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Pathways for enhancing sustainable mobility in emerging markets: Cost-benefit analysis and policy recommendations for recycling of electric-vehicle batteries in Thailand

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ABSTRACT

To transition towards sustainable mobility in emerging economies, fostering the use of electric vehicles (EVs) is required. This necessitates the development of an efficient management system for end-of-life (EoL) EV batteries under a circular economy principle. Using Thailand as a case study, this paper provides a holistic analysis by developing a Cost-Benefit Analysis (CBA) and deriving policy implications from the CBA results that consider stakeholder perspectives at the micro level and the uncertainties of future development. The findings suggest that the economies of scale (plant centralization) and the share of cathode chemistries play pivotal roles. In some cases, investment incentives may be required depending on the inflow of EoL batteries, technological advancements, and market volatility. A policy mix combining EoL volume-focused (i.e., enhancing battery collection rates/imports and establishing a clear policy roadmap for scaling up recycling operations) and monetary measures (i.e., taxes and financial subsidies) is essential to establish recycling facilities.

1. Introduction

To reach the Paris Agreement's goal to limit global warming to 1.5 °C, sector decarbonization has come into consideration, including the transportation sector (UN Environment Programme, 2022), in which carbon dioxide (CO_2) emissions increased by an average of almost 2 % every year from 1990 to 2021 (International Energy Agency, 2022a, 2022b). As a result, it is necessary to promote carbon-neutral mobility systems, and one promising practice is to electrify the transportation sector by increasing EV usage to mitigate the impacts of climate change (Onat et al., 2021). By 2030, EVs will share more than 60 % or almost 350 million vehicles globally (International Energy Agency, 2022a, 2022b).

While the current key players in the EV market are China, Europe, and the United States, emerging markets are also transitioning to EVs (Gahlaut et al., 2023), especially in India, Thailand, and Indonesia. In 2022, the EV sales in these three countries were more than triple compared to 2021 (International Energy Agency, 2023). Focusing on Thailand, the country is one of the leading vehicle productions in Asia and can become a regional EV hub. Moreover, Thailand has set a target called 30@30, meaning that in 2030, 30 % of the car production in the country will be zero-emission vehicles (ZEVs) (Office of the Board of Investment, 2023). According to (Electric Vehicle Association of Thailand, 2023), the number of battery electric vehicle registrations raised more than 900 % from 2019 to 2023. A recent study forecasts that the country needs to reach 100 % EVs (for motorcycles, cars, and buses) in 2035 or around 10 million land-based EVs to achieve a carbon neutrality target by 2050 (CASE for Southeast Asia, 2022). Regarding the EoL scrap, (Barkhausen et al., 2023) estimated that 2035 EoL batteries will range from 4–20 ktons.

Additionally, Thailand is suffering from significant levels of air pollution, particularly $PM_{2.5}$ (particulate matter with a diameter up to 2.5 μm), sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3) and one of the largest emitters is from road vehicles, especially for particulate matter and NO_x (Cheewaphongphan et al., 2017; Cheewaphongphan et al., 2020; Dutta and Chavalparit, 2023). In the Bangkok metropolitan area, with a population of around 11 million (National Statistical Office of Thailand, 2023), a recent study (Chavanaves et al., 2021) found that air pollution caused by transportation will lead to

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Nomenclature

a,b,c	Equipment-specific cost coefficients
cap	Recycling plant size/capacity
DC	Disassembly cost
EC	Equipment cost
Eff	Material recovery efficiencies
HLC	Hourly labor cost
i	Cathode chemistry type in NCX and LFP scenarios
j	Utility type
k	Recycled material
M_d	Manpower (time) requirement for removing a battery pack from a car to disassembling it to a cell level
Net benefits	Net benefits
OLC	Operating labor cost
Pack	Number of battery packs for each cathode chemistry type
PPP	Purchasing power parities
P_{rm}	Raw material price per kg
P_{rv}	Recovery material price per kg
P_u	Utility price per unit
Raw mat	Required raw material amount (kg) used in the recycling process per 1 kg of EoL battery
RC	Recycling cost
Rec amount	Recovery amount of each material from 1 kg of EoL battery
RMC	Raw material cost
RV	Recovery value of the recycled material
TC	Transportation cost
Total benefits	Total benefits
Total costs	Total costs
UC	Utility cost
Utility	Utility amount required per 1 kg of battery

47,331 disability-adjusted life years (DALYs) in 2024. Considering climate and air pollution concerns, Thailand is pushing towards a low-carbon society, and EVs are one of the solutions for the transportation sector. This shows that the number of EVs and EoL batteries is expected to increase significantly over time. Consequently, Thailand must implement an efficient EoL battery management ecosystem to tackle these challenges.

Although promoting an enabling environment for EVs is necessary to achieve climate targets, it, in turn, requires many Lithium-ion batteries (LIBs). Thus, the government should not only consider progressing EV technology diffusion but also setting up a waste management ecosystem for battery waste generated from EVs (Skeete et al., 2020). This is because the production process of LIBs requires (1) scarce/critical raw materials, such as lithium, cobalt, and nickel, and (2) a significant amount of energy, leading to environmental and social impacts from mining, refining, and manufacturing (Albertsen et al., 2021; Beaudet et al., 2020; Lotz et al., 2022).

The circular economy (CE) is the opposite of a traditional linear economic model, meaning that a production and consumption model would retain or extend the life cycle of each product (Albertsen et al., 2021; European Parliament, 2022). The CE concept can advance sustainable production and consumption behaviors, improve operational efficiencies, reduce waste and economic risks of supply shortage, and mitigate environmental impacts, as discussed in (Camilleri, 2020; Choi and Rhee, 2020; Liu et al., 2023). The CE measures for EV batteries include intensifying use, repairing, remanufacturing, reusing, repurposing, and recycling (Albertsen et al., 2021).

The scope of this study focuses on a recycling approach since it has been considered the most common CE measure for EV batteries (Schulz-Mönninghoff and Evans, 2023). Although the measures, such as reusing and repurposing, for second-use applications of EV batteries have environmental benefits and postpone the need for recycling (Bobba et al., 2018; Kamath et al., 2023; Kotak et al., 2021), they still pose some challenges such as those related to costs, necessary safety standards, and battery availability (Börner et al., 2022). In addition, when EV batteries reach their EoL stages (including after second-use applications), recycling technologies are required. EVs also cannot be called sustainable mobility if these conditions are not fulfilled: renewable energy use to electrify the vehicles, local industrial development, and EoL battery recycling (D'Adamo et al., 2023). When the EoL stage is reached, EoL batteries need to be recycled to get raw materials from the cathode to produce new batteries or different products.

As a result, this work aims to develop a comprehensive CBA for EV battery recycling and derive policy recommendations from the CBA findings that account for the perspectives of stakeholders at the micro level and the potential uncertainties in future developments. The results of this study could be the preliminary guidelines for establishing recycling facilities in emerging economies, contributing to achieving the Sustainable Development Goal (SDG) 12 – Responsible Consumption and Production.

2. Literature review

When reviewing the currently available literature on the feasibility of EV battery recycling, it was found that the studies could be divided into two groups. The first group focused on the techno-economic aspects of EV battery recycling, particularly its economic feasibility under given conditions and its environmental impacts. In contrast, the second group dealt with the political aspects of battery recycling feasibility, naming barriers and enablers and discussing policy measures to address them.

2.1. Techno-economic literature

Concerning the techno-economic studies, (Rohr et al., 2017) conducted a techno-economic analysis of EV battery remanufacturing, second-life, and recycling using a cost-benefit and net present value approach. It was concluded that the second-life option is already economically viable, while the feasibility of remanufacturing and recycling depended on the number of EV batteries. Another study focused on a feasibility analysis of EV battery recycling using a cost-benefit approach (Lander et al., 2021). The authors found that economic viability factors include transportation distance (in-country or out-country), wage, battery pack design, and recycling method. A recent study from (Reinhart et al., 2023) also discussed the techno-economic analysis of different pyrometallurgical recycling routes and battery cell compositions. They concluded that cell chemistry is the most critical factor affecting the economic feasibility of EV battery recycling. The high shares of cobalt and nickel in battery cell compositions lead to the increased profitability of EV recycling facilities. In addition, (Blömeke et al., 2022) conducted an environmental and economic impact analysis based on material and energy flow analysis for different industrial battery recycling routes. It was found that mechanical pretreatment recycling has the highest economic benefits and avoided environmental impacts compared to thermal-mechanical and pyrometallurgical pretreatment. (Thompson et al., 2021) also conducted a comparative techno-economic analysis of different hydrometallurgical recycling processes and found that cell disassembly presents a more economically advantageous approach than shredding, highlighting the importance of battery design for disassembly. A publication from (Dunn et al., 2022) also evaluated appropriate recycled content standards (RCS) for the U.S. based on sale projection, techno-economic analysis, life cycle assessment, and material flow analysis. It was suggested that an in-house recycling process is required to increase profitability and decrease environmental impacts.

Additionally, (Popien et al., 2022) and (Scheller et al., 2023) explored different recycling networks (recycling plant sizes and number of recycling sites – centralized vs. decentralized recycling facilities). While (Popien et al., 2022) concluded that large and centralized battery recycling facilities are recommended, (Scheller et al., 2023) indicated that centralized and decentralized can lead to the same level of performance, and decentralization does not refer to lower transportation costs in all situations. (Scheller et al., 2023) also highlighted that energy prices should be considered for new battery recycling plants, and if possible, self-generated electricity from renewable energy sources (e.g., solar power) should be assessed. Moreover, circular factories (integrating battery production and recycling at the same site) can outperform other recycling networks due to their on-site battery production and small transportation costs. Furthermore, (Cao et al., 2023) highlighted the importance of minimizing co-products (such as lithium carbonate, sodium sulfate, and graphite) to reduce environmental impacts and increase the profitability of battery recycling. Some studies also focused on pre-treatment activities or collection modes to understand disassembly costs (Rallo et al., 2020), automatic disassembly processes (Choux et al., 2024; Lander et al., 2023), and feasible collection modes/activities (Zhang et al., 2021). Lastly, several authors centralized their works on the techno-economic feasibility of second-life battery applications that can be utilized for power grid services (Al-Alawi et al., 2022; Fallah and Fitzpatrick, 2022; Sun et al., 2020).

2.2. Policy-related literature

Regarding policy-related research, the current review literature (Beaudet et al., 2020; Lima et al., 2022; Shahjalal et al., 2022) analyzed drivers and bottlenecks of EV battery recycling processes. These barriers include high recycling costs, EoL battery supply problems to make the recycling plant economically viable, sorting problems due to a lack of battery passports, and improper regulations. Moreover, (Albertsen et al., 2021; Olsson et al., 2018; Wrålsen et al., 2021) focused on market/circular business model perspectives. It was found that the business models are context-specific, significantly depend on internal factors, and require close collaboration among stakeholders (especially governments and vehicle manufacturers)/joint ventures. In addition, based on a framework presented in (Tankou, Bieker, and Hall 2023), policy interventions to scale up EoL battery recycling facilities can be categorized into six areas: battery traceability and collection, building domestic capacity, battery information, battery standards, recycling mandates, and R&D. Table 1 summarizes policy interventions/practices from all relevant policy-related studies based on six areas mentioned above (Ahuja et al., 2020; Curtis et al., 2021; Danino-Perraud, 2020; Drabik and Rizos, n.d.; Hampel, 2022; Hao et al., 2022; Harper et al., 2023; Islam and Iyer-Raniga, 2022; Kelleher Environmental, 2020; McNamara, 2023; Neumann et al., 2022; Nurdiawati and Agrawal, 2022; Tang et al., 2019; Tankou et al., 2023).

Focusing on emerging economies, (Gahlaut et al., 2023) analyzed barriers to sustainable EV mobility systems in India, and the three most essential blockades are those related to costs, policy support, and awareness. The authors also suggested a future study of enhancing CE measures for EV batteries to promote sustainable development by utilizing batteries until their EoL stages and properly managing their wastes. (Bhuyan et al., 2022) also adopted a multi-stakeholder and multi-criteria decision-making approach to understand critical enablers and barriers of battery recycling in India. It was found that the most critical barrier is the lack of governmental policy support, while the most promising enablers are back systems included in business models. In addition, (Khumkoa, 2019) investigated the potential of battery recycling development in Thailand and concluded that it is necessary to create proper infrastructure and introduce policies to drive battery recycling facilities in the country.

Table 1
Summary of policy interventions/practices for establishing EoL battery recycling.

Areas	Policy interventions/practices
Battery traceability and collection	• Transparent and traceable EV battery platform to improve the collection rate and report back to the government regarding the recovery quota achieved • Extended producer responsibilities • Take-back systems • Minimum collection target
Building domestic capacity	• Market-pull policies/incentives such as reward-penalty and investment/tax incentives • Innovative financial instruments • Innovative business models such as produce-service systems • Promote national/regional/international collaboration among relevant stakeholders, including importing EoL batteries
Battery information	• Battery passport (transparent battery labeling) to optimize the recycling process
Battery standards	• Standards on manufacturing and safety when handling EoL batteries • Standards on accuracy and reporting of the state-of-health metric • Standards on battery durability • Standards on information accessibility (battery passport)
Recycling mandates	• Battery waste laws/regulations, such as recycled material content requirements, recovery targets/rates, and taxes on primary raw materials • Laws/regulations to prohibit the disposal of batteries
Research and development (R&D)	• Dedicated research funding such as to increase the recovery rate, broaden the range of recycled battery materials and improve the environmental impact • Eco-design (durability, repairability, and recyclability) • Battery recycling pilot project • Joint ventures for R&D (such as public-private partnerships)

In summary, many techno-economic studies present the micro-perspective of companies potentially involved in EV battery recycling. The key question for these actors is: Is EV battery recycling an economically viable option for my company or not? In contrast, policy-related research reveals the macro-perspective of policymakers and their consultants, addressing the key question: What can we do to facilitate EV battery recycling in this country? Obviously, there is a well-known connection between these two questions: If the policy provides framework conditions within which EV battery recycling is economically viable, companies will realize it. A little less obvious is that the answer to both questions is highly dependent on future development, which is uncertain for all actors and, therefore, bedevil the policymaking process. Consequently, this study takes a holistic approach to the research question: How can policies support the economic viability of EV battery recycling in Thailand? It gives special attention to the stakeholders' perspectives at the micro-level and the epistemic uncertainty of future development. Although political decisions need to consider various other factors, such as building capacity (e.g., technical know-how and skilled working force), this study focuses on economic viability as an essential starting point. Additionally, other methods (e.g., dynamic macroeconomic modeling) might highlight different economic aspects that are likewise important. Still, this study aims to transfer perspectives from stakeholders at the economic micro-level (i.e., company representatives) to the policymaking process while considering future uncertainties affecting all actors. Moreover, the results of this study contribute to sustainable and efficient resource use, which are essential to achieving SDG 12.

Therefore, our approach consists of three steps. First, the perspectives of company representatives on factors influencing economic viability are collected through interviews and literature research. Next, the impacts of all identified factors on the economic viability are quantitatively analyzed in a cost-benefit analysis, covering their uncertain future development through a scenario- and sensitivity-based set-up. Finally, conclusions are drawn on policy measures to support economic feasibility appropriately against various possible future developments.

3. Methods

This analysis was divided into three main parts: (1) literature analysis and stakeholder interviews, (2) scenario-/sensitivity-based CBA, and (3) deriving policy recommendations for supporting EV battery recycling. All data and assumptions represent the context of Thailand. The outcomes of the literature analysis/stakeholder interview (1) and CBA analysis (2) are the foundation of the policy recommendations (3), as illustrated in Fig. 1.

3.1. Literature analysis and stakeholder interviews

This step identified factors potentially influencing each cost and benefit component and net benefits of EV battery recycling facilities based on literature analysis (see Section 2) and six online semi-structured stakeholder interviews during 2022–2023. For the stakeholder selection process, since the EV battery ecosystem in Thailand is in a very early stage, we attempted to cover all possible sectors with at least one company, including (1) a car battery-related business focusing on second-life and EoL batteries, (2) a battery testing company, (3) two EV manufacturers, (4) a foreign-based company recycler and (5) a cell battery manufacturer in Thailand. Besides general company information, the interviews ascertained the companies' EoL battery collection and management plan and their expectations on EoL battery amount and management costs. Further, their perspectives on barriers, enablers, and required support through policy were explored. The complete list of questions is listed in a supplementary material (S1). The identified influencing factors were quantitatively analyzed in the next step (CBA). Moreover, the bottlenecks and policy options for fostering EV battery recycling facilities mentioned by the interviewed stakeholders were utilized to derive policy recommendations in step 3.

3.2. Scenario-/sensitivity-based CBA

The CBA is a technique for measuring and comparing a system's positive (benefits) and negative (costs) economic impacts (Chaianong et al., 2019) that can help stakeholders make informed decisions. Since the CBA scope of this analysis was based on a recycling business/company perspective, cost components include transportation, disassembly, and recycling costs, while a benefit component is the recovery value of recycled material, as discussed in (Dunn et al., 2022; Lander et al., 2021; Rohr et al., 2017). Fig. 2 shows the framework diagram of CBA with four scenario factors and four sensitivity parameters tested in this study, which are discussed further in Section 3.2.1.

3.2.1. Scenario and sensitivity analysis

First, the study includes three different time horizons (2035, 2050, and 2065), which were chosen by assuming a 15-year battery lifetime (Haram et al., 2021; Zhang et al., 2021) from 2020 (past), 2035 (short-term) and 2050 (long-term; carbon neutrality goal of Thailand), respectively. Several scenarios (see Fig. 2) were tested for each time horizon based on influencing factors identified from the previous step (Section 3.1). Four scenario factors refer to second-order factors (see Fig. 5) that should affect either cost or benefit components. At the same time, the four sensitivity parameters are primarily first-order factors tested in terms of percentage from the base case.

The first three factors were plant size/capacity (10,000 (small), 50,000 (medium), and 100,000 (large) tons per year; see Section 3.2.2), cathode chemistry (NCX and LFP scenarios; see Fig. 3 and Section 3.2.2), and plant location. For plant location, decentralized and centralized locations were compared, assuming the same amount of the batteries would be recycled and the same disassembling cost per unit would arise. For the former (decentralized site), it is assumed that recycling plants are in the center of each region: Bangkok region (including Bangkok and its vicinity, east, west, and central of Thailand, and according to (Department of Land Transport, 2022), this region has high car demand.), northeast, north, and south of Thailand with smaller plant size, while the centralized location is assumed to be in Bangkok and its vicinity only with larger plant size. In the two cases, transportation and recycling costs are the differentiating factors. Another influencing factor tested in this analysis was investment incentives from the public sector. In some cases, the recycling processes might not be economically attractive, and financial incentives may lead to positive net benefits. Investment incentives to reduce recycling costs, ranging from 10–30 %, were tested in the models. The maximum investment incentives at 30 % were adopted from the Battery and Electric Vehicle Manufacturing Tax Credit of the U.S. (Office of Energy Efficiency and Renewable Energy, 2023).

Sensitivity analysis was also conducted in this study. The parameters studied are equipment cost, raw material cost, recovery value of recycled material, and recycling efficiency (see Fig. 2). Regarding equipment/raw material cost (the main components of recycling costs) and recovery value of recycled material, their costs/prices are sensitive to several factors. They, for example, include technology cost reduction

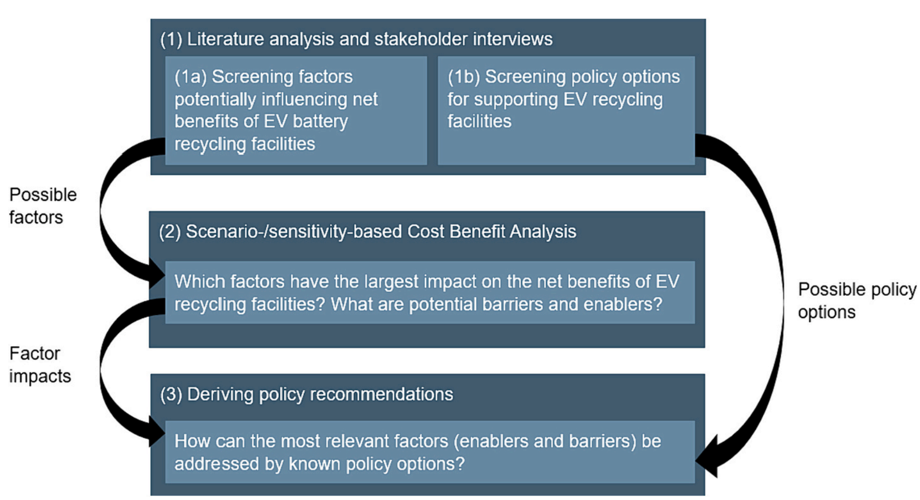


Fig. 1. Research framework diagram.

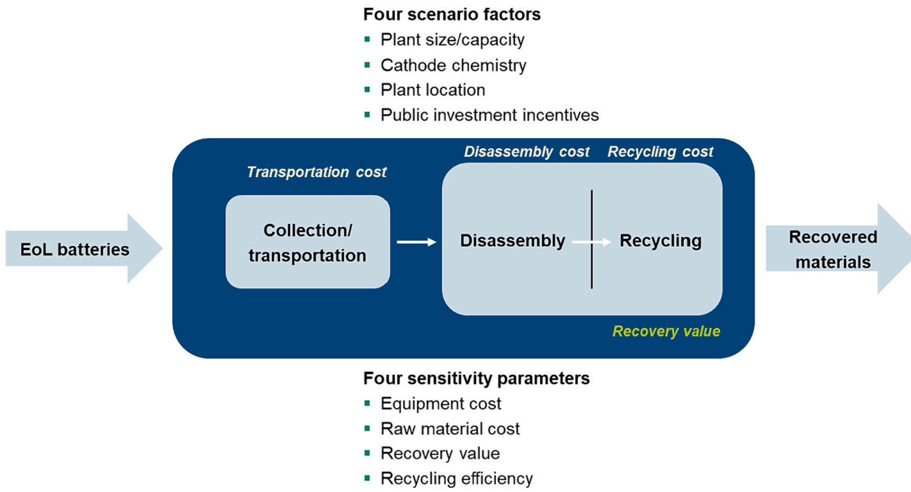


Fig. 2. Framework diagram of scenario-/sensitivity-based CBA.

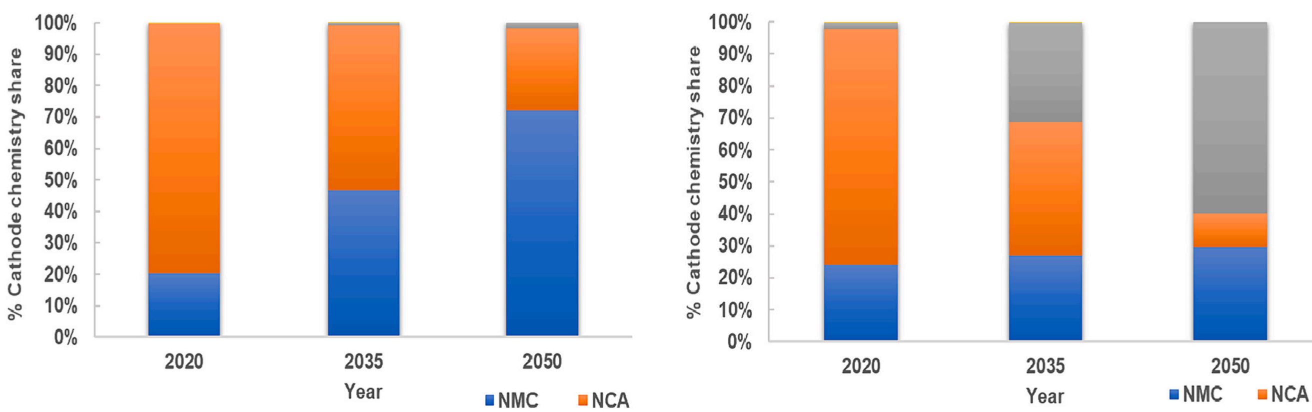


Fig. 3. Share of cathode chemistry in 2020, 2035, and 2050. The left figure represents the NCX scenario, and the right represents the LFP scenario. NMC is Nickel-Manganese-Cobalt Oxide, NCA is Lithium-Nickel-Cobalt Oxide, LFP is Lithium-Iron-Phosphate, and LMO is Lithium-Manganese-Spinel.

and economic and political factors (such as the correlation of chemical engineering plant cost index (CEPCI) and macro-economic indicators as discussed in (Mignard, 2014)). Therefore, testing the impacts of equipment/raw material cost and recovery value change on net benefits is essential. This analysis tested these three parameters by varying from −50 (low) to 500 (high) percent from the base case. This is because, focusing on recovery value, in our base scenario, an average of the Customer Price Index (CPI) during the past ten years was applied to project the future price of each recycled material, which was found to be very conservative at around 1 %. Based on the actual 10-year historical price of recycled materials, it was found that cobalt had the highest standard deviation of the market price (Investing.com, 2023). Thus, we used annual cobalt price change as a baseline to define percent changes (−50 to 500 %) for the sensitivity analysis, which was applied to recycled material values, equipment cost, and material cost to be able to compare all three parameters whether which one has the highest impacts on net benefits. For recycling efficiency, it is essential to assess how well the recycling plants could perform, which would affect the amount of recycled materials. The recycling efficiency of the base scenario was based on (Dai et al., 2019), which is already high for some recycled materials (at 90–98 %). We then assumed the lower bound at 85 % and the upper bound at 99 %, as mentioned in (Zhou et al., 2020), that some recycled materials could achieve a recycling yield of over 99 %. In summary, this parameter varied from 85 (low) to 99 (high) percent efficiency to understand its effects on net benefit values.

3.2.2. *Basic assumptions of the CBA*

In the following, general assumptions are explained. They were taken from the literature as a foundation for the CBA, including basic assumptions on the battery lifecycle, possible battery chemistries, overall EoL battery potential, realistic plant sizes, and recycling method and operation.

First, it is essential to note that only EoL batteries (after the second life or 15 years from the beginning of life as discussed in (Haram et al., 2021; Zhang et al., 2021)) were considered in this analysis (as discussed in Footnote 2). This means that each battery is reused or repurposed for its second life before being processed for recycling.

The cathode chemistries of EoL batteries were forecasted based on two scenarios depending on the major cathode shares chemistries in 2050 – the Nickel and Cobalt-based dominance scenario (short: NCX) and the Lithium-Iron-Phosphate-based dominance scenario (short: LFP). They were adopted by the analysis of (Dunn et al., 2022) and initially presented by (Xu et al., 2020). Details on cathode chemistry shares in the NCX and the LFP scenarios in 2020, 2035, and 2050 are illustrated in Fig. 3.

For three selected time horizons, the amount of EoL batteries in Thailand was estimated to understand the potential demand for EV battery recycling plants, as illustrated in Fig. 4. EoL batteries were assumed only from electric passenger cars and did not include production/cell scrap and potential imported EoL batteries. The low EV adoption (around 4 % share of EVs in 2039) was adopted from (Thailand Development Research Institute, 2022) and projected linearly for the

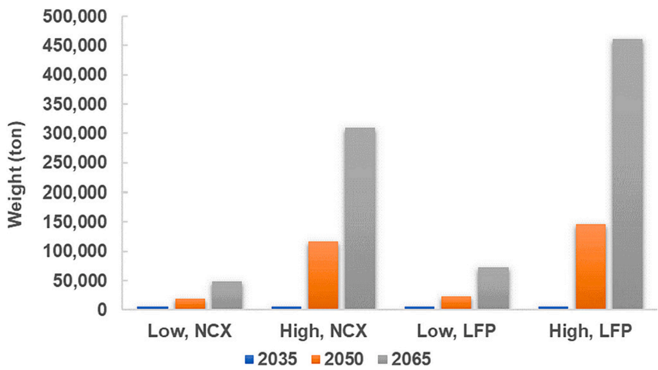


Fig. 4. EoL battery potential for recycling in four different scenarios. Low/high refers to the EV adoption rate, while NCX/LFP refers to cathode chemistry scenarios (see Fig. 3).

rest, while the high EV adoption (10 million EVs in 2035) was adopted from (CASE for Southeast Asia, 2022) and projected linearly for the rest. The Asia's electronic waste collection rate was considered to be 11 % (Neumann et al., 2022), assuming an annual growth rate of 2 %, as used in (Dunn et al., 2022). Moreover, each cathode chemistry's characteristics and total pack weight were adopted from (Lander et al., 2021). As a result, it is found that in 2035, EoL batteries are expected to be around 6000 tons, while in 2050 and 2065, they range from about 20,000–150,000 and 50,000–460,000 tons, depending on EV adoption rate and cathode chemistry (LFP weights are higher than NCX weights). This is also in line with a study from (Barkhausen et al., 2023), which estimated that EoL scrap 2035 ranges from 4–20 kton.

To cover the respective demand, different sizes of recycling plants (small, medium, and high – 10,000, 50,000, and 100,000 tons per year, respectively) were selected to test in this analysis based on existing LIB recycling plants as summarized in (Baum et al., 2022). It is also important to note that the current infrastructure of EV recycling plants is not yet suitable for large-scale plants (Wu et al., 2022); therefore, in this analysis, the maximum EV recycling plant size was set to 100,000 tons per year.

Considering the battery recycling process, the pre-treatment (discharging, disassembly, crushing, and separation) and recycling are the two main components (Hua et al., 2021; Shahjalal et al., 2022; Windisch-Kern et al., 2022). Currently, four recycling methods: pyrometallurgical, hydrometallurgical, bio-hydrometallurgical, and direct recycling are being discussed in the literature. Due to its high recovery rate and low energy consumption, the hydrometallurgical method is considered one of the dominant technology choices. However, the process requires time and high reagent consumption (Hua et al., 2021; Vieceli et al., 2021). The other recycling methods have been reported and summarized by (Chen et al., 2019; Hua et al., 2021; Rajaeifar et al., 2022). As a result, the hydrometallurgical recycling process was selected to focus on in this analysis. Each recycling plant was assumed to operate 320 days per year and 20 h per day, and its lifetime is ten years (Dai et al., 2019).

3.2.3. Detailed CBA calculation

Focusing on cost components, transportation cost (*TC* in USD/kg) was assumed based on the ten-wheel truck cost in Thailand and is dependent on distance and fuel (diesel) price. This truck transportation cost was initially published by the Comptroller General's Department of Thailand but cited in (Thai Local Technician Support Association, n.d.). Two parts of transportation costs were considered in this analysis – transportation costs (1) from end user to collection/disassembly point and (2) from collection/disassembly point to recycling plant, which both were assumed to be around 300 and 500 km (km), respectively. This was assumed from the average distance of each region (such as north, northeast, and south of Thailand) to Bangkok and its vicinity area, which was selected to be the location of a recycling plant. The fuel price (diesel price) was taken from the database of the Bank of Thailand (Bank of Thailand, 2022), which is around 30 Thai Baht per liter or 0.85 US dollars per liter in 2022. This price was averaged from December 2021 to May 2022, and the exchange rate was 1 US Dollar (USD): 35.327 Thai Baht (THB) as of June 30th, 2022. The fuel price was projected to increase over time, according to an average Customer Price Index (CPI) over the past ten years. According to (National Statistical Office of Thailand, 2022), the CPI is approximately 1 %.

As shown in Eq. (1), the disassembly cost was calculated, where *DC* is the total disassembly cost (USD). *HLC* is hourly labor cost (USD/h), which was adopted from an average of the maximum and minimum hourly wage of mechanical labor in Thailand (around 1.9 USD/h) (iTax, 2022) and is assumed to increase 2 % every year (Ministry of Labor, 2022). M_d is the manpower (time) requirement for removing a battery pack from a car to disassembling it to a cell level, which was assumed to be 27 h per battery pack (Rallo et al., 2020). The *pack* is the number of battery packs for each cathode chemistry type, calculated from the cathode chemistry shown in Fig. 3, weight per pack of each cathode chemistry, and total recycling capacity (cap; ton per year). *i* refers to each cathode chemistry type in NCX and LFP scenarios.

$$DC = \sum (HLC \times M_d \times Pack)_i \tag{1}$$

Regarding recycling cost (*RC*), it consists of three main categories: capital investment, manufacturing cost, and others (such as administrative cost and R&D cost). The equipment cost, raw material cost, operating labor, and utilities cost are discussed below with some parameter adjustments to the Thai context, while the details of other cost categories calculation were taken from Table 15 of (Dai et al., 2019).

Equipment cost for hydrometallurgical recycling process (such as conveyers, calciner, wet granulator, and density separator) was derived from Eq. (2). Where *EC* is equipment cost (USD). *a,b, and c* are equipment-specific cost coefficients. They were reported in 2017 by (Dai et al., 2019) and applied annual chemical engineering plant cost index (CEPCI), reported in chemical engineering magazine (cited from (Maxwell, 2022)), for converting each equipment price from 2017 to 2035, 2050, and 2065. *PPP* is purchasing power parities, referring to the equalization of purchasing power of different countries compared to the U.S. The PPP value of Serbia from (OECD, 2022) was used in this analysis since Thailand and Serbia have the same Gross Domestic Product (GDP). *cap* is recycling plant size/capacity in tons per hour.

$$EC = a \times PPP \times cap^b + c \tag{2}$$

Raw material cost (*RMC* in USD, such as ammonium hydroxide, hydrochloric acid, and hydrogen peroxide) was modeled as shown in Eq. (3). *Raw mat* is the required raw material amount (kg) used in the recycling process per 1 kg of EoL battery, which was adopted from (Dai et al., 2019). P_{rm} is the raw material price per kg. The PPP and CPI were applied to the raw material prices to reflect their future cost and Thai context, as discussed earlier in the equipment cost calculation. *cap* is the recycling plant size/capacity in kg per year.

$$RMC = Raw\ mat \times P_{rm} \times cap \tag{3}$$

Operating labor cost (*OLC* in USD) was calculated based on Eq. (4), where *HLC* is an hourly labor cost (USD/h) as discussed in the disassembly cost section. M_r is the manpower (time) requirement for the hydrometallurgical recycling process (212 person-hour per day and 320 days per year, as stated in (Dai et al., 2019).

$$OLC = HLC \times M_r \tag{4}$$

Lastly, utility costs (*UC* in USD) were derived as shown in Eq. (5), where *utility* refers to each utility amount required per 1 kg of battery, which was adopted from (Dai et al., 2019). P_u is the utility price per unit. Utility prices are 0.002 USD/gal for water (average across all block rates in July 2022) (Metropolitan Waterworks Authority, 2022), 0.03 USD/MJ for diesel (similar data source to the transportation cost section), 0.01 USD/MJ for natural gas (average from poor price from November 2021 to April 2022) (Energy Planning and Policy Office, 2022), and 0.04 USD/MJ for electricity (average from large-scale's energy charge across all voltages in July 2022) (Metropolitan Electricity Authority, 2022). Again, the CPI was also applied to the utility price per unit to represent its future cost. *cap* is recycling plant size/capacity in kg per year. *j* refers to each utility type (water, diesel, natural gas, and electricity).

$$UC = \sum (utility \times P_U \times cap)_j \tag{5}$$

The benefit component refers to the recovery value (*RV*) of the recycled material (active cathode materials (lithium, cobalt, nickel, and manganese), copper, aluminum, graphite, and steel in USD). It is important to note that based on (Dai et al., 2019), plastics and electrolytes were assumed to be burnt for energy, while carbon black and polyvinylidene fluoride (PVDF) were not considered in this analysis. The recovery value of each recycled material was calculated as shown in Eq. (6). It is based on the recovery amount (*rec amount*) of each material (*j*) from 1 kg of EoL battery, material recovery efficiencies (*eff*) and recovery material price per kg (P_{rv}), as discussed in (Dai et al., 2019). The PPP and CPI were also applied to the recovered material price per kg. *cap* is the recycling plant size/capacity in kg per year. *k* refers to each recycled material.

$$RV = \sum (rec\ amount \times eff \times P_{rv} \times cap)_k \tag{6}$$

Next, net benefits were calculated from total costs and total benefits and converted into USD/kg (Eqs. (7.1)–(7.3); cap in kg per year). Two possibilities of CBA interpretation include (1) positive net benefits, where total benefits are greater than total costs of the EV recycling plant (attractive investment), and (2) negative net benefits, meaning in the opposite direction that total costs are greater than total benefits (unattractive investment).

$$Total\ costs = TC + \left(\frac{DC + RC}{cap}\right) \tag{7.1}$$

$$Total\ benefits = \frac{RV}{cap} \tag{7.2}$$

$$Net\ benefits = Total\ benefits - Total\ costs \tag{7.3}$$

3.3. Policy recommendations

In this step, starting from the influence of each factor according to the scenario−/sensitivity-based CBA, potential leverages to increase the net benefits of EV battery recycling facilities were evaluated. Policy options addressing these leverages were chosen from the literature analysis and stakeholder interviews, as discussed in Section 3.1, and their advantages/disadvantages and potential impacts were assessed. Based on this assessment, policy recommendations were derived for fostering EV battery recycling facilities in Thailand.

4. Results and discussion

The result and discussion section was divided into three main subsections: identified influencing factors (from the literature analysis and stakeholder interviews), quantitative effect of each influencing factor on net benefits as determined by scenario−/sensitivity-based CBA (general results, and influence of four factors, and three sensitivity parameters), and policy recommendations.

4.1. Identified influencing factors

Fig. 5 represents factors identified from the literature and stakeholder interviews (see Sections 2 and 3.1) that potentially affect the net benefits of EV battery recycling facilities. Regarding second-order factors, recycling efficiency and recovery material prices were identified to positively impact recovery material values. On the other hand, the share of LFP chemistry in batteries leads to adverse effects on recovery material values. Concerning recycling costs, four relevant parameters cause positive or negative impacts. Equipment and raw material costs increase recycling costs; in contrast, financial incentives from the public sector and plant size/amount of EoL batteries decrease recycling costs. Lastly,

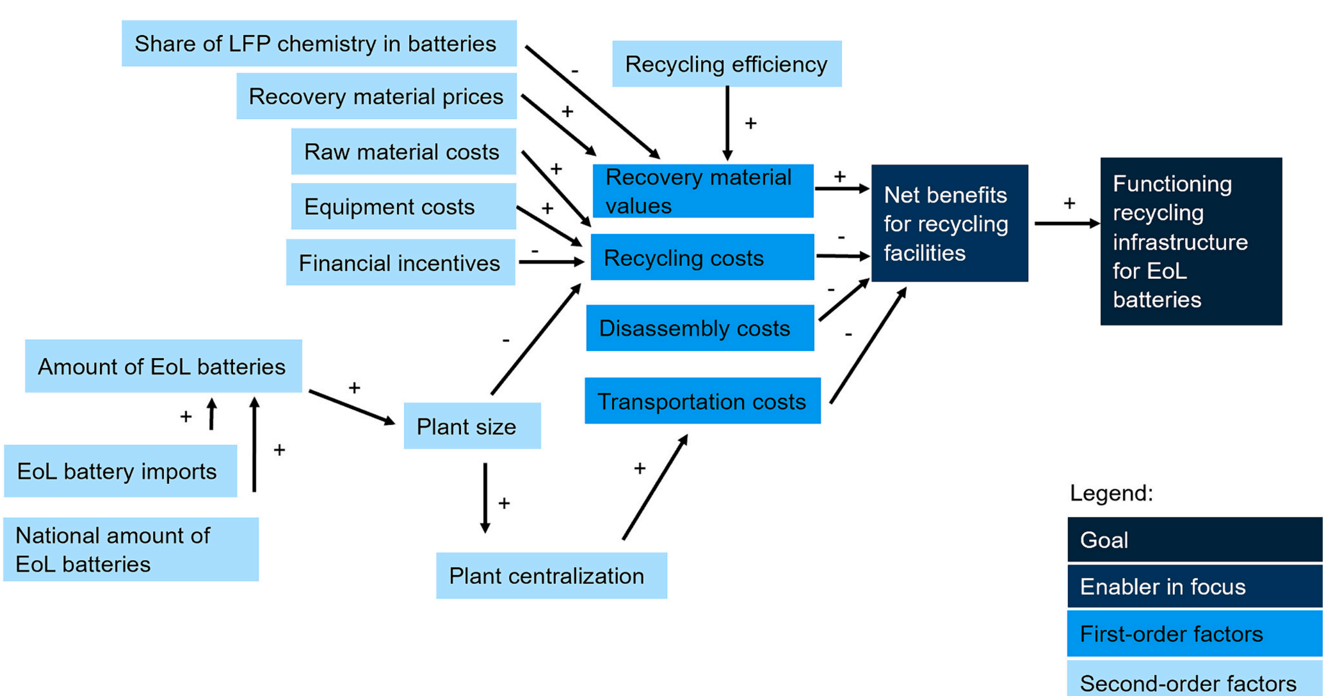


Fig. 5. Causal loop diagram (CLD) of factors identified as relevant based on literature and stakeholder interviews.

plant centralization increases transportation costs. The respective quantitative impacts derived by CBA are described in the next section.

4.2. Quantitative effect of each influencing factor on net benefits as determined by scenario-/sensitivity-based CBA

4.2.1. General CBA results

Regarding total costs (Fig. 6-a), the main cost component is the recycling cost, which shares around 87 %, followed by disassembly cost (10 %) and transportation cost (3 %). These results align with (Lander et al., 2021) considering a recycling plant in China and quoted transportation costs. The total costs range from around 4–10, 2–4, and 1–3 USD/kg for small, medium, and large plants, respectively. Total costs were assumed to increase over time due to economic and political factors (such as CPI), and its technology cost reduction is considered only in the sensitivity analysis section. Total benefits (Fig. 6-b) range around 2–3 USD/kg across years and cathode chemistries. For both scenarios, total benefits were also assumed to increase over time due to CPI. Depending on plant size and cathode chemistry, the net benefits range from about −2 to 1, −4 to 1, and -8 to 0.1 USD/kg in 2035, 2050, and 2065, respectively (Fig. 6-c). The results also suggest that the net benefits become smaller over time due to a higher increase in total costs than in total benefits.

4.2.2. Influence of plant size

The economy of scale significantly affects total costs. Larger plant sizes lead to lower total costs of EV battery recycling (Fig. 6-a). It is also important to note that the total costs, or recycling costs, in particular, decrease significantly until a certain level of plant size. The recycling costs are almost stable after they reach a breakeven point of battery volumes. This is also confirmed by (Dunn et al., 2022; Lander et al., 2021). According to Fig. 7, in 2035, 2050, and 2065, recycling costs decrease sharply, with a plant size between 1000–5000 tons per year, and continue to fall until the plant size reaches 50,000 tons per year. After that, recycling costs will start to become constant.

4.2.3. Influence of cathode chemistry

Across the three different time horizons, total costs are slightly different between the two types of cathode chemistry due to a difference in disassembly costs (Fig. 6-a). In contrast, transportation and recycling costs are equal. Unlike total costs, total benefits (Fig. 6-b) are significantly different between NCX and LFP cases, especially in the later years, while they are slightly different between plant sizes. In 2035, the total benefits of both cases are similar because the share of cathode chemistry is almost unaltered (Fig. 3). On the other hand, in the later years, the total benefits of the NCX scenario increase while they decrease in the LFP scenario over time. This is because of the increasing shares of LFP batteries in the LFP scenario and their recovery values being lower than those from NCX batteries.

It can also be concluded that EV battery recycling in Thailand will become economically feasible at around 50,000 tons per year for NCX and LFP scenarios in 2035. In contrast, in 2050 and 2065, only a large plant (100,000 tons per year) with NCX scenarios is profitable. Thus, economies of scale and cathode chemistry are essential, and larger plant sizes with NCX batteries lead to the highest net benefits. In contrast, small plants are not economically attractive, especially for the LFP scenarios and later years (such as in 2065).

4.2.4. Influence of plant location

Regarding plant locations, considering the same amount of EoL batteries at around 300,000 tons (a high & NCX scenario in 2065 in Fig. 4), the total costs differ between centralized and decentralized options. In other words, the centralized option lowers total costs by around 9 %. It is because of the economy of scale of the centralized option (larger plant size than the decentralized option). This aligns with a study by (Popien et al., 2022) that recommended centralized battery recycling facilities. Although transportation costs increase for the centralized option by around 20 %, the economy of scale plays a more critical role than transportation costs. This factor leads to the conclusion that area-based prioritization should be considered, as proposed in (Chaianong and Pharino 2022). The recycling plants in Thailand should be built first near the high-demand (high expected battery wastes) areas, such as the Bangkok Metropolitan Region, where the demand for passenger cars is high (Department of Land Transport, 2023). It is expected that if they are changed to EVs, it will lead to high EoL batteries in the future.

4.2.5. Influence of public investment incentives

Concerning public investment incentives, net benefits at different levels of incentives are summarized in Table 2. The high investment incentives strongly increase net benefits. For the medium plants with NCX dominance, some incentives (around 10 % in 2050 and 30 % in 2065) could increase the total benefits over total costs, as highlighted in red in Table 2. However, for the LFP dominance scenario and medium plant size, only a high incentive at about 30 % in 2050 could lead to positive net benefits. For the remaining cases of negative net benefits, reaching positive net benefits with incentives up to 30 % is impossible.

4.2.6. Influence of sensitivity parameters

4.2.6.1. Equipment and material costs and recovery value. Due to the high uncertainties of future equipment/material costs and recovery values, a sensitivity analysis of these costs/values was performed, as shown in Fig. 8. For small plants, equipment cost tends to have the highest impact on net benefits, followed by recovery value, while material cost is less important.

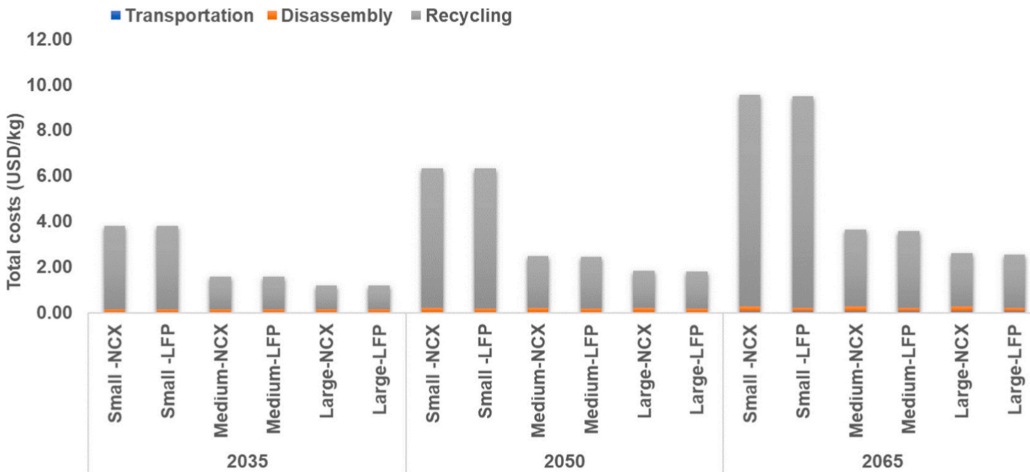
On the other hand, for medium and large plants, net benefits are more sensitive to recovery value than equipment cost but still less sensitive to material cost. This is due to an economy of scale and the amount of recycled materials. As a result, larger plants are less sensitive to equipment/material cost but more dependent on the recovery value.

4.2.6.2. Recycling efficiency. Regarding the tested recycling efficiency range (85–99 %), it has more minor effects on net benefits, similar to material cost. Due to the considerable amount of recycled materials, recycling efficiency significantly influences large plants more than small plants compared to the base case.

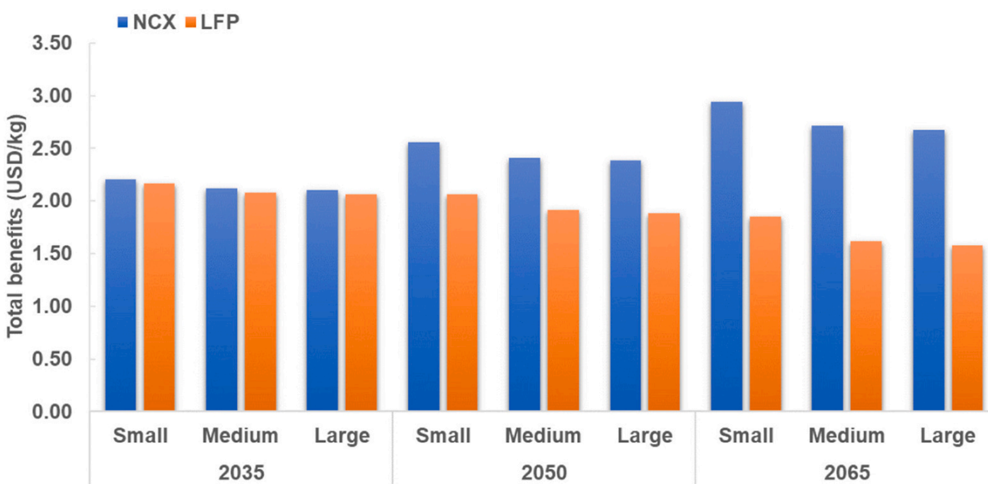
The sensitivity results suggest that cost/price-sensitive issues significantly impact the net benefit values, as discussed in (Dunn et al., 2022). Lower recycling costs and higher recovery value could bring net benefits from negative to positive, even for small plant sizes, where this is not the case for investment incentives (at a maximum of 30 %). Moreover, the results on net benefits in 2050 and 2065 could exceed those in 2035 if the recycling technology cost reduction is considered and/or recovery value is assumed to increase more than our base case. It would lead to attractive investments in the later years, unlike in the base scenario, where net benefits become worse over time.

In conclusion, the economy of scale (combined with plant centralization) and cathode composition are crucial factors. The sensitivity results also highlight how the uncertainty of equipment/material costs and recovery value (due to technological development and market volatility) can affect the net benefits. To illustrate this point, in some cases, these can lead to positive net benefits even without public investment incentives. Fig. 9 summarizes the effects of each influencing factor on net benefits.

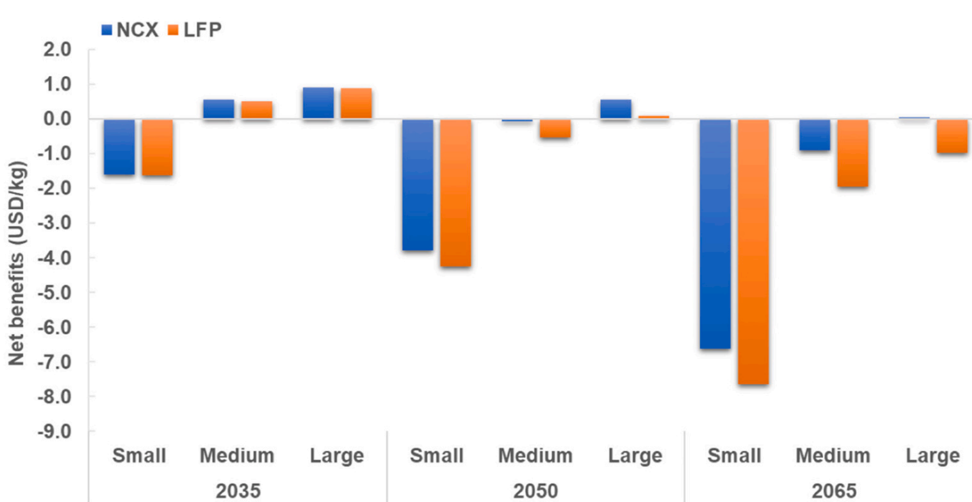
In addition, concrete recommendations regarding the suitable plant size for investment can be derived from the CBA results. Depending on the level of technological development and market volatility (such as the high-sensitivity cases), it will be possible to start building small recycling plants at the beginning stage (in 2035) when in-country EoL battery demand is still low. However, if the cost/price sensitivity level is not high (such as in a base case), investing in a small recycling plant (10,000



(a) Total costs



(b) Total benefits



(c) Net benefits

Fig. 6. Total costs, total benefits, and net benefits (USD/kg) for two scenarios on cathode chemistry shares (NCX vs. LFP dominance) and different assumptions on plant sizes (small, medium, large) in 2035, 2050, and 2065.

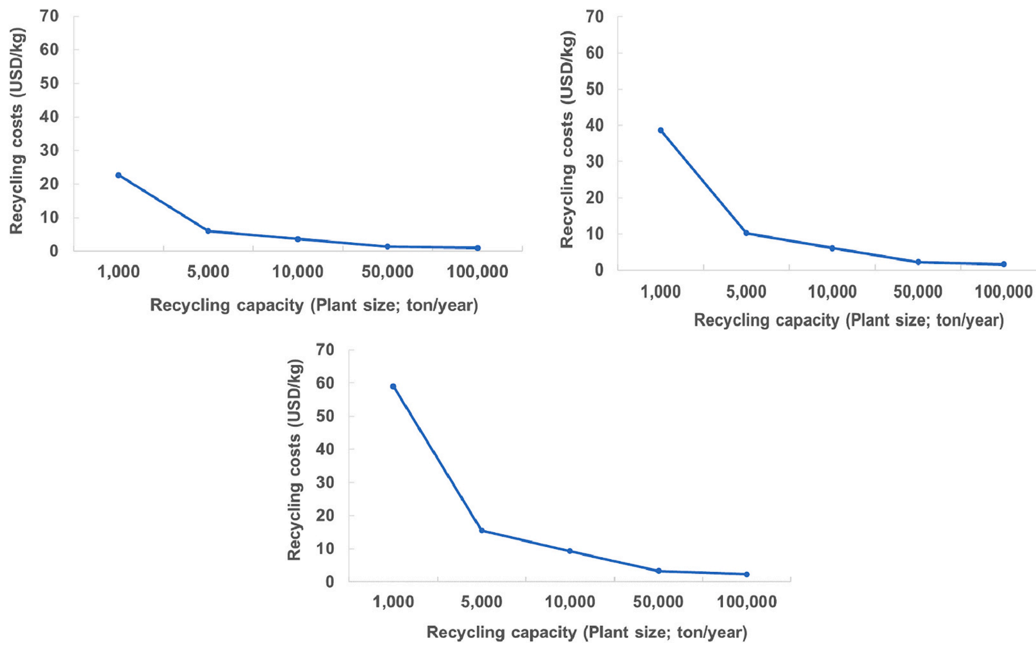


Fig. 7. Economies of scale impacts on recycling costs (Top left- 2035, Top right- 2050, and Bottom- 2065).

Table 2

Net benefits (USD/kg) in 2035, 2050, and 2065 for different plant sizes and cathode chemistries assuming different incentive levels (0–30 %). Green marks positive net benefits, and red highlights the cases where positive net benefits are achieved through incentives.

Year/% Incentive	2035				2050				2065			
	0%	10%	20%	30%	0%	10%	20%	30%	0%	10%	20%	30%
Small												
NCX	-1.53	-1.17	-0.80	-0.44	-3.81	-3.20	-2.59	-1.98	-6.78	-5.85	-4.92	-4.00
LFP	-1.57	-1.20	-0.84	-0.48	-4.28	-3.67	-3.06	-2.45	-7.81	-6.88	-5.95	-5.03
Medium												
NCX	0.57	0.71	0.85	0.99	-0.08	0.15	0.37	0.60	-0.97	-0.63	-0.30	0.03
LFP	0.53	0.67	0.81	0.95	-0.55	-0.33	-0.10	0.13	-2.00	-1.66	-1.33	-1.00
Large												
NCX	0.92	1.02	1.13	1.23	0.55	0.71	0.87	1.03	0.02	0.25	0.48	0.72
LFP	0.89	0.99	1.09	1.19	0.08	0.24	0.40	0.56	-1.01	-0.78	-0.55	-0.31

tons per year) is recommended only when the government can provide high incentives (such as investment incentives at more than 30 %). Otherwise, the recycling capacity needs to reach around 50,000 tons per year. Furthermore, when the demand for EoL batteries is high enough, a larger plant size would be recommended due to its higher investment attractiveness. Under the current assumptions, the centralized option, such as at the Bangkok Metropolitan Region, where expected EoL battery demand is high, should be promoted for plant location since the economies of scale impact net benefits more than transportation costs.

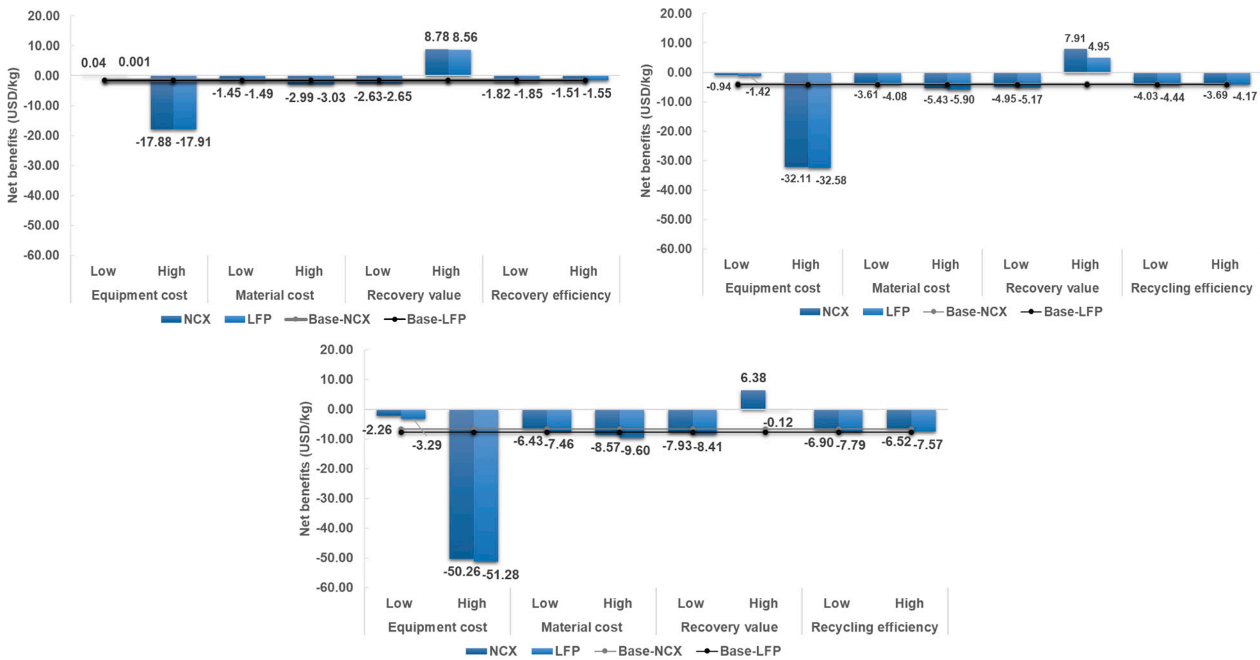
Moreover, the flexibility of the automotive industry plays a role in either facilitating or hindering the adoption of EVs and the establishment of recycling facilities in emerging markets. The rapid adoption of EV technologies by automotive manufacturers, coupled with advancements in design and manufacturing processes and an efficient supply chain, can significantly accelerate the EoL volumes, leading to the economy of scale of recycling. Furthermore, it is essential for recyclers and the automotive industries to synergize and ensure that the designs are appropriate for recycling and that an effective and targeted collection system is in place. These collaborative efforts are crucial in creating a sustainable mobility ecosystem, focusing on sustainable production throughout the value chain, from material parts/resource acquisitions to manufacturing and end-of-life management systems.

As discussed, the research framework developed and used in this research integrated CBA into the policy recommendation process, focusing on incorporating stakeholders' viewpoints and acknowledging uncertainties regarding future development, which can be adopted in other studies to improve the inclusion of micro-level perspectives and future uncertainties in policymaking processes, particularly in emerging economies.

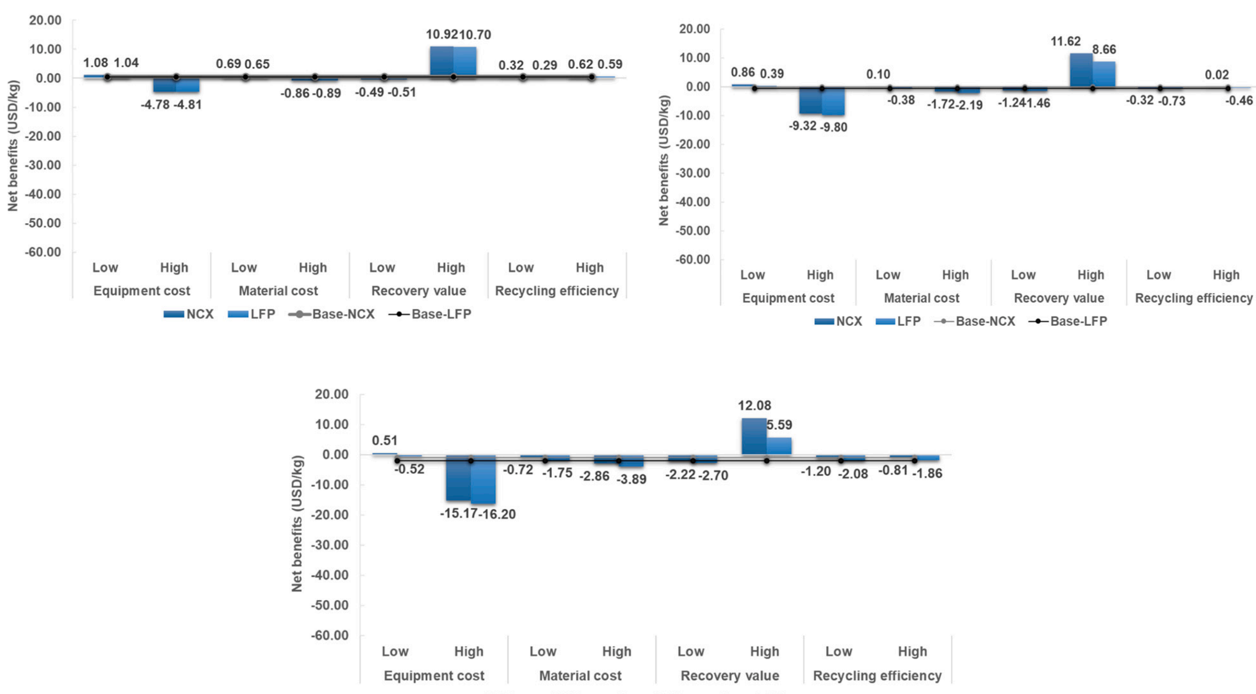
Concerning the model limitations, while the model is thorough and methodical, applying it requires geographically specific assumptions. Moreover, the identifying factors and sensitivity analysis may differ, and it is necessary to explore these based on each country's context.

4.3. Policy recommendations

For establishing economically feasible EV battery recycling, the policymakers should support influencing factors that strongly increase net benefits (darker green boxes; Fig. 9) and mitigate factors that strongly decrease net benefits (darker orange boxes; Fig. 9). A summary of potential policy measures (selected from the literature analysis and stakeholder interviews as discussed in Sections 2 and 3.1) addressing all



(a) Small plant size (Top left- 2035, Top right- 2050, and Bottom- 2065).



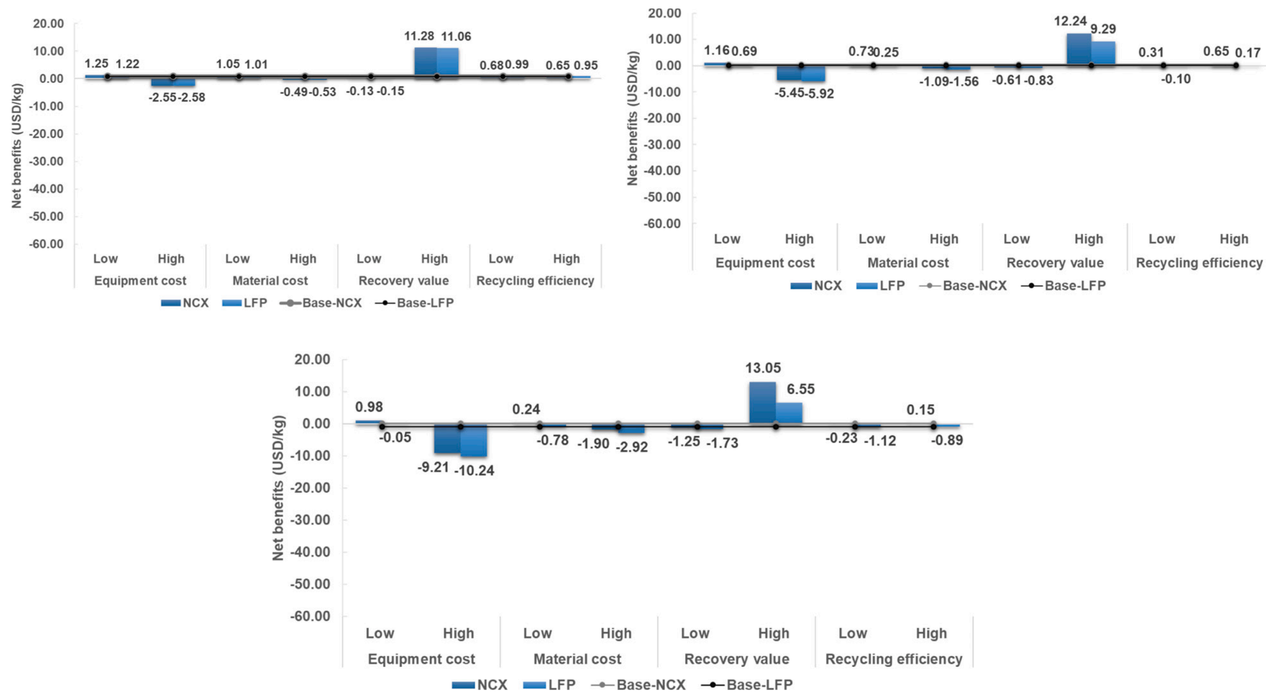
(b) Medium plant size (Top left- 2035, Top right- 2050, and Bottom- 2065).

Fig. 8. Sensitivity analysis of equipment cost, material cost, recovery value, and recycling efficiency on net benefits in 2035, 2050, and 2065 for different plant sizes and cathode chemistries.

strongly influential factors and brief assessments of the advantages, disadvantages, and trade-offs of these policy measures are given in Table 3.

The technology-specific policy measure mitigating the LFP share (marked in red in Table 3) was excluded due to severe trade-offs with general sustainable development goals. Limiting the market share of the LFP battery technology might increase recycling revenues. Still, it would contradict overall environmental policy goals since the LFP technology is more environmentally favorable than the NCX technology. Nonetheless, the other policy measures supporting the remaining factors in Table 3 are generally compatible with sustainable development goals.

Each policy measure has advantages and disadvantages, and



(c) Large plant size (Top left- 2035, Top right- 2050, and Bottom- 2065).

Fig. 8. (*continued*).

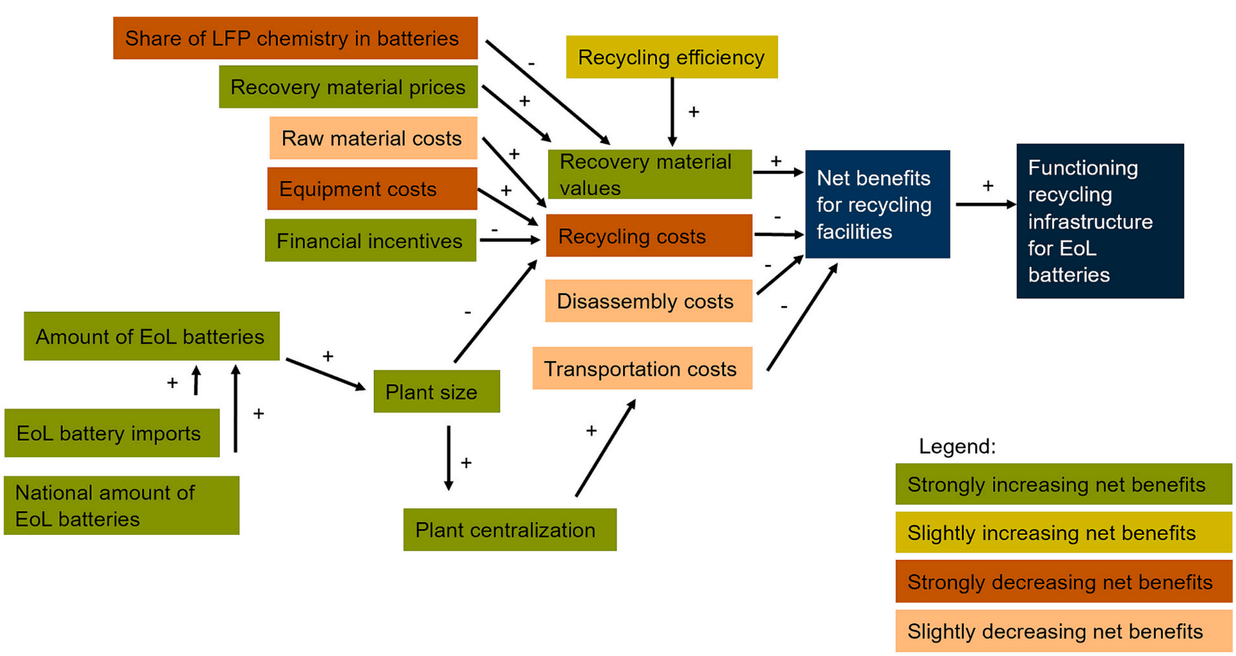


Fig. 9. Impacts of the factors on net benefits according to scenario-/sensitivity-based CBA.

according to the CBA results, none of them can ensure economically viable EV battery recycling in Thailand in all scenarios on its own. Therefore, combining these measures into a policy mix appears to be the most constructive policy strategy (for a general introduction and discussion of the policy mix concept – see (Kern et al., 2019)). Correlations between the different policy instruments can lead to additional benefits but also adverse effects, so potential correlations and dependencies will be discussed in the following.

The measures addressing the national amount of EoL batteries, EoL battery imports, plant size, and plant centralization (EoL amount-focused measures) aim to increase economies of scale by providing a high amount of EoL battery material at one recycling site. Enhanced electrification of traffic, high battery collection rates in Thailand, and international cooperation for high imports help to facilitate a sufficient inflow of battery material. Moreover, centralizing and enlarging recycling plants through public investments, policy programs, reliable policy

Table 3
Policy options are suggested and briefly assessed for all main influential factors identified in Fig. 9.

Main influential factors (identified in Fig. 9)	Policy options	Advantages/drivers	Disadvantages/challenges
EoL amount-focused measures			
National amount of EoL batteries	Support electrification of traffic and high battery collection rates (e.g., through transparent and traceable EV battery platforms).	The electrification of the mobility sector is an established goal of the Thai decarbonization roadmap.	Collection is an additional challenge, especially on infrastructure.
EoL battery import	Support international cooperation, e.g., joint ventures.	This generally accepted policy principle in Thailand can have additional economic benefits.	There might be competition from other countries.
Plant size	Support construction of larger plants, e.g., by investing in larger plant projects, encouraging industrial networks, and providing planning reliability through binding policy roadmaps.	It can be done in a pilot phase first.	These measures include major organizational challenges for policymaking.
Plant centralization	Support centralization of plants, e.g., by investment and policy programs with a regional focus.	It can be done in a pilot phase first.	A possible trade-off is the additional support of already economically advanced regions with high amounts of EoL batteries instead of supporting less economically developed regions.
Monetary measures			
Recovered material prices	Taxes on primary raw materials to increase market prices.	It can be done through law enactment, which can be powerful.	This is only functional if batteries are produced in Thailand, and mitigation measures need to be defined for primary raw material sellers.
Financial incentives	Subsidies for recycling, e.g., responsibilities/costs, are allocated to the public.	It generates positive externalities for promoting a circular economy and sustainable resources.	Public financial resources are limited/also needed for other important issues.
	Regulation for mandatory recycling, i.e., responsibilities/costs are allocated to producers or consumers of EV batteries.	It can be done through law enactment, which can be powerful.	Costs are shifted to their origin as a generally established mechanism of sustainability policy, but this needs to be accepted by the respective actors (producers or consumers of EV batteries).
Equipment costs	Subsidies for recycling, e.g., investment incentives to reduce recycling costs.	This is a generally accepted policy principle, especially for the first stage of technology development.	Public financial resources are limited/also needed for other important issues.
Technology-focused measure			
Share of LFP chemistry in batteries	Limit market share of the LFP technology.		Since LFP is the environmentally most favorable material, such limitations are incompatible with general environmental policy goals.

roadmaps, and network initiation support the concentration of this inflow into a few large plants. Therefore, these measures go hand in hand and add to a constructive policy mix.

Nonetheless, these EoL amount-focused measures may still be insufficient to enable economically viable EV battery recycling, making additional monetary measures by policymakers (such as investment incentives (Table 2), tax credits, reward-penalty, and deposit-refund, as discussed in (Hao et al., 2022; Tang et al., 2019)) necessary. Increasing market prices for the recovered materials through a tax on primary raw materials is one potentially useful addition, but it only works if the batteries are manufactured in Thailand. Furthermore, incentives can address recycling costs through either subsidies or regulations for mandatory recycling (such as a producer or consumer responsibility). While the latter is often seen as the advantageous alternative (for potentially initiating additional favorable behavior of producers/consumers and saving public money), both measures can also be combined.

However, possible challenges could be observed for all measures, such as battery collection infrastructure, battery import competitors, organizational challenges for policymaking, possible trade-offs, public resource feasibility, and cost-shifting (see Table 3). As a result, relevant stakeholders must be prepared. Particularly, policymakers need to provide policy roadmaps that prioritize policy measures over time according to the stage of technology development. Moreover, the government must allocate financial resources to develop EV battery recycling properly. Increasing producer/consumer responsibility, awareness, and research and development in recycling technologies is also necessary.

In summary, all policy measures identified for supporting factors of net benefits for EV battery recycling can be combined into an effective policy mix without negative correlations. This aligns with Fig. 9, where no contradictory influences of the underlying influential factors were found. Further measures identified through other means than CBA might also be helpful and necessary to complement this policy mix suggestion, which mainly combines measures necessary from the perspective of relevant companies. Besides, all recommendations are based on theoretical considerations about causal connections, but no guarantee can be given for their success. Hence, policymakers must decide on a suitable and acceptable policy mix, and a stakeholder process would be an essential next step in creating a policy roadmap.

5. Conclusions

Increasing the adoption of electric vehicles (EVs) is essential for moving towards sustainable mobility. Consequently, this requires sustainable and efficient resource utilization through the value chain (SDG12). A nation like Thailand needs effective battery waste management, including a recycling scheme once batteries reach their end-of-life (EoL) phases. The CBA of recycling EV batteries was conducted in this study, extracting policy recommendations from the quantitative findings while considering individual stakeholders' experiences and points of view and potential uncertainties in future development.

The main findings are that the economies of scale (plant centralization) and the share of cathode chemistries are essential factors for economically feasible EoL battery recycling facilities. The presented research also shows that preliminary guidelines for establishing economically feasible EV battery recycling facilities depend on market price volatility. In extreme cases, when recycling costs are low, and recovery values are high, it is recommended to start building small recycling plants (e.g., 10,000 tons per year) at the beginning of 2035. Otherwise, the government must provide financial support (such as investment incentives at more than 30 %) or import battery wastes from neighboring countries until the medium plant size (e.g., 50,000 tons per year) can be operated. Then, large and centralized recycling plants are preferable to support long-term strategies in the later years. The plant locations should be prioritized in areas with high battery waste demand, such as the Bangkok Metropolitan Region.

A policy mix resulting from scenario-/sensitivity-based CBA is most promising in establishing economically feasible recycling facilities for EV batteries in Thailand. It combines financial incentives and/or regulation for mandatory recycling (where producers and/or consumers cover recycling costs) with taxes on primary materials, support for EoL battery import, and a green mobility transformation, including high battery collection rates. To implement these, all relevant stakeholders must prepare for the structural changes based on their roles in the ecosystem.

Although, the results above arise from the examination of CBA from a micro-level (company) perspective. However, it is possible to extend the scope of work to consider from the societal perspective, including externalities, and to combine the CBA with the environmental assessment analysis. Further work on outlining implementation steps and prioritizing each measure based on a stakeholder process considering possible future scenarios of EV deployment and the amount of EoL batteries is recommended to create concrete policy recommendations.

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CRediT authorship contribution statement

Aksornchan Chaianong: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Chanathip Pharino:** Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Validation, Writing – review & editing. **Sabine Langkau:** Funding acquisition, Methodology, Resources, Validation, Writing – review & editing. **Pimpa Limthongkul:** Methodology, Resources, Writing – review & editing. **Nattanai Kunanusont:** Methodology, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Ahuja, Jyoti, Dawson, Louis, Lee, Robert, 2020. A circular economy for electric vehicle batteries: driving the change. J. Prop. Plan. Environ. Law 12 (3), 235–250. https://doi.org/10.1108/JPPEL-02-2020-0011.

Al-Alawi, Mohammed Khalifa, Cugley, James, Hassanin, Hany, 2022. Techno-economic feasibility of retired electric-vehicle batteries repurpose/reuse in second-life applications: a systematic review. Energy Clim. Chang. 3, 100086 https://doi.org/10.1016/j.egycc.2022.100086.

Albertsen, Levke, Richter, Jessika Luth, Peck, Philip, Dalhammar, Carl, Plepys, Andrius, 2021. Circular business models for electric vehicle lithium-ion batteries: an analysis of current practices of vehicle manufacturers and policies in the EU. Resour. Conserv. Recycl. 172, 105658 https://doi.org/10.1016/j.resconrec.2021.105658.

Bank of Thailand, 2022. Statistics-Important Industrial Goods (in Thai). Retrieved July 16, 2022. https://www.bot.or.th/App/BTWS_STAT/statistics/BOTWEBSTAT.aspx?reportID=90&language=TH.

Barkhausen, Robin, Besler, Malte, Chaianong, Aksornchan, Hettesheimer, Tim, Langkau, Sabine, Neef, Christoph, Pharino, Chanathip, Stephan, Maximilian, 2023. How Can a Successful Formal Recycling Infrastructure Be Utilized in Thailand?.

Baum, Zachary J., Bird, Robert E., Xiang, Yu, Ma, Jia, 2022. Lithium-ion battery recycling—overview of techniques and trends. ACS Energy Lett. 7 (2), 712–719. https://doi.org/10.1021/acsenergylett.1c02602.

Beaudet, Alexandre, Larouche, François, Amouzegar, Kamyab, Bouchard, Patrick, Zaghib, Karim, 2020. Key challenges and opportunities for recycling electric vehicle battery materials. Sustainability 12 (14), 5837. https://doi.org/10.3390/su12145837.

Bhuyan, Atanu, Asit Tripathy, R.K., Padhy, and Amitosh Gautam., 2022. Evaluating the lithium-ion battery recycling industry in an emerging economy: a multi-stakeholder and multi-criteria decision-making approach. J. Clean. Prod. 331, 130007 https://doi.org/10.1016/j.jclepro.2021.130007.

Blömeke, Steffen, Scheller, Christian, Cerdas, Felipe, Thies, Christian, Hachenberger, Rolf, Gonter, Mark, Herrmann, Christoph, Spengler, Thomas S., 2022. Material and energy flow analysis for environmental and economic impact assessment of industrial recycling routes for lithium-ion traction batteries. J. Clean. Prod. 377, 134344 https://doi.org/10.1016/j.jclepro.2022.134344.

Bobba, Silvia, Mathieux, Fabrice, Ardente, Fulvio, Blengini, Gian Andrea, Cusenza, Maria Anna, Podias, Andreas, Pfrang, Andreas, 2018. Life cycle assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows. J. Energy Storage 19, 213–225. https://doi.org/10.1016/j.est.2018.07.008.

Börner, Martin F., Frieges, Moritz H., Späth, Benedikt, Spütz, Kathrin, Heimes, Heiner H., Sauer, Dirk Uwe, Li, Weihan, 2022. Challenges of second-life concepts for retired electric vehicle batteries. Cell Rep. Phys. Sci. 3 (10), 101095 https://doi.org/10.1016/j.xcrp.2022.101095.

Camilleri, Mark Anthony, 2020. European environment policy for the circular economy: implications for business and industry stakeholders. Sustain. Dev. 28 (6), 1804–1812. https://doi.org/10.1002/sd.2113.

Cao, Yuanyu, Li, Liang, Zhang, Ying, Liu, Zengwen, Wang, Liqi, Fan, Wu, You, Jing, 2023. Co-products recovery does not necessarily mitigate environmental and economic tradeoffs in lithium-ion battery recycling. Resour. Conserv. Recycl. 188, 106689 https://doi.org/10.1016/j.resconrec.2022.106689.

CASE for Southeast Asia, 2022. Towards a Collective Vision of Thai Energy Transition: National Long-term Scenarios and Socioeconomic Implications.

Chaianong, Aksornchan, Bangviwat, Athikom, Menke, Christoph, Darghouth, Naïm R., 2019. Cost–benefit analysis of rooftop PV systems on utilities and ratepayers in Thailand. Energies 12 (12), 2265. https://doi.org/10.3390/en12122265.

Chavanaves, Sinthunon, Fantke, Peter, Limpaseni, Wongpun, Attavanich, Witsanu, Panyametheekul, Sirima, Gheewala, Shabbir H., Prapaspongsa, Trakarn, 2021. Health impacts and costs of fine particulate matter formation from road transport in Bangkok Metropolitan Region. Atmos. Pollut. Res. 12 (10), 101191 https://doi.org/10.1016/j.apr.2021.101191.

Cheewaphongphan, Penwadee, Junpen, Agapol, Garivait, Savitri, Chatani, Satoru, 2017. Emission inventory of on-road transport in Bangkok Metropolitan Region (BMR) development during 2007 to 2015 using the GAINS model. Atmosphere 8 (9), 167. https://doi.org/10.3390/atmos8090167.

Cheewaphongphan, Penwadee, Hanaoka, Tatsuya, Chatani, Satoru, 2020. Long-Term trend of regional passenger road transport demand and emission estimation under exhaust emission regulation scenario in Thailand. Environ. Res. Commun. 2 (5), 051009 https://doi.org/10.1088/2515-7620/ab8f11.

Chen, Mengyuan, Ma, Xiaotu, Chen, Bin, Arsenault, Renata, Karlson, Peter, Simon, Nakia, Wang, Yan, 2019. Recycling end-of-life electric vehicle lithium-ion batteries. Joule 3 (11), 2622–2646. https://doi.org/10.1016/j.joule.2019.09.014.

Choi, Yong, Rhee, Seung-Whee, 2020. Current status and perspectives on recycling of end-of-life battery of electric vehicle in Korea (Republic Of). Waste Manag. 106, 261–270. https://doi.org/10.1016/j.wasman.2020.03.015.

Choux, Martin, Pripp, Simon Waldemar, Kvalnes, Frode, Hellström, Magnus, 2024. To shred or to disassemble – a techno-economic assessment of automated disassembly vs. shredding in lithium-ion battery module recycling. Resour. Conserv. Recycl. 203, 107430 https://doi.org/10.1016/j.resconrec.2024.107430.

Curtis, Taylor, Smith, Ligia, Buchanan, Heather, Heath, Garvin, 2021. A Circular Economy for Lithium-Ion Batteries Used in Mobile and Stationary Energy Storage: Drivers, Barriers, Enablers, and U.S. Policy Considerations. NREL/TP–6A20-77035, 1768315, MainId:24998. https://doi.org/10.2172/1768315.

D'Adamo, Idiano, Gastaldi, Massimo, Ozturk, Ilhan, 2023. The sustainable development of mobility in the green transition: renewable energy, local industrial chain, and battery recycling. Sustain. Dev. 31 (2), 840–852. https://doi.org/10.1002/sd.2424.

Dai, Qiang, Spangenberger, Jeffrey, Ahmed, Shabbir, Gaines, Linda, Kelly, Jarod C., Wang, Michael, 2019. EverBatt: A Closed-Loop Battery Recycling Cost and Environmental Impacts Model. ANL-19/16, 1530874. https://doi.org/10.2172/1530874.

Danino-Perraud, Raphaël, 2020. The Recycling of Lithium-ion Batteries: A Strategic Pillar for the European Battery Alliance. Retrieved October 7, 2023. https://www.ifri.org/en/publications/etudes-de-lifri/recycling-lithium-ion-batteries-strategic-pillar-european-battery.

Department of Land Transport, 2022. Transportation Statistics Report 2022 (in Thai).

Department of Land Transport, 2023. Car Registration Statistics (in Thai). Retrieved October 6, 2023. https://web.dlt.go.th/statistics/.

Drabik, Eleanor, and Vasileios Rizos. n.d. "Prospects for Electric Vehicle Batteries in a Circular Economy".

Dunn, Jessica, Kendall, Alissa, Slattery, Margaret, 2022. "Electric Vehicle Lithium-Ion Battery Recycled Content Standards for the US – Targets, Costs, and Environmental Impacts." Resources, Conservation and Recycling, 185, 106488. https://doi.org/10.1016/j.resconrec.2022.106488.

Dutta, Abhishek, Chavalparit, Orathai, 2023. Assessment of health burden due to the emissions of fine particulate matter from motor vehicles: a case of Nakhon Ratchasima Province, Thailand. Sci. Total Environ. 872, 162128 https://doi.org/10.1016/j.scitotenv.2023.162128.

Electric Vehicle Association of Thailand, 2023. Thailand Electric Vehicle Current Status. Retrieved February 9, 2024. https://evat.or.th/images/evinfo/current-status/102566-Poster-HEV-PHEV-BEV-2023_TH-EN.jpg.

Energy Planning and Policy Office, 2022. Natural Gas Price (in Thai). Retrieved July 17, 2022. http://www.eppo.go.th/epposite/index.php/th/petroleum/gas/ngv-situation?start=9.

European Parliament, 2022. Circular Economy: Definition, Importance and Benefits | News | European Parliament. Retrieved December 11, 2022. https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits.

Fallah, Narjes, Fitzpatrick, Colin, 2022. How will retired electric vehicle batteries perform in grid-based second-life applications? a comparative techno-economic evaluation of used batteries in different scenarios. J. Clean. Prod. 361, 132281 https://doi.org/10.1016/j.jclepro.2022.132281.

Gahlaut, Tushar, Dwivedi, Gourav, Dwivedi, Ashish, 2023. Analyzing the blockades to electric vehicle mobility in an emerging economy: toward a triple bottom line sustainable development. Sustain. Dev. https://doi.org/10.1002/sd.2709.

Hampel, Carrie, 2022. "Battery Reuse & Recycling Expand to Scale in China." Electrive. Com. Retrieved October 7, 2023. https://www.electrive.com/2022/01/29/battery-reuse-recycling-expands-to-scale-in-china/.

Hao, Hao, Wenxian, Xu, Wei, Fangfang, Chuanliang, Wu, Zhaoran, Xu., 2022. Reward–penalty vs. deposit–refund: government incentive mechanisms for EV battery recycling. Energies 15 (19), 6885. https://doi.org/10.3390/en15196885.

Haram, Mohammed Hussein, Mohammed, Saleh, Lee, Jia Woon, Ramasamy, Gobbi, Ngu, Eng Eng, Thiagarajah, Siva Priya, Lee, Yuen How, 2021. Feasibility of utilising second life EV batteries: applications, lifespan, economics, environmental impact, assessment, and challenges. Alex. Eng. J. 60 (5), 4517–4536. https://doi.org/10.1016/j.aej.2021.03.021.

Harper, Gavin D.J., Kendrick, Emma, Anderson, Paul A., Mrozik, Wojciech, Christensen, Paul, Lambert, Simon, Greenwood, David, Das, Prodip K., Ahmeid, Mohamed, Milojevic, Zoran, Wenjia, Du, Brett, Dan J.L., Shearing, Paul R., Rastegarpanah, Alireza, Stolkin, Rustam, Sommerville, Roberto, Zorin, Anton, Durham, Jessica L., Abbott, Andrew P., Thompson, Dana, Browning, Nigel D., Layla Mehdi, B., Bahri, Mounib, Felipe Schanider-Tontini, D., Nicholls, Christin Stallmeister, Friedrich, Bernd, Sommerfeld, Marcus, Driscoll, Laura L., Jarvis, Abbey, Giles, Emily C., Slater, Peter R., Echavarri-Bravo, Virginia, Maddalena, Giovanni, Horsfall, Louise E., Gaines, Linda, Dai, Qiang, Jethwa, Shiva J., Lipson, Albert L., Leeke, Gary A., Cowell, Thomas, Farthing, Joseph Gresle, Mariani, Greta, Smith, Amy, Iqbal, Zubera, Golmohammadzadeh, Rabeeh, Sweeney, Luke, Goodship, Vannessa, Li, Zheng, Edge, Jacqueline, Lander, Laura, Nguyen, Viet Tien, Elliot, Robert J.R., Heidrich, Oliver, Slattery, Margaret, Reed, Daniel, Ahuja, Jyoti, Cavoski, Aleksandra, Lee, Robert, Driscoll, Elizabeth, Baker, Jen, Littlewood, Peter, Styles, Iain, Mahanty, Sampriti, Boons, Frank, 2023. Roadmap for a sustainable circular economy in lithium-ion and future battery technologies. J. Phys. Energy 5 (2), 021501. https://doi.org/10.1088/2515-7655/acaa57.

Hua, Yang, Liu, Xinhua, Zhou, Sida, Huang, Yi, Ling, Heping, Yang, Shichun, 2021. Toward sustainable reuse of retired lithium-ion batteries from electric vehicles. Resour. Conserv. Recycl. 168, 105249 https://doi.org/10.1016/j.resconrec.2020.105249.

International Energy Agency, 2022a. "Technology and Innovation Pathways for Zero-Carbon-Ready Buildings by 2030 – Analysis." *IEA*. Retrieved December 10, 2022. https://www.iea.org/reports/technology-and-innovation-pathways-for-zero-carbon-ready-buildings-by-2030.

International Energy Agency, 2022b. "Transport – Analysis." *IEA*. Retrieved December 10, 2022. https://www.iea.org/reports/transport.

International Energy Agency, 2023. "Global EV Outlook 2023 – Analysis." *IEA*. Retrieved October 3, 2023. https://www.iea.org/reports/global-ev-outlook-2023.

Investing.com, 2023. "Cobalt Futures Historical Prices." Investing.Com. Retrieved February 19, 2023 (https://www.investing.com/commodities/cobalt-historical-data).

Islam, Md Tasbirul, Iyer-Raniga, Usha, 2022. Lithium-ion battery recycling in the circular economy: a review. Recycling 7 (3), 33. https://doi.org/10.3390/recycling7030033.

iTax, 2022. "Minimum Wage for 112 Occupations (in Thai)." Retrieved August 17, 2022 (shorturl.at/ezAJP).

Kamath, Dipti, Moore, Sharlissa, Arsenault, Renata, Anctil, Annick, 2023. A system dynamics model for end-of-life management of electric vehicle batteries in the US: comparing the cost, carbon, and material requirements of remanufacturing and recycling. Resour. Conserv. Recycl. 196, 107061 https://doi.org/10.1016/j.resconrec.2023.107061.

Kelleher Environmental, 2020. Research Study on Reuse and Recycling of Batteries Employed in Electric Vehicles: The Technical. Environmental, Economic, Energy and Cost Implications of Reusing and Recycling EV Batteries.

Kern, Florian, Rogge, Karoline S., Howlett, Michael, 2019. Policy mixes for sustainability transitions: new approaches and insights through bridging innovation and policy studies. Res. Policy 48 (10), 103832. https://doi.org/10.1016/j.respol.2019.103832.

Khumkoa, Sakhob, 2019. A Study on Situation of Recycling Technology Development of Lithium Containing Batteries Waste in Thailand. Retrieved December 3, 2022. https://waa.inter.nstda.or.th/stks/pub/2020/20200128-situation-recycling-lithium-battery.pdf.

Kotak, Yash, Fernández, Carlos Marchante, Casals, Lluc Canals, Kotak, Bhavya Satishbhai, Koch, Daniel, Geisbauer, Christian, Trilla, Lluís, Gómez-Núñez, Alberto, Schweiger, Hans-Georg, 2021. End of electric vehicle batteries: reuse vs. recycle. Energies 14 (8), 2217. https://doi.org/10.3390/en14082217.

Lander, Laura, Cleaver, Tom, Rajaeifar, Mohammad Ali, Nguyen-Tien, Viet, Elliott, Robert J.R., Heidrich, Oliver, Kendrick, Emma, Edge, Jacqueline Sophie, Offer, Gregory, 2021. Financial viability of electric vehicle lithium-ion battery recycling. iScience 24 (7), 102787. https://doi.org/10.1016/j.isci.2021.102787.

Lander, Laura, Tagnon, Chris, Nguyen-Tien, Viet, Kendrick, Emma, Elliott, Robert J.R., Abbott, Andrew P., Edge, Jacqueline S., Offer, Gregory J., 2023. Breaking it down: a techno-economic assessment of the impact of battery pack design on disassembly costs. Appl. Energy 331, 120437. https://doi.org/10.1016/j.apenergy.2022.120437.

Lima, Maria Cecília, Costa, Luana Pereira, Pontes, Andrea Sarmento, Vasconcelos, Maia, de Araujo, Washington, Junior, Silva, Kunlin, Wu., 2022. Economic aspects for recycling of used lithium-ion batteries from electric vehicles. Energies 15 (6), 2203. https://doi.org/10.3390/en15062203.

Liu, Min, Liu, Wenqiu, Liu, Wei, Chen, Zhihui, Cui, Zhaojie, 2023. To what extent can recycling batteries help alleviate metal supply shortages and environmental pressures in China? Sustain. Prod. Consump. 36, 139–147. https://doi.org/10.1016/j.spc.2023.01.004.

Lotz, Meta Thurid, Barkhausen, Robin, Herbst, Andrea, Pfaff, Matthias, Durand, Antoine, Rehfeldt, Matthias, 2022. Potentials and prerequisites on the way to a circular economy: a value chain perspective on batteries and buildings. Sustainability 14 (2), 956. https://doi.org/10.3390/su14020956.

Maxwell, Charles, 2022. Cost Indices. Retrieved August 17, 2022. https://www.toweringskills.com/financial-analysis/cost-indices/.

McNamara, Marie, 2023. "How Policy Can Advance a Circular Battery Economy." *RMI*. Retrieved October 7, 2023. https://rmi.org/how-policy-can-advance-a-circular-battery-economy/.

Metropolitan Electricity Authority, 2022. "Large-scale Electricity Tariff (in Thai)." *www.mea.or.th*. Retrieved July 17, 2022 (http://www.mea.or.th/profile/109/114).

Metropolitan Waterworks Authority, 2022. Water Tariff (in Thai). Retrieved July 17, 2022. https://web.mwa.co.th/ewt_news.php?nid=303&filename=index.

Mignard, Dimitri, 2014. Correlating the chemical engineering plant cost index with macro-economic indicators. Chem. Eng. Res. Des. 92 (2), 285–294. https://doi.org/10.1016/j.cherd.2013.07.022.

Ministry of Labor, 2022. Minimum Wage (in Thai). Retrieved August 16, 2022. https://www.mol.go.th/en/minimum-wage.

National Statistical Office of Thailand, 2022. Trade Statistics and Prices. Retrieved December 16, 2022. http://statbbi.nso.go.th/staticreport/page/sector/th/14.aspx.

National Statistical Office of Thailand, 2023. Population Statistics. Retrieved February 8, 2024. http://statbbi.nso.go.th/staticreport/page/sector/th/01.aspx.

Neumann, Jonas, Petranikova, Martina, Meeus, Marcel, Gamarra, Jorge D., Younesi, Reza, Winter, Martin, Nowak, Sascha, 2022. Recycling of lithium-ion batteries—current state of the art, circular economy, and next generation recycling. Adv. Energy Mater. 12 (17), 2102917 https://doi.org/10.1002/aenm.202102917.

Nurdiawati, Anissa, Agrawal, Tarun Kumar, 2022. Creating a circular EV battery value chain: end-of-life strategies and future perspective. Resour. Conserv. Recycl. 185, 106484 https://doi.org/10.1016/j.resconrec.2022.106484.

OECD, 2022. Conversion Rates - Purchasing Power Parities (PPP) - OECD Data. Retrieved July 18, 2022. http://data.oecd.org/conversion/purchasing-power-parities-ppp.htm.

Office of Energy Efficiency and Renewable Energy, 2023. Battery Policies and Incentives. Energy.Gov. Retrieved February 20, 2023. https://www.energy.gov/eere/vehicles/battery-policies-and-incentives-search.

Office of the Board of Investment, 2023. Opportunities and Support Measures for EV Activities.

Olsson, Linda, Fallahi, Sara, Schnurr, Maria, Diener, Derek, Van Loon, Patricia, 2018. Circular business models for extended EV battery life. Batteries 4 (4), 57. https://doi.org/10.3390/batteries4040057.

Onat, Nuri Cihat, Abdella, Galal M., Kucukvar, Murat, Kutty, Adeeb A., Al-Nuaimi, Munera, Kumbaroğlu, Gürkan, Bulu, Melih, 2021. How eco-efficient are electric vehicles across Europe? a regionalized life cycle assessment-based eco-efficiency analysis. Sustain. Dev. 29 (5), 941–956. https://doi.org/10.1002/sd.2186.

Popien, Jan-Linus, Thies, Christian, Spengler, Thomas S., 2022. Exploring recycling options in battery supply chains – a life cycle sustainability assessment. Proc. CIRP 105, 434–439. https://doi.org/10.1016/j.procir.2022.02.072.

Rajaeifar, Mohammad Ali, Ghadimi, Pezhman, Raugei, Marco, Yufeng, Wu, Heidrich, Oliver, 2022. Challenges and recent developments in supply and value chains of electric vehicle batteries: a sustainability perspective. Resour. Conserv. Recycl. 180, 106144 https://doi.org/10.1016/j.resconrec.2021.106144.

Rallo, H., Benveniste, G., Gestoso, I., Amante, B., 2020. Economic analysis of the disassembling activities to the reuse of electric vehicles Li-ion batteries. Resour. Conserv. Recycl. 159, 104785 https://doi.org/10.1016/j.resconrec.2020.104785.

Reinhart, Linda, Vrucak, Dzeneta, Woeste, Richard, Lucas, Hugo, Rombach, Elinor, Friedrich, Bernd, Letmathe, Peter, 2023. Pyrometallurgical recycling of different lithium-ion battery cell systems: economic and technical analysis. J. Clean. Prod. 416, 137834 https://doi.org/10.1016/j.jclepro.2023.137834.

Rohr, Stephan, Wagner, Stephan, Baumann, Michael, Müller, Stefan, Lienkamp, Markus, 2017. "A Techno-Economic Analysis of End of Life Value Chains for Lithium-Ion Batteries from Electric Vehicles." Pp. 1–14 in 2017 Twelfth International Conference on Ecological Vehicles and Renewable Energies (EVER).

Scheller, Christian, Schmidt, Kerstin, Spengler, Thomas S., 2023. Effects of network structures on the production planning in closed-loop supply chains – a case study based analysis for lithium-ion batteries in Europe. Int. J. Prod. Econ. 262, 108892 https://doi.org/10.1016/j.ijpe.2023.108892.

Schulz-Mönninghoff, Magnus, Evans, Steve, 2023. Key tasks for ensuring economic viability of circular projects: learnings from a real-world project on repurposing electric vehicle batteries. Sustain. Prod. Consump. 35, 559–575. https://doi.org/10.1016/j.spc.2022.11.025.

Shahjalal, Mohammad, Roy, Probir Kumar, Shams, Tamanna, Fly, Ashley, Chowdhury, Jahedul Islam, Rishad Ahmed, Md., Liu, Kailong, 2022. A review on second-life of Li-ion batteries: prospects, challenges, and issues. Energy 241, 122881. https://doi.org/10.1016/j.energy.2021.122881.

Skeete, Jean-Paul, Wells, Peter, Dong, Xue, Heidrich, Oliver, Harper, Gavin, 2020. Beyond the event horizon: battery waste, recycling, and sustainability in the United Kingdom electric vehicle transition. Energy Res. Soc. Sci. 69, 101581 https://doi.org/10.1016/j.erss.2020.101581.

Sun, Bingxiang, Xiaojia, Su, Wang, Dan, Zhang, Lei, Liu, Yingqi, Yang, Yang, Liang, Hui, Gong, Minming, Zhang, Weige, Jiang, Jiuchun, 2020. Economic analysis of lithium-ion batteries recycled from electric vehicles for secondary use in power load peak shaving in China. J. Clean. Prod. 276, 123327 https://doi.org/10.1016/j.jclepro.2020.123327.

Tang, Yanyan, Zhang, Qi, Li, Yaoming, Li, Hailong, Pan, Xunzhang, Mclellan, Benjamin, 2019. The social-economic-environmental impacts of recycling retired EV batteries under reward-penalty mechanism. Appl. Energy 251, 113313. https://doi.org/10.1016/j.apenergy.2019.113313.

Tankou, Alexander, Bieker, Georg, Hall, Dale, 2023. Scaling up Reuse and Recycling of Electric Vehicle Batteries: Assessing Challenges and Policy Approaches.

Thai Local Technician Support Association. n.d. "Ten-wheel Transportation Cost in Thailand (in Thai)." *Pubhtml5*. Retrieved July 16, 2022 (shorturl.at/dkzS5).

Thailand Development Research Institute, 2022. Impact of Zero-Emission Vehicle (ZEV) Policy and Its Implication for Thailand (in Thai).

Thompson, Dana, Hyde, Charlotte, Hartley, Jennifer M., Abbott, Andrew P., Anderson, Paul A., Harper, Gavin D.J., 2021. To shred or not to shred: a comparative techno-economic assessment of lithium ion battery hydrometallurgical recycling retaining value and improving circularity in LIB supply chains. Resour. Conserv. Recycl. 175, 105741 https://doi.org/10.1016/j.resconrec.2021.105741.

UN Environment Programme, 2022. "Emissions Gap Report 2022." UNEP - UN Environment Programme. Retrieved November 18, 2023. http://www.unep.org/resources/emissions-gap-report-2022.

Vieceli, Nathália, Casasola, Raquel, Lombardo, Gabriele, Ebin, Burçak, Petranikova, Martina, 2021. Hydrometallurgical recycling of EV lithium-ion batteries: effects of incineration on the leaching efficiency of metals using sulfuric acid. Waste Manag. 125, 192–203. https://doi.org/10.1016/j.wasman.2021.02.039.

Windisch-Kern, Stefan, Gerold, Eva, Nigl, Thomas, Jandric, Aleksander, Altendorfer, Michael, Rutrecht, Bettina, Scherhaufer, Silvia, Raupenstrauch, Harald, Pomberger, Roland, Antrekowitsch, Helmut, Part, Florian, 2022. Recycling chains for lithium-ion batteries: a critical examination of current challenges, opportunities and process dependencies. Waste Manag. 138, 125–139. https://doi.org/10.1016/j.wasman.2021.11.038.

Wrålsen, Benedikte, Prieto-Sandoval, Vanessa, Mejia-Villa, Andres, O'Born, Reyn, Hellström, Magnus, Faessler, Bernhard, 2021. Circular business models for lithium-ion batteries - stakeholders, barriers, and drivers. J. Clean. Prod. 317, 128393 https://doi.org/10.1016/j.jclepro.2021.128393.

Wu, Fan, Li, Liang, Crandon, Lauren, Cao, Yuanyu, Cheng, Fei, Hicks, Andrea, Zeng, Eddy Y., You, Jing, 2022. Environmental hotspots and greenhouse gas reduction potential for different lithium-ion battery recovery strategies. J. Clean. Prod. 339, 130697 https://doi.org/10.1016/j.jclepro.2022.130697.

Xu, Chengjian, Dai, Qiang, Gaines, Linda, Mingming, Hu, Tukker, Arnold, Steubing, Bernhard, 2020. Future material demand for automotive lithium-based batteries | communications materials. Commun. Mater. 1 (99) https://doi.org/10.1038/s43246-020-00095-x.

Zhang, Qi, Tang, Yanyan, Bunn, Derek, Li, Hailong, Li, Yaoming, 2021. Comparative evaluation and policy analysis for recycling retired ev batteries with different collection modes. Appl. Energy 303, 117614. https://doi.org/10.1016/j.apenergy.2021.117614.

Zhou, Li-Feng, Yang, Dongrun, Tao, Du, He, Gong, Luo, Wen-Bin, 2020. The current process for the recycling of spent lithium ion batteries. Front. Chem. 8.