario, up to 40% of the EVB cells are replaced, while the BMS and cooling system are reused and the battery pack is modified to be used in stationary energy storage applications (Maharajan et al., 2019). Repurposing involves adapting REVBs for secondary applications, where performance requirements are less stringent, such as grid storage or backup power systems (Schulz et al., 2020). This strategy not only extends the useful life of the batteries, but also supports the integration of renewable energy sources by providing storage solutions. Environmental benefits include reduced demand for new batteries and lower overall emissions (Messagie et al., 2010). However, the repurposing process may require significant modifications and safety testing to ensure that the batteries are suitable for their new applications.

4.2.2.4 Recycling scenario

The recycling scenario (EOL4) is used with REVBs with SOHs below 60%, where REVB cell cannot be used in any applications. In this scenario, BMS, cooling systems, and battery packs are recycled to recover valuable materials like aluminum, copper, steel, and plastic (Catton et al., 2019). Recycling involves dismantling the battery and processing REVB cells through pyrometallurgical and hydrometallurgical methods to extract rare metals, such as lithium, cobalt, nickel, and manganese (Beghi et al., 2023). With limited technology for li-ion EVBs recycling, the process can extract up to 95% of the original material mass due to losses during the pyrometallurgical and hydrometallurgical processes. The recovered materials can be used in the production of new batteries, thus closing the loop in the material lifecycle (Olsson et al., 2018). This scenario significantly reduces the environmental footprint by minimizing the need for virgin material extraction and mitigating hazardous waste. However, the process can be energy-intensive and requires advanced technologies to achieve high recovery rates.

4.2.2.5 Inventory data of treated components in EOL management

The inventory data per kg of treated components used for EVB cells, BMS, cooling system, and battery packs are in Table 4.3. They are crucial for evaluating the material and energy flows associated with various EOL scenarios and understanding their environmental impacts. In the EOL1, REVBs are entirely landfilled, resulting in a significant resource wastage. Although this process requires minimal energy consumption (i.e., 10 kWh of purchased electricity, see Table 4.3), it does not recover raw materials from REVBs. Landfill disposal adds environmental risks from leakage of hazardous substances into soil and water (Wirasingha et al., 2012). In the EOL2 scenario, REVBs are remanufactured. This process requires moderate energy consumption (i.e., 360 kWh of purchased electricity) but significantly reduces raw material consumption (i.e., about 80% of materials are recovered) (Li et al., 2020a). REVBs with SOHs between 60-79% in the EOL3 scenario are adapted to be used in stationary energy storage systems. This process consumes higher energy consumption compared with the EOL1 and EOL2 scenarios, and recovers less materials compared with the EOL2 and EOL4 scenarios. Though the EOL4 scenario consumes most of electricity in the recycling process, it recovers materials the most, thus reducing the need for virgin materials and supporting the circular economy principle.

4.3 LCA results

4.3.1 CO_{2eq} emission

The CO_{2eq} emission was calculated in each EOL management process, see Table 4.4. For example, the EOL2 scenario requires 360 kWh of electricity to remanufacture a 75-kWh battery (see Table 4.3). This amount of electricity consumption generates 219.34 kg of CO_{2eq} emission (Wilaipon et al., 2002). In the repurposing and recycling scenarios, the electricity of 840 and 3514 kWh is required, which is equivalent to 671.28 and 3,661.74 kg of CO_{2eq} emissions, respectively (Wilaipon et al., 2002). The recycling scenario consumes the highest amount of electricity, resulting in the highest CO_{2eq} emission and highlighting significant environmental impacts from the energy-intensive process (Bobb et al., 2018).

Table 4.3 Inventory data associated with the EOL management

Data	Detail		Value				Unit
			EOL1	EOL2	EOL3	EOL4	
Energy	Discharged electricity		13	13	13	13	kWh
	Purchased electricity		10	360	840	3514	kWh
Raw material	Cu	Consumption	47	9.4	18.8	5.7	kg
		Recovered	-	37.6	28.2	41.4	kg
	Al	Consumption	141	28.2	56.4	17	kg
		Recovered	-	112.8	84.6	124	kg
	Ni	Consumption	32.1	6.4	12.8	3.9	kg
		Recovered	-	25.6	19.3	28.2	kg
	Ma	Consumption	5	1	2	0.5	kg
		Recovered	-	4	3	4.5	kg
	Co	Consumption	10.65	2.1	4.3	1.3	kg
		Recovered	-	8.5	6.4	9.4	kg
	Li	Consumption	8.65	1.7	3.5	1	kg
		Recovered	-	6.9	5.2	7.7	kg
	Steel	Consumption	32	-	-	-	kg
		Recovered	-	32	32	32	kg
Pyro- and hydro-metallurgical process	Natural gas		-	-	-	27.2	m^3
	Process gas		-	-	-	46.7	Nm^3
	Liquid oxygen		-	-	-	45.4	kg
	Purchased water		-	-	-	4.6	L
	Air		-	-	-	46.6	Nm^3
	Carbon		-	-	-	7.8	kg

Note: References include Wirasingha et al., 2012; Ko et al., 2014; Usapein and Chavalparit, 2017; Lewchalermwong et al., 2018; Li et al., 2020a; Schulz et al., 2020; Tintelecan et al., 2020; Rajchapanupat and Poramapojana, 2021

The consumption and recovered materials in the EOL management processes affect CO_{2eq} emissions. For instance, the remanufacturing scenario (EOL2) recovers

37.64 kg of copper, thus reducing the CO_{2eq} emission from the mining process by 140.89 kg (Bobb et al., 2018). Nevertheless, the consumption of 9.41 kg of copper in the EVB remanufacturing is required to replace the REVB cells. This produces 35.22 kg of CO_{2eq} emission (Bobb et al., 2018). Table 4.4 shows that the EOL2 is the best scenario in reducing CO_{2eq} emission with the overall reduction of 1,178.31 kg CO_{2eq} emission. It is noted that the calculated negative values represent the reduction of the impacts, while the positive values generate the impacts. The main reduction is from the saving of materials (i.e., lithium, nickel, and copper) in EVB production. Though the EOL4 scenario achieves the highest material recovery, it requires high electricity consumption in the recycling process.

Table 4.4 CO_{2eq} emission results from EOL management scenarios

Data	Detail		CO_{2eq} emission (kg CO_{2eq})			
			EOL1	EOL2	EOL3	EOL4
Electricity	Discharged electricity		-7.3	-7.3	-7.3	-7.3
	Purchased electricity		5	219.3	671.2	3,661.7
Raw material	Copper	Consumption	176.1	35.2	45.2	7.2
		Recovered	0	-140.8	-105.6	-148.7
	Aluminum	Consumption	3.8	0.7	1	0.2
		Recovered	0	-3	-2.2	-3.2
	Nickel	Consumption	372	74.4	95.6	15.3
		Recovered	0	-297.6	-223.2	-314.1
	Manganese	Consumption	16.6	3.3	4.3	0.7
		Recovered	0	-13.3	-10	-14
	Cobalt	Consumption	99.5	19.9	25.6	4.1
		Recovered	0	-79.6	-59.7	-84
	Lithium	Consumption	1,414.9	282.9	242.5	70.7
		Recovered	0	-1,131.9	-565.9	-1,344.1
	Steel	Consumption	155.1	0	0	0
		Recovered	0	-155.1	-155.1	-155.1
Overall CO_{2eq} emission			2,235.8	**-1,192.9**	-43.6	1,689.1

4.3.2 Human toxicity

Table 4.5 shows various levels of human toxicity in kg 1,4-dichlorobenzene equivalents (kg 1,4-DB_{eq}), representing the potential toxic impact of emitted substances. It is shown that the current practice (i.e., the EOL1 scenario: landfilling) is highly harmful to human health. In contrast, the EOL4 is the best scenario considering the consumption and recovered materials, as it recovers 95% of raw materials from the REVBs (Kampker et al., 2020). Material recovery avoids toxic emissions in the mining process. The EOL2 scenario also reduces the demand of virgin materials in the EVB production, specifically lithium and copper.

Table 4.5 Human toxicity results from EOL management scenarios

Data	Detail		Human toxicity (kg 1,4-DB_{eq})			
			EOL1	EOL2	EOL3	EOL4
Electricity	Discharged electricity		-0.002	-0.002	-0.002	-0.002
	Purchased electricity		0.001	0.06	0.13	1
Raw material	Copper	Consumption	8,377.1	1,675.4	3,361.3	418.8
		Recovered	0	-6,701.7	-5,026.3	-14,166.5
	Aluminum	Consumption	1	0.20	0.40	0.05
		Recovered	0	-0.80	-0.60	-1.7
	Nickel	Consumption	1,774	354.8	711.8	88.7
		Recovered	0	-1,419.2	-1,064.4	-3,000.0
	Manganese	Consumption	10.9	2.18	4.37	0.5
		Recovered	0	-8.72	-6.54	-18.4
	Cobalt	Consumption	83.3	3.7	7.5	0.9
		Recovered	0	-79.6	-59.7	-84
	Lithium	Consumption	31,725.1	6,345	8,486.5	1,586.2
		Recovered	0	-25,380.1	-12,690	-30,138.9
	Steel	Consumption	620.2	0	0	0
		Recovered	0	-620.2	-620.29	-620.2
Overall human toxicity			42,591.9	-25,764.6	-6,847.4	**-45,934.6**

4.3.3 Terrestrial acidification

EVB production and EOL management moderately affect the environment in terms of terrestrial acidification, see Table 4.6. The results show that the EOL4 is the best scenario to reduce this impact by recovering materials, mainly lithium and nickel. The reduction is primarily due to the avoidance of sulfur and nitrogen compound emissions associated with the material extraction and raw material processing (Bobb et al., 2018). Table 4.6 shows that all scenarios, except the EOL1 scenario, provide benefits to the environment in terms of terrestrial acidification (with negative impact values).

Table 4.6 Terrestrial acidification results from EOL management scenarios

Data	Detail		Terrestrial acidification (kg SO_{2eq})			
			EOL1	EOL2	EOL3	EOL4
Electricity	Discharged electricity		-0.01	-0.01	-0.01	-0.01
	Purchased electricity		0.004	0.26	0.34	4.7
Raw material	Copper	Consumption	13.1	2.6	3.9	0.6
		Recovered	0	-10.5	-9.1	-12.4
	Aluminum	Consumption	0.03	0.01	0.01	0.005
		Recovered	0	-0.02	-0.02	-0.03
	Nickel	Consumption	97.1	19.4	29.1	4.8
		Recovered	0	-77.7	-68.0	-92.2
	Manganese	Consumption	0.12	0.02	0.04	0.01
		Recovered	0	-0.1	-0.09	-0.1
	Cobalt	Consumption	1	0.2	0.3	0.05
		Recovered	0	-0.8	-0.7	-1
	Lithium	Consumption	331.6	66.3	99.5	16.5
		Recovered	0	-265.3	-232.1	-315.1
	Steel	Consumption	31.4	0	0	0
		Recovered	0	-31.4	-31.4	-31.4
Overall terrestrial acidification			474	-297	-208	**-425**

4.3.4 PM formation

Table 4.7 shows that the EVB production and EOL management slightly generate PM formation. The EOL4 is the most favorable scenario in reducing $PM10_{eq}$, mainly from the recovered lithium and nickel used in the EVB production. Without the material recovery process (i.e., the EOL1 scenario: landfilling), this impact is substantial.

Table 4.7 PM formation results from EOL management scenarios

Data	Detail		PM formation (kg $PM10_{eq}$)			
			EOL1	EOL2	EOL3	EOL4
Electricity	Discharged electricity		-0.42	-0.42	-0.42	-0.42
	Purchased electricity		0.031	1.12	2.61	20.25
Raw material	Copper	Consumption	3.92	0.78	1.18	0.20
		Recovered	0	-3.14	-2.35	-6.41
	Aluminum	Consumption	0.012	0.002	0.003	0.0006
		Recovered	0	-0.01	-0.01	-0.02
	Nickel	Consumption	20.66	4.13	6.20	1.03
		Recovered	0	-16.53	-12.40	-33.76
	Manganese	Consumption	0.12	0.02	0.04	0.01
		Recovered	0	-0.10	-0.07	-0.20
	Cobalt	Consumption	0.58	0.12	0.17	0.03
		Recovered	0	-0.46	-0.35	-0.95
	Lithium	Consumption	76.15	15.23	22.85	3.81
		Recovered	0	-60.92	-30.46	-72.35
	Steel	Consumption	7.1	0	0	0
		Recovered	0	-7.10	-7.10	-7.10
Overall PM formation			108.15	-67.27	-20.10	**-95.87**

4.3.5 Photochemical oxidant formation

The EOL4 scenario has the lowest photochemical oxidant formation, though it generates the non-methane volatile organic compounds (NMVOCs) from electricity generation. The lowest impact of this scenario is due to the substantial reduction of lithium and nickel in EVB production. Table 4.8 shows that the EOL1 scenario (i.e., landfilling) is the only scenario that increases the impact of photochemical oxidant formation.

Table 4.8 Photochemical oxidant formation results from EOL management scenarios

Data	Detail		Photochemical oxidant formation (kg NMVOC)			
			EOL1	EOL2	EOL3	EOL4
Electricity	Discharged electricity		-0.01	-0.01	-0.01	-0.01
	Purchased electricity		0.30	0.01	0.70	5.43
Raw material	Copper	Consumption	2.93	0.59	0.88	0.15
		Recovered	0	-2.34	-2.05	-2.78
	Aluminum	Consumption	0.04	0.01	0.01	0.002
		Recovered	0	-0.03	-0.03	-0.04
	Nickel	Consumption	10.08	2.02	3.02	0.50
		Recovered	0	-8.06	-7.05	-9.57
	Manganese	Consumption	0.11	0.02	0.03	0.01
		Recovered	0	-0.09	-0.08	-0.11
	Cobalt	Consumption	1.11	0.22	0.33	0.06
		Recovered	0	-0.89	-0.78	-1.06
	Lithium	Consumption	26.36	5.27	7.91	1.32
		Recovered	0	-21.09	-18.45	-25.04
	Steel	Consumption	3.45	0	0	0
		Recovered	0	-3.45	-3.45	-3.45
Overall photochemical oxidant formation			44.08	-28.11	-20.39	**-45.43**

4.3.6 Water depletion

Material extraction, EVB production, EOL management of REVBs, and electricity generation use water in the processes (Liu et al., 2018). The EOL4 scenario (i.e., recycling) has the highest reduction of water consumption, making it the most favorable option among the four scenarios.

Table 4.9 Water depletion results from EOL management scenarios

Data	Detail		Water depletion (m^3_{eq})			
			EOL1	EOL2	EOL3	EOL4
Electricity	Discharged electricity		13.2	13.2	13.2	13.2
	Purchased electricity		10.1	365.4	852.8	6,613.3
Raw material	Copper	Consumption	9,410	1,882	3,764	1,130
		Recovered	0	-7528	-5646	-8280
	Aluminum	Consumption	39,480	7,896	15,792	4,760
		Recovered	0	-31,584	-23,688	-34,720
	Nickel	Consumption	9,630	1,926	3,852	1,167
		Recovered	0	-7,704	-5,778	-8,463
	Manganese	Consumption	600	120	240	64.8
		Recovered	0	-480	-360	-535.2
	Cobalt	Consumption	3,195	639	1,278	381
		Recovered	0	-2,556	-1,917	-2,814
	Lithium	Consumption	10,812	2,162	4,325	1,237.5
		Recovered	0	-8,650	-6,487.5	-9,575
	Steel	Consumption	4,800	0	0	0
		Recovered	0	-4,800	-4,800	-4,800
Overall water depletion			77,950	-48,297	-18,559	**-53,820**

4.3.7 Metal depletion

The EOL management of REVBs highly reduces the virgin material requirement, thus minimizing the metal depletion. The recycling and remanufacturing scenarios (i.e., EOL4 and EOL2) save virgin materials, i.e., lithium and copper in the EOL management processes, thus lowering the demand for virgin materials and mining activities; see Table 4.10. It is clear that the current practice (i.e., the EOL1 scenario) is highly harmful to the environment and poses high risks in resource depletion.

Table 4.10 Metal depletion results from EOL management scenarios

Data	Detail		Metal depletion (kg Fe_{eq})			
			EOL1	EOL2	EOL3	EOL4
Electricity	Discharged electricity		-0.001	-0.001	-0.001	-0.001
	Purchased electricity		0.0001	0.03	0.04	0.1
Raw material	Copper	Consumption	2,461.8	492.38	633	211.8
		Recovered	0	-1,969.5	-1,477.1	-4,024.8
	Aluminum	Consumption	0.0005	0.0001	0.0001	0.0001
		Recovered	0	-0.0004	-0.0003	-0.0008
	Nickel	Consumption	1406	281.22	361.5	120.9
		Recovered	0	-1,124.8	-843.6	-2,298.7
	Manganese	Consumption	893.39	178.68	229.7	76.8
		Recovered	0	-714.71	-536	-1,460.5
	Cobalt	Consumption	14.26	2.85	3.6	1.23
		Recovered	0	-11.41	-8.5	-23.3
	Lithium	Consumption	14,382.8	2,876.5	2,465.6	719.14
		Recovered	0	-11,506.3	-5,753.1	-13,663.7
	Steel	Consumption	492.3	0	0	0
		Recovered	0	492.3	633	211.8
Overall metal depletion			19,806	-11,002.6	-4,291.7	**-20,129.2**

4.3.8 Ozone depletion

Surprisingly, the EVB production and EOL management barely have impacts on ozone depletion (see Table 4.11). However, it may have a significant impact when the amount of REVBs increases. Chipperfield et al. (2014) mentioned that even a small amount of ozone-depleting substance could have a long-lasting effect on the ozone layer and climate change. It is important to minimize such emissions to zero to protect the atmosphere and ecosystem

Table 4.11 Ozone depletion results from EOL management scenarios

Data	Detail		Ozone depletion (kg CFC-11$_{eq}$)			
			EOL1	EOL2	EOL3	EOL4
Electricity	Discharged electricity		0	0	0	0
	Purchased electricity		0	0	0	0
Raw material	Copper	Consumption	0.00001	0.0000010	0.000001	0.000009
		Recovered	0	-0.000009	-0.00001	-0.00001
	Aluminum	Consumption	0.000001	0.0000001	0.000001	0.0000005
		Recovered	0	-0.000001	-0.000001	-0.00001
	Nickel	Consumption	0.00002	0.0000020	0.0000020	0.000018
		Recovered	0	-0.000018	-0.000014	-0.000034
	Manganese	Consumption	0.000001	0.0000001	0.000001	0.000001
		Recovered	0	-0.000001	-0.000001	-0.000002
	Cobalt	Consumption	0.000008	0.0000008	0.000001	0.000006
		Recovered	0	-0.000007	-0.000005	-0.000013
	Lithium	Consumption	0.00011	0.0000110	0.000011	0.000063
		Recovered	0	-0.000099	-0.00005	-0.000118
	Steel	Consumption	0.00001	0	0	0
		Recovered	0	-0.00001	-0.00001	-0.00001
Overall ozone depletion			0.00016	**-0.00013**	-0.00007	-0.00009

4.3.9 Fossil depletion

Table 4.12 shows that the EOL2 scenario (i.e., remanufacturing) is the best scenario to reduce fossil depletion, though it has less material recovery compared with the EOL4 scenario. If renewable energy is used in electricity generation, the EOL4 scenario may provide less impact on the purchased electricity.

Table 4.12 Fossil depletion results from EOL management scenarios

Data	Detail		Fossil depletion (kg oil_{eq})			
			EOL1	EOL2	EOL3	EOL4
Electricity	Discharged electricity		1.05	1.05	1.05	1.05
	Purchased electricity		1.05	37.8	88.2	683.97
Raw material	Copper	Consumption	42.95	8.59	11.04	2.85
		Recovered	0	-34.36	-25.77	-61.87
	Aluminum	Consumption	1.3	0.26	0.33	0.09
		Recovered	0	-1.04	-0.78	-1.87
	Nickel	Consumption	86.77	17.35	22.31	5.76
		Recovered	0	-69.42	-52.06	-125.01
	Manganese	Consumption	4.29	0.86	1.10	0.28
		Recovered	0	-3.43	-2.57	-6.18
	Cobalt	Consumption	24.75	4.95	6.36	1.64
		Recovered	0	-19.80	-14.85	-35.65
	Lithium	Consumption	424.75	84.95	72.81	18.61
		Recovered	0	-339.80	-169.90	-403.51
	Steel	Consumption	42.95	0	0	0
		Recovered	0	-37.46	-37.46	-37.46
Overall fossil depletion			629.86	**-349.5**	-100.19	42.7

4.4 Normalization impact

To better understand the magnitude of the overall impact and select the best scenario for the implementation, it is necessary to normalize the environmental impacts relative to their total impacts on the global scales (see Table 4.13). For example, the CO_{2eq} of -1,178.31 kg in the EOL2 scenario is divided by the global CO_{2eq} value of 5,020.66 kg to achieve the normalized value of -0.23. The human toxicity in the EOL3 scenario (i.e., -6,847.4 kg 1,4-DB_{eq}) is also divided by the global 1,4-DB_{eq} value of 245.96 kg to achieve the normalized value of -27.84. The normalized value of -65.88 in metal depletion in the EOL4 scenario is also achieved by dividing the metal depletion of -20,129.2 kg Fe_{eq} by the global value of 305.53 kg Fe_{eq}.

Table 4.13 Global values of the environmental impacts

Environmental impact	Value	Unit
CO_{2eq} emission	5,020.66	kg CO_{2eq}
Human toxicity	245.96	kg 1,4-DB_{eq}
Terrestrial acidification	29.41	kg SO_{2eq}
PM formation	9.08	kg $PM10_{eq}$
Photochemical oxidant formation	21.13	kg NMVOC
Water depletion	361,000	m^3 H_2O_{eq}
Metal depletion	305.53	kg Fe_{eq}
Ozone depletion	0.04	kg CFC-11_{eq}
Fossil depletion	908.94	kg oil_{eq}

Note: References include Hauschild and Huijbregts, 2015; Sala et al., 2015.

The results from Table 4.14 reveal that the current practice, i.e., landfilling (EOL1), is the worst scenario with the highest final impact on the environment. It is harmful to human health and releases toxins, such as cadmium, arsenic, and cyanide (Aichberger and Jungmeier, 2020). This scenario also consumes a high number of materials in EVB production without reusing and recovering.

The EOL4 scenario has the best final impact score among the four scenarios (i.e., -279.57). Though it generates more CO_{2eq} emission and consumes more fossils compared with the EOL2 and EOL3 scenarios, it highly reduces human toxicity and metal depletion, making it superior in reducing the overall impact. The high recovery rate of materials (i.e., 95%) in this scenario helps mitigate the environmental burden associated with the material extraction process. Several studies pinpoint the importance of the recycling process in minimizing the environmental impacts. For instance, Liu et al. (2018) mentioned that recycling significantly reduces the need for virgin material extraction and minimizes GHG emissions. Bobba et al. (2018) claimed that the recycling of li-ion batteries reduces the overall environmental impact by 60% compared with landfill disposal. Hao et al. (2017) indicated that the recycling process reduces human toxicity and terrestrial acidification up to 75% compared with landfilling and repurposing processes.

Table 4.14 Final impacts of EOL management scenarios

Environmental impact	Normalized impact			
	EOL1	EOL2	EOL3	EOL4
CO_{2eq} emission	0.45	-0.23	-0.05	0.34
Human toxicity	173.17	-104.75	-27.84	-186.75
Terrestrial acidification	16.14	-10.10	-7.09	-14.47
PM formation	12.00	-6.26	-0.46	-10.56
Photochemical oxidant formation	2.09	-1.33	-0.96	-2.15
Water depletion	0.22	-0.13	-0.05	-0.15
Metal depletion	64.83	-36.01	-14.05	-65.88
Ozone depletion	0.0043	-0.0035	-0.0019	-0.0024
Fossil depletion	0.69	-0.38	-0.11	0.05
Final impact	269.59	-159.19	-50.61	**-279.57**

Remark: The emission may be higher compared to developed countries.

The EOL2 scenario is the second-best scenario in managing the REVB's EOL with a final impact score of -159.19. This scenario reduces human toxicity and metal depletion and recovers a substantial portion of materials (i.e., 80%) in the remanufacturing process. However, the process requires about 20% of new materials to produce the new EVBs, contributing to human toxicity and metal depletion. Despite this, the overall implementation of the remanufacturing process (i.e., the EOL2 scenario) yields net benefits with the negative normalized score.

The EOL3 scenario has the final impact score of -50.61, reflecting the benefits to the environment. It recovers 60% of materials that are repurposed and used in the stationary storage systems. Compared with the EOL4 and EOL2 scenarios, this scenario consumes many new materials (i.e., 40%), making it less favorable in the EOL management of REVBs. Despite this, the repurposing process (i.e., the EOL3 scenario) demonstrates the reduction in the overall environmental impact.

4.5 Enhancement of the recycling scenario

Table 4.14 proves the significance of the EOL4 scenario (i.e., recycling) in minimizing the environmental impacts of the EVB's EOL management. However, closer examination reveals that this scenario incurs high CO_{2eq} emissions compared with EOL2 and EOL3 scenarios. This is due to the high use of electricity in the recycling process. Usapein and Chavalparit (2017) stated that Thailand's energy mix relies heavily on natural gas (NG) (65%) and coal (C) (20%), and only 15% is from the renewable energy (RE). Transitioning to renewable energy can dramatically reduce CO_{2eq} emissions (Olsson et al., 2018). To further reduce the final impact of the EOL4 scenario, various percentages of renewable energy used in the electricity production are examined: 15% (base scenario), 50%, 75%, and 100% (Kost et al., 2021). The results in Table 4.15 show that pursuing an increased share of renewable energy provides benefits to the environment. At least half of the energy used in electricity generation should be renewable to minimize the critical impacts of EVB production and EOL management (i.e., all the impacts become negative, explaining the benefits to the environment). This is consistent with Mandsaurwala and Rangwala (2024) that the Indian government planned that half of its electricity should come from renewable sources by 2030 to serve the charging demand of EVBs.

Table 4.15 highlights the higher environmental benefits of expanding renewable energy usage. It shows that shifting from fossil fuel to renewable energy, particularly solar energy, impacts all environmental indicators. In Thailand, solar energy is a cornerstone of renewable energy strategy due to its availability, scalability, and alignment with the country's sustainable development goals (MHM, 2023). Solar energy has an advantage in both geographic and economic in Thailand (Wernet et al., 2016). For instance, Thailand receives high solar irradiance, particularly in its central, northeastern, and southern regions (Sirasoontorn and Koomsup, 2021). This makes solar energy the most accessible and abundant renewable resource. In addition, solar energy systems have low operating costs (Faircloth et al., 2019). This cost efficiency contributes to long-term sustainability and affordability for both consumers and industries. To maximize the benefits of renewable energy, Thai government should invest in large-scale solar farms and rooftop solar program. This approach also can integrate with industrial applications which require highly intensive sources of energy such as recycling processes of REVBs. Government supporting policies, such as banning natural gas and coal, are also required to accelerate the transition to a more sustainable energy in Thailand (Aungyut and Wattana, 2021). Future research should be encouraged to enhance recycling efficiency. Advanced technologies, such as hydrometallurgical and pyro metallurgical processes have shown potential in increasing efficiency and reducing environmental impacts (Tantisattayakul et al., 2016). There is also a need to establish recycling networks for REVBs. Developing infrastructure and logistical framework facilitates the efficient collection and transportation, thus boosting the recycling of REVBs (Silvestri et al., 2021). Incentives from the government for manufacturers and customers to participate in the recycling programs play a crucial role in enhancing this efficiency (Chen et al., 2022). Regulatory frameworks to support the transition to a higher share of renewable energy in electricity production should be initiated. This transition is significant for reducing the environmental impacts associated with EVB production and its EOL management (Dranka and Ferreira, 2020). Such policies may include incentivizing renewable energy investments, phasing out natural gas subsidies, and promoting technological innovations in renewable energy sources.

Table 4.15 Final impacts of the EOL4 scenario with different energy mixes

Environmental impact	Base scenario (15% RE)	50% RE scenario	75% RE scenario	100% RE scenario
CO_{2eq} emission	0.34	-0.10	-0.25	-0.39
Human toxicity	-186.75	-230.33	-261.45	-280.13
Terrestrial acidification	-14.47	-18.86	-21.99	-23.88
PM formation	-10.56	-11.69	-11.71	-12.74
Photochemical oxidant formation	-2.15	-2.55	-3.05	-3.20
Water depletion	-0.15	-0.15	-0.16	-0.17
Metal depletion	-65.88	-68.95	-71.15	-72.47
Ozone depletion	-0.0024	-0.0031	-0.0036	-0.0038
Fossil depletion	0.05	-0.2	-0.53	-0.71
Final impact	-279.57	-332.83	-370.30	**-393.68**

Remark: The emission may be higher compared to developed countries.

CHAPTER 5
SYSTEM DYNAMICS MODEL OF REVB'S EOL MANAGEMENT

5.1 General overview

This chapter presents the development of an SD model of REVB's EOL management and its simulation results. The secondary data related to the EOL management processes are collected and used as input into the SD model. The environmental impacts in Chapter 4 are converted to the environmental costs and input into the SD model. The NCF, NPV and IRR values achieved from the simulation results are used to make decisions about the REVB's EOL management. The developed SD model was validated with the sensitivity analysis to confirm its validity for actual implementation.

5.2 Data collection

Secondary data are mainly used as input in SD model development. They cover the 10-year period information (i.e., data from 2014-2024), where EVs were adopted in Thailand (EVAT, 2023). 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. Collected data include information about BEV and EVB market (such as BEV selling price, EVB selling price, EVB capacity, REVB buyback price, remanufactured EVB price, and stationary storage battery price), factors affecting the BEV demand (such as incomes, number of fast charging stations, average driving ranges, new brand increasing rates, subsidies, tax reductions, and BEV parking spaces), EOL management processes, costs related to the EOL processes (such as investment, electricity, material, inventory, material handling, labor, and overhead costs), and environmental costs converted from the environmental impacts in Chapter 4.

Examples of data are the average BEV and EVB selling prices of $56,789 and $6,690 that are retrieved from Li and Chen (2020) and EVAT (2023). The buyback price of REVBs with the SOHs of at least 80% is 40% of its initial price (Price et al., 2012). The remanufactured EVB's selling price is $5,696 per battery (which is about 15% lower than the new EVB price) (Thananusak et al., 2020). SCB (2023) stated that to afford the BEVs, about half of customer's income should be adequate to pay the BEV loan. Government policies to support the remanufactured EVBs include the excise tax reduction of 8% and the subsidy for domestic BEV production of up to $2,760 per vehicle. This subsisdy program is eligible for BEV's prices of less than $57,000 (Thananusak et al., 2020). The remanufacturing capacity of 1 GWh in Thailand, which is equivalent to 16,540 batteries, was achieved from the EA Annual Report (2023). Sathitsuksomboon and Pornpapatkul (2019) mentioned that the available landfill space for the REVB disposal in Thailand is 2566.5 m^2. The average investment cost of an EOL management facility and storage (considering the remanufacturing, repurposing, and recycling) is $210 million (EA Annual Report, 2023, Tesla, 2021). In Thailand, carbon credits are traded at $0.0052 per kg of CO_{2eq} (Chunark et al., 2017). The cost associated with human toxicity leakage is approximately $0.59 per kg 1,4-$DB_{eq}$. Odermatt (2018) mentioned that the EVB recycling process requires a significant amount of water that costs about $0.58 per m^3 H^2O_{eq}.

Table 5.1 summarizes data related to the BEVs, EVBs, and REVBs. Table 5.2 provides information related to key factors affecting BEV demand. Costs related to EOL management processes are listed in Tables 5.3 and 5.4. Full data information is in Appendix A.

Table 5.1 EV, EVB, and REVB data used in the SD model development

Information	Detail
BEV	• Average BEV selling price: $56,789 per vehicle
EVB	• Average EVB selling price: $6,690 per battery • EVB capacity: 11-114 kWh (average at 75 kWh) • EVB capacity increasing rate: 3% annually • Lifespan: 10 years
REVB	• Percentage of REVBs for the remanufacturing process: 28%, on average (based on SOH ≥ 80%)

	• Percentage of REVBs for the repurposing process: 52%, on average (based on 60% ≤ SOH < 80%) • Percentage of REVBs for the recycling process: 18%, on average (based on SOH < 60%) • Percentage of REVBs disposed of in landfills: 2%, on average (based on BEV accidental rate in Thailand) • Buyback price: 40% of the initial price (based on SOH ≥ 80%) : 30% of the initial price (based on based on 60% ≤ SOH < 80%) : 15% of the initial price (based on SOH < 60%) • Remanufactured EVB selling price: $5,696 per battery • Stationary storage battery selling price: $6,554 per battery

Note: References include Chorbrod (2018), Reiter et al. (2018), Guerra and Daziano (2020), Tesla (2021), Toyota (2022), EVAT (2023), EA Annual Report (2023).

Table 5.2 Data related to factors affecting BEV demand

Information	Detail
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 station: 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	• Average driving range: 350 km per charge • Improved driving range: 20 km per model, on average • Thai BEV user's driving range: 25000 km annually, on average • 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): 79.7% of the total BEV models • BEVs (with at least 50 kWh) increasing rate: 3% per year • BEVs (with the prices below $56,789): 46.3% of total BEV model • BEVs (with the prices below $56,789) increasing rate: 3% per year • 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 space: 28,595 parking spaces • BEV parking space increasing rate: 3% annually

	• Designated parking space for BEV users: 30% of the total parking spaces • Increased customers from the parking privilege factor: 20.5% of the BEV demand

Note: References include Murnane and Ghazel (2002), Guerra and Daziano (2020), Thananusak et al. (2020), SCB (2023), Li et al. (2021), EVAT (2023).

Table 5.3 Data related to the EOL management process

Information	Detail
Remanufacturing	• Initial production capacity: 16,540 batteries annually • Maximum production capacity: 132,320 batteries annually • Production capacity expansion: 16,540 batteries each expansion • Production capacity expansion cost: $1.33 million each expansion • Electricity consumption in the remanufacturing process: 360 kWh per battery • Material requirement in remanufacturing process: 15 kWh per battery (i.e., 20% of 75-kWh battery)
Repurposing	• Initial production capacity: 29,607 batteries annually • Maximum production capacity: 236,856 batteries annually • Production capacity expansion: 29,607 batteries each expansion • Production capacity expansion cost: $6.31 million each expansion • Electricity consumption in the repurposing process: 840 kWh per battery • Material requirement in repurposing process: 30 kWh per battery (i.e., 40% of 75-kWh battery)
Recycling	• Initial production capacity: 25,893 batteries annually • Maximum production capacity: 207,144 batteries annually

	• Production capacity expansion: 25,893 batteries each expansion • Production capacity expansion cost: $21.6 million each expansion • Electricity consumption in the recycling process: 3514 kWh per battery • Material requirement in recycling process: 3.75 kWh per battery (i.e., 5% of 75-kWh battery)
Landfilling	• Maximum capacity: 245,098 batteries • Electricity consumption in the landfilling process: 10 kWh per battery
Storage	• Prioritization of storage utilization: Remanufacturing, repurposing, and recycling • Initial storage capacity: 65,814 batteries annually • Maximum storage capacity: 197,442 batteries annually • Storage capacity expansion: 65,814 batteries each expansion • Storage capacity expansion cost: $0.59 million each expansion

Note: References include Tesla (2021), Teerapat (2022), EA Annual Report (2023), EVAT (2023), Statista (2024a).

Table 5.4 Data related to costs of EOL management

Information	Detail
Investment cost	• Remanufacturing process: $17 million, including land for future purposes • Repurposing process: $30 million, including land for future purposes • Recycling process: $210 million, including land for future purposes
Electricity cost	• $0.12 per kWh

	• Electricity cost increasing rate: 3% annually
Material cost	• Material cost: \$139 per kWh • Minimum material cost: \$58 per kWh • Material decreasing rate: 15% annually
Inventory cost	• Inventory cost: \$161 per battery • Inventory cost increasing rate: 3% annually
Material handling cost	• Time duration from the drop-off to storage: 20 minutes • Time duration from the storage to EOL management facility: 30 minutes • Forklift electricity consumption: 8 kWh • Forklift capacity: 2 REVBs per round
Labor cost	• Annual salary: \$5,539 per person per year, on average • Salary increasing rate: 5% annually • Labor remanufacturing productivity: 206 batteries per person per year • Labor repurposing productivity: 156 batteries per person per year • Labor recycling productivity: 133 batteries per person per year
Overhead cost	• 10% of the total production cost
Landfill charge	• Local charge: \$62.18 per battery • Landfill charge in neighboring countries: \$248.72 per battery
Environmental cost	• \$0.0052 /kg CO_{2eq} • \$0.0169/kg 1,4-DB_{eq} • \$1.22 /kg SO_{2eq} • \$0.45 /kg $PM10_{eq}$ • \$3.57 /kg $NMVOC_{eq}$ • \$0.58 /m^3 H_2O_{eq} • \$0.25 /kg Fe_{eq}

	• \$24,387 /kg CFC-11_{eq} • \$0.26 /kg oil_{eq}

Note: References include Babin et al. (2018), Chunark and Limmeechokchai (2018), Odermatt (2018), Sathitsuksomboon and Pornpapatkul (2019), Guerra and Daziano (2020), Li and Chen (2020), Lu et al. (2020), Thananusak et al. (2020), SCB (2023), Li et al. (2021), Kotak et al. (2021), Teerapat (2022), EA Annual Report (2023), EVAT (2023), Statista (2024a).

5.3 Development of an SD model of REVB's EOL management

The SD model of REVB's EOL management comprises three sub-models: REVBs, EOL management process, and benefits and costs.

5.3.1 REVBs sub-model

The flow of BEV demand is in Figure 5.1 and Appendix B. It depends on its average increasing rate, key factors influencing the BEV demand, and loyal customers who repurchase BEVs every 10 years. Murnane and Ghazel (2002) mentioned that with a good and reliable BEV market, loyal customers will repurchase BEVs after 10 years. Once retired, the BEVs are bought back for the EOL management process. The remanufactured EVBs, once used as second-life EVBs for the BEV market, cannot be remanufactured and must be disposed of in landfills, see Equations 5.1-5.3.

$$\mathrm{REVB} = \mathrm{R} - \mathrm{LFR} \quad (5.1)$$

$$\mathrm{R} = \mathrm{History}(\mathrm{EVD}, \mathrm{Y} - 10) \quad (5.2)$$

$$\mathrm{LFR} = \mathrm{History}\ (\mathrm{RMEVB}, \mathrm{Y} - 10) \quad (5.3)$$

Where REVB = Retired EVBs (batteries)

R = Repurchased BEVs (vehicles)

RMEVB = Remanufactured EVBs (batteries)

Y = Year

EVD = BEV demand (vehicles)

LFR = Landfilled RMEVBs (batteries)

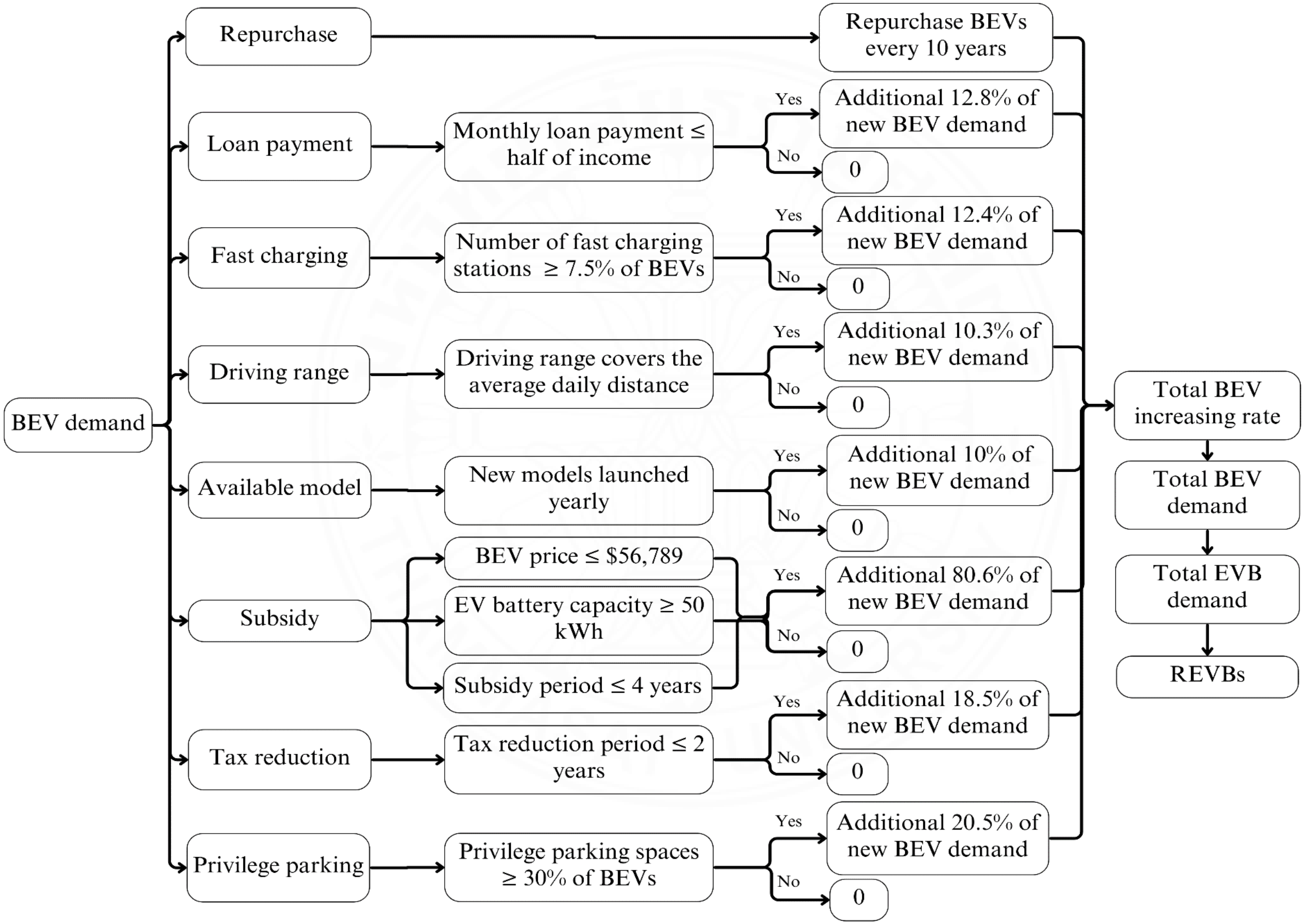


Figure 5.1 Flow of the BEV demand and REVBs

About 12.8% of customers may purchase new BEVs when they have the ability to pay loan and other related BEV expenses, see Equations 5.4 and 5.5 (Lu et al., 2020). According to SCB (2023), the average income in Thailand is $8,856 per year with an average increasing rate of 5% per year. SCB (2023) mentioned that at least half of the customer's income should be provided for the vehicle's loan payment. The average interest rate for vehicle loans is 4.75% per year, with a maximum loan period of six years (SCB, 2023).

$$\text{LP} \quad = \text{If}\ [[\text{S} \times (1.05)^{y-1}\ ]/2 \geq (\text{ALP} + \text{EVE})]\ \text{Then}\ 0.128\ \text{Else}\ 0 \tag{5.4}$$

$$\text{ALP} = (\text{EVP}/\text{I}) \times (1.0475)^{y-1} \tag{5.5}$$

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

S = Annual income ($)

ALP = Annual loan payment ($)

EVE = Annual BEV expenses ($)

EVP = BEV price ($)

I = Loan duration (years)

Carro (2023) 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 Equation 5.6. Based on Statista (2024a), the number of fast charging stations has increased by an average 6% annually in the past six years. However, with tax reduction of 8% from the EV 3.5 Policy, the number of fast charging stations is doubled in 2023 (EVAT, 2023). In this study, the increasing rate of fast charging stations is set at 100% until 2027 (i.e., four years of simulation) following the EV 3.5 Policy, see Equation 5.7. After that, the increasing rate is set at 6% (EVAT, 2021)

$$\text{CS} = \text{If}\ [\text{EVD} \times 0.075 \leq \left((1{+}\text{ACS}^{\text{Y}-1})\right) - \text{ACS}]\ \text{Then}\ 0.1243\ \text{Else}\ 0 \tag{5.6}$$

$$\mathrm{ACS} = \text{If } \mathrm{Y} \leq 4 \text{ Then } 1 \text{ Else } 0.06 \tag{5.7}$$

Where CS = Increasing rate of BEV customers from the fast-charging station factor (%)

ACS = Annual fast charging stations (stations)

The growth of the BEV market motivates manufacturers to enhance their production quality, particularly the driving ranges, to attract more BEV customers. Currently, the maximum driving range for BEVs is 491 km (with the battery capacity of 114 kWh), and the initial driving range is 53 km with an improved driving range of 20 km per year (Liu et al., 2023). Approximately 10.3% more customers may purchase BEVs if the driving ranges can accommodate their daily travel distances, which is 68.5 km per day on average, see Equations 5.8 and 5.9 (Lu et al., 2020).

$$\mathrm{DR} = \text{If History}(\mathrm{ADR}, \mathrm{Y} - 1) \geq 491 \text{ Then } 0 \text{ Else } (\text{If } (\mathrm{ADR} \geq 68.5) \text{ Then } 0.103 \text{ Else } 0) \tag{5.8}$$

$$\mathrm{ADR} = 53 + (\mathrm{IMDR} \times \mathrm{Y}) \tag{5.9}$$

Where DR = Increasing rate of BEV customers from the driving range factor (%)

ADR = Average driving range per battery (km)

IMDR = Improved driving range (km)

The rapid BEV sales welcome several brands to launch new models in the market. According to Wong et al. (2010), a new brand is introduced when the BEV demand is increased by half. It is expected that 10% more customers may purchase BEVs when they perceive various brands in the market, see Equation 5.10 (Yang and Tan, 2019).

$$\mathrm{AM} = \text{If } \mathrm{EVD} \geq [\text{History}(\mathrm{EVD}, \mathrm{Y} - 1) \times 1.5] \text{ Then } 0.1 \text{ Else } 0 \tag{5.10}$$

Where AM = Increasing rate of BEV customers from the available model factor (%)

The Thai government supports the BEV market through subsidies and tax reduction. Toyd (2021) stated that the subsidy of $2,760, which is about 5% of the average BEV price, can potentially attract new BEV customers by 80.6% (see Equation 5.11). This subsidy program lasts four years and applies to BEVs with battery capacities of at least 50 kWh and prices of up to $56,789 (EVAT, 2023). EVAT (2023) reported that battery capacities in Thailand range from 11 - 114 kWh, with 79.7% having the capacities of at least 50 kWh. Duangsrikaew et al. (2019) added that with advances in technologies, the EVB capacity improves by 2% annually, see Equation 5.12. The BEV prices in Thailand range from $11,428 - $342,857. About 46.3% of BEVs are in the ranges of up to $56,789 (EVAT, 2023). According to Bangkok Post (2023), the BEV price increases by 3% annually, see Equation 5.13.

$$\mathrm{SS} = \mathrm{If\ Y} \leq 4\ \mathrm{Then\ Min\ (EVC, PEP)} \times 0.806\ \mathrm{Else}\ 0 \qquad (5.11)$$

$$\mathrm{EVC} = \mathrm{If\ History\ (EVC, Y} - 1) \leq 1\ \mathrm{Then}\ 0.797 + (0.02 \times \mathrm{Y})\ \mathrm{Else}\ 1 \qquad (5.12)$$

$$\mathrm{PEP} = \mathrm{If\ History\ (PEP, Y} - 1) \leq 1\ \mathrm{Then}\ 0.463 + (0.03 \times \mathrm{Y})\ \mathrm{Else}\ 1 \qquad (5.13)$$

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

Thananusak et al. (2020) reported that the Thai government promotes the BEV market with the tax reduction of 40% in the next two year. This could attract up to 18.5% of new BEV customers, see Equation 5.14.

$$\mathrm{TR} = \mathrm{If\ Y} \leq 2\ \mathrm{Then}\ 0.185\ \mathrm{Else}\ 0 \qquad (5.14)$$

Where TR = Increasing rate of BEV customers from the tax reduction (%)

Thananusak et al. (2020) 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. Guerra and Daziano (2020) commented that the reserved or privileged parking spaces for BEVs should be at least 30% of the total BEVs to attract 20.5% more BEV customers, see Equation 5.15.

$$\text{PP} = \text{If}\ [\text{PS} \times (1.03)^{\text{Y}-1} \geq \text{EV} \times 0.3]\ \text{Then}\ 0.205\ \text{Else}\ 0 \quad (5.15)$$

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 5.16 and Appendix B. The BEV demand each year is then calculated, see Equation 5.17.

$$\text{IN} = \text{LP} + \text{CS} + \text{DR} + \text{AM} + \text{SS} + \text{TR} + \text{PP} \quad (5.16)$$

$$\text{EVD} = [\text{History}\ (\text{EVD}, \text{Y} - 1) \times (1 + \text{IN})] + \text{R} \quad (5.17)$$

Where IN = Additional increasing rate of BEV from key factors (%)

5.3.2 EOL management process sub-model

The calculation flow of EOL management process of REVBs is in Figure 5.2 and Appendix C.

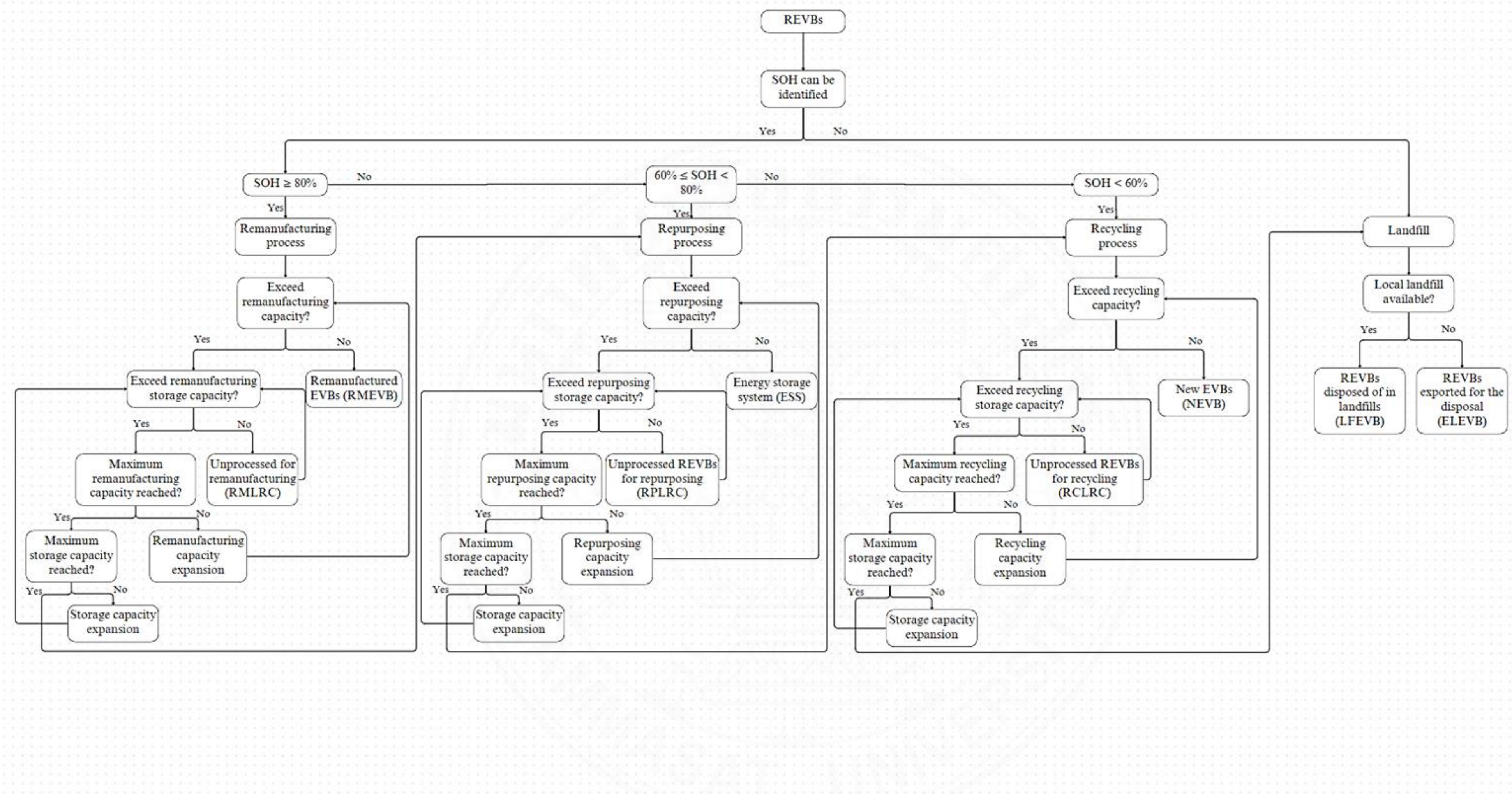


Figure 5.2 Flow of EOL management processes

The REVBs after a 10-year lifespan are examined with the SOHs to determine the possibility for proper EOL management (Harper et al., 2023). If the production capacity of the EOL management processes (i.e., remanufacturing, repurposing, and recycling) are lower than the number of incoming REVBs, then unprocessed REVBs are stocked in the storages and will be processed once the capacities are adequate. In this study, it is expected that the production capacities are double when the REVBs are twofold the current production capacities. Once the maximum production capacities are reached, the storage capacity is expanded, if possible, by 65,814 batteries each expansion to accommodate the stocked REVBs (Lee et al., 2021). The storage expansion continues until it reaches its maximum capacity of 197,442 batteries (EA Report, 2022). The exceeded unprocessed REVBs are then sent to landfills for disposal.

Based on Table 5.1, about 28% of REVBs with SOHs of at least 80% are designated for the remanufacturing process. The number of remanufactured EVBs (RMEVB) depends on the number of REVBs, stocked REVBs to be remanufactured (RMLRC), and remanufacturing capacities (RMC), see Equation 5.18 and Appendix C.

$$\mathrm{RMEVB} = \mathrm{If}\ [(\mathrm{REVB} \times 0.28) + \mathrm{RMLRC} \geq \mathrm{RMC}]\ \mathrm{Then\ RMC\ Else}\ [(\mathrm{REVB} \times 0.28) + \mathrm{RMLRC}] \quad (5.18)$$

Where RMEVB = Remanufactured EVBs (batteries)

RMLRC = Stocked REVBs to be remanufactured (batteries)

RMC = Remanufacturing capacity (batteries)

When the number of REVBs exceeds the remanufacturing capacity, the unprocessed REVBs are stocked in the storage available for all EOL management processes (i.e., remanufacturing, repurposing, and recycling), see Equation 5.19.

$$\mathrm{RMLRC} = (\mathrm{REVB} \times 0.28) + \mathrm{SREVB} - \mathrm{RPLRC} - \mathrm{RCLRC} - \mathrm{RMEVB} \quad (5.19)$$

Where SREVB = Stocked REVBs (batteries)

RPLRC = Stocked REVBs to be repurposed (batteries)

RCLRC = Stocked REVBs to be recycled (batteries)

The stocked REVBs (see Appendix C), accumulate annually, see Equation 5.20. Once the stocked REVBs are double the remanufacturing capacity, the remanufacturing capacity is expanded to increase the number of remanufactured EVBs, see Equation 5.21.

$$\mathrm{SREVB} = \mathrm{If\ History\ (SREVB, Y-1) + RMLRC + RPLRC + RCLRC \geq SC\ Then\ SC\ Else\ History\ (SREVB, Y-1) + RMLRC + RPLRC + RCLRC} \quad (5.20)$$

$$\mathrm{RMC} = \mathrm{If\ [(REVB \times 0.28) + RMLRC \geq History\ (RMC, Y-1) \times 2]\ Then\ History\ (RMC, Y-1) \times 2\ Else\ History\ (RMC, Y-1)} \quad (5.21)$$

Where SC = Storage capacity (batteries)

When the maximum remanufacturing capacity is reached and cannot remanufacture all REVBs, the storage capacity is expanded, if possible, see Equation 5.22.

$$\mathrm{SC} = \mathrm{If\ (RMC = Max\ RMC)\ and\ (SREVB = SC)\ Then\ History\ (SC, Y-1) + 65814\ Else\ SC} \quad (5.22)$$

The storage capacity continues to expand until it reaches its maximum capacity. Subsequently, the REVBs that cannot be remanufactured proceed with the repurposing process, see Equation 5.23.

$$\mathrm{RPFRM} = \mathrm{If\ (SC = Max\ SC)\ Then\ (RMLRC - SC) Else\ 0} \quad (5.23)$$

Where RPFRM = Un-remanufactured REVBs forwarded for repurposing (batteries)

The unprocessed REVBs that are proceeded with the repurposing process and REVBs with the SOHs between 60 to 79% (i.e., 52% of total REVBs) are considered for the repurposing process (Skeete et al., 2020). The number of energy storage system (ESS) provided from the repurposed REVBs depends on the number of REVBs, stocked REVBs to be repurposed (RPLRC), and repurposing capacities (RPC), see Equation 5.24.

$$\mathrm{ESS} = \mathrm{If}\ [(\mathrm{REVB} \times 0.52) + \mathrm{RPLRC} \geq \mathrm{RPC}]\ \mathrm{Then\ RPC\ Else}\ [(\mathrm{REVB} \times 0.52) + \mathrm{RPLRC}] \tag{5.24}$$

Where ESS = Energy storage system (batteries)

RPC = Repurposing capacity (batteries)

When the number of REVBs exceeds the repurposing capacity, the unprocessed REVBs are stored in storage, if the space is available, see Equations 5.25 and 5.26. Otherwise, the repurposing capacity (RPC) expansion is considered, see Equation 5.27.

$$\mathrm{RPLRC} = \mathrm{If}\ (\mathrm{REVB} \times 0.52) + \mathrm{SREVB} - \mathrm{RMLRC} - \mathrm{RCLRC} - \mathrm{ESS} + \mathrm{RPFRM} \geq \mathrm{RPSC\ Then\ RPSC\ Else}(\mathrm{REVB} \times 0.52) + \mathrm{SREVB} - \mathrm{RMLRC} - \mathrm{RCLRC} - \mathrm{ESS} + \mathrm{RPFRM} \tag{5.25}$$

$$\mathrm{RPSC} = \mathrm{SC} - \mathrm{RMLRC} \tag{5.26}$$

$$\mathrm{RPC} = \mathrm{If}\ [(\mathrm{REVB} \times 0.52) + \mathrm{RPLRC} \geq \mathrm{History}\ (\mathrm{RPC}, \mathrm{Y} - 1) \times 2]\ \mathrm{Then\ History}\ (\mathrm{RPC}, \mathrm{Y} - 1) \times 2\ \mathrm{Else\ History}\ (\mathrm{RPC}, \mathrm{Y} - 1) \tag{5.27}$$

Where RPSC = Repurposing storage capacity (batteries)

Once the repurposing expansion reaches its maximum capacity, the un-repurposed REVBs are forwarded to the recycling station, see Equation 5.28.

$$\text{RCFRP} = \text{If}\ (\text{SC} = \text{Max SC})\ \text{Then}\ (\text{RPLRC} - \text{RPSC})\ \text{Else}\ 0 \qquad (5.28)$$

Where RCFRP = Un-repurposed REVBs forwarded for recycling (batteries)

The unprocessed REVBs that are proceeded with the recycling process and REVBs with SOHs below 60% (i.e., 18% of total REVBs) are proceeded with the recycling process (Casals et al., 2017). The number of new EVBs (NEVB) from recycled REVBs depends on the number of REVBs, stocked REVBs to be recycled (RCLRC), and recycling capacities (RCC), see Equation 5.29 and Appendix C.

$$\text{NEVB} = \text{If}\ [(\text{REVB} \times 0.18) + \text{RCLRC} \geq \text{RCC}]\ \text{Then RCC Else}\ [(\text{REVB} \times 0.18) + \text{RCLRC}] \qquad (5.29)$$

Where NEVB = New EVBs (batteries)
RCC = Recycling capacity (batteries)

When the number of REVBs exceeds the recycling capacity, the unprocessed REVBs are stored in storage if the space is available or else the recycling capacity is expanded (see Equations 5.30-5.32).

$$\text{RCLRC} = \text{If}\ (\text{REVB} \times 0.52) + \text{SREVB} - \text{RMLRC} - \text{RPLRC} - \text{NEVB} + \text{RCFRP} \geq \text{RCSC Then RCSC Else}(\text{REVB} \times 0.52) + \text{SREVB} - \text{RMLRC} - \text{RPLRC} - \text{NEVB} + \text{RPFRM} \qquad (5.30)$$

$$\text{RCSC} = \text{RPSC} - \text{RPLRC} \qquad (5.31)$$

$$\text{RCC} = \text{If } (\text{REVB} \times 0.18) + \text{RCLRC} \geq \text{History } (\text{RCC}, \text{Y} - 1) \times 2 \text{ Then History } (\text{RCC}, \text{Y} - 1) \times 2 \text{ Else History } (\text{RCC}, \text{Y} - 1) \quad (5.32)$$

Where RCSC = Recycling storage capacity (batteries)

The REVBs that cannot be recycled are sent to landfills for disposal, see Equation 5.33.

$$\text{LFFRC} = \text{If } (\text{SC} = \text{Max SC}) \text{ Then } (\text{RCLRC} - \text{RCSC}) \text{ Else } 0 \quad (5.33)$$

Where LFFRC = Un-recycled REVBs forwarded for landfilling (batteries)

The space at local landfills is limited. The unprocessed REVBs are sent to neighboring countries for disposal when the local landfill's capacity is reached, which is 245,098 batteries (see Equations 5.34-5.36 and Appendix C) (Casals et al., 2017).

$$\text{ALEVB}(\text{t}) = \text{ALEVB}(\text{t} - \text{dt}) + (\text{ALEVB} \times \text{dt}) \quad (5.34)$$

$$\text{ALEVB} = (\text{REVB} \times 0.02) + \text{LFFRC} \quad (5.35)$$

$$\text{ELEVB} = \text{If ALEVB} > \text{MLC Then ALEVB} - \text{MLC Else } 0 \quad (5.36)$$

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

5.3.3 Benefits and costs sub-model

Benefits and costs, including the environmental costs, of EOL management depend on the processes (i.e., remanufacturing, repurposing, recycling, and landfilling), see Figure

5.3 and Appendix D. Benefits are achieved from selling the remanufactured EVBs, energy storage system, and new EVBs from recycled materials at the prices of \$5,696, \$6,554, and \$6,690 per battery, respectively (see Equations 5.37-5.40) (EA Report, 2022; EVAT, 2023; Toyota, 2023).

$$\text{TB} = \text{RMB} + \text{RPB} + \text{RCB} \tag{5.37}$$

$$\text{REB} = \text{RMEVB} \times 5696 \tag{5.38}$$

$$\text{ESB} = \text{ESS} \times 6554 \tag{5.39}$$

$$\text{NEB} = \text{NEVB} \times 6690 \tag{5.40}$$

Where TB = Total benefits (\$)
REB = Benefits from remanufactured EVBs (\$)
ESB = Benefits from energy storage system (\$)
NEB = Benefits from new EVBs provided from recycled materials (\$)

Costs, on the other hand, include buyback, investment, electricity, material, inventory, material handling, labor, overhead, expansion, and landfill charge (see Appendix D). The investment cost (INC) of the remanufacturing facility, with a maximum capacity of 132,320 batteries, is \$17 million while the repurposing and recycling facility investment cost are \$30 million and \$210 million, respectively (EA Report, 2022; Tesla, 2021). The buyback rate of REVBs for remanufacturing, repurposing, and recycling are 40%, 30%, and 15% of the original EVB price, respectively (see Equations 5.41-5.44) (Casals et al., 2017; Kotak et al., 2021). REVBs with low SOHs (i.e., less than 60%) are disposed of in landfills with landfill charges of (see Equation 5.73) (Casals et al., 2017).

$$\text{TBC} = \text{REBC} + \text{ESBC} + \text{NEBC} \tag{5.41}$$

$$\mathrm{REBC} = 0.4 \times \mathrm{BP} \times \mathrm{REVB} \times 0.28 \quad (5.42)$$

$$\mathrm{ESBC} = 0.3 \times \mathrm{BP} \times \mathrm{REVB} \times 0.52 \quad (5.43)$$

$$\mathrm{NEBC} = 0.15 \times \mathrm{BP} \times \mathrm{REVB} \times 0.18 \quad (5.44)$$

Where TBC = Total buyback cost of REVBs ($)
REBC = Buyback cost of REVBs for remanufacturing ($ per battery)
ESBC = Buyback cost of REVBs for repurposing ($ per battery)
NEBC = Buyback cost of REVBs for recycling ($ per battery)
BP = Battery price ($)

The electricity cost for the remanufacturing, repurposing, and recycling processes is average at $0.12 per kWh with an increasing rate of 3% annually (Sato and Nakata, 2019; Golinska and Kawa, 2021). The remanufacturing, repurposing and recycling processes consume electricity of 360, 840, and 3514 kWh per battery, respectively (see Equations 5.45-5.48) (Gu et al., 2018; Tesla, 2021).

$$\mathrm{TEC} = \mathrm{REEC} + \mathrm{ESEC} + \mathrm{NEEC} \quad (5.45)$$

$$\mathrm{REEC} = 0.12 \times 360 \times (1.03)^{y-1} \times \mathrm{RMEVB} \quad (5.46)$$

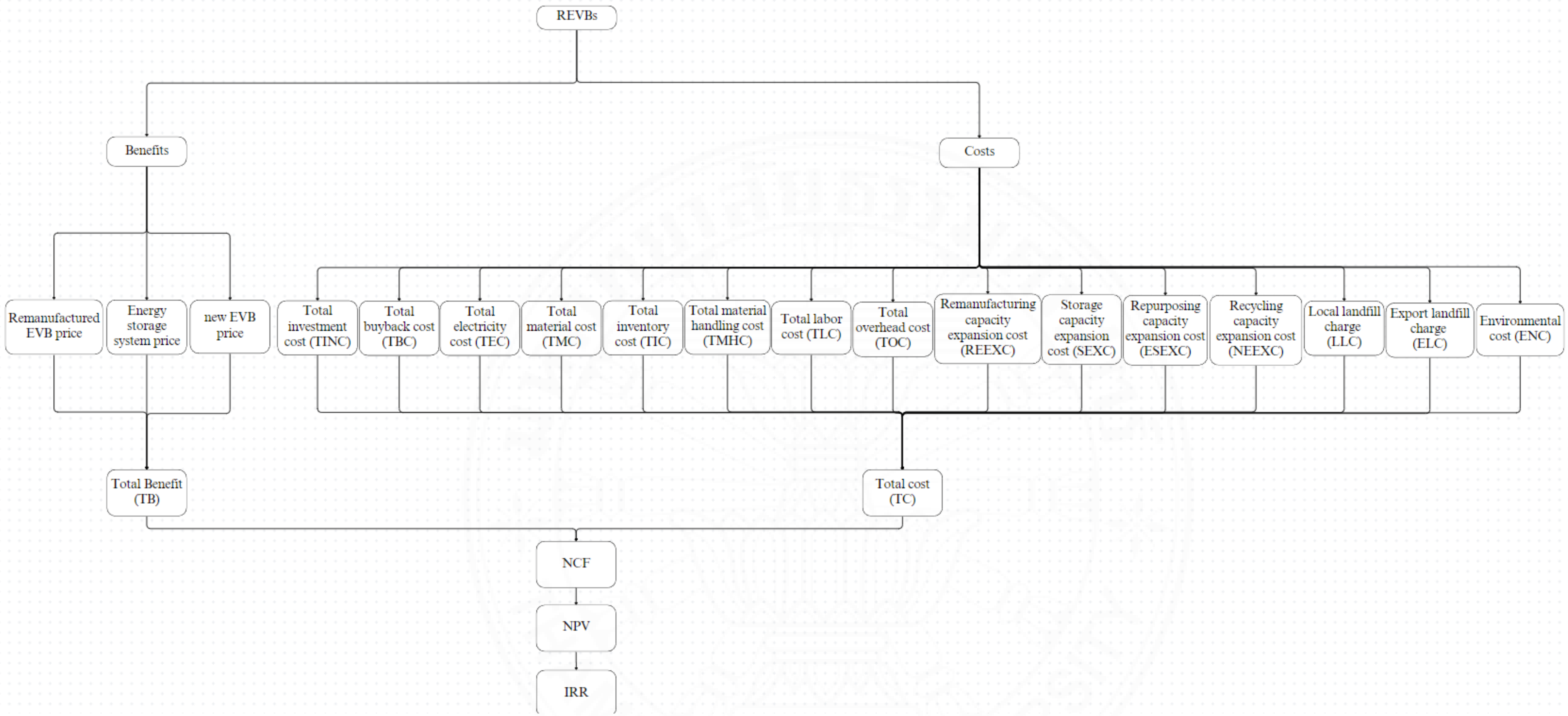


Figure 5.3 Flow of benefits and costs of EOL management processes

$$\text{ESEC} = 0.12 \times 840 \times (1.03)^{y-1} \times \text{ESS} \tag{5.47}$$

$$\text{NEEC} = 0.12 \times 3514 \times (1.03)^{y-1} \times \text{NEVB} \tag{5.48}$$

Where TEC = Electricity cost ($)
REEC = Electricity cost for remanufacturing ($)
ESEC = Electricity cost for repurposing ($)
NEEC = Electricity cost for recycling ($)

Materials required for the EOL management processes depend on the battery cell replacement. For instance, in the remanufacturing process, about 20% of the battery cells (with an average capacity of 75 kWh) are replaced. REVBs for repurposing require more extensive cell replacement, with 40% of the cells being replaced due to lower quality compared with those for remanufacturing process. Conversely, the recycling process recovers most of the materials, with 95% of materials being reclaimed, thus requiring only 5% of the new battery cells to produce new EVBs (see Equations 5.49-5.52). Statista (2024b) stated that the material prices have decreased by 15% annually over the past 10 years and are projected to drop to a minimum of $58 per kWh.

$$\text{TMC} = \text{REMC} + \text{ESMC} + \text{NEMC} \tag{5.49}$$

$$\text{REMC} = \text{If History (MP, Y} - 1) > 58 \text{ Then [History (MP, Y} - 1) \times 0.85] \times 0.2 \times 75 \times \text{RMEVB Else } 58 \times 0.2 \times 75 \times \text{RMEVB} \tag{5.50}$$

$$\text{ESMC} = \text{If History (MP, Y} - 1) > 58 \text{ Then [History (MP, Y} - 1) \times 0.85] \times 0.3 \times 75 \times \text{ESS Else } 58 \times 0.3 \times 75 \times \text{ESS} \tag{5.51}$$

$$\text{NEMC} = \text{If History (MP, Y} - 1) > 58 \text{ Then [History (MP, Y} - 1) \times 0.85] \times 0.05 \times 75 \times \text{NEVB Else } 58 \times 0.05 \times 75 \times \text{NEVB} \tag{5.52}$$

Where TMC = Total material cost ($)
REMC = Material cost for remanufacturing ($)

ESMC = Material cost for repurposing ($)
NEMC = Material cost for recycling ($)
MP = Material price ($ per kWh)

The stocked REVBs incur an annual inventory cost (IC) of $161 per battery, with an increasing rate of 3% per year, see Equations 5.53-5.56 (Guerra and Daziano, 2020).

$$\mathrm{TIC} = \mathrm{REIC} + \mathrm{ESIC} + \mathrm{NEIC} \tag{5.53}$$

$$\mathrm{REIC} = (161 \times (1.03)^{y-1}) \times \mathrm{RMLRC} \tag{5.54}$$

$$\mathrm{ESIC} = (161 \times (1.03)^{y-1}) \times \mathrm{RPLRC} \tag{5.55}$$

$$\mathrm{NEIC} = (161 \times (1.03)^{y-1}) \times \mathrm{RCLRC} \tag{5.56}$$

Where TIC = Total inventory cost ($)
REIC = Inventory cost for remanufacturing ($)
ESIC = Inventory cost for repurposing ($)
NEIC = Inventory cost for recycling ($)

The material handling process in EOL management encompasses three transportations: from the drop-off to the storage, from the storage to the facility, and from the facility to the storage. Chen et al. (2021b) stated that the handling in the remanufacturing process uses forklifts and incurs the expense of $0.12 per kWh. Each 8-kWh forklift is required to transport two batteries between the facilities, which takes about an hour per round (Lu et al., 2020). The material handling cost (MHC) is in Equations 5.57-5.60.

$$\mathrm{TMHC} = \mathrm{RMMHC} + \mathrm{RPMHC} + \mathrm{RCMHC} \tag{5.57}$$

$$\mathrm{RMMHC} = (0.12 \times 8 \times \mathrm{DOS} \times (\mathrm{REVB} \times 0.28)/2) + (0.12 \times 8 \times \mathrm{SRF} \times \mathrm{RMEVB}/2) + (0.12 \times 8 \times \mathrm{FRS} \times \mathrm{RMEVB}/2) \quad (5.58)$$

$$\mathrm{ESMHC} = (0.12 \times 8 \times \mathrm{DOS} \times (\mathrm{REVB} \times 0.52)/2) + (0.12 \times 8 \times \mathrm{SRF} \times \mathrm{ESS}/2) + (0.12 \times 8 \times \mathrm{FRS} \times \mathrm{ESS}/2) \quad (5.59)$$

$$\mathrm{NEMHC} = (0.12 \times 8 \times \mathrm{DOS} \times (\mathrm{REVB} \times 0.18)/2) + (0.12 \times 8 \times \mathrm{SRF} \times \mathrm{NEVB}/2) + (0.12 \times 8 \times \mathrm{FRS} \times \mathrm{NEVB}/2) \quad (5.60)$$

Where TMHC = Total material handling cost ($)

RMMHC = Material handling cost for remanufacturing ($)

RPMHC = Material handling cost for repurposing ($)

RCMHC = Material handling cost for recycling ($)

DOS = Time duration from the drop-off to the storage (hour)

SRF = Time duration from the storage to the facilities (hour)

FRS = Time duration from the facilities to the storage (hour)

Fulltime workers in the automotive industry receive an average annual salary of $5,539 with an annual increasing rate of 5% (Thai Publica, 2021). The labor cost (LC) depends on the number of REVBs to be processed, labor productivity, and worker's salary, see Equations 5.61-5.64.

$$\mathrm{TLC} = \mathrm{RELC} + \mathrm{ESLC} + \mathrm{NELC} \quad (5.61)$$

$$\mathrm{RELC} = [((\mathrm{REVB} \times 0.28\ ) + \mathrm{RMLRC})/\mathrm{RMCP}] \times \mathrm{ALS} \times (1.05)^{\mathrm{Y}-1} \quad (5.62)$$

$$\mathrm{ESLC} = [((\mathrm{REVB} \times 0.52\ ) + \mathrm{RPLRC})/\mathrm{RPCP}] \times \mathrm{ALS} \times (1.05)^{\mathrm{Y}-1} \quad (5.63)$$

$$\mathrm{NELC} = [((\mathrm{REVB} \times 0.18\ ) + \mathrm{RCLRC})/\mathrm{RCCP}] \times \mathrm{ALS} \times (1.05)^{\mathrm{Y}-1} \quad (5.64)$$

Where TLC = Total labor cost ($)

RELC = Labor cost for remanufacturing ($)

RMCP = Remanufacturing labor productivity per person per year (batteries)

ALS = Annual salary in the automotive industry ($)

ESLC = Labor cost for repurposing ($)

RPCP = Repurposing labor productivity per person per year (batteries)

NELC = Labor cost for recycling ($)

RCCP = Recycling labor productivity per person per year (batteries)

The overhead cost (OC) of the EOL management processes includes the facility maintenance, utilities, administrative, and other indirect expenses not tied to the units processed (Muller, 2003). It constitutes an additional 10% of the total production cost, see Equations 5.65-5.68 (Brom et al., 2016).

$$\mathrm{TOC} = \mathrm{REOC} + \mathrm{ESOC} + \mathrm{NEOC} \tag{5.65}$$

$$\mathrm{REOC} = (\mathrm{REEC} + \mathrm{REMC} + \mathrm{REIC} + \mathrm{REMHC} + \mathrm{RELC}) \times 0.1 \tag{5.66}$$

$$\mathrm{ESOC} = (\mathrm{ESEC} + \mathrm{ESMC} + \mathrm{ESIC} + \mathrm{ESMHC} + \mathrm{ESLC}) \times 0.1 \tag{5.67}$$

$$\mathrm{NEOC} = (\mathrm{NEEC} + \mathrm{NEMC} + \mathrm{NEIC} + \mathrm{NEMHC} + \mathrm{NELC}) \times 0.1 \tag{5.68}$$

Where TOC = Total overhead cost ($)

REOC = Overhead cost for remanufacturing ($)

ESOC = Overhead cost for repurposing ($)

NEOC = Overhead cost for recycling ($)

The facility expansion is crucial to accommodate the second-life products of REVBs. According to Gaines and Cuenca (2020), the expansion costs for remanufacturing and storage capacities are $1.33 million (for 16,584 batteries) and $0.59 million (for 65,814 batteries) (EA Report, 2022). The repurposing process requires more machinery, resulting in an expansion cost of $2.01 million (for 29,607 batteries) (Casals and Garcia, 2016). The recycling process also requires complex facilities, thus costing \$2.66 million per expansion (for 25,893 batteries) (see Equations 5.69-5.72) (Foster et al., 2014).

$$\mathrm{REEXC} = \mathrm{If}\ [\mathrm{History}\ (\mathrm{RMC}, \mathrm{Y}-1)/\mathrm{RMC}] = 1\ \mathrm{Then}\ 0\ \mathrm{Else}\ 1330000 \times [\mathrm{RMC} - \mathrm{History}\ (\mathrm{RMC}, \mathrm{Y}-1)/16584] \quad (5.69)$$

$$\mathrm{SEXC} = \mathrm{If}\ [\mathrm{History}\ (\mathrm{SC}, \mathrm{Y}-1)/\mathrm{SC}] = 1\ \mathrm{Then}\ 0\ \mathrm{Else}\ 590000 \times [\mathrm{SC} - \mathrm{History}\ (\mathrm{SC}, \mathrm{Y}-1)/65814] \quad (5.70)$$

$$\mathrm{ESEXC} = \mathrm{If}\ [\mathrm{History}\ (\mathrm{RPC}, \mathrm{Y}-1)/\mathrm{RPC}] = 1\ \mathrm{Then}\ 0\ \mathrm{Else}\ 6030000 \times [\mathrm{RPC} - \mathrm{History}\ (\mathrm{RPC}, \mathrm{Y}-1)/29607] \quad (5.71)$$

$$\mathrm{NEEXC} = \mathrm{If}\ [\mathrm{History}(\mathrm{RCC}, \mathrm{Y}-1)/\mathrm{RCC}] = 1\ \mathrm{Then}\ 0\ \mathrm{Else}\ 21600000 \times [(\mathrm{RCC} - \mathrm{History}(\mathrm{RCC}, \mathrm{Y}-1))/25893] \quad (5.72)$$

Where REEXC = Remanufacturing capacity expansion cost (\$)
SEXC = Storage capacity expansion cost (\$)
ESEXC = Repurposing capacity expansion cost (\$)
NEEXC = Recycling capacity expansion cost (\$)

Landfill cost depends on the number of REVBs disposed of in landfill and landfill charges, see Equation 5.73 and Appendix D.

$$\mathrm{LEVBC} = \mathrm{If}\ \mathrm{ALEVB} > \mathrm{MLC}\ \mathrm{Then}\ [(\mathrm{MLC} \times 62.18) + (\mathrm{ELEVB} \times 248.72)]\ \mathrm{Else}\ \mathrm{ALEVB} \times 62.18 \quad (5.73)$$

Where TLFC= Total landfill cost (\$)

The environmental cost is achieved by converting environmental impacts in Chapter 4 to the cost data. The EOL management process that reduces the environmental impacts has negative environmental costs, i.e., producing benefits from the EOL management process. In contrast, the EOL management process that generates the environmental impacts incurs the environmental cost and will be added to the total cost. For instance, the remanufacturing process reduces CO_{2eq} by 1,193 kg per battery (see Table 4.4). The CO_{2eq} reduction is converted to the environmental cost by multiplying the CO_{2eq} reduction with the carbon credit of $0.0052 per kg of CO_{2eq} (see Table 5.4). This gives negative environmental costs, i.e., benefits from the remanufacturing process. Based on Table 4.4, the remanufacturing and repurposing processes gain benefits from CO_{2eq} reduction, while the recycling and landfilling processes generate the environmental costs from CO_{2eq} generation.

The environmental costs from the environmental impacts in Chapter 4 are calculated in Equations 5.74-5.82.

$$\mathrm{TCOC} = (\mathrm{RMCO} \times \mathrm{RMEVB}) + (\mathrm{RPCO} \times \mathrm{ESS}) + (\mathrm{RCCO} \times \mathrm{NEVB}) + (\mathrm{LFCO} \times \mathrm{ALEVB}) \times 0.0052 \quad (5.74)$$

$$\mathrm{THTC} = (\mathrm{RMHTC} \times \mathrm{RMEVB}) + (\mathrm{RPHTC} \times \mathrm{ESS}) + (\mathrm{RCHTC} \times \mathrm{NEVB}) + (\mathrm{LFHTC} \times \mathrm{ALEVB}) \times 0.59 \quad (5.75)$$

$$\mathrm{TTAC} = (\mathrm{RMTAC} \times \mathrm{RMEVB}) + (\mathrm{RPTAC} \times \mathrm{ESS}) + (\mathrm{RCTAC} \times \mathrm{NEVB}) + (\mathrm{LFTAC} \times \mathrm{ALEVB}) \times 1.22 \quad (5.76)$$

$$\mathrm{TPMC} = (\mathrm{RMPMC} \times \mathrm{RMEVB}) + (\mathrm{RPPMC} \times \mathrm{ESS}) + (\mathrm{RCPMC} \times \mathrm{NEVB}) + (\mathrm{LFPMC} \times \mathrm{ALEVB}) \times 0.45 \quad (5.77)$$

$$\mathrm{TPOC} = (\mathrm{RMPOC} \times \mathrm{RMEVB}) + (\mathrm{RPPOC} \times \mathrm{ESS}) + (\mathrm{RCPOC} \times \mathrm{NEVB}) + (\mathrm{LFPOC} \times \mathrm{ALEVB}) \times 125.06 \quad (5.78)$$

$$\mathrm{TWDC} = (\mathrm{RMWDC} \times \mathrm{RMEVB}) + (\mathrm{RPWDC} \times \mathrm{ESS}) + (\mathrm{RCWDC} \times \mathrm{NEVB}) + (\mathrm{LFWDC} \times \mathrm{ALEVB}) \times 0.58 \quad (5.79)$$

$$\mathrm{TMDC} = (\mathrm{RMMDC} \times \mathrm{RMEVB}) + (\mathrm{RPMDC} \times \mathrm{ESS}) + (\mathrm{RCMDC} \times \mathrm{NEVB}) + (\mathrm{LFMDC} \times \mathrm{ALEVB}) \times 1.09 \quad (5.80)$$

$$\mathrm{TODC} = (\mathrm{RMODC} \times \mathrm{RMEVB}) + (\mathrm{RPODC} \times \mathrm{ESS}) + (\mathrm{RCODC} \times \mathrm{NEVB}) + (\mathrm{LFODC} \times \mathrm{ALEVB}) \times 24387 \quad (5.81)$$

$$\mathrm{TFDC} = (\mathrm{RMFDC} \times \mathrm{RMEVB}) + (\mathrm{RPFDC} \times \mathrm{ESS}) + (\mathrm{RCFDC} \times \mathrm{NEVB}) + (\mathrm{LFFDC} \times \mathrm{ALEVB}) \times 0.26 \quad (5.82)$$

Where TCOC = Total CO_{2eq} cost ($)

RMCO = CO_{2eq} emission of remanufacturing (kg CO_{2eq})

RPCO = CO_{2eq} emission of repurposing (kg CO_{2eq})

RCCO = CO_{2eq} emission of recycling (kg CO_{2eq})

LFCO = CO_{2eq} emission of landfilling (kg CO_{2eq})

THTC = Total human toxicity cost ($)

RMHTC= Human toxicity of remanufacturing (kg 1,4-DB_{eq})

RPHTC= Human toxicity of repurposing (kg 1,4-DB_{eq})

RCHTC= Human toxicity of recycling (kg 1,4-DB_{eq})

LFHTC= Human toxicity of landfilling (kg 1,4-DB_{eq})

TTAC = Total terrestrial acidification cost ($)

RMTAC= Terrestrial acidification of remanufacturing (kg SO_{2eq})

RPTAC= Terrestrial acidification of repurposing (kg SO_{2eq})

RCTAC= Terrestrial acidification of recycling (kg SO_{2eq})

LFTAC= Terrestrial acidification of landfilling (kg SO_{2eq})

TPMC = Total PM formation cost ($)

RMPMC= PM formation of remanufacturing (kg $PM10_{eq}$)

RPPMC= PM formation of repurposing (kg $PM10_{eq}$)

RCPMC= PM formation of recycling (kg $PM10_{eq}$)

LFPMC= PM formation of landfilling (kg $PM10_{eq}$)

TPOC = Total photochemical oxidant formation cost ($)

RMPOC= Photochemical oxidant formation of remanufacturing (kg NMVOC)

RPPOC= Photochemical oxidant formation of repurposing (kg NMVOC)

RCPOC= Photochemical oxidant formation of recycling (kg NMVOC)

LFPOC= Photochemical oxidant formation of landfilling (kg NMVOC)

TWDC = Total water depletion cost ($)

RMWDC= Water depletion of remanufacturing (m^3 H_2O_{eq})

RPWDC= Water depletion of repurposing (m^3 H_2O_{eq})

RCWDC= Water depletion of recycling (m^3 H_2O_{eq})

LFWDC= Water depletion of landfilling (m^3 H_2O_{eq})

TMDC = Total metal depletion cost ($)

RMMDC= Metal depletion of remanufacturing (kg Fe_{eq})

RPMDC= Metal depletion of repurposing (kg Fe_{eq})

RCMDC= Metal depletion of recycling (kg Fe_{eq})

LFMDC= Metal depletion of landfilling (kg Fe_{eq})

TODC = Total ozone depletion cost ($)

RMODC= Ozone depletion of remanufacturing (kg CFC-11_{eq})

RPODC= Ozone depletion of repurposing (kg CFC-11_{eq})

RCODC= Ozone depletion of recycling (kg CFC-11_{eq})

LFODC= Ozone depletion of landfilling (kg CFC-11_{eq})

TFDC = Total fossil depletion cost ($)

RMFDC= Fossil depletion of remanufacturing (kg oil_{eq})

RPFDC= Fossil depletion of repurposing (kg oil_{eq})

RCFDC= Fossil depletion of recycling (kg oil_{eq})

LFFDC= Fossil depletion of landfilling (kg oil_{eq})

The total cost is achieved by summing all costs, see Equation 5.83. The net cash flow (NCF) and internal rate of return (IRR) values are then calculated, see Equations 5.84 and 5.85.

$$\mathrm{TC} = \mathrm{TINC} + \mathrm{TBC} + \mathrm{TEC} + \mathrm{TMC} + \mathrm{TIC} + \mathrm{TMHC} + \mathrm{TLC} + \mathrm{TOC} + \mathrm{REEXC} + \mathrm{ESEXC} + \mathrm{NEEXC} + \mathrm{TLFC} + \mathrm{TCOC} + \mathrm{THTC} + \mathrm{TTAC} + \mathrm{TPMC} + \mathrm{TPOC} + \mathrm{TWDC} + \mathrm{TMDC} + \mathrm{TODC} + \mathrm{TFDC} \quad (5.83)$$

$$\mathrm{NCF} = \mathrm{TB} - \mathrm{TC} \quad (5.84)$$

$$\text{IRR} = \left(\sum_{y=1}^{n} \text{NCF} / \text{NCF}_{y=1}\right) - 1 \quad (5.85)$$

Where TC = Total cost ($)

NCF = Net cash flow ($)

IRR = Internal rate of return (%)

n = Project duration (years)

Full SD equations of the REVB's EOL management dynamics model are in Appendix E.

5.4 Simulation results

The SD model of EOL management of REVBs was simulated to examine the feasibility and its long-term effects. Table 5.5 shows the trend of BEV demand and REVBs in the next 30 years. The BEV demand builds up to 78 million units in 30 years. The highest jump in demand occurs in year 4, where the increasing rate from the previous year becomes the highest (i.e., 139.54%). This projection aligns with the Thailand National EV Goal, anticipating the number of BEVs to reach 30% of total passenger vehicle sales, or approximately 2.5 million vehicles, in the next 20 years, i.e., year 2040 (EVAT, 2021). Consequently, the increase in BEV demand brings a substantial rise in REVBs, which is expected to grow ten-fold in nine years and twenty-fold in 12 years, reaching 4.2 million REVBs in 30 years.

Table 5.5 The long-term trend of BEV demand and REVBs

Year	BEV demand (vehicles)	Increasing rate from its previous year (%)	REVBs (batteries)	Increasing rate from its previous year (%)
1	7,705	0	517	0
2	11,771	52.77	1,034	100.00
3	17,505	48.72	1,292	24.95
4	41,932	139.54	1,615	25.00
5	68,769	64.00	2,019	25.02
6	85,859	24.85	2,524	25.01

7	108,675	26.57	3,155	25.00
8	137,564	26.58	3,944	25.01
9	174,128	26.58	4,931	25.03
10	220,406	26.58	6,164	25.01
11	346,570	57.24	7,560	22.65
12	449,510	29.70	11,254	48.86
13	582,036	29.48	16,471	46.36
14	830,196	42.64	40,640	146.73
15	1,112,678	34.03	67,154	65.24
16	1,459,325	32.70	83,840	24.85
17	1,920,206	32.70	106,151	26.61
18	2,527,234	32.70	134,409	26.62
19	3,326,908	32.70	170,184	26.62
20	4,380,563	32.70	215,475	26.61
21	6,037,677	32.70	340,406	57.98
22	7,986,076	32.70	441,950	29.83
23	10,560,093	32.70	570,782	29.15
24	14,258,220	32.70	813,725	42.56
25	18,992,985	32.70	1,072,038	31.74
26	25,180,897	32.70	1,392,171	29.86
27	33,408,777	32.70	1,836,367	31.91
28	44,327,861	32.70	2,421,083	31.84
29	58,819,127	32.70	3,192,498	31.86
30	78,052,059	32.70	4,210,378	31.88

Figure 5.4 reveals key factors influencing BEV demand. The results show that the provision of parking privileges to BEV users and reduction in BEV prices from advanced technology significantly boosts the BEV demand. Offering this privilege ensures that BEV users have access to designated parking spaces in major city areas, making the use of BEVs more convenient and attractive. Additionally, the provision of

charging facilities at these parking spots facilitates users to charge while parking (Luo and Qiu, 2020).

Table 5.6 shows the number of REVBs with four EOL management options: remanufacturing, repurposing, recycling, and landfilling. With a small number of REVBs in the early years, the second-life products, i.e., remanufactured EVBs, energy storage systems, and new EVBs from the recycled materials are small. The manufacturers initially stock REVBs prior to expanding their production capacities. It allows the demand to increase to the point where the expansion is worth the investment.

The results show that remanufacturing capacity can accommodate the REVBs until year 20 when the first expansion occurs. On the other hand, the repurposing and recycling capacities are first expanded in years 19 and 20, respectively.

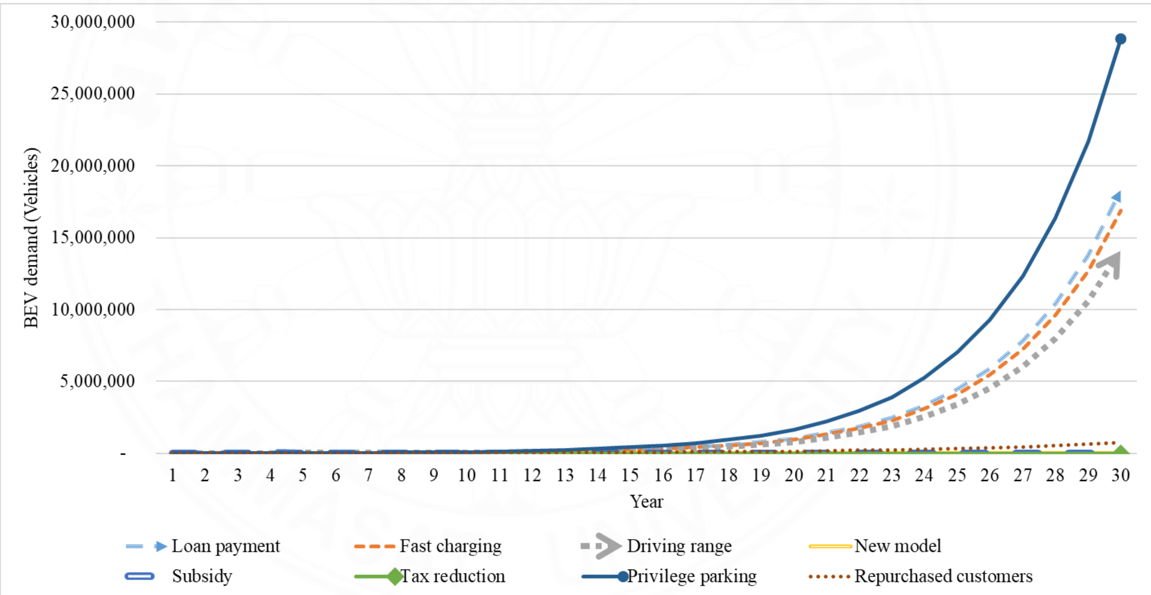


Figure 5.4 Graphical results of BEV demand

Table 5.6 The second-life EVBs applications

Year	Remanufactured EVBs (batteries)	Energy storage system (batteries)	New EVBs (batteries)	Landfilled REVBs (batteries)
1	145	269	93	10
2	290	538	186	21
3	362	672	233	26

4	452	840	291	32
5	565	1,050	363	40
6	707	1,312	454	50
7	883	1,641	568	63
8	1,104	2,051	710	79
9	1,381	2,564	888	99
10	1,726	3,205	1,110	123
11	4,274	7,977	2,850	308
12	5,372	10,056	3,659	390
13	6,680	12,505	4,550	484
14	11,386	21,270	7,640	822
15	15,038	28,084	10,068	1,086
16	16,540	29,607	11,357	1,220
17	16,540	29,607	14,369	1,545
18	16,540	29,607	18,181	1,955
19	16,540	59,214	25,893	5,246
20	33,080	59,214	25,893	3,133
21	66,160	59,214	25,893	4,274
22	66,160	118,428	51,786	61,746
23	66,160	118,428	103,572	6,838
24	132,320	236,856	103,572	268,865
25	132,320	236,856	207,144	369,972
26	132,320	236,856	207,144	665,158
27	132,320	236,856	207,144	901,035
28	132,320	236,856	207,144	1,418,415
29	132,320	236,856	207,144	2,339,152
30	132,320	236,856	207,144	3,496,981

Once REVBs are processed, benefits are initiated through the sales of the second-life products. Figure 5.5 highlights the benefits of the EOL management processes. The results show that the benefits become higher in the long term when more

REVBs are processed. The high jumps of benefits occur when the remanufacturing, repurposing, and recycling capacities are expanded to accommodate more REVBs.

The costs associated with EOL management vary process by process. The initial investment of $250 million is considered for the facilities and storage. In the remanufacturing process, the buyback cost contributes the highest cost, i.e., up to 60% of the total cost (see Figure 5.6). This high buyback price is from high SOHs of REVBs (about 40% of the initial EVB price). In contrast, the repurposing process requires more cell replacement among EOL management processes, resulting in a little lower buyback cost (about 30% of the initial EVB price) and higher material cost (i.e., 45% of total cost), see Figure 5.7. The recycling process requires the highest electricity for material extraction and new EVB production, resulting in the highest electricity cost among the EOL management processes (i.e., 41% of total cost) (see Figure 5.8).

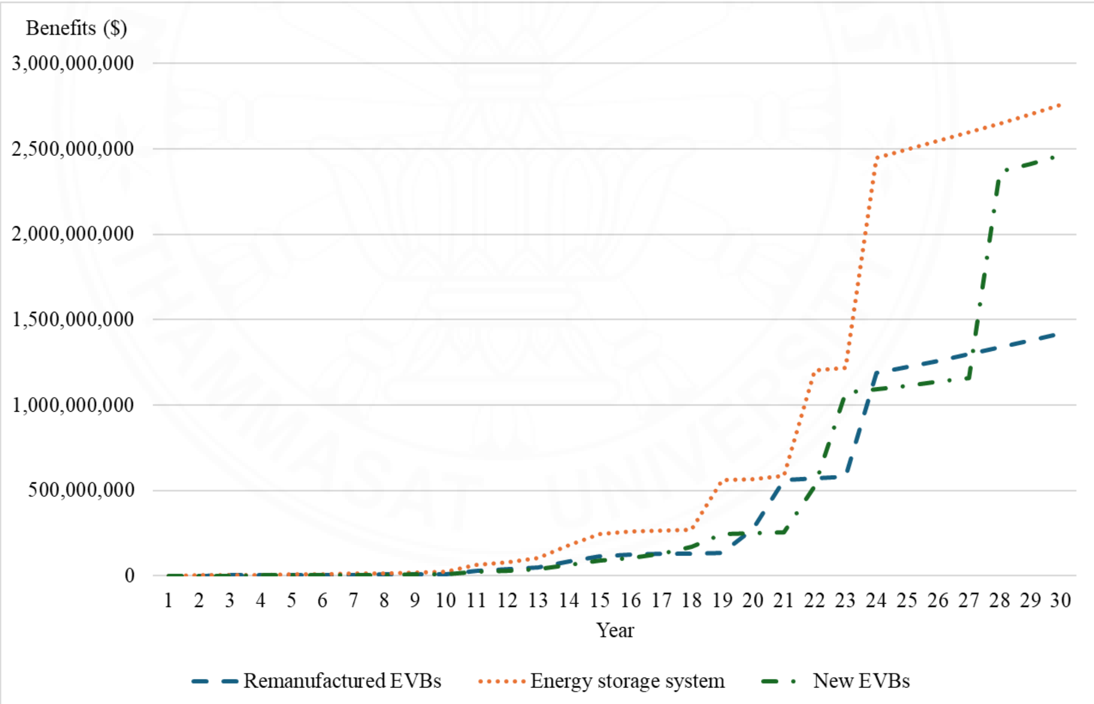


Figure 5.5 Graphical results of benefits of the EOL management processes

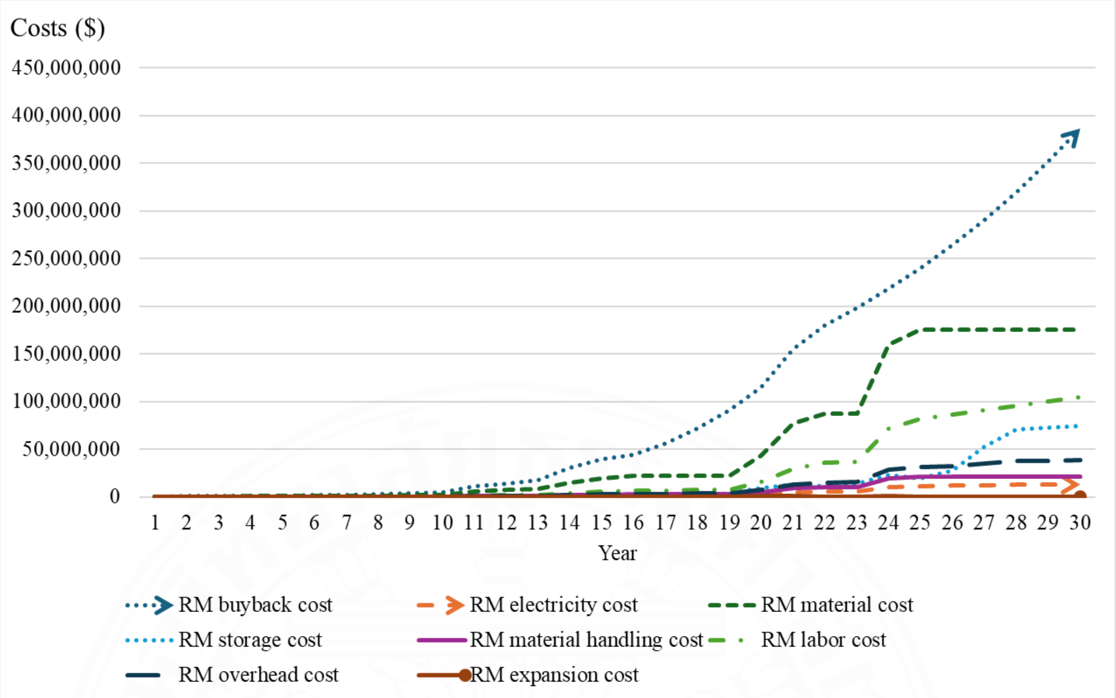


Figure 5.6 Graphical results of the remanufacturing costs

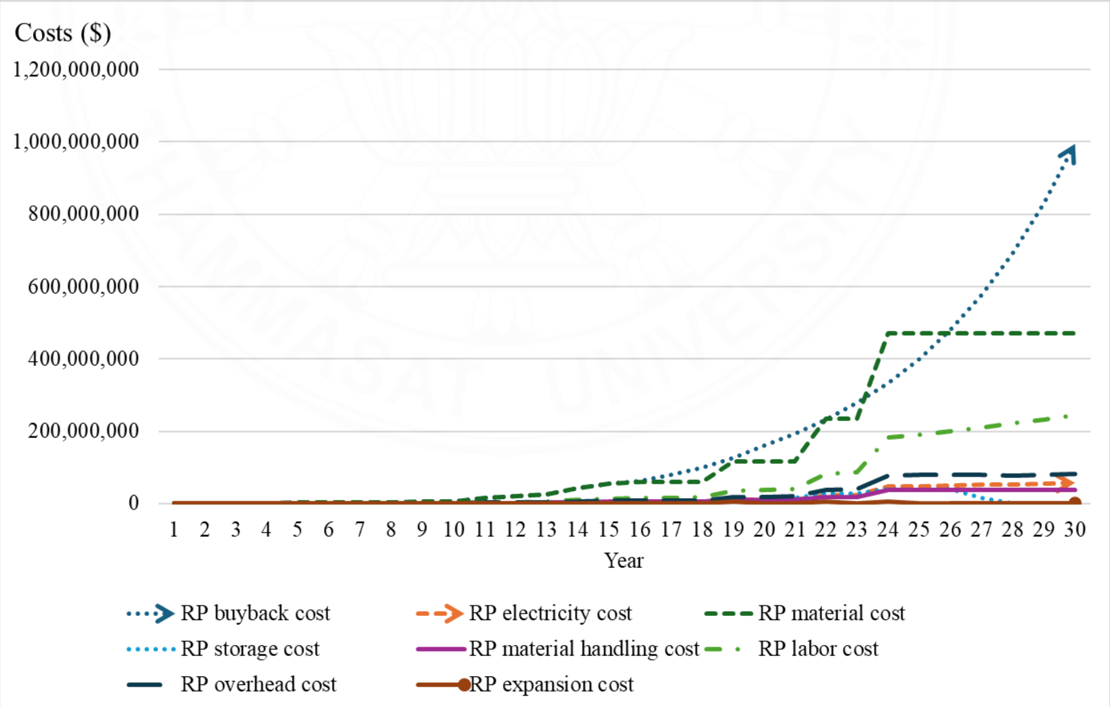


Figure 5.7 Graphical results of the repurposing costs

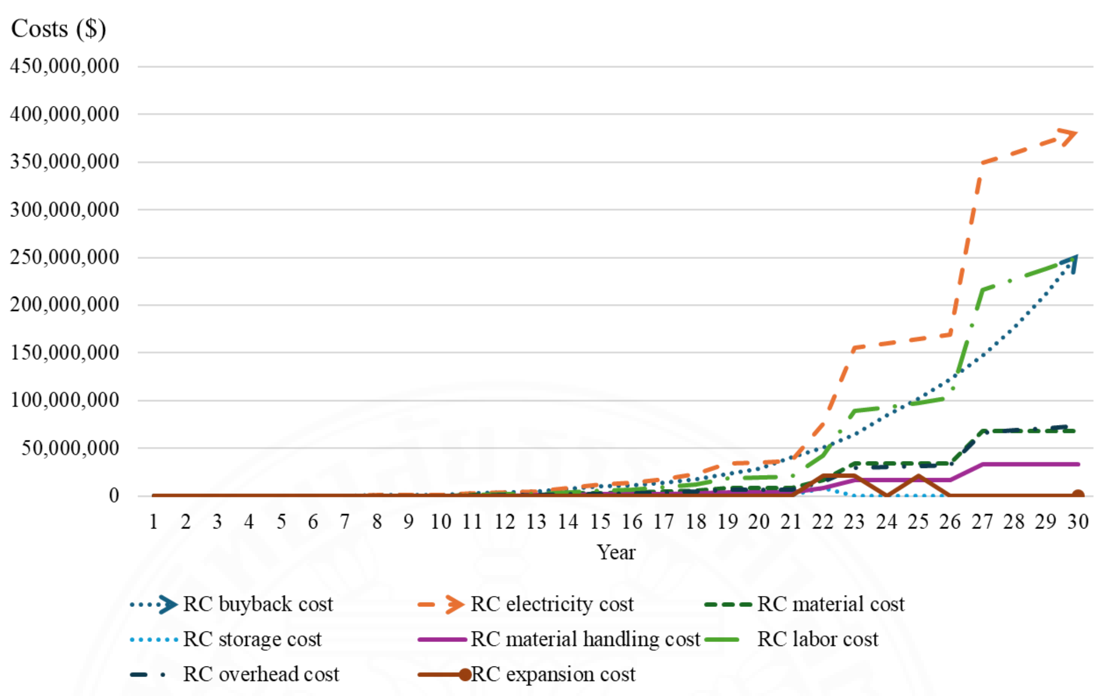


Figure 5.8 Graphical results of the recycling costs

Table 5.7 summarizes all costs of four EOL management processes (i.e., remanufacturing, repurposing, recycling, and landfilling). The buyback cost contributes the most, accounting for half of the total cost. This is due to several factors. The market demand for REVBs remains high due to small competitors (Bai et al., 2019). The quality of REVBs also varies, with those in good conditions commanding high prices. It is noted that the negative environmental costs could be considered as benefits to refer to the reduction on the environmental impacts. The capacity expansion occurs seven times between years 19-25, while the storage is expanded two times in years 22 and 24.

Table 5.8 concludes the benefits and costs of the EOL management project (i.e., combining all EOL management processes). At the beginning, the investment of $250 million results in negative cash flow. Once the REVBs are processed with EOL management, benefits begin to accumulate from the second-life products. The NCF is achieved by subtracting benefits with costs, resulting in positive cash flows from year 1 onwards. Figure 5.9 reveals the IRR values of the REVB's EOL management project. It reaches the minimum acceptable value, i.e., 14% for the automotive-related projects at the end of year 20 (Beck and Britzelmaier, 2013; Anwarsyah and Ahyudanari, 2019). The maximum IRR value of 18.89% is achieved at the end of year 30.

Table 5.7 Costs of REVB's EOL management (combining the remanufacturing, repurposing, recycling, and landfilling processes)

Year	Buyback ($)	Electricity ($)	Material ($)	Inventory ($)	Material handling ($)	Labor ($)	Overhead ($)	Production expansion ($)	Storage expansion ($)	Landfill ($)	Environmental ($)
1	1,590,971	106,075	1,192,099	0	52,855	122,498	147,353	0	0	622	-795,091
2	2,866,930	218,515	2,148,162	0	112,052	257,246	273,598	0	0	1,306	-1,585,825
3	3,226,413	281,677	2,417,463	0	148,410	337,553	318,510	0	0	1,617	-1,982,609
4	3,632,223	362,422	2,721,810	0	196,551	442,842	372,362	0	0	1,990	-2,478,590
5	4,091,105	465,958	3,065,181	0	260,331	580,962	437,243	0	0	2,487	-3,096,666
6	4,609,748	600,127	3,452,237	0	345,008	762,632	516,000	0	0	3,109	-3,872,864
7	5,742,111	773,212	3,889,058	0	457,247	1,001,292	612,081	0	0	3,917	-4,838,923
8	7,609,251	995,492	5,700,954	0	605,852	1,314,176	861,647	0	0	4,912	-6,047,986
9	9,618,969	1,282,278	7,205,758	0	765,837	1,725,449	1,097,932	0	0	6,156	-7,562,836
10	12,023,352	1,650,919	9,006,866	0	957,257	2,264,577	1,387,962	0	0	7,648	-9,456,149
11	29,954,891	4,322,716	22,417,325	0	2,392,904	5,953,017	3,508,596	0	0	9,576	-11,835,881
12	37,783,680	5,683,501	28,260,680	0	3,024,526	7,907,721	4,487,643	0	0	12,125	-14,969,708
13	46,985,765	7,279,542	35,142,780	0	3,761,048	10,325,066	5,650,844	0	0	15,048	-18,616,980
14	79,881,810	12,641,030	59,773,802	0	6,385,304	18,394,025	9,719,416	0	0	25,556	-31,589,181
15	105,465,628	17,168,594	78,922,154	0	8,428,487	25,491,361	13,001,060	0	0	33,764	-41,689,689
16	118,520,935	19,593,705	84,355,565	0	9,112,084	28,945,616	14,200,697	0	0	37,930	-46,879,920
17	150,028,483	23,959,669	85,351,333	593,189	9,589,365	32,321,444	15,181,500	0	0	42,966	-53,121,680
18	189,913,194	29,603,555	86,611,580	4,649,713	10,193,415	36,500,333	16,755,860	0	0	48,687	-60,195,789
19	240,402,922	45,835,183	147,889,612	13,418,434	16,106,984	61,588,061	28,483,827	6,030,000	0	55,154	-68,209,282

20	304,318,428	48,463,168	169,762,108	18,580,245	18,727,912	72,723,472	32,825,690	1,330,000	0	62,491	-77,292,820
21	388,335,447	51,910,888	203,554,718	29,409,594	22,777,199	89,428,351	39,708,075	1,330,000	0	80,399	-93,481,049
22	462,840,745	102,829,150	339,524,216	47,708,538	37,455,824	160,355,255	68,787,298	27,630,000	590,000	92,337	-96,845,538
23	540,601,009	183,478,044	356,644,668	40,606,270	45,661,834	212,807,848	83,919,866	21,600,000	0	105,955	-100,729,351
24	636,529,411	217,210,597	663,967,783	62,736,688	73,104,570	346,831,861	136,385,150	7,360,000	590,000	128,526	-117,646,952
25	742,019,349	224,728,376	679,048,433	57,885,987	74,911,648	371,262,505	140,783,695	21,600,000	0	150,413	-185,050,484
26	866,425,681	231,470,227	679,048,433	66,557,352	74,911,648	389,825,630	144,181,329	0	0	1,361,618	-103,643,847
27	1,013,313,525	413,012,310	713,289,336	68,554,073	91,323,667	517,338,539	180,351,792	0	0	201,277	-184,949,158
28	1,186,939,208	425,402,680	713,289,336	70,610,695	91,323,667	543,205,466	184,383,184	0	0	233,051	-283,290,486
29	1,392,386,327	438,164,760	713,289,336	72,729,016	91,323,667	570,365,739	188,587,252	0	0	269,923	-301,711,022
30	1,635,728,797	451,309,703	713,289,336	74,910,886	91,323,667	598,884,026	192,971,762	0	0	312,703	-376,194,129

Table 5.8 NCFs of the REVB's EOL management processes

Year	Total benefit ($)	Total cost ($)	NCF ($)
Initial	0	250,000,000	-250,000,000
1	3,211,116	2,417,382	793,734
2	6,550,677	4,291,984	2,258,692
3	8,349,220	4,749,034	3,600,186
4	10,640,459	5,251,610	5,388,849
5	13,561,154	5,806,603	7,754,551
6	17,293,416	6,415,997	10,877,419
7	22,055,443	7,639,996	14,415,447
8	28,120,443	11,044,298	17,076,145
9	35,866,078	14,139,544	21,726,534
10	45,727,547	17,842,433	27,885,114
11	116,648,577	50,999,787	65,648,791
12	150,429,201	64,954,380	85,474,820
13	190,802,603	81,545,475	109,257,128
14	330,348,113	139,958,863	190,389,250
15	444,761,858	186,660,920	258,100,938
16	490,211,611	206,139,446	284,072,165
17	527,677,860	245,080,683	282,597,176
18	573,940,766	298,465,361	275,475,405
19	941,864,090	479,644,731	462,219,359
20	1,092,224,373	537,780,863	554,443,510
21	1,403,602,612	621,361,922	782,240,690
22	2,301,411,101	1,019,306,732	1,282,104,369
23	2,873,203,789	1,253,035,048	1,620,168,741
24	4,729,035,148	1,750,247,645	2,978,787,503
25	4,835,500,857	1,860,555,063	2,974,945,795
26	4,944,452,431	2,086,815,881	2,857,636,550
27	5,055,950,283	2,549,113,171	2,506,837,112
28	6,352,752,329	2,712,316,703	3,640,435,626

29	6,493,184,055	2,966,629,116	3,526,554,940
30	6,636,825,716	3,206,988,624	3,429,837,092

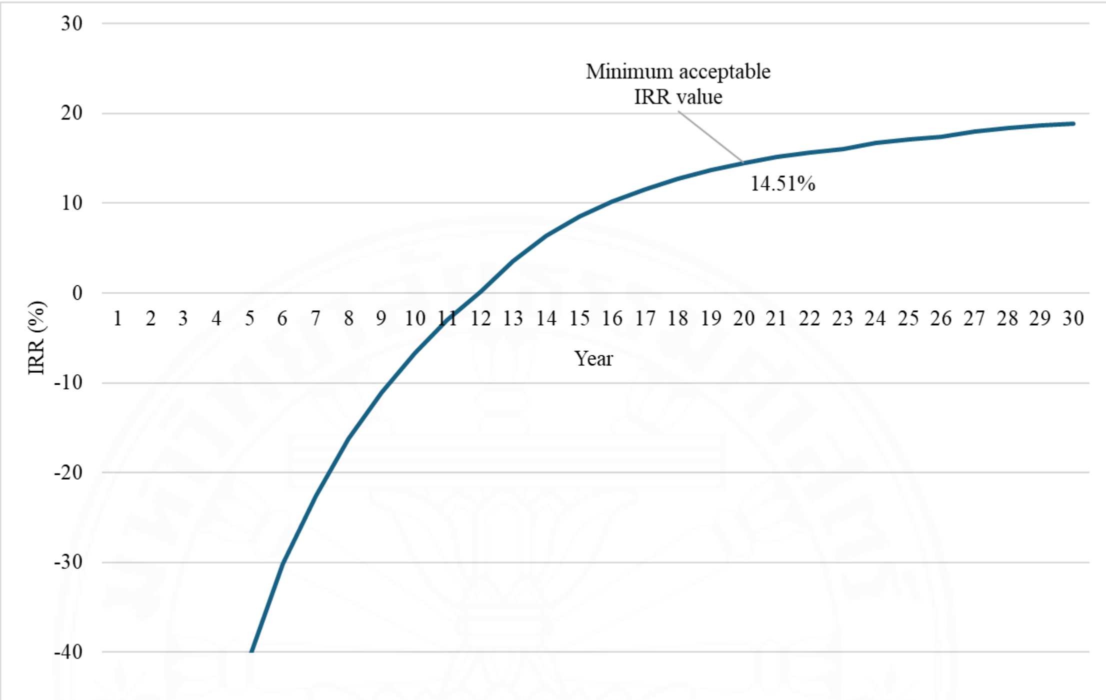


Figure 5.9 IRR values of the REVB's EOL management project

5.5 Model validation

The SD model of REVB's EOL management is verified and validated to ensure that it accurately reflects real-world practices, provides confidence in the model's predictions, and helps identify potential inaccuracies and limitations (Mohamad et al., 2017; Karagoz et al. (2019)). It ensures that the model structure and behavior align with empirical data and theoretical expectations, making it a reliable tool for decision-making and policy analysis (Knusel et al., 2020). Several methods may be used to validate the developed SD model. In this study, structural and behavior tests are performed as they are frequently used in automotive-related studies (Xiang et al., 2017).

5.5.1 Structure test

The structure test is conducted to verify the model's structures and parameters (Zang et al., 2008). Structure testing involves examining the model's components, relationships, and assumptions to ensure that they accurately represent the system

(Mudjahidin et al., 2019). It helps ensure that the model's structure is sound and produces realistic results. In this study, the simulation results of BEV demand and REVBs align with the Thailand National EV Goal, explaining that the number of BEVs will reach 2.5 million vehicles in the next 20 years (EVAT, 2023). The number of REVBs is forecasted based on the BEV demand in the market, ensuring consistency with real-world data. Additionally, all data used in this model are standardized to SI units and universally recognized measurement, ensuring uniformity across the model to prevent errors. Example of units used in the SD model are kilograms (kg) for weight, cubic meters (m^3) for volume, and dollars ($) for currency.

5.5.2 Behavior test

Behavior testing compares the model's output against real-world data or expected trends to verify that the model behaves as anticipated under various scenarios (Sargent, 2013). Behavior test or sensitivity analysis serves as a validation technique by testing the model's responses to changes in key parameters (Barlas, 1996). In this study, the sensitivity analysis focuses on the investment cost as it highly influences the total costs of EOL management. By using different investment costs, the analysis assesses how sensitive the model's outcomes are to this variation and ensures that the model remains robust and reliable under different conditions. In this study, the investment in recycling facility could be increased by 70% with advanced machinery having various functions, such as environmental control system, advanced material separation and extraction technology, and safety system (Zhou and Rong, 2019). In contrast, the investment cost may be reduced by 30% through in port tax reduction (Xiang et al., 2017). The behavior test is then performed by varying the investment costs from 70% to 170% of the initial investment cost (Huster et al., 2022). The results in Figure 5.10 reveal that by changing the investment cost, only magnitude of the SD model changes, and the model behavior remains the same. This proves the model validity to be used in the real world. The results also reveal that low investment costs give high IRR values. When the investment cost is low, the manufacturers may be encouraged to provide second-life products and sell at lower prices, thus increasing the second life product market.

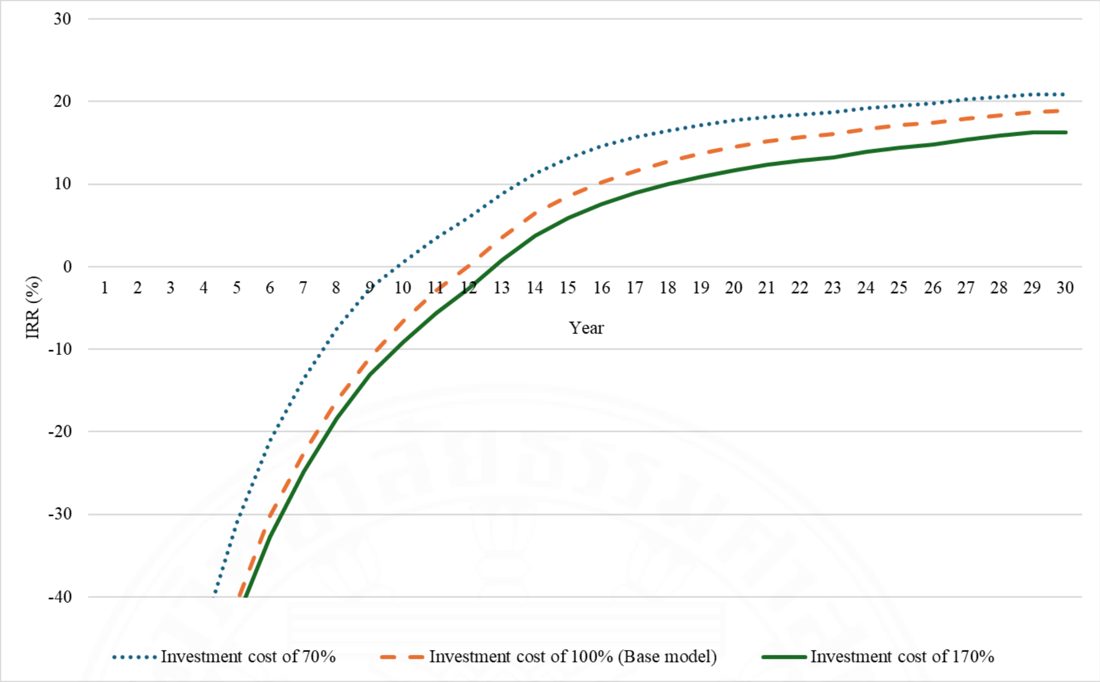


Figure 5.10 Behavior testing using various investment costs

CHAPTER 6
POLICY ANALYSIS

6.1 General overview

This chapter presents several policy analyses for REVB's EOL management in Thailand through the sensitivity analysis. The results suggest strategies that are suitable for companies' practices.

6.2 Policy analysis with various EOL management strategies

The baseline strategy of REVB's EOL management combines the remanufacturing (RM), repurposing (RP), and recycling (RC) processes in the project. The policy analysis is performed by considering single and combined EOL management options. They include the RM-only, RP-only, RC-only, RM and RP, RM and RC, and RP and RC options. The analysis results provide various IRR values for different options. Figure 6.1 reveals that the RM-only option gives the highest IRR value (i.e., 45.85%) among seven EOL management options. This is due to a substantial reduction in the facility investment (i.e., from $250 million in the base run for remanufacturing, repurposing, and recycling facilities to $17 million for only the RM facility). Moreover, this process offers a reduction in the environmental costs (i.e., benefits) of $2,600 per battery. This scenario provides over 1.4 times higher IRR value in the next 30 years compared with the base run results.

The RP-only option is the second-best scenario for REVB's EOL management. Compared with the RM-only process, the RP-only process provides wider applications of second-life products, such as stationary energy storage system, backup power system, portable power solutions, EV charging stations, and off-grid energy systems (Bai et al., 2019). The IRR in the next 30 years of this scenario is 35.53%, which is higher than the base run model by 87%.

The results also reveal that investing in all EOL management processes (i.e., remanufacturing, repurposing, and recycling) may not be appropriate in Thailand at this moment because they require high investment and operation costs compared to benefits from second-life products sales.

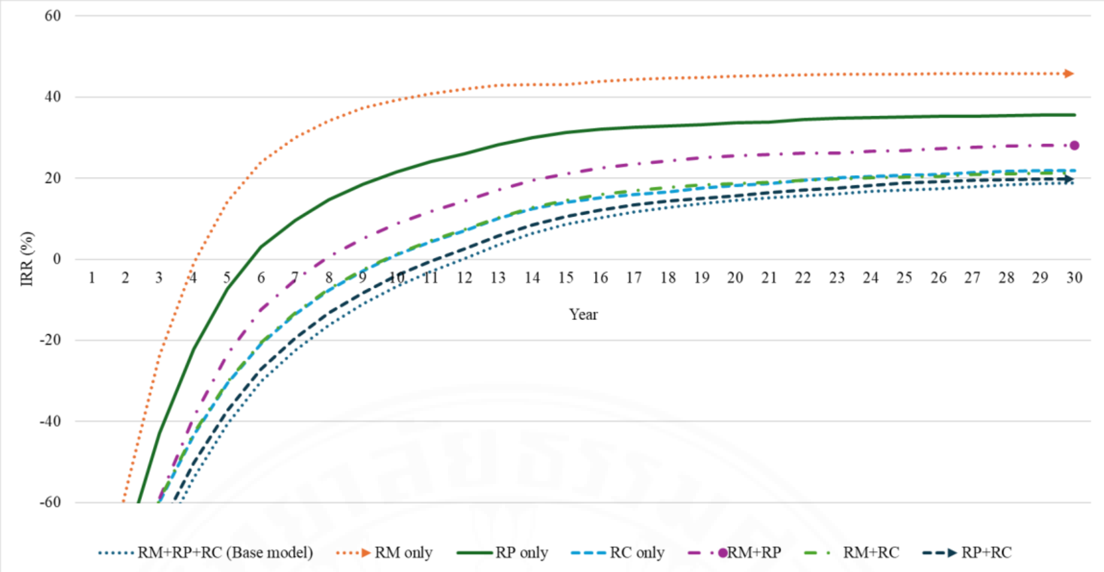


Figure 6.1 Policy analysis results when EOL management strategy is changed

6.3 Policy analysis with various privilege parking increasing rates

The RM-only option is examined further to search for strategies to enhance the IRR values in the long term. As the growth of BEV market is highly influenced by the privilege parking factor (see Figure 5.4), the sensitivity analysis is performed by varying the increasing rates of parking privilege from 20.5-30% (Xu et al., 2020; Liu et al, 2023). The analysis results in Figure 6.2 show that increasing parking spaces for BEV users does not have significant effects on BEV demand in the early years. This may be because the number of BEVs in the market is still low and the existing parking spaces are adequate. With more BEVs in the future, the results show that higher privilege parking spaces increase IRR values (i.e. achieving a 50.55% IRR when 30% of parking spaces are provided).

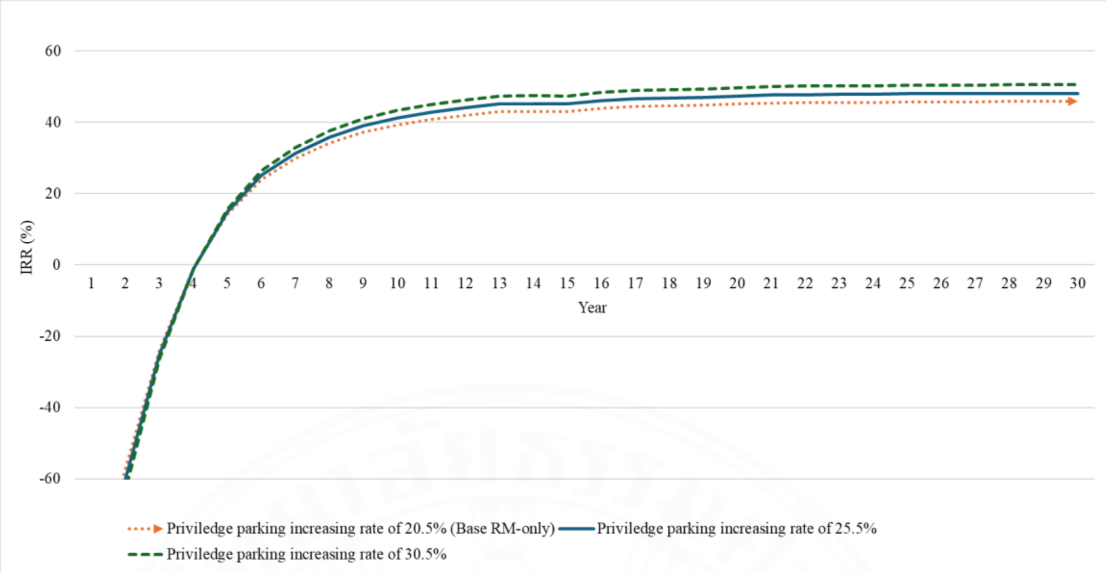


Figure 6.2 Policy analysis results of the RM-only option when the privilege parking increasing rate is changed

6.4 Policy analysis with various lithium material availabilities

EVB production relies mainly on the resource's availability. According to USGS (2023), the global lithium reserve is estimated at 28 million metric tons, with an annual discovery rate of 15%. On the other hand, the global extraction rate is 180,000 metric tons per year with an annual increasing rate of 30.33% (Statista, 2024b). Thus, it is expected that the amount of lithium will be enough for 50 years. However, with the lower discovery rate than expected (i.e., only 4% instead of 15% per year), this material may last for only 27 years. This may result in material depletion and may interrupt the EVB production in the long term (USGS, 2023).

The sensitivity analysis is performed by varying the annual discovery rate of lithium reserves from 15% (base value) to none. The simulation results, see Figure 6.3, indicate that when lithium is diminished and no other materials are replaced, the project is not feasible because the production of EVB will rely only on the recovered lithium from the RC process. It is clear that the EVB production becomes impossible after 20 years if no lithium is discovered.

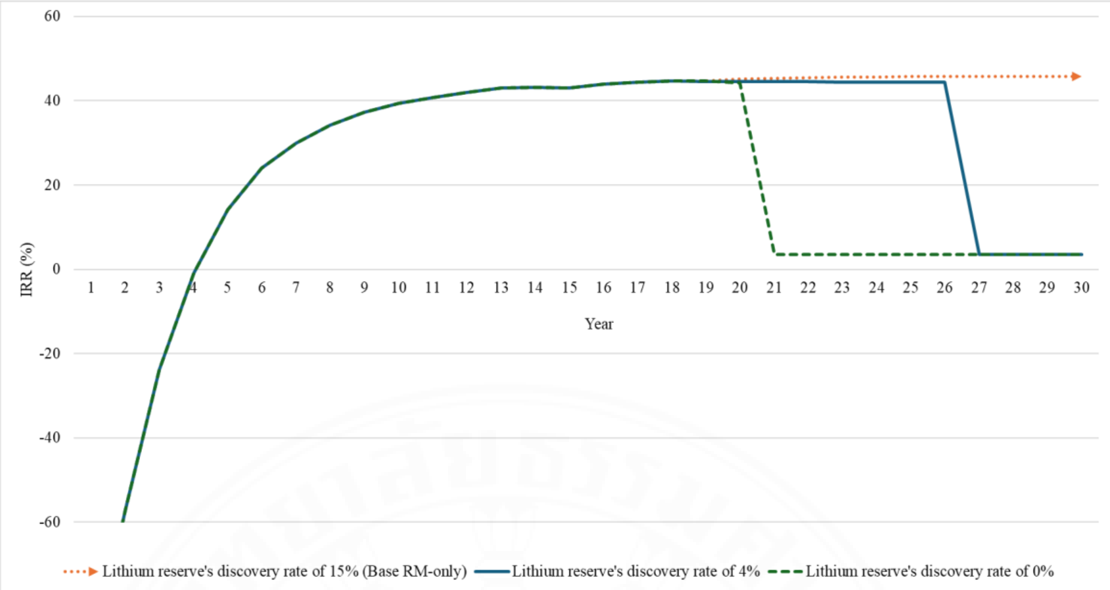


Figure 6.3 Policy analysis results of the RM-only option when the lithium reserve discovery rate is changed

6.5 Policy analysis with various buyback costs

The buyback cost contributes the largest portion of the remanufacturing expenses. According to Bernhart et al. (2010), the buyback cost could be reduced by half with advancements in the EOL management technology. The sensitivity analysis is performed by varying the buyback costs from 20-40% of the EVB price. The results, see Figure 6.4, reveal that low buyback costs highly increase the IRR values of the RM-only option, reaching 63.10% when the buyback cost is 20% of the EVB price. High buyback costs not only increase manufacturing expenses, but also discourage manufacturers from manufacturing REVBs. This underscores the importance of government incentives, such as tax reduction and subsidies to achieve the feasibility of the project. Advancement in technology may improve process efficiency, maintain the SOH stability, and reduce the buyback cost.

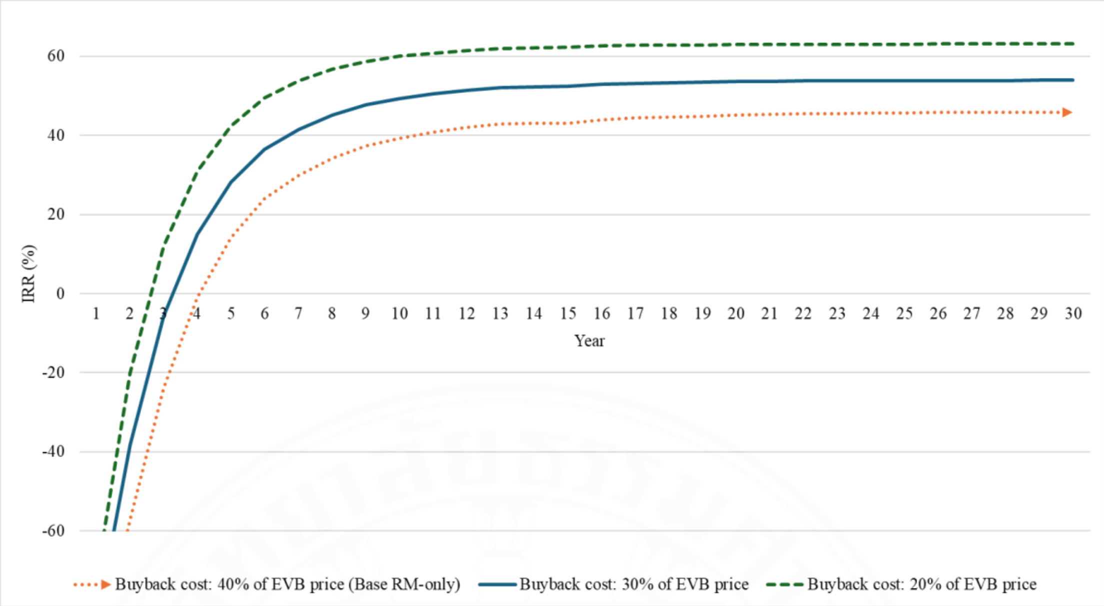


Figure 6.4 Policy analysis results of the RM-only option when the buyback cost is changed

6.6 Policy analysis with various human toxicity costs

The environmental cost plays a crucial role in the EOL management costs. Human toxicity is a major concern for the EVB-related industry worldwide (Anthony and Cheung, 2017). The cost associated with human toxicity is estimated at $0.59 per kg in developing countries, while in developed countries, this cost can increase up to three times due to strict environmental regulations and high healthcare costs (Orloff and Falk, 2003; TGO, 2024). ECHA (2024) has implemented frameworks, such as Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) to manage risks associated with chemical substances, resulting in high human toxicity cost. In this study, the sensitivity is performed with various human toxicity costs, ranging from $0.59 to $1.77 per kg 1,4-$DB_{eq}$ (Hong et al., 2015; Norberg-King et al., 2018; Price et al., 2021). The simulation results, see Figure 6.5, show that high human toxicity costs give low IRR values, as the RM process requires the material extraction process that highly affects human health. To mitigate human toxicity impact, more environmentally friendly processes must be adopted. This includes advancing green extraction technologies to minimize the release of harmful substances, improving waste management practices, and adopting alternative materials that pose less risk to human health and the environment (Chemat et al., 2012).

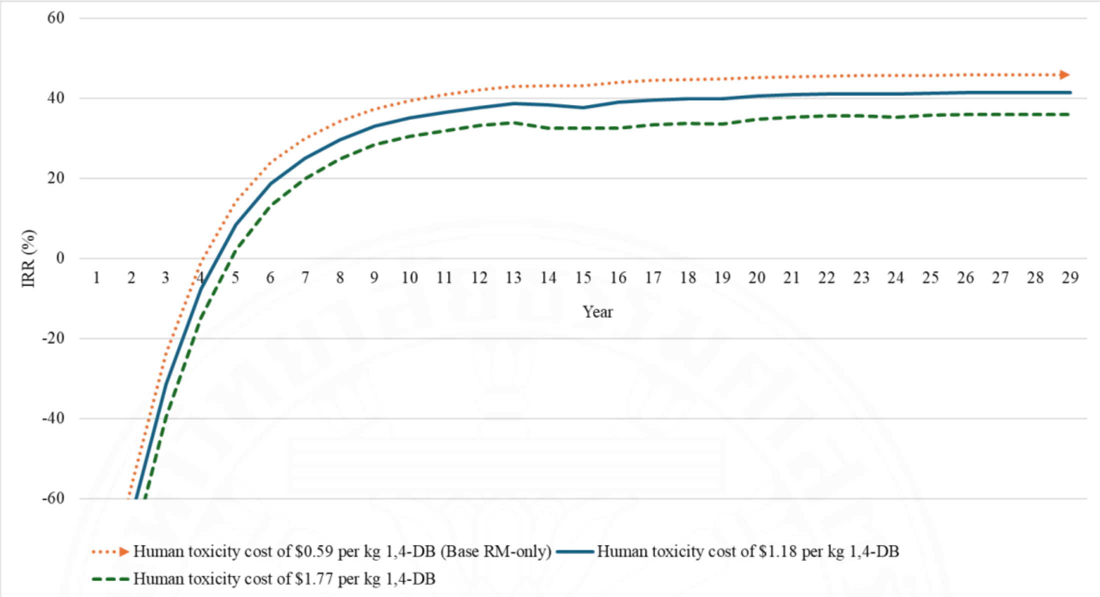


Figure 6.5 Policy analysis results of the RM-only option when the human toxicity cost is changed

6.7 Policy analysis with various subsidies increasing rates

Thailand's national BEV goal, known as @30, aims for 30% of total vehicle production or approximately 725,000 BEVs to consist of BEVs by 2030 (EVAT, 2023). This target is established for all BEV manufacturers operating in Thailand. Subsidies play a crucial role in driving BEV demand (Bobba et al., 2018). In this study, a sensitivity analysis was conducted with varying subsidy percentages ranging from 50% to 80% per year (Pettinger, 2019; Ma, 2022; Peng and Sun, 2024). The simulation results, see Figure 6.6, indicate that an 80% subsidy increasing rate is necessary to meet the national goal by 2030, whereas lower subsidy percentages may result in failure to achieve the target. To implement higher subsidy percentages effectively, the government must establish clear requirements and standards for manufacturers. Key measures include collaboration between the government and manufacturers, lower subsidy approval requirements, and enhancing BEV awareness through targeted promotional campaigns.

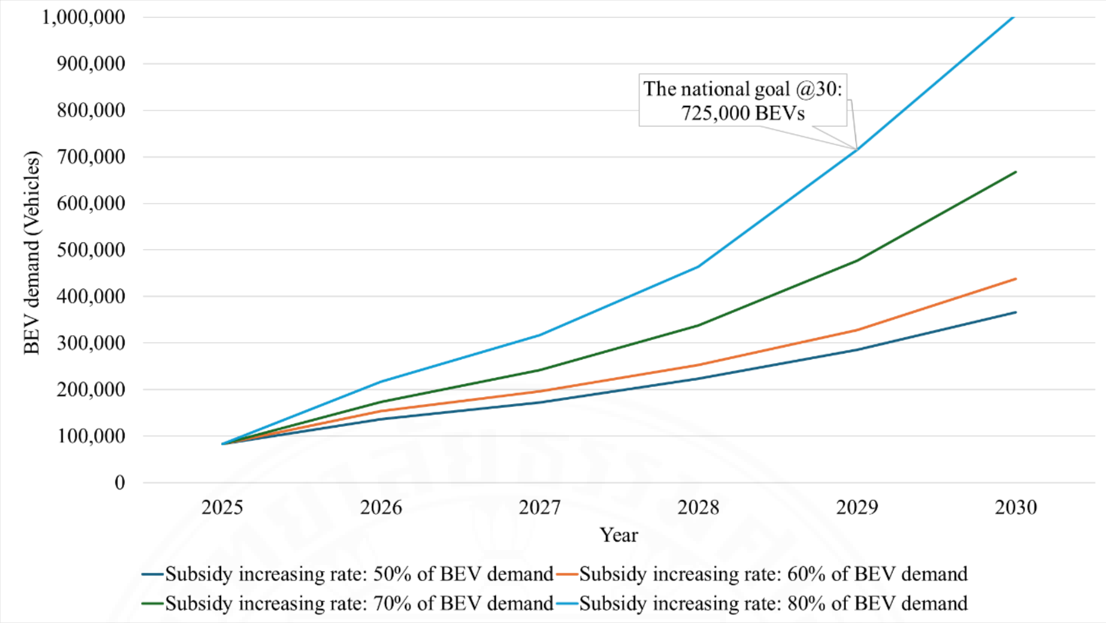


Figure 6.6 Policy analysis results of the BEV demand when the subsidy percentage is changed

CHAPTER 7
CONCLUSION

7.1 General overview

This chapter summarizes major findings and contributions to the existing body of knowledge. The limitations of this study and recommendations for future studies are discussed at the end of the chapter.

7.2 Major findings

The study examines environmental impacts and benefits and costs of REVB's EOL management utilizing the LCA and SD modelling approaches. The LCA results reveal the environmental impacts from EOL management processes, namely CO_{2eq} emission, human toxicity, terrestrial acidification, PM formation, photochemical oxidant formation, water depletion, metal depletion, ozone depletion, and fossil depletion. It shows that recycling is the most favorable process to minimize the environmental impacts, especially in human toxicity, metal depletion, terrestrial acidification and PM formation impacts. They are particularly concerned about their serious effects on human health and the environment. Reducing human toxicity is crucial for ensuring the safety of workers and protecting communities near processing facilities from harmful emissions. Implementing green technologies, such as cleaner extraction methods or closed-loop systems that capture and neutralize harmful substances, can significantly mitigate these risks (Holland, 2020). On the other hand, reducing metal depletion involves maximizing the recovery and reuse of metals and materials through efficient recycling processes. By adopting advanced recycling technologies that increase recovery rates and reduce waste, the EVB industry can slow down the depletion of these essential resources and lessen the environmental footprint of battery production (Arambarri et al., 2019). Terrestrial acidification and PM formation are other significant impacts. Both impacts can be mitigated through the adoption of green technologies that reduce emissions, such as cleaner energy sources, advanced filtration systems, and environmentally friendly processing methods (Meshram et al., 2020).

The EOL management processes through remanufacturing, repurposing, and recycling benefit the industry in various ways. Remanufacturing extends the EVB lifespan, reducing the demand for new batteries, resource extraction, and environmental degradation (Pozzato et al., 2021). It minimizes waste through circular loops, though it still requires energy and resources for refurbishment (Bobba et al., 2020). Repurposing extends the EVB lifespan and reduces the need for new materials. However, this process requires a high amount of energy to modify and repurpose the batteries and may require additional infrastructure for production (Kotak et al., 2021). Recycling is crucial for recovering valuable materials and reducing waste. Although recycling is the most favorable process for minimizing environmental impacts, it is an energy intensive process (Fan et al., 2020). By adopting more sustainable recycling practices, such as using renewable energy sources, improving material recovery rates, and reducing emissions, the environmental impacts of this process can be significantly reduced (Ono et al., 2020).

The environmental impacts achieved from the LCA results are converted to the environmental costs and are input into the SD model to examine the feasibility of the EOL management project. The causal loop diagram is developed to examine the relationships among benefits, costs, and factors influencing REVBs and EOL management processes. These relationships are transformed to equations in the SD model. The SD model assists policymakers in deciding long-term strategies for implementing effective EOL management of REVBs in Thailand. The simulation results reveal that the Thai's BEV market is still in its early stages with limited REVBs. Consequently, the production of second-life products from EOL management is small, making the EOL management project not feasible. Government support is crucial in this stage to promote the BEV market. With continuous growth of the market, the REVBs increase, and the project achieves the minimum acceptable IRR value of 14% within 20 years. At this stage, manufacturers may consider expanding facilities and improving EOL management processes to handle the increasing volume of REVBs. The IRR value becomes 18.89% at the end of the project (i.e., 30 years).

The developed SD model is validated using structure and behavior tests to ensure its applications in actual practices. Policy analysis is conducted to test different strategies to improve EOL management processes of REVBs. The results suggest that manufacturers should prioritize the remanufacturing process in the short term as it has proved to be the most feasible EOL management option with an IRR value of 45.58% in 30 years. Manufacturers should focus on efficient and cost-effective remanufacturing facilities since investment cost is one of the most influential factors affecting IRR values. Investing in technology that streamlines the process and minimizes waste may reduce operational costs (Chaowanapong et al., 2018). Manufacturers should cooperate with suppliers to secure a steady number of REVBs.

Governments worldwide, including Thailand, are increasingly prioritizing BEVs due to their substantial environmental, economic, and social benefits. BEVs produce zero tailpipe emissions, significantly reducing GHG emissions and harmful air pollutants such as nitrogen oxides and particulate matter. This shift plays a crucial role in achieving global climate goals, such as the Paris Agreement (Yan, 2018). However, governments may still find reasons to provide limited support for ICEs for specific reasons. For instance, phasing out ICEs too rapidly could disrupt industries reliant on ICE production and sales, resulting in economic hardships and job losses (Peng and Sun, 2024). Additionally, many consumers in developing countries like Thailand still depend on affordable ICEs due to the high upfront cost of BEVs, even with subsidies (EVAT, 2023). Therefore, Thai government should consider strategies that increase the BEV adoption and gradually reduce the ICE section, such as increasing financial incentives for BEV customers and manufacturers, developing infrastructure in charging networks in rural area, encouraging the renewable energy integration for electricity generation, and phasing out ICE incentive gradually to ensure a smooth transition for both industries.

For manufacturers with limited investment capacity, the RM-only strategy appears to be the most viable option for sustaining operations in the EVB industry. It requires the lowest investment cost compared to the other EOL management options, making it more accessible for manufacturers with limited resources. The remanufacturing process is also less complex, demanding less specialized training for workers (Kampker et al., 2020). Moreover, second-life EVBs have durable demand compared to energy storage systems that are for niche markets (Casals and Garcia, 2016). The RM-only approach allows manufacturers to focus on a single streamlined process, which can be scaled up gradually as the BEV market matures. With government support, they may also navigate advanced remanufacturing techniques through partnerships with research institutions or foreign technology providers (Guidat et al., 2017).

According to the LCA and simulation results, recycling yields the best environmental score, and RM-only is more suitable economically. To balance the environmental benefits of recycling and the economic advantage of remanufacturing, the manufacturer requires a strategic approach for practical applications. For instance, REVBs that are in relatively good condition should be remanufactured first, as this process is more economically viable and extends the battery's lifecycle with minimal environmental impact. Recycling should be reserved for batteries that are no longer suitable for remanufacturing, ensuring that valuable materials are recovered rather than landfilled. For Thailand, where BEV adoption is growing, the manufacturers can focus on short- and long-term approaches. In the short term, the manufacturer can focus on RM-only to address the immediate demand for affordable second-life batteries while keeping investment and production costs low. Simultaneously, the manufacturer can ramp up investment in recycling infrastructure to prepare for the influx of REVBs in the long term. In the long term, the manufacturer may integrate recycling as a key process of the supply chain, ensuring that recovered materials feed directly into new EVB production and remanufacturing process to reduce dependency on imports and raw materials.

The investment in the complete EOL management processes (i.e., remanufacturing, repurposing, and recycling) is not recommended in Thailand in current years due to small BEV market, lack of clear government support, and reliance on foreign technologies (Vivatpinyo and Pharino, 2019). EOL management technology also relies on collaboration with developed countries for advanced technologies, incurring high investment costs. However, these costs can be offset by lower production expenses through increased efficiency, such as AI and automation factories. The study results show that though EOL management requires high investment cost, it is still more favor strategy for REVBs compared with the landfilling option. This is largely due to its ability to save raw materials and significantly reduce environmental costs. Therefore, the government should prioritize setting a clear goal and support, and sustaining EOL management processes by introducing various initiatives, such as technological adoption, international collaborations, and providing financial support for infrastructure development to adopt local production in Thailand.

Policy analysis was performed to explore strategies to enhance the BEV market and EOL management processes. The results show that providing parking spaces with charging stations at major locations may attract more BEV customers. This approach aligns well with Thai cultural, as convenience is a major factor influencing consumer decisions. Thai people often value accessibility and ease of use, and providing reserved parking spots for BEVs in busy areas, such as shopping malls, office buildings, and transit hubs, would contribute this preference to BEVs. The exclusive spaces could also appeal to social status consciousness, an important aspect of consumer behavior in Thailand. However, challenges related to limited parking infrastructure in urban areas may arise. Space constraints in major cities like Bangkok, where land availability is scarce and expensive, could limit the number of dedicated BEV parking spots. To address this, collaboration between the government, private developers, and businesses is necessary. Such initiatives would not only improve the convenience of BEVs but also create a privilege and exclusivity for BEV users, aligning with the Thai market's preference for value-added experiences. Offering less loan requirements, especially for BEVs, may also stimulate BEV demand (Wu et al., 2019). The buyback cost is crucial to achieving a sustainable improvement, as it contributes the highest cost. Reducing this cost significantly enhances the IRR values, with an IRR of 63.10% when the buyback cost is half price. To achieve Thailand national goal @30, the subsidy is important factor to achieve the goal within 2030. To meet Thailand's national @30 goal of having 30% of vehicle production as BEVs by 2030, subsidies are a pivotal factor, with an 80% subsidy rate enabling the goal's achievement. Collaboration between the private sector, manufacturers, and government is encouraged to maximize the benefits of EOL management in the long term. Clear guidelines and eligibility criteria must be established to streamline the subsidy process. Additionally, significant investments in charging infrastructure, especially in high-traffic areas, are crucial. Incentivizing private developers to construct and manage these facilities can accelerate infrastructure expansion and promote BEVs. These establishments will drive up the BEV demand and adoption in Thailand. Manufacturers play a key role in reducing costs and adopting BEV. Collaborative efforts with material suppliers to lower production and buyback costs are necessary to enhance sustainability. Educating customers about the economic and environmental benefits of BEVs through awareness campaigns can also drive demand. Additionally, manufacturers should work closely with policymakers to develop subsidy approvals and provide input on standards for BEV and EVB recycling in long term.

7.3 Contributions to the existing body of knowledge

A number of studies have been conducted on examine the feasibility of EOL management of REVBs both economically and environmentally. However, no study has yet examined complex causal relationships among BEV demand, REVBs, and EOL management processes. The developed SD model that considers both economic and environmental perspectives of the BEV market and its EOL management contributes to the existing body of knowledge as follows.

- This study assesses the environmental impacts of REVB's EOL management processes, including remanufacturing, repurposing, recycling, and landfilling processes. The results show possible impacts of each process and suggest suitable strategies to minimize the environmental impacts in the long term.
- The study explores complex relationships among BEV demand, REVBs, and EOL management using causal loop diagrams, making them easy to understand. The developed SD model shows costs and benefits and their complex relationships in a figure format, making it easy to comprehend and test various strategies. Researchers, related industries, and government can use the study results to plan for effective EOL management of REVBs in the long term.
- The policy analysis in this study assists policymakers to enhance the EOL management processes by selecting strategies that are suitable for their work practices. For example, manufacturers with investment capabilities and good relationships with BEV manufacturers may invest in the remanufacturing process to produce second-life EVBs and supply them to the BEV market. On the other hand, manufacturers with limited investment

capacity might opt for a single EOL management process, such as RM-only and RP-only, to achieve high IRR values in the long term.

- In the short term, it is suggested that the government and manufacturers should prioritize the remanufacturing process, as it offers the highest IRR value and requires low investment cost. By focusing on this approach, REVBs can be reused in BEVs, thus extending the life cycle and reducing waste. Manufacturers should also establish strong partnerships with the Thai government to promote the BEV adoption. Government incentives, such as subsidies and tax reduction, can significantly increase BEV sales, leading to a greater supply of REVBs for future EOL management (Kerdlap and Gheewala, 2016). Developing a cost-effective buyback program is a critical short-term strategy, as it improves the financial feasibility of remanufacturing operations and enhances profitability (Park and Kim, 2021).
- In the long term, it is crucial to gradually expand EOL management facilities to accommodate a high volume of REVBs. The investment of repurposing and recycling facilities may be considered to produce variations of second-life products. Manufacturers should invest in process innovation and technology upgrades to improve production efficiency. They include adopting advanced recycling technologies and automation to reduce the environmental impacts (Sahajwalla and Hossain, 2023). Innovations in green extraction practices may help reduce the environmental damage, further aligning with long-term sustainability goals (Ongbali et al., 2021).
- Collaboration with the government to promote circular economy of the EVB market is crucial for the long-term success of EOL management in Thailand. Supportive strategies, such as tax reduction, skill training, and use of second-life products, should be encouraged to minimize waste throughout the entire EVB lifespan.
- The results of EOL management project in this study guide the Thai government to plan for suitable strategies to align with countries worldwide to minimize global impacts. Apart from that, economic development will be driven by the expansion of the EVB industry, creating jobs and contributing

to economic growth (Nakapreecha et al., 2020). By collaborating with manufacturers on EOL management strategies, the government can enhance the country's competitiveness in the EVB sector, attracting foreign investment, and positioning the country as a leader in sustainable REVB management.

7.4 Limitations and suggestions for future research

This study has some limitations. The data used in SD model development are retrieved from literature in developed and developing countries. Data are, however, converted to reflect Thai practices prior to inputting in the SD model. The EVB adoption in Thailand is in the early stages. Significant changes or disruptions may occur before the market stabilizes. As technology advances and the adoption of BEVs in Thailand progresses rapidly, it is recommended to regularly update the model's parameters to reflect actual practices.

Suggestions for future research are as follows.

- The SD model can be adjusted to examine the REVB's EOL management in neighboring countries to compare and suggest strategies for different working cultures.
- Other factors, such as social factors, environmental warranties, and regulation-related costs, may be added into the SD model to allow for more comprehensive analysis of the sustainability of REVBs.
- Technological factors, such as solid-state batteries and hydrogen fuel cells, which are gaining popularity in BEVs may be added into the SD model as new comparative processes. These alternatives could be evaluated alongside the LCA and feasibility studies of EVBs to provide a comprehensive comparison of their economic and environmental impacts.
- Advancements in factory factors, such as AI-driven automation, big data analytics, and blockchain integration, could significantly influence EOL management processes. Adding these factors into the SD model could enhance its accuracy by accounting for their potential to improve efficiency and reduce total costs.

- Case studies may be performed to examine scenarios with specific conditions, such as limited budget and know-how of EOL management.

7.5 Closure

This study examines the environmental impacts of REVB's EOL management processes. The impacts are converted to the environmental costs and are input with benefits and other factors into the SD model to examine the feasibility of the EOL management project. The developed SD model depicts complex dynamic relationships among key costs and benefits of EOL management processes and suggests strategies for the government and related stakeholders to achieve long-term sustainability. It is useful for the academic and guides possible improvements for future research.

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APPENDICES

APPENDIX A

DATA USED IN SD MODEL DEVELOPMENT

Information	Detail	Reference
BEV	• Average BEV selling price: $56,789 per vehicle	EVAT (2023)
EVB	• Average EVB selling price: $6,690 per battery • EVB capacity: 11-114 kWh (average at 75 kWh) • EVB capacity increasing rate: 3% annually • Lifespan: 10 years	Tesla (2021), EVAT (2023), and EA Annual Report (2023).
REVB	• Percentage of REVBs for the remanufacturing process: 28%, on average (based on SOH ≥ 80%) • Percentage of REVBs for the repurposing process: 52%, on average (based on 60% ≤ SOH < 80%) • Percentage of REVBs for the recycling process: 18%, on average (based on SOH < 60%) • Percentage of REVBs disposed of in landfills: 2%, on average (based on BEV accidental rate in Thailand) • Buyback price: 40% of the initial price (based on SOH ≥ 80%) : 30% of the initial price (based on based on 60% ≤ SOH < 80%) : 15% of the initial price (based on SOH < 60%)	Chorbrod (2018), Reiter et al. (2018), Guerra and Daziano (2020), Toyota (2022), and EA Annual Report (2023).

	• Remanufactured EVB selling price: $5,696 per battery • Stationary storage battery selling price: $6,554 per battery	
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	Murnane and Ghazel (2002), SCB (2023), Li et al. (2021), EVAT (2023).
Fast charging station	• Number of fast charging station: 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	Guerra and Daziano (2020) and EVAT (2023).
Driving range	• Average driving range: 350 km per charge • Improved driving range: 20 km per model, on average • Thai BEV user's driving range: 25000 km annually, on average • Increased customers from the driving range factor: 10.3% of the BEV demand	Thananusak et al. (2020), Li et al. (2021), EVAT (2023).

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): 79.7% of total the BEV models • BEVs (with at least 50 kWh) increasing rate: 3% per year • BEVs (with the prices below $56,789): 46.3% of total BEV model • BEVs (with the prices below $56,789) increasing rate: 3% per year • Campaign duration: 4 years • Increased customers from the subsidy factor: 80.6% of the BEV demand	Li et al. (2021) and EVAT (2023).
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	Thananusak et al. (2020) and EVAT (2023).
Parking privilege	• BEV parking space: 28,595 parking spaces • BEV parking space increasing rate: 3% annually • Designated parking space for BEV users: 30% of the total parking spaces • Increased customers from the parking privilege factor: 20.5% of the BEV demand	Guerra and Daziano (2020) and EVAT (2023)

Remanufacturing	• Initial production capacity: 16,540 batteries annually • Maximum production capacity: 132,320 batteries annually • Production capacity expansion: 16,540 batteries each expansion • Production capacity expansion cost: $1.33 million each expansion • Electricity consumption in the remanufacturing process: 360 kWh per battery • Material requirement in remanufacturing process: 15 kWh per battery (i.e., 20% of 75-kWh battery)	Tesla (2021), EA Annual Report (2023) and EVAT (2023).
Repurposing	• Initial production capacity: 29,607 batteries annually • Maximum production capacity: 236,856 batteries annually • Production capacity expansion: 29,607 batteries each expansion • Production capacity expansion cost: $6.31 million each expansion • Electricity consumption in the repurposing process: 840 kWh per battery • Material requirement in repurposing process: 30 kWh per battery (i.e., 40% of 75-kWh battery)	Toyota (2022), EA Annual Report (2023) and EVAT (2023).
Recycling	• Initial production capacity: 25,893 batteries annually • Maximum production capacity: 207,144 batteries annually	EA Annual Report (2023) and EVAT (2023)

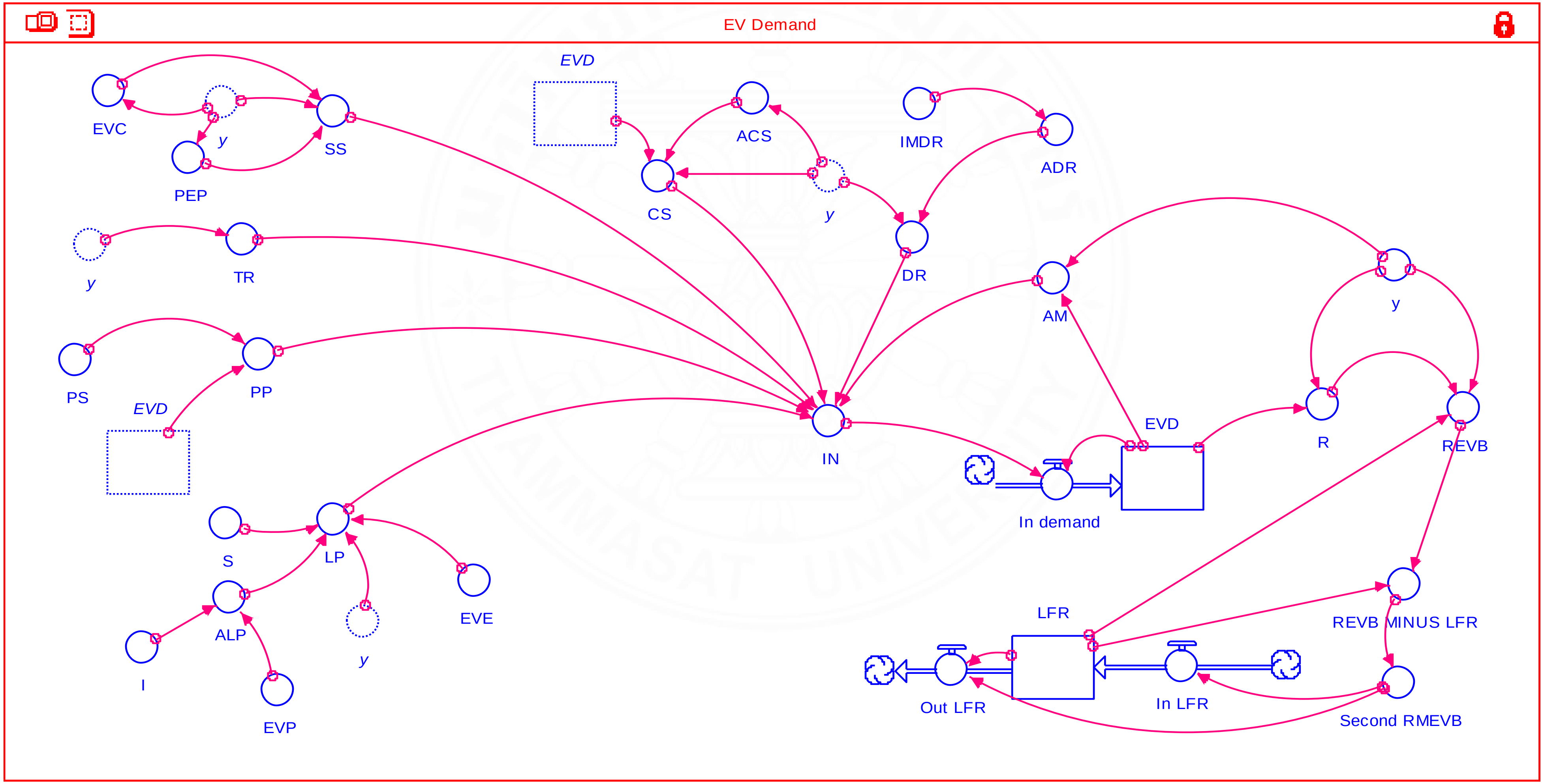
	• Production capacity expansion: 25,893 batteries each expansion • Production capacity expansion cost: $21.6 million each expansion • Electricity consumption in the recycling process: 3514 kWh per battery • Material requirement in recycling process: 3.75 kWh per battery (i.e., 5% of 75-kWh battery)	
Landfilling	• Maximum capacity: 245,098 batteries • Electricity consumption in the landfilling process: 10 kWh per battery	Chinda (2022), Statista (2024a) and EVAT (2023)
Storage	• Prioritization of storage utilization: Remanufacturing, repurposing, and recycling • Initial storage capacity: 65,814 batteries annually • Maximum storage capacity: 197,442 batteries annually • Storage capacity expansion: 65,814 batteries each expansion • Storage capacity expansion cost: $0.59 million each expansion	Siriruttanaruk and Sumrit (2020), EA Annual Report (2023).
Investment cost	• Remanufacturing process: $17 million, including land for future purposes • Repurposing process: $30 million, including land for future purposes • Recycling process: $210 million, including land for future purposes	Guerra and Daziano (2020), SCB (2023), EA Annual Report (2023) and Statista (2024a).
Electricity cost	• $0.12 per kWh • Electricity cost increasing rate: 3% annually	Sathitsuksomboon and Pornpapatkul (2019) and Thananusak et al. (2020).

Material cost	• Material cost: \$139 per kWh • Minimum material cost: \$58 per kWh • Material decreasing rate: 15% annually	Standridge and Corneal (2014), Anthony and Cheung (2017), Brough and Jouhara (2020), Thananusak et al. (2020),
Inventory cost	• Inventory cost: \$161 per battery • Inventory cost increasing rate: 3% annually	Standridge and Corneal (2014), Gu et al. (2018) and Harper et al. (2019)
Material handling cost	• Time duration from the drop-off to storage: 20 minutes • Time duration from the storage to EOL management facility: 30 minutes • Forklift electricity consumption: 8 kWh • Forklift capacity: 2 REVBs per round	Standridge and Corneal (2014) and Dewantoro et al. (2021).
Labor cost	• Annual salary: \$5,539 per person per year, on average • Salary increasing rate: 5% annually • Labor remanufacturing productivity: 206 batteries per person per year • Labor repurposing productivity: 156 batteries per person per year • Labor recycling productivity: 133 batteries per person per year	Chayutthanabun and Chinda (2018), BYD Report (2023) and EA Annual Report (2023).
Overhead cost	• 10% of the total production cost	Standridge and Corneal (2014) and Hamza et al. (2021)
Landfill charge	• Local charge: \$62.18 per battery • Landfill charge in neighboring countries: \$248.72 per battery	Damghani et al. (2008) and Apisitniran and Torrermvasana (2018).
Environmental cost	• \$0.0052 /kg CO_{2eq} • \$0.59/kg 1,4-DB_{eq} • \$1.22 /kg SO_{2eq} • \$0.45 /kg $PM10_{eq}$	Cui and Zhang (2008), Diabat et al. (2013), Ellingsen et al. (2016), Ahmed et al. (2017), Kelly et al. (2019), Amato et al. (2019), Aichberger and Jungmeier (2020),

	• \$125.06 /kg $NMVOC_{eq}$ • \$0.58 /m^3 H_2O_{eq} • \$1.09 /kg Fe_{eq} • \$24,387 /kg $CFC\text{-}11_{eq}$ • \$0.26 /kg oil_{eq}	Darabi and Hosseinichimeh (2020), ECHA. (2024)

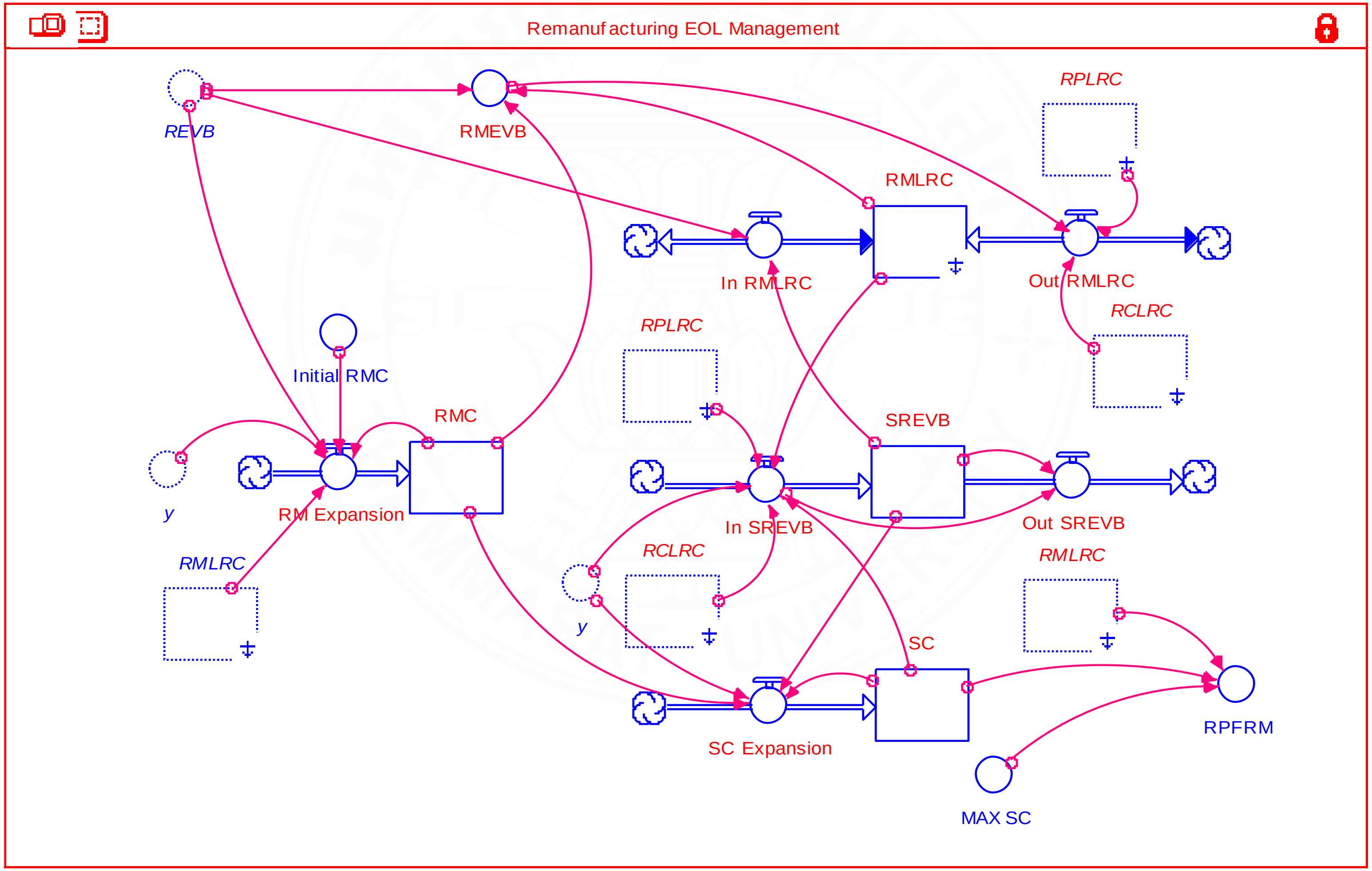
APPENDIX B

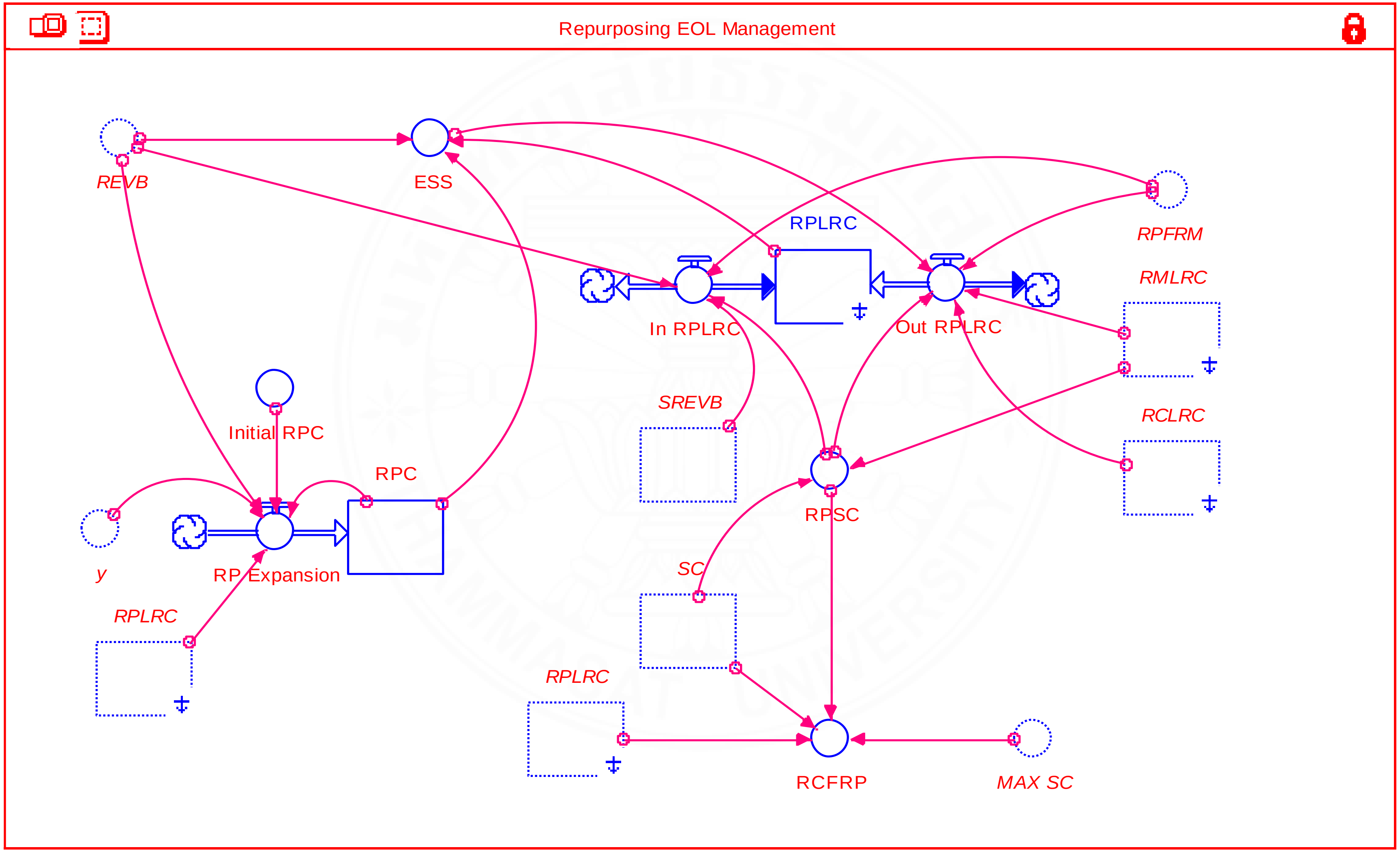
REVB SUB-MODEL

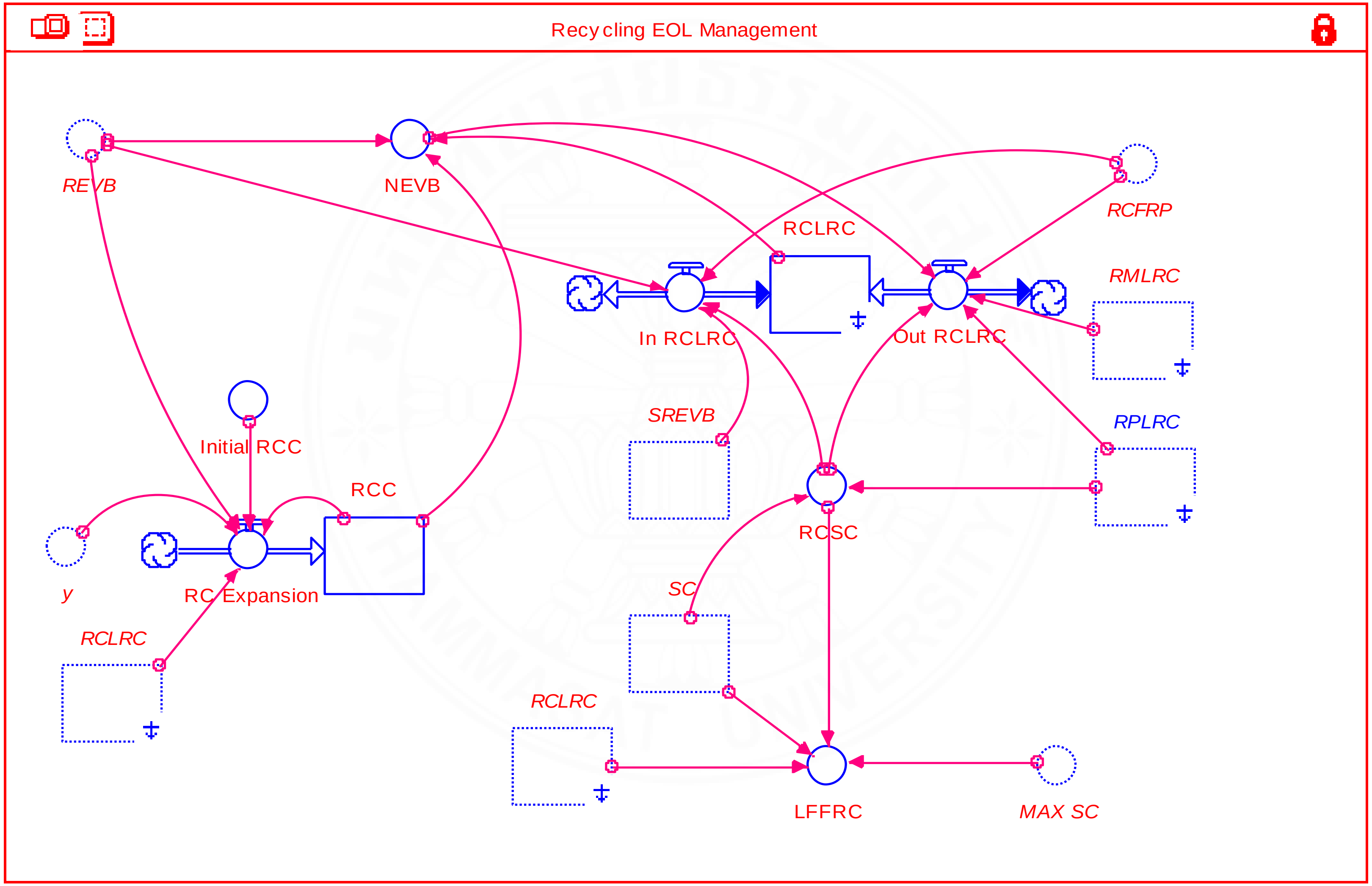


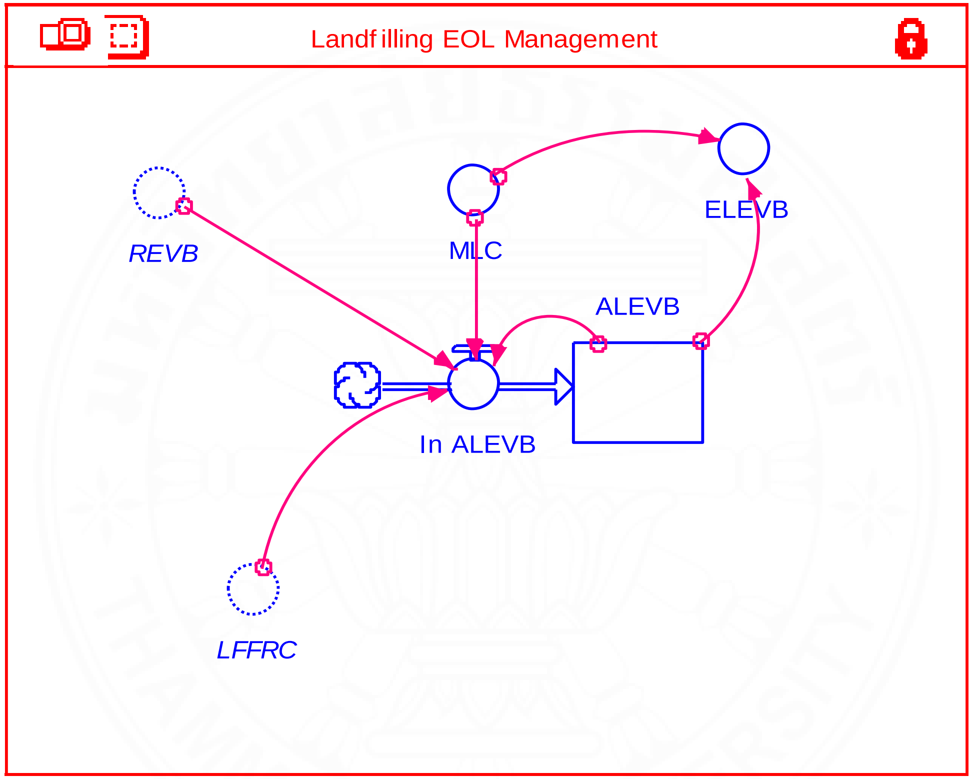
APPENDIX C

EOL MANAGEMENT SUB-MODEL



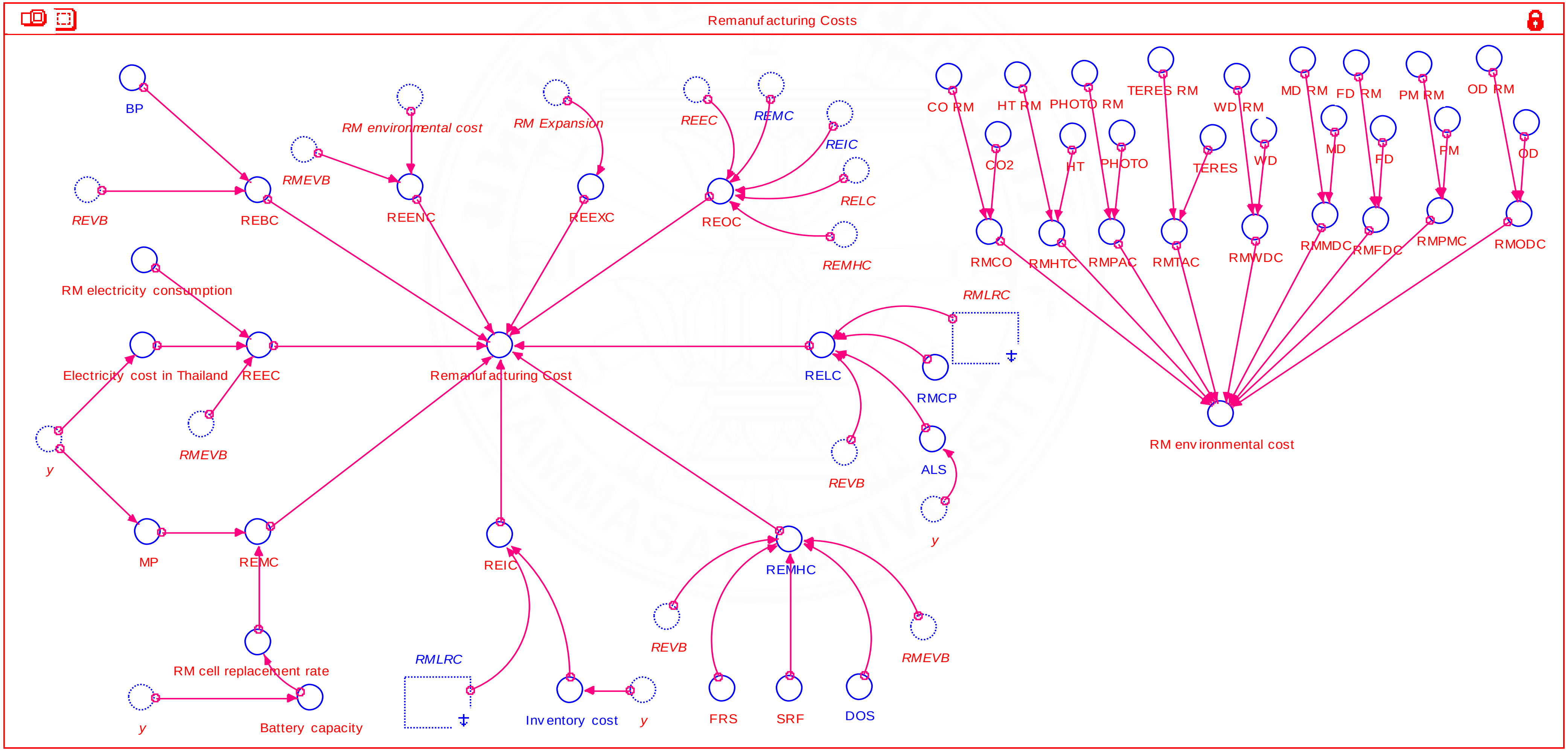

Repurposing EOL Management
REVB
ESS
RPLRC
RPFRM
RMLRC
In RPLRC
Out RPLRC
SREVB
RCLRC
Initial RPC
RPC
RPSC
y
RP Expansion
RPLRC
SC
RPLRC
RCFRP
MAX SC

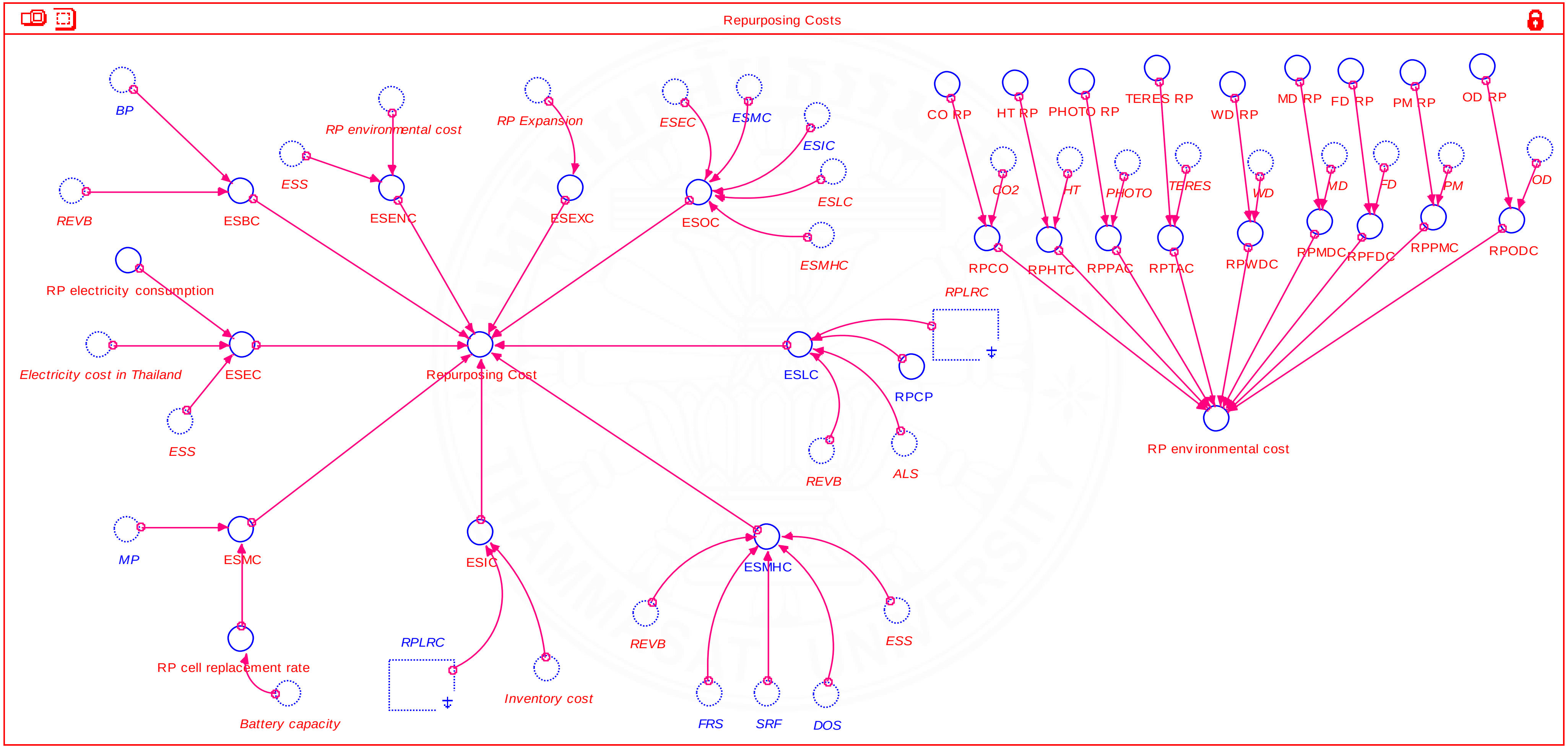

Recycling EOL Management
REVB
NEVB
RCFRP
RCLRC
In RCLRC
Out RCLRC
RMLRC
SREVB
RPLRC
Initial RCC
RCC
RCSC
y
RC Expansion
RCLRC
SC
RCLRC
LFFRC
MAX SC

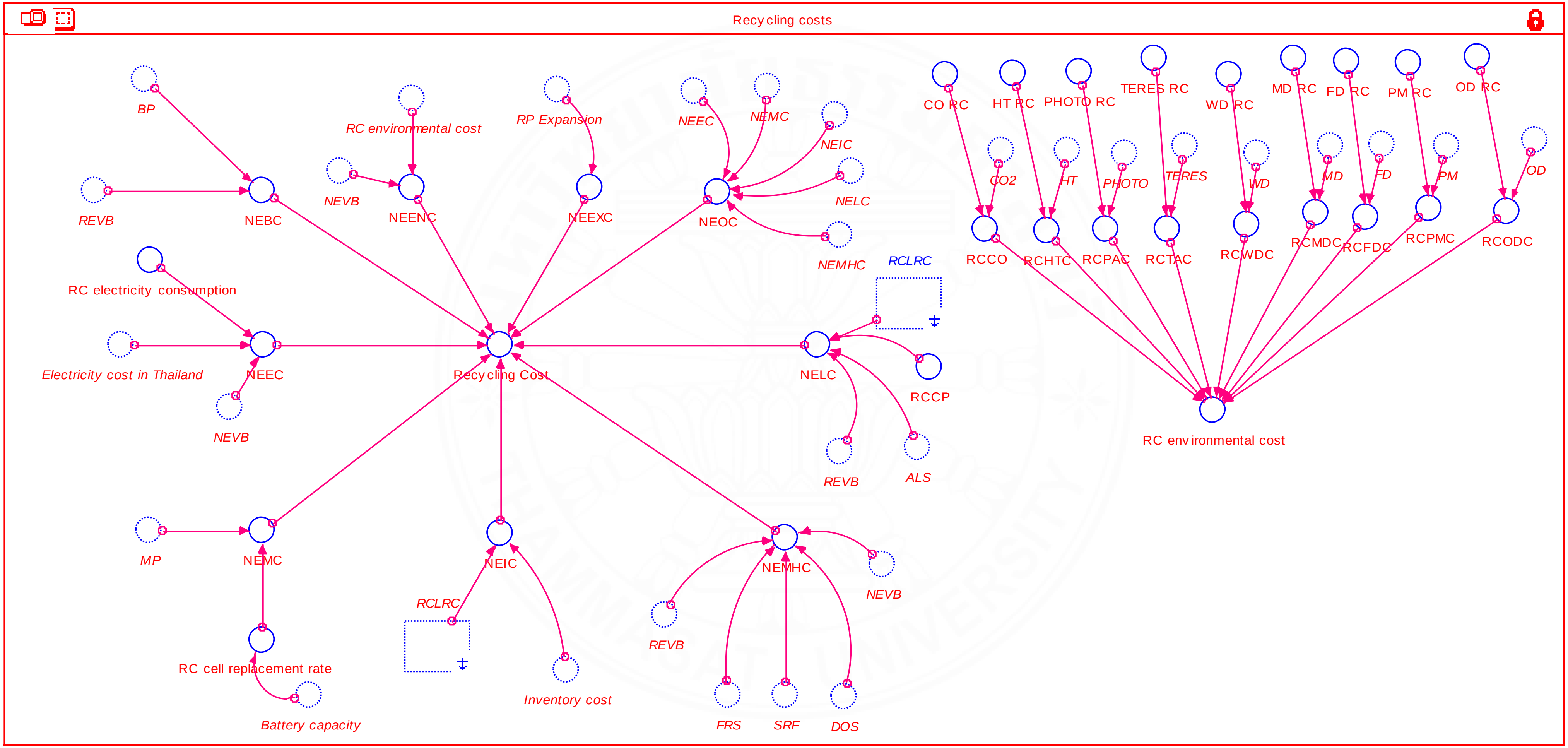

Landfilling EOL Management
REVB
MLC
ELEVB
ALEVB
In ALEVB
LFFRC

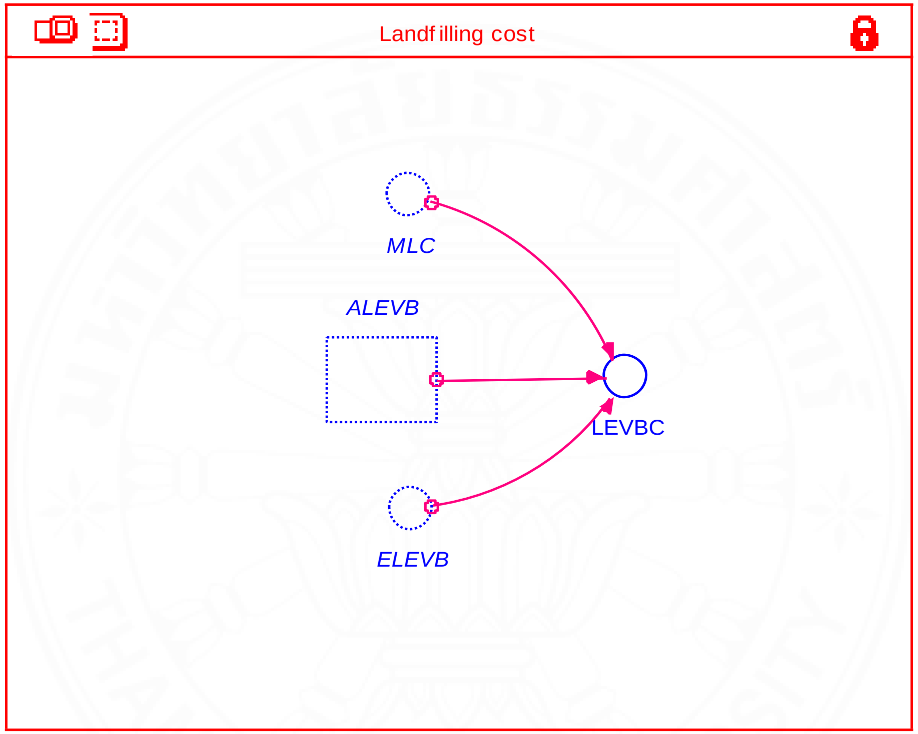
APPENDIX D

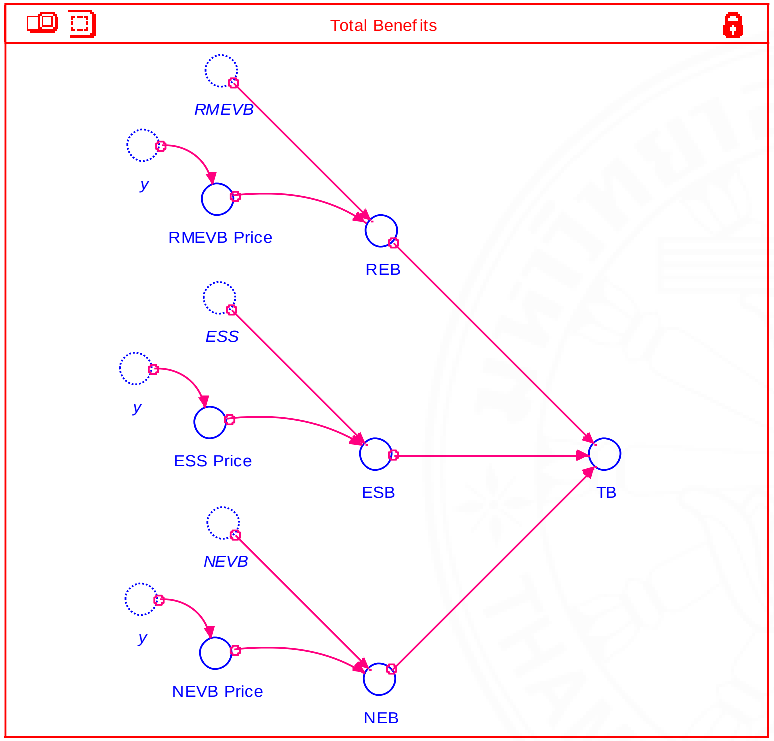
BENEFITS AND COSTS SUB-MODEL

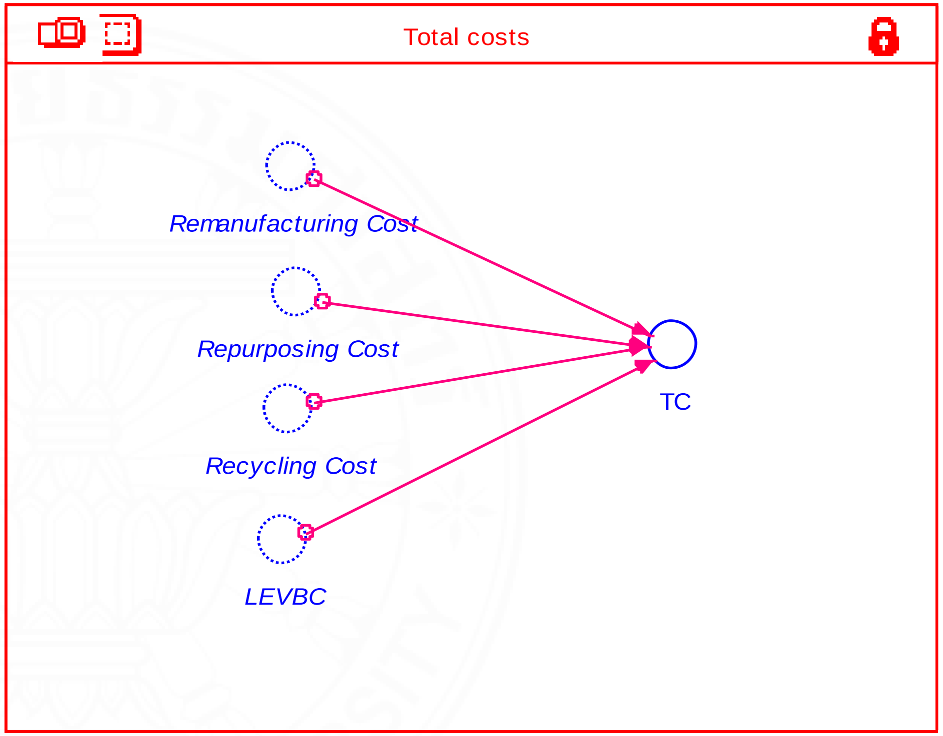


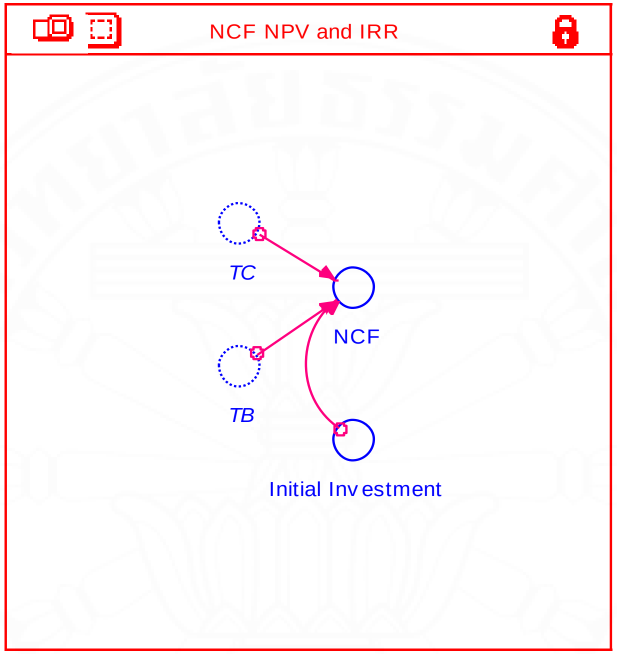

Repurposing Costs
BP
REVB
ESBC
ESS
RP environmental cost
ESENC
RP Expansion
ESEXC
ESEC
ESMC
ESIC
ESLC
ESOC
ESMHC
RP electricity consumption
Electricity cost in Thailand
ESEC
ESS
Repurposing Cost
ESLC
RPLRC
RPCP
REVB
ALS
MP
ESMC
RP cell replacement rate
Battery capacity
ESIC
RPLRC
Inventory cost
ESMHC
REVB
FRS
SRF
DOS
ESS
CO RP
HT RP
PHOTO RP
TERES RP
WD RP
MD RP
FD RP
PM RP
OD RP
CO2
HT
PHOTO
TERES
WD
MD
FD
PM
OD
RPCO
RPHTC
RPPAC
RPTAC
RPWDC
RPMDC
RPFDC
RPPMC
RPODC
RP environmental cost


Recycling costs
BP
REVB
NEBC
RC environmental cost
NEVB
NEENC
RP Expansion
NEEXC
NEEC
NEMC
NEIC
NELC
NEOC
NEMHC
RCLRC
RC electricity consumption
Electricity cost in Thailand
NEEC
NEVB
Recycling Cost
NELC
RCCP
REVB
ALS
MP
NEMC
NEIC
RCLRC
RC cell replacement rate
Battery capacity
Inventory cost
NEMHC
NEVB
REVB
FRS
SRF
DOS
CO RC
HT RC
PHOTO RC
TERES RC
WD RC
MD RC
FD RC
PM RC
OD RC
CO2
HT
PHOTO
TERES
WD
MD
FD
PM
OD
RCCO
RCHTC
RCPAC
RCTAC
RCWDC
RCMDC
RCFDC
RCPMC
RCODC
RC environmental cost


Landfilling cost
MLC
ALEVB
LEVBC
ELEVB


Total Benefits
RMEVB
y
RMEVB Price
REB
ESS
y
ESS Price
ESB
TB
NEVB
y
NEVB Price
NEB


Total costs
Remanufacturing Cost
Repurposing Cost
Recycling Cost
LEVBC
TC


NCF NPV and IRR
TC
NCF
TB
Initial Inv estment

APPENDIX E
SD EQUATIONS OF THE REVB'S EOL MANAGEMENT DYNAMIC MODEL

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

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

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

LP $= \text{If } [[\text{S} \times (1.05)^{y-1}]/2 \geq (\text{ALP} + \text{EVE})] \text{ Then } 0.128 \text{ Else } 0$

ALP $= (\text{EVP}/\text{I}) \times (1.0475)^{y-1}$

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

ACS $= \text{If Y} \leq 4 \text{ Then } 1 \text{ Else } 0.06$

DR $= \text{If History(ADR}, \text{Y} - 1) \geq 491 \text{ Then } 0 \text{ Else (If (ADR} \geq 68.5) \text{ Then } 0.103 \text{ Else } 0)$

ADR $= 53 + (\text{IMDR} \times \text{Y})$

AM $= \text{If EVD} \geq [\text{History(EVD}, \text{Y} - 1) \times 1.5] \text{ Then } 0.1 \text{ Else } 0$

SS $= \text{If Y} \leq 4 \text{ Then Min (EVC}, \text{PEP}) \times 0.806 \text{ Else } 0$

EVC $= \text{If History (EVC}, \text{Y} - 1) \leq 1 \text{ Then } 0.797 + (0.02 \times \text{Y}) \text{ Else } 1$

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

TR $= \text{If } Y \leq 2 \text{ Then } 0.185 \text{ Else } 0$

PP $= \text{If } [PS \times (1.03)^{Y-1} \geq EV \times 0.3] \text{ Then } 0.205 \text{ Else } 0$

IN $= LP + CS + DR + AM + SS + TR + PP$

EVD $= [\text{History } (EVD, Y-1) \times (1 + IN)] + R$

RMEVB $= \text{If } [(REVB \times 0.28) + RMLRC \geq RMC] \text{ Then } RMC \text{ Else } [(REVB \times 0.28) + RMLRC]$

RMLRC $= (REVB \times 0.28) + SREVB - RPLRC - RCLRC - RMEVB$

SREVB $= \text{If History } (SREVB, Y-1) + RMLRC + RPLRC + RCLRC \geq SC \text{ Then } SC \text{ Else History } (SREVB, Y-1) + RMLRC + RPLRC + RCLRC$

RMC $= \text{If } [(REVB \times 0.28) + RMLRC \geq \text{History } (RMC, Y-1) \times 2] \text{ Then History } (RMC, Y-1) \times 2 \text{ Else History } (RMC, Y-1)$

SC $= \text{If } (RMC = \text{Max } RMC) \text{ and } (SREVB = SC) \text{ Then History } (SC, Y-1) + 65814 \text{ Else } SC$

RPFRM $= \text{If } (SC = \text{Max } SC) \text{Then } (RMLRC - SC) \text{ Else } 0$

ESS $= \text{If } [(REVB \times 0.52) + RPLRC \geq RPC] \text{ Then } RPC \text{ Else } [(REVB \times 0.52) + RPLRC]$

RPLRC $= \text{If } (\text{REVB} \times 0.52) + \text{SREVB} - \text{RMLRC} - \text{RCLRC} - \text{ESS} + \text{RPFRM} \geq \text{RPSC Then RPSC Else} (\text{REVB} \times 0.52) + \text{SREVB} - \text{RMLRC} - \text{RCLRC} - \text{ESS} + \text{RPFRM}$

RPSC $= \text{SC} - \text{RMLRC}$

RPC $= \text{If } [(\text{REVB} \times 0.52) + \text{RPLRC} \geq \text{History } (\text{RPC}, \text{Y} - 1) \times 2] \text{Then History } (\text{RPC}, \text{Y} - 1) \times 2 \text{ Else History } (\text{RPC}, \text{Y} - 1)$

RCFRP $= \text{If } (\text{SC} = \text{Max SC}) \text{ Then } (\text{RPLRC} - \text{RPSC}) \text{ Else } 0$

NEVB $= \text{If } [(\text{REVB} \times 0.18) + \text{RCLRC} \geq \text{RCC}] \text{ Then RCC Else } [(\text{REVB} \times 0.18) + \text{RCLRC}]$

RCLRC $= \text{If } (\text{REVB} \times 0.52) + \text{SREVB} - \text{RMLRC} - \text{RPLRC} - \text{NEVB} + \text{RCFRP} \geq \text{RCSC Then RCSC Else} (\text{REVB} \times 0.52) + \text{SREVB} - \text{RMLRC} - \text{RPLRC} - \text{NEVB} + \text{RPFRM}$

RCSC $= \text{RPSC} - \text{RPLRC}$

RCC $= \text{If } (\text{REVB} \times 0.18) + \text{RCLRC} \geq \text{History } (\text{RCC}, \text{Y} - 1) \times 2 \text{ Then History } (\text{RCC}, \text{Y} - 1) \times 2 \text{ Else History } (\text{RCC}, \text{Y} - 1)$

LFFRC $= \text{If } (\text{SC} = \text{Max SC}) \text{ Then } (\text{RCLRC} - \text{RCSC}) \text{ Else } 0$

ALEVB(t) $= \text{ALEVB}(t - dt) + (\text{ALEVB} \times dt)$

ALEVB $= (\text{REVB} \times 0.02) + \text{LFFRC}$

ELEVB $= \text{If ALEVB} > \text{MLC Then ALEVB} - \text{MLC Else } 0$

TB $= RMB + RPB + RCB$

REB $= RMEVB \times 5696$

ESB $= ESS \times 6554$

NEB $= NEVB \times 6690$

TBC $= REBC + ESBC + NEBC$

REBC $= 0.4 \times BP \times REVB \times 0.28$

ESBC $= 0.3 \times BP \times REVB \times 0.52$

NEBC $= 0.15 \times BP \times REVB \times 0.18$

TEC $= REEC + ESEC + NEEC$

REEC $= 0.12 \times 360 \times (1.03)^{y-1} \times RMEVB$

ESEC $= 0.12 \times 840 \times (1.03)^{y-1} \times ESS$

NEEC $= 0.12 \times 3514 \times (1.03)^{y-1} \times NEVB$

TMC $= REMC + ESMC + NEMC$

REMC $= \text{If History}(MP, Y-1) > 58 \text{ Then } [\text{History}(MP, Y-1) \times 0.85] \times 0.2 \times 75 \times RMEVB \text{ Else } 58 \times 0.2 \times 75 \times RMEVB$

ESMC $= \text{If History}(MP, Y-1) > 58 \text{ Then } [\text{History}(MP, Y-1) \times 0.85] \times 0.3 \times 75 \times ESS \text{ Else } 58 \times 0.3 \times 75 \times ESS$

NEMC $= \text{If History (MP, Y} - 1) > 58 \text{ Then [History (MP, Y} - 1) \times 0.85] \times 0.05 \times 75 \times \text{NEVB Else } 58 \times 0.05 \times 75 \times \text{NEVB}$

TIC $= \text{REIC} + \text{ESIC} + \text{NEIC}$

REIC $= (161 \times (1.03)^{y-1}) \times \text{RMLRC}$

ESIC $= (161 \times (1.03)^{y-1}) \times \text{RPLRC}$

NEIC $= (161 \times (1.03)^{y-1}) \times \text{RCLRC}$

TMHC $= \text{RMMHC} + \text{RPMHC} + \text{RCMHC}$

RMMHC $= (0.12 \times 8 \times \text{DOS} \times (\text{REVB} \times 0.28)/2) + (0.12 \times 8 \times \text{SRF} \times \text{RMEVB}/2) + (0.12 \times 8 \times \text{FRS} \times \text{RMEVB}/2)$

ESMHC $= (0.12 \times 8 \times \text{DOS} \times (\text{REVB} \times 0.52)/2) + (0.12 \times 8 \times \text{SRF} \times \text{ESS}/2) + (0.12 \times 8 \times \text{FRS} \times \text{ESS}/2)$

NEMHC $= (0.12 \times 8 \times \text{DOS} \times (\text{REVB} \times 0.18)/2) + (0.12 \times 8 \times \text{SRF} \times \text{NEVB}/2) + (0.12 \times 8 \times \text{FRS} \times \text{NEVB}/2)$

TLC $= \text{RELC} + \text{ESLC} + \text{NELC}$

RELC $= [((\text{REVB} \times 0.28) + \text{RMLRC})/\text{RMCP}] \times \text{ALS} \times (1.05)^{Y-1}$

ESLC $= [((\text{REVB} \times 0.52) + \text{RPLRC})/\text{RPCP}] \times \text{ALS} \times (1.05)^{Y-1}$

NELC $= [((\text{REVB} \times 0.18) + \text{RCLRC})/\text{RCCP}] \times \text{ALS} \times (1.05)^{Y-1}$

TOC $= \text{REOC} + \text{ESOC} + \text{NEOC}$

REOC $= (REEC + REMC + REIC + REMHC + RELC) \times 0.1$

ESOC $= (ESEC + ESMC + ESIC + ESMHC + ESLC) \times 0.1$

NEOC $= (NEEC + NEMC + NEIC + NEMHC + NELC) \times 0.1$

REEXC $= \text{If } [\text{History } (RMC, Y-1)/RMC] = 1 \text{ Then } 0 \text{ Else } 1330000 \times [RMC - \text{History } (RMC, Y-1)/16584]$

SEXC $= \text{If } [\text{History } (SC, Y-1)/SC] = 1 \text{ Then } 0 \text{ Else } 590000 \times [SC - \text{History } (SC, Y-1)/65814]$

ESEXC $= \text{If } [\text{History } (RPC, Y-1)/RPC] = 1 \text{ Then } 0 \text{ Else } 6030000 \times [RPC - \text{History } (RPC, Y-1)/29607]$

NEEXC $= \text{If } [\text{History}(RCC, Y-1)/RCC] = 1 \text{ Then } 0 \text{ Else } 21600000 \times [(RCC - \text{History}(RCC, Y-1))/25893]$

LEVBC $= \text{If } ALEVB > MLC \text{ Then } [(MLC \times 62.18) + (ELEVB \times 248.72)] \text{ Else } ALEVB \times 62.18$

TCOC $= (RMCO \times RMEVB) + (RPCO \times ESS) + (RCCO \times NEVB) + (LFCO \times ALEVB) \times 0.0052$

THTC $= (RMHTC \times RMEVB) + (RPHTC \times ESS) + (RCHTC \times NEVB) + (LFHTC \times ALEVB) \times 0.59$

TTAC $= (RMTAC \times RMEVB) + (RPTAC \times ESS) + (RCTAC \times NEVB) + (LFTAC \times ALEVB) \times 1.22$

TPMC $= (RMPMC \times RMEVB) + (RPPMC \times ESS) + (RCPMC \times NEVB) + (LFPMC \times ALEVB) \times 0.45$

TPOC $= (RMPOC \times RMEVB) + (RPPOC \times ESS) + (RCPOC \times NEVB) + (LFPOC \times ALEVB) \times 125.06$

TWDC $= (RMWDC \times RMEVB) + (RPWDC \times ESS) + (RCWDC \times NEVB) + (LFWDC \times ALEVB) \times 0.58$

TMDC $= (RMMDC \times RMEVB) + (RPMDC \times ESS) + (RCMDC \times NEVB) + (LFMDC \times ALEVB) \times 1.09$

TODC $= (RMODC \times RMEVB) + (RPODC \times ESS) + (RCODC \times NEVB) + (LFODC \times ALEVB) \times 24387$

TFDC $= (RMFDC \times RMEVB) + (RPFDC \times ESS) + (RCFDC \times NEVB) + (LFFDC \times ALEVB) \times 0.26$

BIOGRAPHY

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