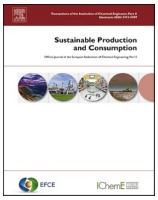
Sustainable Production and Consumption 42 (2023) 351–366

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc



Second life use of Li-ion batteries in the heavy-duty vehicle industry: Feasibilities of remanufacturing, repurposing, and reusing approaches

Koteshwar Chirumalla [a], Ignat Kulkov [a,*], Felix Vu [b], Melanie Rahic [b]

[a] *Digital and Circular Industrial Services (DigiCircle) Research Group, Innovation and Product Realisation Research Environment, Mälardalen University, Eskilstuna, Sweden*
[b] *Independent researcher*

ARTICLE INFO

Editor: Dr Rodrigo Salvador

Keywords:
Circular economy
Stakeholder collaboration
Regulatory framework
Investment analysis
Battery circularity
Battery second life
Circular business models
Techno-economic analysis

ABSTRACT

As the adoption of electric vehicles (EVs) accelerates, the efficient management of end-of-life lithium-ion (Li-ion) batteries becomes a pressing concern. This case study investigates sustainable second life approaches for Li-ion batteries within a leading manufacturing company in the heavy-duty vehicle industry. Employing an exploratory methodology, the study evaluates three distinct circularity approaches for second life applications: remanufacturing, repurposing, and reusing. Based on a financial model and sustainability metrics, remanufacturing emerged as the most economically viable and environmentally sustainable strategy for the company. The study also explores supplementary approaches, such as repurposing used batteries for smaller power applications and reusing them in large-scale Energy Storage Systems (ESS). Regulatory inconsistencies in battery second life are identified as a significant barrier to widespread implementation. The study concludes by advocating for a multi-stakeholder ecosystem approach and calls for the establishment of universal circularity regulations to streamline the second life of Li-ion batteries.

Nomenclature

Abbreviations

ESS	Energy Storage Systems
EVs	electric vehicles
ICE	internal combustion engine
Li-ion	lithium-ion
OEMs	Original Equipment Manufacturers

Symbols used in the equations

ABP	number of BPs
a, b, and c	variables related to scenarios
BP	battery pack
CH	repurposing cost per hour
CI	EV battery installation cost
CM	cost of material per electrical vehicle battery pack
Csum	repurposing total costs
CT	transpiration cost of EV battery pack
H	repurposing time in hours
kWh	kilowatt hour
mWh	megawatt hour
PE	projected electrification percentage
PESS unit	ESS unit price
Q	number of containers
SEK	Swedish Krona
T	time intervals
UP	starter battery, price per unit
USD	United States dollars
VEM	market volume
VM	present market volume
y1, y2 and y3	scenarios

1. Introduction

Environmental concerns have fueled the development of new vehicle technologies, leading to significant growth in the electric vehicles (EVs) market. It is expected to exceed 145 million EVs by 2030 (International Energy Agency, 2021). EVs run on Li-ion batteries and typically have a lifespan ranging from 5 to 15 years, during which they experience a capacity reduction of as much as 20 % (Yang et al., 2022). Although 80

---

* Corresponding author.
E-mail addresses: koteshwar.chirumalla@mdu.se (K. Chirumalla), ignat.kulkov@mdu.se (I. Kulkov).

https://doi.org/10.1016/j.spc.2023.10.007
Received 23 July 2023; Received in revised form 5 October 2023; Accepted 8 October 2023

% capacity remains, safety, performance, and regulation concerns prevent further use in vehicles, prompting the exploration of new opportunities such as second life for EV batteries (Yang et al., 2022).

The approach of "battery second life" refers to the remanufacturing, repurposing, and reuse of batteries once they reach the end of their primary usage (Jiao, 2019). By extending their service life, these second life opportunities add economic value to batteries and promote circular economy, as well as sustainability in general (Chirumalla et al., 2022). There is a significant price difference between EVs and internal combustion engine vehicles, largely due to the high cost of lithium-ion (Li-ion) batteries. Reusing used EV batteries in second life applications has the potential to lower EV prices (Al-Alawi et al., 2022). Many automotive manufacturers are exploring second life applications, particularly in Energy Storage Systems (ESS) (Shahjalal et al., 2022).

The second life approach is a crucial area of development, as Li-ion batteries are critical components in electric and hybrid vehicles. Enhancing our knowledge of battery lifecycles is vital due to their high costs, limited lifespans, and environmental impacts (Haram et al., 2021; Lai et al., 2022). Further research and development are needed to reduce resource strain by reusing battery components through second life approaches. Even though the secondary use of Li-ion batteries from EVs is not yet thoroughly entrenched in industries, it's acknowledged as a prospective avenue for income and profitability (Marques et al., 2019).

Despite the growing body of literature on the reuse and repurposing of EV batteries, a discernible gap persists in the examination of the economic feasibility of various second life battery approaches (Schulz-Mönninghoff and Evans, 2023) within the context of heavy-duty vehicle manufacturing. Moreover, while many studies acknowledge the potential for profitability in battery second life applications, there remains a lack of concrete analysis and empirical data to substantiate these assertions, particularly in real-world industrial settings (Reinhardt et al., 2019). Additionally, while the principles of sustainability and circular economy are increasingly recognized as critical elements of battery lifecycle management, comprehensive studies that integrate these principles with the economic analysis of second life battery approaches are scarce. The role of decreasing Li-ion battery prices in shaping the profitability trajectory of these approaches also remains under-explored (Hesse et al., 2017; Rahimi, 2021). This study, therefore, seeks to address these gaps by undertaking a nuanced economic feasibility analysis of three distinct second life battery approaches within the framework of a leading manufacturing company in the heavy-duty vehicle industry. The study used a 20 kWh EV Li-ion battery pack from this company and investigated various second life approaches. It not only gauges the potential profitability of these approaches but also assesses their alignment with the company's existing resources and expertise.

The guiding research question for this investigation is: What are the economic feasibility approaches for second life use of Li-ion electric vehicle battery packs in the heavy-duty vehicle industry? To answer this, the study aims to assess the economic feasibility of various second life battery approaches.

The novelty of this study lies in its nuanced economic feasibility analysis of three distinct second life battery approaches within the framework of a leading manufacturing company in the heavy-duty vehicle industry. Unlike existing studies that either focus on the technical aspects (Mol et al., 2010) or provide a generalized economic analysis (Alonso-Villar et al., 2022), this study integrates both, offering a comprehensive view. The study also fills a gap in the literature by providing empirical data to substantiate the potential for profitability in second life battery applications, particularly in real-world industrial settings.

In summary, this study provides valuable insights into the feasibility and profitability of three second life approaches for Li-ion batteries: repurposed aftermarket starter battery, remanufacturing of Li-ion battery packs, and direct reuse in ESS. The results demonstrate that the remanufacturing approach offers the most significant long-term profitability and aligns best with the company's existing expertise and resources. Furthermore, the investigation highlights the importance of incorporating sustainability and circular economy principles into battery lifecycle management.

The remainder of this paper is organized as follows: Section 2 presents an overview of the existing feasibility studies and concludes the key gaps in the area. Section 3 describes the research method and case description. Section 4 describes the development of second life battery approaches and comprehensive calculation methodology. Section 5 presents the theoretical and practical implications of results, and finally, Section 6 provides concluding remarks and highlights future research directions.

2. Literature review

The exploration of second life for EV batteries has been a burgeoning area of study over the past decade, revealing interesting insights into the economic feasibility and viability of remanufacturing, reusing, and repurposing approaches.

Ahmadi et al. (2014) embarked on an innovative journey to understand the potential of repurposing Nissan Leaf batteries for home energy storage applications. Their comprehensive analysis unveiled that while the transition from EV use to domestic energy storage presented substantial initial costs, the long-term benefits outweighed these expenses. This economic viability arises from the enduring lifespan of the repurposed batteries and the high value attached to the new application, creating a robust case for repurposing EV batteries (Shahjalal et al., 2022). Simultaneously, researchers took a broader perspective by evaluating the repurposing of EV batteries for grid-scale energy storage (Al-Alawi et al., 2022). Their research, considering the surging demand for grid stabilization services, proposed a strong argument for the financial feasibility of repurposing. They underlined the potential profitability of redirecting EV batteries to this application due to the considerable value it adds to the energy sector.

Switching the focus from repurposing to remanufacturing, Foster et al. (2014) engaged in an insightful comparison between the costs and benefits of remanufacturing versus recycling EV batteries. Their results illuminated the potential for remanufacturing to be an economically viable approach, provided the remanufactured batteries can command a premium in the EV market or in other high-value applications. Moreover, research supplements the economic argument for remanufacturing with an environmental perspective (Govindan, 2022; Knäble et al., 2022). Their studies elucidated that remanufacturing can substantially reduce the environmental impact of battery disposal, bringing an extra layer to the economic viability by considering the broader costs of environmental degradation.

Moving on to the approaches of reusing, researchers assessed the feasibility of employing EV batteries in less-demanding applications (Colarullo and Thakur, 2022; Hantanasirisakul and Sawangphruk, 2023). Their study disclosed a surprising potential for profitability due to the inherently low costs of this application and the burgeoning demand for electric bikes. However, they also highlighted potential pitfalls, emphasizing the need for stringent safety assurance measures, which could tip the cost balance and impact profitability. Building upon the theme of reusing, Sarker et al. (2015) investigated the potential of reusing EV batteries for demand response services within the electricity market. Their study concluded that reusing could indeed be economically viable due to the high value of demand response services. However, they also signaled potential complications arising from regulatory uncertainty and the need for thorough performance verification and safety assurance.

While existing feasibility studies provide valuable insights into the economic viability of remanufacturing, reusing, and repurposing approaches for second life EV batteries, they lack a comprehensive and comparative analysis among these strategies. These studies fail to show comprehensive methodology on how to assess the feasibility of EV battery second life approaches. These studies predominantly focus on singular approaches, leaving a gap in understanding the relative advantages, costs, and profitability of each approach under varying conditions. Therefore, the current study aims to bridge this gap, offering a comprehensive economic evaluation of remanufacturing, reusing, and repurposing approaches for second life EV batteries, which can enhance decision-making for businesses in this industry.

3. Method

To provide a clear and structured overview of our research methodology, we recommend referring to Fig. 1 below. This flowchart outlines the key steps involved in the study, offering a snapshot of the process from start to finish.

Following the figure, we delve into each step of the methodology in greater detail to offer a comprehensive understanding of the research process.

3.1. Setting and context

This research was conducted in partnership with a leading Swedish manufacturing company that specializes in the development and production of components like axles and transmissions for articulated haulers and wheel loaders. The company has a global footprint, operating multiple production plants and offering various services through dealerships in various countries. The services offered include, among others, financing, rental, servicing, and used equipment. With a commitment to sustainability, the company has set science-based targets for achieving climate-neutral transportation and net-zero emission construction sites by 2030 (Bonsu, 2020). The focus of this study lies in the company's aftermarket operations department, which is responsible for maintenance, service repair, customer support, and other need-based services.

3.2. Research objectives

The primary aim of this study was to perform a feasibility analysis of second life application approaches for EV batteries that would align with the company's sustainability goals and business models. The company introduced EV batteries in 2020 and plans to make them available for second life applications from 2025 onwards. The company is also in the process of launching a semi-stationary power unit with batteries to charge vehicles at customer construction sites.

3.3. Idea generation and data collection

A multi-faceted approach was adopted to generate ideas and collect data for this study. The methodology involved a combination of unstructured interviews, semi-structured interviews, and workshops to engage with various stakeholders. A comprehensive list of these sessions, detailing the type of interview, number of participants, their roles, the main topics discussed, how each session started, and the duration, is provided in Appendix 1.

3.3.1. Interviews

For the interviews, key stakeholders involved in the innovation ecosystem were interviewed across 14 sessions. These included executives, managers, and engineers who were actively involved in different aspects of the innovation process. Semi-structured interviews were guided by a set of predetermined questions focused on three main themes: Secondary use of batteries, Financial and numerical considerations, and Recycling considerations. The exact questions used for these interviews can be found in Appendix 2.

Unstructured interviews, on the other hand, were more open-ended and explorative in nature. These sessions allowed for the discussion of broader themes and were pivotal in understanding the nuances and emerging issues that were not covered by the semi-structured interviews.

3.3.2. Workshops

In addition to interviews, seven workshops were conducted to allow for a more collaborative form of idea generation and problem-solving. These sessions included multiple stakeholders and enabled a dialogue between parties that may not usually interact in a business context. The workshops also provided an opportunity for validating the ideas and feedback received during individual interviews.

Each session, regardless of its type, was designed to be flexible enough to allow the participants to introduce new ideas and concepts. The objective was not just to gather data but to foster an environment that encouraged free thought and the exchange of innovative ideas.

3.3.3. Duration and participants

The number of participants in these sessions ranged from just one in some interviews to as many as eight in the workshops. The duration of these sessions varied significantly, ranging from brief 25-minute conversations to in-depth discussions that lasted up to 130 min.

By employing this varied and flexible methodology, we were able to capture a comprehensive and multi-dimensional view of the factors affecting innovation in the ecosystem. This approach also enabled the

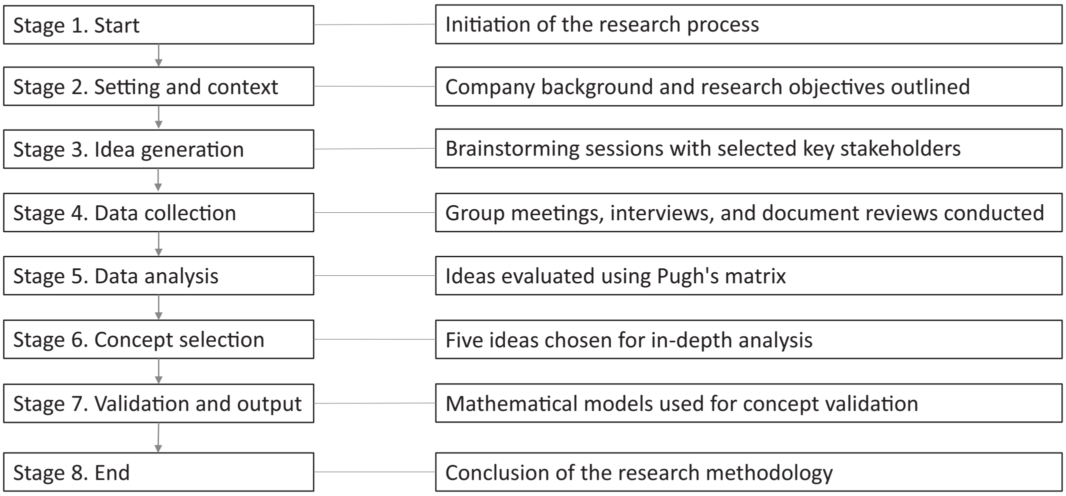


Fig. 1. Methodology flowchart.

triangulation of data, thereby adding robustness to the findings.

3.4. *Data analysis and approach selection*

After data collection, the ideas were evaluated using Pugh's matrix, a decision-making tool that considers various perspectives such as market, logistics, manufacturing, and sales, see Table 1 (Frey et al., 2009). The matrix was populated based on discussions with stakeholders and the collected data.

Our analysis utilizes a technical criteria table culminating in the formulation of five initial ideas, which are subsequently assessed through a Pugh's matrix. The table incorporates multiple facets of the value chain—encompassing market, logistics, manufacturing, and sales dimensions—for comprehensive evaluation. For benchmarking, a remanufactured Li-ion BP was chosen as the reference object. This choice is motivated by the study's focus on secondary usage scenarios for Li-ion BPs.

The remanufactured EV Li-ion BP serves as the reference object for several reasons. Primarily, the study explores approaches that involve Li-ion BPs in a secondary usage context, rendering a remanufactured BP as the logical point of comparison. Furthermore, Li-ion technology is currently under research and development in the case company and has incorporated into their existing industrial machinery. The aim is to explore the feasibility of extending the life cycle of Li-ion BPs and to ascertain its economic viability.

3.5. *Analysis and findings from Pugh's matrix*

The Pugh's matrix helped us identify three promising circular approaches from the initial five: repurposed aftermarket starter battery, remanufacturing of Li-ion BP, and direct reuse of BP in ESS. In terms of weighted totals in the matrix, ESS and Remanufacturing scored 0 points each, while the Aftermarket led with 7 points.

Each of these shortlisted approaches were explored in separate cases. This includes calculations encompassing financial metrics, key performance indicators, and customer variables. Marketing strategies for each approach were also discussed. To definitively identify the most lucrative approach, we employed mathematical functions and diagrams for an economic comparison, aligned with the case company's specific needs and criteria.

3.6. *Validation and output for stakeholders*

Mathematical models and illustrative diagrams were formulated to evaluate the economic viability of the selected approaches. Three potential approaches emerged as most profitable based on weighted totals and criteria: repurposed aftermarket starter battery, remanufacturing of Li-ion BPs, reusing BPs in ESS. These were presented as viable alternatives for stakeholders as the company's second life battery application strategy. The results of this study offer actionable insights for stakeholders, particularly in identifying profitable second life applications for EV batteries. These findings not only align with the company's sustainability goals but also offer new avenues for revenue generation.

3.7. *Development of potential second life application approaches*

To provide a comprehensive understanding of the processes involved in each proposed approach, a detailed exploration was conducted, outlining the preliminary steps, operational requirements, and anticipated outcomes. It's important to note that certain elements are common to all approaches, and to maintain coherence and clarity, these elements are reiterated where applicable to each approach.

For the sake of consistency across all approaches, we make a presumption that the energy capacity of the battery pack remains constant

Table 1
Pugh's matrix evaluation concept.

Criteria selection	Weight	Remanufacturing of Li-Ion BP	1-Lawn mover (repurposing)	2-Forklift	4-ESS (reuse)	5-Aftermarket (repurposing)
Viable for secondary use	4	0	−1	+1	+1	−1
Potential for sales	3	0	−1	+1	+1	0
Proficiency in the application domain	5	0	−1	−1	−1	+1
Cost-effective	4	0	−1	−1	+1	+1
Reduced power and energy density	2	0	−1	0	0	0
Supplier preparedness	4	0	−1	−1	−1	+1
Worldwide manufacturing presence	5	0	−1	−1	−1	−1
Annual sales volume (quantity sold each year)	2	0	+1	+1	+1	+1
Market competitiveness, level of maturity, and entry barriers	2	0	−1	−1	0	0
Service life duration (in years)	1	0	0	+1	+1	+1
Total +		0	1	4	5	5
Total −		0	8	5	3	2
Total score		0	−7	−1	2	3
Weighted total		0	−27	−10	0	7
Comments		The repurposed/remanufactured Li-ion battery acts as the standard reference because it needs to be compatible with all application areas.	The concept of remanufacturing satisfies the majority of the high-priority criteria.	Although the concept is economically viable and suitable for secondary use, it regrettably doesn't apply in this instance.	The ESS concept is apt for second-life reuse, meeting numerous critical requirements.	From the company's viewpoint, the Aftermarket concept is one of the most fitting choices, representing a valuable proposition.
Development		Feasible	Not feasible	Not feasible	Feasible	Feasible

at 20 kWh throughout the process of examination. This assumption is critical to ensure comparable outcomes across all three approach investigations. It's worth noting that the battery packs used in the EVs are provided by the company's clients, essentially eliminating the procurement expenses. The absence of purchasing costs creates a favorable financial circumstance for the case company and supports the profitability of each approach.

The three unique approaches - each centered on a distinct approach of remanufacturing, repurposing, and reuse, and - were explored separately. Each of these methodologies necessitates its specific operational environment or facility to carry out the associated processes. While the location of these facilities will be selected based on the viability and chosen direction of the final approach, it's important to consider their potential locations and requirements as part of each approach's examination. Additionally, each approach requires its unique investment plan, outlining the specific equipment and resources needed to bring each approach to fruition. This aspect is paramount as it determines the initial investment required and the potential return on investment each approach can deliver.

The three approaches under scrutiny and evaluation are visualized in Fig. 2.

This diagram serves as a guiding tool for better understanding and comparison of the approaches, helping to illustrate their distinct methodologies and potential outcomes. Through this rigorous evaluation process, we aim to provide an in-depth understanding of each approach and the potential benefits and challenges associated with its implementation.

3.7.1. *Repurposing EV batteries for aftermarket use – Approach 1*

The first approach, motivated by Pugh's matrix analysis, explored repurposing EV Li-ion battery packs for aftermarket applications. The goal is to convert an EV battery pack into 11 starter batteries for the company's internal combustion engine (ICE) industrial vehicles. Each starter battery has a capacity of 1,68 kWh. The company inspects and tests the battery pack for cells functionality before repurposing. The transportation costs for the battery pack to and from the facility amount to 1920 SEK, including all fees (SEK stands for a Swedish Krona. 1 Euro equals to 12 SEK).

Based on Rohr et al. (2017) and the studied company, the stages of repurposing include disassembly, inspection, and testing. The cumulative time taken for repurposing is accounted for each stage. The current research and development endeavor is focused on substituting lead-acid starter batteries with Li-ion ones. The approach of second life comes into play five years post their initial usage, considering their lifespan up to 15 years.

The case company has provided numerical data that are used as underlying assumptions for pertinent calculations within this study. Repurposing an EV battery pack into starter batteries entails various expenses, such as 1500 SEK for materials like Battery Management Systems, housing, terminals, and wires. No additional costs apply since the battery pack comes from the case company. 1000 SEK/h are expected repurposing cost is established based on the company's engine remanufacturing data in Sweden. From an initial EV battery pack, 11 starter batteries are produced, with each unit priced at XXX SEK (hereinafter, XXX is used by agreement with the company under study that we do not disclose the exact cost of the product) for the future second life market.

3.7.2. *Remanufacturing of Li-ion battery pack – Approach 2*

The second approach focuses on remanufacturing Li-ion batteries for their initial application in electric industrial vehicles. This involves remanufacturing EV battery packs for their primary purpose. The remanufacturing process includes disassembly, inspection, testing, remanufacturing, cleaning, and final testing. Throughout this procedure, aged lithium-ion cells are swapped with new ones.

Given that the case company hasn't previously engaged in remanufacturing lithium-ion batteries, a hypothetical cost of 1000 SEK/h is employed. The material expenses consist of procuring new battery cells, assuming that all other components are in working order. The transportation expenditure is fixed at 1920 SEK. The cost associated with the remanufacturing process is intrinsically dependent on the number of hours required to carry out the said process. Once the process is finalized, the battery pack is recirculated for its initial application. The unit cost for a remanufactured battery pack is established at XXX SEK, which is 20 % less than the price of a new battery pack.

3.7.3. *Battery pack reuse in ESS application – Approach 3*

The approach examined is the reuse of battery packs for ESS container applications. Rather than engaging in remanufacturing or repurposing, this approach takes a more direct approach. The case company's battery packs are tested for functionality and, if viable, are promptly dispatched to the ESS application site, negating any need for preliminary processing.

In terms of cost, the installation expense is calculated to be 1448 SEK per kWh. This figure covers a spectrum of costs, from incidental outlays and balance of system hardware to costs associated with Engineering, Procurement, and Construction (EPC) processes.

Each ESS container is designed to possess a capacity of 4 MWh. To fill this requirement, approximately 200 EV battery packs, each containing a capacity of 20 kWh, are necessary. As for the pricing strategy, the

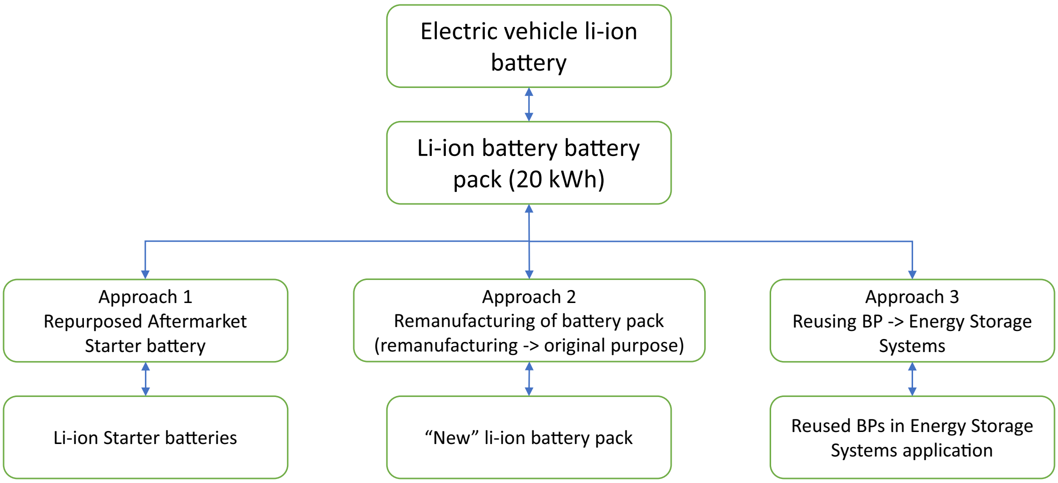


Fig. 2. Evaluation of proposed approaches.

company has referenced Kane (2018), setting the selling price for each kWh at $512, or 4633 SEK. The price of a fully furnished and operational ESS container is 18,500,000 SEK. It's an attractive proposition that encourages the direct reuse of battery packs and might serve as a strong driver for sustainability and cost-effectiveness in the sector.

4. Calculation methodology for three second life application approaches

This segment introduces the mathematical models and equations for the three suggested approaches, devised in partnership with the case company to yield trustworthy data. These computations consider various parameters to form unique functions symbolizing the potential factors pertinent to each approach.

Each approach is built upon a fixed investment, premised on the assumption that out-of-service EV batteries will be accessible in 2025. The investment is projected to occur two years prior, in 2023, to facilitate planning and readiness, which includes processes and transportation. A time frame of 15 years (2023–2038) is set to scrutinize the viability of the approaches, as this is a standard period for appraising innovative propositions. This timeframe is applicable to all three approaches.

In the upcoming calculations, a variety of factors is considered. This includes costs related to remanufacturing, reuse, repurposing operations, as well as forward-looking estimates of the company's percentage of EV electrification, and the resulting profit diagrams. The authors detail the characteristics of the return rates for each approach over a 15-year recuperation period.

To facilitate visual tracking and comprehension, all calculations and equations is entered into an Excel spreadsheet, which graphically represents the yearly evolution. A comprehensive diagram will be generated to help pinpoint the approach that provides the highest potential for profitability and alignment with the company's strategic objectives.

While each approach's calculations are presented in a similar format to maintain consistency, there may be minor variations in the variables displayed, owing to the unique attributes of each approach. This nuanced approach enables a thorough, comparative evaluation of the potential benefits and drawbacks of each approach, ultimately informing the selection of the optimal solution for the second life of batteries.

4.1. Approach calculations of repurposing EV batteries for aftermarket use – Approach 1

4.1.1. Cost of material per electrical vehicle battery pack (CM)

Operating under the premise that the company obtains the EV battery packs through lease contracts, it is expected that customers will return these batteries to the company at no additional charge once they demonstrate a 20 % capacity decrease or malfunction. The onus of recycling costs is expected to rest on the shoulders of the customers. Before the battery pack can be dispatched to the repurposing facility, it must be extracted from the electric vehicle. The estimated expenditure for the new materials necessary for the starter batteries, which include elements such as the casing, Battery Management System, and various electronic components, is projected to hover around 1500 SEK per starter battery. This cost projection considers current market prices and industry standards, providing a realistic framework for budgeting and financial planning for the repurposing operation.

4.1.2. Transportation cost of EV battery pack (CT)

The cost of transport for batteries was calculated to be 30 SEK/kWh in the year 2016. The same report projects this cost to decline to approximately 16 SEK/kWh by the year 2030 for a distance spanning 500 km. Hence, an average transportation cost of about 23 SEK/kWh has been established for the coming years to give a balanced, future-proof estimate. Given the stipulated capacity of 20 kWh for the EV battery pack, the overall fee for transporting a single pack to the facility is computed to be 450 SEK. The same is anticipated for the return journey of the repurposed starter batteries back to the company's premises. Consequently, the combined cost of these two-way logistics comes to a sum of 920 SEK.

Additional factors are taken into consideration to create a comprehensive financial outline for this operation. Accounting for a myriad of elements such as regulatory requirements, applicable customs duties, and the transportation of hazardous goods, an extra allocation of 1000 SEK is added to the logistics budget. This results in a total transportation expenditure of 1920 SEK. It should be noted that the final cost may be subject to variations due to the differing policies and regulations across various countries. However, for the purpose of this study, this cost is regarded as being constant. The management of the repurposing operation presents a choice to the company. It could be handled in-house, leveraging the company's own resources and manpower, or it could be outsourced to an external entity specializing in such operations. Each option presents its own set of advantages and potential challenges, necessitating a thorough analysis to determine the best course of action.

Hence, the total transportation cost $= 2\ (\text{ways}) \times (23 \times 20) + 1000 = 1920$ SEK.

4.1.3. Repurposing time in hours (H)

When the EV battery pack arrives at the repurposing facility, it undergoes a series of well-defined steps to transform it into multiple Li-ion starter batteries. These stages have been derived and adapted from a process with certain modifications tailored to accommodate the production requirements of the end-product. Each of these steps also corresponds to a certain duration of time that has been considered in the overall process timeline. The EV battery pack, as per our working assumption, is expected to have 20 kWh. Upon completion of the repurposing process, each individual Li-ion starter battery is predicted to have an energy capacity of 1,68 kWh. Considering specifications of 140 Ah and 12 V for each starter batteries, we can calculate their respective energy capacities in kWh, as was demonstrated earlier in the study.

Using this process, a single 20 kWh EV battery pack can be repurposed to yield around 11 starter batteries. To clarify, the precise calculated number is 11,9, but this has been rounded down to 11, as the energy content of the EV battery pack is sufficient to produce 11 starter batteries but falls short for the creation of a 12th unit.

The variable ‘R’ in this scenario denotes the function of the energy capacities of both the original EV battery pack.

$$\text{BP} = \text{Energy capacity in kWh} \tag{1}$$

$$\text{R} = \text{Number of batteries} \tag{2}$$

$$\text{R} = \frac{BP\ (kWh)}{(Ah \times V)/1000} = \frac{20}{(140 \times 12)/1000} = 11,9 \approx 11 \text{ starter batteries} \tag{3}$$

Based on 11 starter batteries we delve deeper into the entire duration of the repurposing process and its associated activities, as outlined in Table 2.

Initiating the repurposing procedure, the first step involves the disassembly of the battery pack. This procedure dismantles the pack,

Table 2
Tasks and timeframes for repurposing 11 starter batteries.

	Repurposing activities for 11 starter batteries	Time (h)
1	Disassembly	0.7
2	Inspection	0.5
3	Test of BP (equipment)	3.8
4	Test of electronics (operator)	2.5
5	Repurposing BP to starter batteries	8.8
6	Cleaning of components	2
7	Final test of starter batteries	2
	Total time for repurposing process:	20.3

breaking it down into its component parts. The next step, the second one in the sequence, is an intensive inspection phase during which the battery pack and its individual components are scrutinized in detail. After the completion of the inspection, the third step engages the battery pack in thorough testing to ensure the integrity and functionality of the battery system. This is followed by the fourth step which involves rigorous testing of the electronic systems within the battery pack. These steps are critical in ensuring the viability of the battery pack for repurposing. Once the battery pack has been approved in the preliminary steps, the transformation process starts. The fifth step comprises the primary conversion operation where the electric vehicle battery pack is repurposed into 11 individual starter batteries. Following the conversion, the sixth step ensures that all the components undergo a meticulous cleaning procedure. This is to ensure the removal of any potential contaminants or unwanted particles that may have been introduced during the transformation process. The seventh and final step involves a comprehensive functional test carried out on each of the produced starter batteries. This is to confirm their operational capabilities and to ensure that they meet the necessary performance standards. It's essential to highlight that the initial steps, from the first to the fourth, are performed on the entire electric vehicle battery pack. In contrast, the subsequent steps, from the fifth to the seventh, are conducted on each of the 11 resulting starter batteries individually.

When it comes to the cost of repurposing (variables a, b, c & CH), we turn to the estimated remanufacturing process cost from a facility in Sweden, pegged at 1000 SEK/h. This cost is considered as the baseline for repurposing, primarily due to the lack of specific data on battery repurposing in existing research or company records. It is crucial to bear in mind that the actual repurposing costs can vary, influenced by factors such as volume size and regulations specific to different countries. To constrain the functional scope, the authors have elected to operate within the framework of three predefined variables, which address both the quantities and costs involved in the process.

The initial variable that has been selected stipulates a repurposing cost of 1000 SEK for every hour spent on the process. This is applicable when the quantity under consideration amounts to a total of 1000 battery packs. To explore the impact of reduced repurposing costs, a second scenario assumes a minimum cost of 700 SEK/h given the same volume. In the third case, with a significantly lower volume (10 EV battery packs), the repurposing cost is projected at 5000 SEK/h. While it's improbable to have a low volume of just 10 EV battery packs, this scenario helps illuminate different possibilities and demonstrates how cost estimations can be influenced by varying assumptions.

The hourly cost for the repurposing process can be defined as follows:

$$y = \frac{a}{x^b} + c \tag{4}$$

The condition (a,b,c > 0) illustrates the influence of increasing volume on the repurposing cost.

C_H for repurposing is calculated the following way:

$$C_H = y = \frac{a}{x^b} + c \text{ where } (a, b, c > 0) \tag{5}$$

In this study, three distinctive scenarios have been thoughtfully considered, each representing different combinations of costs per hour and volumes. The aim is to formulate a non-linear function rather than a static cost, offering a more dynamic and realistic depiction of potential outcomes. In this model, the variables a, b, and c are stated by the anticipated options identified as y_1, y_2, and y_3. These hypothetical scenarios serve to provide a wider perspective on the varying possibilities that may occur within the bounds of our chosen variables.

4.1.4. Estimated repurposing costs for y_1, y_2, and y_3

In the first scenario, denoted as y_1, the supposition is that there is a high volume of EV battery packs being repurposed – surpassing a threshold of 1000 units. Alongside this high volume, the repurposing cost per hour is presumed to be at the lower end of the scale, standing at 700 SEK/h. This scenario could be seen as an example of economies of scale in action, where the cost per unit decreases as the volume of output increases.

The second scenario, labeled as y_2, establishes a middle ground in terms of repurposing costs and the volume of EV battery packs. In this scenario, the researchers have fixed the cost at 1000 SEK/h, coinciding with 1000 EV battery packs. This scenario could reflect a situation where the production process has been optimized to handle a moderate volume of battery packs, with the corresponding repurposing cost per hour set at an affordable level.

Lastly, the third scenario, identified as y3, assumes a considerably low volume of EV battery packs - just 10 units. This is paired with a notably high repurposing cost of 5000 SEK/h. This scenario could be indicative of a situation where a company is just starting up its repurposing operations, or perhaps dealing with a custom, low-volume order, hence the elevated cost per hour.

$$\mathrm{y1}\ (\mathrm{x1} > 1000) = 700 \tag{6}$$

$$\mathrm{y2}\ (\mathrm{x2} = 1000) = 1000 \tag{7}$$

$$\mathrm{y3}\ (\mathrm{x3} = 10) = 5000 \tag{8}$$

The primary purpose of C_H function is to establish the specific values of 'a', 'b', and 'c' - these being key components of the function itself. The variables 'x' and 'y', in this context, represent the volume of EV battery packs being repurposed and the corresponding repurposing cost per hour, respectively. By inserting these variables into the C_H function, we can model the relationship between volume and cost within the scope of this study. To specify 'a', 'b', and 'c', the authors take scenarios y1, y2, and y3 - each of which represents a unique combination of volume and cost - and plug them into the C_H function. Through this integration of scenarios into the function, the values for 'a', 'b', and 'c' are effectively determined. These values then serve to shape the function and ultimately help illustrate the correlation between the volume of EV battery packs and their repurposing costs. This mathematical modeling provides crucial insights into the operational efficiency and financial implications of different repurposing scenarios.

$$C_H = y = \frac{a}{x^b} + c \tag{9}$$

$$y_1 = 700\ (c) \tag{10}$$

$$y_2 = 1000 = \frac{a}{1000^b} + c \tag{11}$$

$$y_3 = 5000 = \frac{a}{10^b} + c \tag{12}$$

C is equal to 700, allowing for calculation of the a and b values as follows:

$$c = 700 \qquad \frac{a}{1000^b} = 300 \qquad \frac{a}{10^b} = 4,300 \tag{13}$$

After performing the required calculations, the three variables are determined as below:

$$a = 4,300 \times 10^b \rightarrow 4300 \times 10^{0,58} = 16,348 \tag{14}$$

$$b = log_{100}\ 14 = 0,58 \tag{15}$$

$$C_H = y = \frac{16,348}{x^{0,58}} + 700 \tag{16}$$

4.1.5. Projected electrification percentage (PE) - company's EVs

Grasping the forecast data and the associated volume percentages is paramount for a comprehensive evaluation of the expected growth in the company's presence in the EV market. This forward-looking data serves as a useful tool for approximating the quantity of battery packs that might be available in the future. This, in turn, directly influences the forecasted electrification percentage (PE), a key metric that signifies the degree of electrification the company could achieve. The data is adapted from research studies (Pelegov and Chanaron, 2022) and (Sato and Nakata, 2019) and has been verified by the company's representatives, as illustrated in Fig. 3.

$$\text{Percentage of electrification } (P_E) = 0,054t^2 - 0,14t + 0,0992$$

$$(P_E) = mt^2 + nt + q \tag{17}$$

For instance, if ‘t = 1’ is plugged into the P_E equation, it would predict a 1 % escalation in 2020. However, the outcome is susceptible to change depending on the value of ‘t’ that is entered into the equation, as demonstrated in the subsequent table.

Given the authors' emphasis on time intervals, (T) and ‘t’ variables arranged to mathematical expressions. This method aids in breaking down the projected EV market expansion into manageable periods, making it easier to track and predict future developments.

$$T = 5t + 2020, t = \frac{T - 2020}{5} \rightarrow T = t \tag{18}$$

In this case 5 years is set as the lag years to the machine delivery time (DT). It symbolizes the duration required for new EV battery packs to be ready for a second life application.

$$\text{Volume of the market} = \text{Present market volume} \times \text{Percentage of EV}$$

$$V_{EM} = V_M \times P_E \tag{19}$$

4.1.6. Starter battery, price per unit (UP)

The anticipated market price for a Li-ion starter battery is projected to be XXX SEK per battery, reflecting the estimated future market value for such batteries. As a result of being repurposed, these starter batteries should be cheaper than new batteries.

4.1.7. Repurposing total costs (Csum)

In this final calculation, we integrate all the previously defined metrics and computations to arrive at the total cost involved in repurposing one EV battery pack into 11 starter batteries. This incorporates all relevant expenses, such as repurposing operations, transportation fees, material costs, and additional associated costs. This final figure offers a complete overview of the financial commitment required for this battery repurposing process.

4.1.8. Total costs

$$C_{Sum} = (C_R + C_M + C_T) \times V_{EM} \tag{20}$$

4.1.9. All parameters in Csum

In this stage, all the introduced variables are integrated to construct a comprehensive summary.

4.1.10. Diagram creation

After calculating the total cost and assigning values to each variable as shown in Table 3, these numbers are input into Excel. This enables us to calculate the cost over a 15-year span, from 2023 to 2038. Although most variables are constant, four variables, namely CM, C_T, H, and U_P, may change. These are used in our function to estimate the profit made from repurposing EV battery packs.

4.1.11. Formulating the cost calculation

After determining the total cost and establishing the values for each variable, numerical data is added into an Excel spreadsheet. This enables the tracking of all costs from 2023 for a period of 15 years. Although most of the variables are constant throughout this period, four of them - C_M, C_T, H, and U_P - can fluctuate. These specific variables are crucial in the computation of the profits derived from repurposing the EV battery packs.

Formula of profit calculation:

Table 3
Parameters for the repurposing process.

Parameters	Constant/varies (V)
C_M (SEK)	16,500 (V)
C_T (SEK)	1920 (V)
H (hours)	20,3 (V)
a	16,348
b	0.58
c	700
V_M (SEK)	40,000
m	0.0541
n	−0.142
q	0.0992
U_P (SEK)	XXX (V)
DT (years)	5

C_M - EV Battery Pack Material Cost; C_T - Transportation cost of EV Battery Pack; Repurposing time – measured in hours (H); Volume market (V_M); Unit price - Starter battery (U_P)delivery time (DT).

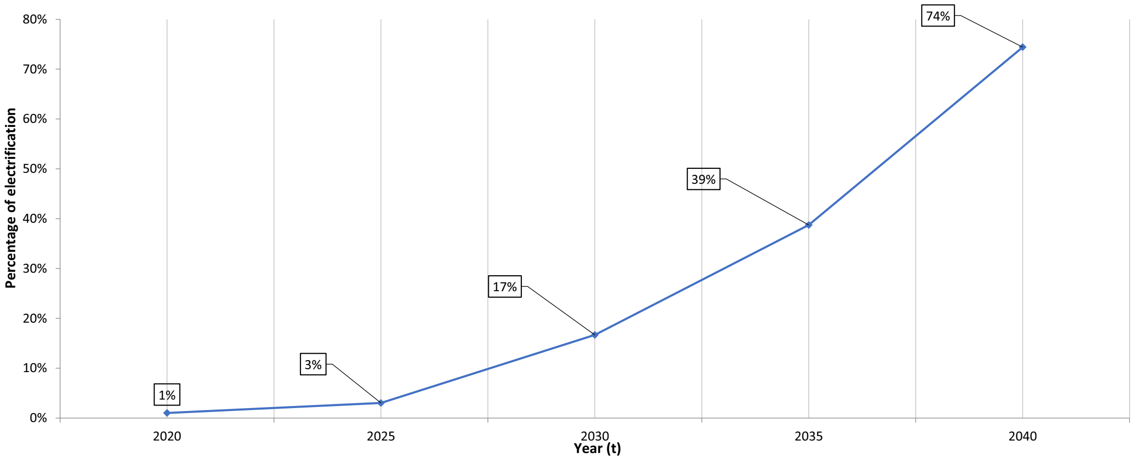


Fig. 3. Case company forecast - EV 2020–2040.

$$\frac{(U_P \times R \times V_{EM}) - (C_M + C_T + C_R) \times V_{EM}}{1\,000\,000} \tag{21}$$

Formula of detailed profit calculation:

$$\frac{(U_P \times R \times V_M(mt^2+nt+q)\,) - \left(C_M + C_T + H\left(\frac{a}{(V_M(mt^2+nt+q)\,)^b} + c\right)\right) \times V_M\,(mt^2+nt+q)}{1\,000\,000} \tag{22}$$

In summary, this subchapter provides an exhaustive analysis of the financial and operational aspects of repurposing EV batteries for aftermarket use, particularly in the creation of Li-ion starter batteries. A range of variables including material costs, transportation expenses, and repurposing time have been examined in detail, under different scenarios. The study utilizes equations and models to predict costs and volumes, considering variables like economies of scale and changing market conditions. It also incorporates anticipated market trends and electrification percentages to project future repurposing opportunities. The total cost calculations, time required for repurposing, and the influence of variable factors such as volume, make this study a comprehensive guide for companies contemplating battery repurposing initiatives.

4.2. Approach calculations of repurposing Li-ion battery packs – Approach 2

This approach focuses on remanufacturing battery packs for their original purpose rather than for a different application. Like the first approach, each step is divided into individual categories, with all calculations discussed and evaluated in collaboration with the company. Some variables from the first approach apply here, while others are different. This section concentrates on the differences.

4.2.1. Material costs (CM)

In this approach, the material cost is not fixed but it varies. It is necessary to replace all the battery cells to reuse the battery packs in EVs. Therefore, it is crucial to consider the declining price of Li-ion batteries.

4.2.2. Forecasted decline in Li-Ion battery costs from 2010 to 2030

The authors have collected information on the price decline of Li-ion batteries, which enables the creation of a function to demonstrate the fluctuating battery cell price. In this case, the battery cell price serves as a representation of the material cost. The function is formulated using USD as the currency but is later converted to SEK for the calculations to ensure consistency.

$$s = 1,098 \tag{23}$$

$$r = 1283,5 \tag{24}$$

$$y = 1283,5x^{-1,098} \tag{25}$$

$$t = x = \frac{T - 2008}{2} \tag{26}$$

4.2.3. Time of remanufacturing, hours (H)

The duration of the remanufacturing process varies from that of repurposing because only the battery cells undergo replacement in remanufacturing. The steps involved in the remanufacturing process are akin to the ones in Approach 1 for the initial four phases, with identical timeframes. However, the procedures from the fifth to the seventh step are unique to remanufacturing. The aggregate time and activities linked with remanufacturing are sourced from the activity table along with proprietary company data, all of which are displayed in Table 4. The overall time required for the remanufacturing process amounts to 13,5 h.

4.2.4. Unit price (UP) – remanufactured battery packs

A 20 % price decrease is expected for a remanufactured EV battery pack compared to a new one, as the cell exchange renews the pack. The price is lower since some components are reused. The unit price calculation considers the cell price (XXX SEK/kWh), the EV battery pack capacity (20 kWh), and the 20 % price reduction.

$$\text{Unit Price} : \text{XXX SEK/kWh} \times 20\ \text{kWh} \times 0.8\ (80\%) = \text{XXX SEK}$$

4.2.5. BP cost remanufacturing (Csum)

Table 5 showcases a summary for the Remanufacturing approach. These variables bear resemblance to those employed in Approach 1, except for the changed components of CM (which include r and s), H, and UP.

Formula:

Table 4
Actions and processing durations for one EV battery pack remanufacturing.

Remanufacturing activities for a BP	Time (h)
Disassembly	0.7
Inspection	0.5
Test of battery cells (equipment)	3.8
Test of electronics (operator)	2.5
Replacement of battery cells	3
Cleaning of components	1
Final tests of entire BP	2
Total time of remanufacturing process:	13.5

Table 5
Parameters for the remanufacturing process.

Parameters	Constant, varies (V)
C_M	(V)
r	1283.50
s	−1.098
t in C_M	(T-2008)/2
Energy (kWh)	20
USD to SEK	9.05
C_T (SEK)	1920 (V)
H (hours)	13,5 (V)
a	16,348
b	0.58
c	700
V_M (units)	40,000
t in V_M	(T-2015-DT)/2
m	0.0541
n	−0.142
q	0.0992
U_P (SEK)	XXX (V)
DT (years)	5

delivery time (DT); Unit price of a Starter battery (U_P); Volume market (V_M); Time – measured in hours (H); C_T - Transportation costs.

$$C_{sum} = \left(C_M + C_T + H\left(\frac{a}{x^b} + c\right)\right) \times V_M\left(mt_{VM}{}^2 + nt_{VM} + q\right) \tag{27}$$

$$x = V_M\left(mt_{VM}{}^2 + nt_{VM} + q\right) \tag{28}$$

$$t_{CM} = \frac{T - 2008}{2} \tag{29}$$

$$t_{VM} = \frac{T - 2015 - DT}{5} \tag{30}$$

4.2.6. *Profit calculation*

Remanufacturing approach profit mirrors Approach 1, albeit with the modification to accommodate the remanufactured EV battery pack, thereby removing the variable associated with 11 starter batteries. The updated equation is as given below:

$$\frac{(U_P \times V_{EM}) - (C_M + C_T + C_R) \times V_{EM}}{1\,000\,000} \tag{31}$$

Formula in details:

$$\frac{\left(U_P \times V_M(mt^2 + nt + q)\right) - \left(Energy \times r \times (t_{CM})^s + C_T + H\left(\frac{a}{\left(V_M\left(mt_{VM}{}^2 + nt_{VM} + q\right)\right)^b} + c\right)\right) \times V_M\left(mt_{VM}{}^2 + nt_{VM} + q\right)}{1\,000\,000} \tag{32}$$

In this subchapter, Approach 2 of repurposing Li-ion battery packs is explored, focusing on remanufacturing them for their original application in EVs. Unlike the first approach that targets varied end-uses, this approach strictly involves replacing the battery cells to extend their lifecycle in EVs. Factors such as material costs, forecasted price declines in Li-ion cells, and the time required for remanufacturing are analyzed. Based on collected data and proprietary company information, a 20 % cost reduction is anticipated for a remanufactured battery pack compared to a new one. Detailed calculations and equations are provided to account for variables like the declining cost of materials, unit price, and total cost of remanufacturing. The subchapter concludes that remanufacturing could offer a cost-effective, environmentally friendly alternative for extending the life of Li-ion batteries in their original application.

4.3. *Approach calculations of reusing Li-ion battery packs for ESS applications*

This section presents the methodology for calculating the ESS approach, which is distinct from the other two approaches as it does not involve any repurposing or remanufacturing processes. Instead, the battery packs are directly reused for another purpose in their second life. Some variables from the previous approaches are used, with adjustments made to suit this specific approach.

4.3.1. *EV battery installation cost (C_I)*

In this design, there is no financial expenditure for procuring used battery packs, but there is an associated expense for the installation of the ESS container. The cost of installation considers EPC, incidental expenses, balance-of-system hardware, and logistics, as identified by Frankel et al. (2018) to be 1448 SEK/kWh. The equation illustrating the declining price of Li-ion batteries, as highlighted in Approach 2, is also employed in this context.

$$C_I = 1448\ SEK/kWh \tag{33}$$

4.3.2. *Li-ion battery decreasing cost (C_M)*

The same function for the decreasing cost of Li-ion batteries outlined in Approach 2 is employed here, considering the anticipated reduction in battery prices over time.

The anticipated reduction in the cost of batteries can be expressed as a function:

$$C_M = Energy\ (kWh) \times r \times (t)^s, \text{where x = t, see Eq.(29)} \tag{34}$$

4.3.3. *Planned number of electrical machines*

The equation used to predict the volume of electrified machines is applied in a manner consistent with the other approaches, see Eq. (19), where

$$V_M = (number\ of\ sold\ machines\ )$$

$$P_E = mt^2 + nt + q \tag{35}$$

4.3.4. *ESS applications*

200 battery packs are required for a single ESS container.

$$ESS = 4\,000\ kWh \tag{36}$$

$$Energy_{BP} = 20\ kWh \tag{37}$$

$$A_{BP} = Number\ of\ BPs \tag{38}$$

$$A_{BP} = \frac{ESS}{Energy_{BP}} = \frac{4000\ kWh}{20\ kWh} = 200\ BPs \tag{39}$$

4.3.5. *Number of ESS containers (Q)*

The number of ESS containers needed can be calculated for the years 2023 to 2038.

$$Q = Number\ of\ containers \tag{40}$$

$$V_{EM} = Number\ of\ future\ electrified\ machines \tag{41}$$

$$A_{BP} = Number\ of\ BPs \tag{42}$$

$$Q = \frac{V_{EM}}{A_{BP}} \tag{43}$$

4.3.6. *Price per each ESS (C_{ESS})*

As CI is equal to 1448 SEK/kWh (initial cost), each container is 4000 kWh. The cost for each ESS container is calculated as follows, in SEK.

$$C_{ESS} = \frac{Container\ ESS \times \mathrm{C}_I}{1\,000\,000} \tag{44}$$

$$C_{ESS} = \frac{1,448{*}4,000}{1\,000\,000} = 5,800,000\ SEK \tag{45}$$

4.3.7. *ESS unit price ($P_{ESS\ unit}$)*

The determination of the selling price for one ESS container involves several steps. First, the required number of battery packs is identified. Then, the kWh price is considered, which is $512 (Kane, 2018). The next step involves applying the currency exchange rate of 1 USD equivalent to 9,05 SEK to convert the price from dollars to SEK. The final selling price, once computed, is then expressed in millions of SEK for simplicity

Table 6
Parameters for the ESS concept.

Parameters	Constant, varies (V)
C_M	
r	1283.5
s	−1.098
t in C_M	(T-2008)/2
$\mathbf{C_I}$ (SEK)	1448
Energy(kWh)	20
USD ($) to SEK	9.05
$\mathbf{V_M}$ (unit)	40,000
t in V_M	(T-2015-DT)/2
P_E	
m	0.0541
n	−0.142
q	0.0992
ESS container (kWh)	4000
$\mathbf{A_{BP}}$ (units)	200
P_{ESS} (MSEK)	18.5
C_{ESS} (MSEK)	5.79
DT (year)	5
Selling price (USD)	512

C_I - The cost of installation; Volume market (V_M); Amount of battery packs required (A_{BP}); DT - delivery time.

and ease of understanding.

$$P_{ESS\ unit} = \frac{ESS \times Sales\ in\ USD \times C_{USD \rightarrow SEK}}{1\ 000\ 000} \tag{46}$$

$$P_{ESS\ unit} = \frac{4\ 000 \times 512 \times 9,05}{1\ 000\ 000} \tag{47}$$

$$P_{ESS\ unit} = 18,5\ million\ SEK \tag{48}$$

4.3.8. *Total cost*

All costs for application in ESS are calculated as follows:

$$C_{sum} = \frac{(C_I \times ESS\ (kWh) + (C_{USD\ to\ SEK} \times A_{BP} \times Energy_{BP} \times r \times t^s \times T)\ )}{1\ 000\ 000} \tag{49}$$

where T is selected for a specific year.

4.3.9. *Summarized profit*

The summarized profit is equal to number for a year (T) and the price for each container.

$$Q\ (T) \times PESS\ unit \tag{50}$$

4.3.10. *Summary of variables*

All variables for reusing battery packs in ESS applications are summarized in Table 6.

To conclude this chapter, we introduce the methodology specific to the ESS approach, which diverges from the other two examined approaches in a critical way. Unlike remanufacturing or repurposing, the ESS approach involves directly reusing the battery packs for an alternate function in their second life. While some variables from the previously discussed approaches are employed here as well, necessary adjustments have been made to tailor them to this unique application. This sets the ESS approach apart as it capitalizes on the direct reuse of battery packs, bypassing the need for remanufacturing or repurposing processes.

5. Results

This section provides a detailed financial and sustainability analysis for each of the three circular approaches for second life Li-ion batteries: remanufacturing, repurposing, and reusing. This research quantitatively evaluates the long-term profitability and environmental sustainability of three circular approaches for second life Li-ion batteries. We aim to provide a comprehensive financial model for each approach and identify the most promising approach for businesses and policymakers. Before we delve into the individual specifics of each approach, it is critical to have a holistic understanding of their interplay and their impacts on the sustainability of the battery lifecycle. Fig. 4 provides a comprehensive visual representation of these approaches, thereby setting the stage for the in-depth discussions to follow.

The projected profit trajectory for the Aftermarket approach (approach 1) considers the cumulative profit against the backdrop of the initial investment. It incorporates other critical financial parameters such as accrued profit, initial outlay, payback period, and rate of return in the visualization. It is assumed in the Aftermarket approach that there will be an investment to the tune of 75 million SEK. Given the company's insights and past experiences, a 50 million investment is deemed plausible for this type of venture. The Aftermarket approach, due to its novelty and increased demands for knowledge and resources, necessitates a more significant investment since it represents a new endeavor for the company.

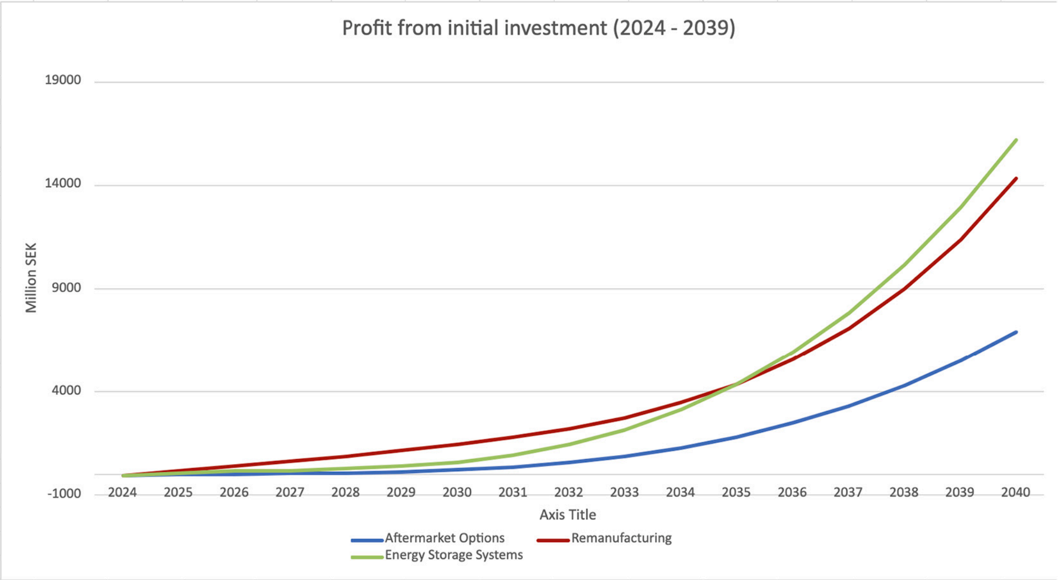


Fig. 4. Investment requirements for implementing the three proposed approaches.

The scope of the investment extends to fixed assets such as new infrastructure, machinery, tools, knowledge acquisition, recruitment, and training of new staff, procuring certifications and patents, and setting up new test rigs, among other expenditures. The assumption is that the investment takes place in 2023 year, given that the repurposing process entails two years of preparatory work. This illustrates the profit yielded from the primary investment.

The opportune moment to invest in the repurposing approach is in 2023, given that the first batch of retired EV batteries is anticipated to arrive in 2025, five years post their market introduction. These five years symbolize the batteries' approximate minimum operational life, with a maximum potential lifespan of up to 15 years. The function diagram is predicated on the integration of the initial investment and the annual accumulated profit, yielding the aggregate profit generated from 2023 for 15 years. The graphic representation of the first approach demonstrates a robust return rate of around 12,5 % stretched across 15 years. This is indicative of the yearly profit that can be reaped from the initial investment in this approach.

The function diagram delineates that the expected breakeven point, marking the commencement of profitability, is anticipated in the year 2030 - eight years following the inception of the investment. The enterprise envisions that the recoupment of the investment will take place within a maximum span of five years. As soon as the breakeven point is surpassed, the profitability by 2038 is forecasted to progressively escalate, potentially touching a staggering sum of nearly 1,8 billion SEK.

Projecting the likely profit trajectory for the Remanufacturing approach (approach 2) from 2023 to 2038, we utilize the total cost and profit equations. The presumption is that this approach would demand an investment outlay of 50 million SEK in 2023, coinciding with the inception of investment for Approach 1. The capital commitment for the Remanufacturing approach is somewhat reduced, as the remanufacturing operations can be accommodated within the existing Swedish facility. Much of the necessary infrastructure, comprising facilities, equipment, tools, and in-house expertise, is already accessible, which alleviates expenditures tied to establishing new facilities, procuring machinery, or engaging external collaboration. However, akin to Approach 1, the same factors are assimilated into the investment cost. Drawing upon these calculations, it is projected that the investment will be recuperated within five years, indicating profitability by 2027 with a steady growth trajectory thereafter. The forecasted total profit by 2038 amounts to an impressive 7,1 billion SEK. Given that all cells are replaced with new ones, the remanufactured battery pack matches the capacity of a brand-new pack, which justifies the high unit price of 64,000 SEK and the consequential considerable profit. The robust profit, yielding a return rate of 27.8 % over a 15-year period, is additionally bolstered by the comparatively brief duration of the remanufacturing process, spanning only 13,5 h. In alignment with the criterion outlined in Approach 1, the payback period must not exceed five years, a condition that the Remanufacturing approach satisfactorily meets.

With respect to the ESS approach (approach 3), the firm's current limited expertise and infrastructural inadequacies render its implementation the most complex. The deficiency in the requisite skills, strategic alliances, and dedicated facilities for ESS inevitably results in a sizable initial investment of 100 million SEK. This financial implication is attributed to the substantial time and fiscal commitments demanded during the foundational stage of establishing this new line of operation.

The introduction of this novel application area necessitates the hiring and comprehensive training of a team proficient in the ESS discipline. Additionally, the acquisition of pertinent industry knowledge and certifications is a requisite. This upfront investment encompasses similar constituents as defined under Approach 1. Aligned with the timelines of the preceding approaches, the investment for the ESS approach is actioned in 2023. As a result, the expected payback period, the timeframe within which the initial investment is recouped, is envisaged to be three years following the initial investment. This comfortably fulfills the firm's stipulated criterion of a maximum payback period of five years. Considering the hefty unit price of 18,5 million SEK per ESS container, the projected profit by 2038 stands at an impressive 8,7 billion SEK. This signifies a return rate of 22 % spanning the 15-year timeframe. The projected increase in profitability is substantially driven by the forecasted depreciation in Li-ion prices over the years, a factor that is incorporated into the unit price calculation. The ESS container, with its substantial storage capacity of 4000 kWh, incurs an installation expense of 1448 SEK/kWh, thereby accruing a total installation cost of around 5,79 million SEK. This calculation implies a consequential profit margin of 12,7 million SEK for each individual ESS container.

In stark contrast to the other propositions, this approach sidesteps the complex process of repurposing or remanufacturing battery packs. Instead, it centers on the direct reuse of the batteries and the subsequent installation of the container as the primary operational phases. Consequently, this approach precludes the need for any supplementary scrutiny or testing procedures.

From a profitability perspective, the Aftermarket approach records the smallest initial return on investment in comparison to the other two approaches. This outcome is predominantly influenced by its lower unit price. However, the profit curve demonstrates a steady, uniform increase over time, though ultimately realizing a smaller overall profit. In contrast, the Remanufacturing approach profit trajectory exhibits a notable acceleration over the years. This substantial upward trend is attributed to its higher unit price, significantly exceeding that of the Aftermarket approach. This unit price is justified given that the remanufacturing process involves a complete cell replacement, effectively revitalizing the battery to a ‘new’ state and therefore warranting a price tag equivalent to a brand-new EV battery pack. Another factor contributing to this upward shift could be the incorporation of the depreciating value of the Li-ion battery into the financial calculations.

In summation, each of the three approaches demonstrates a consistent profit escalation for the initial decade. The pattern could largely hinge on future market dynamics and the continual price reduction of Li-ion batteries, a factor not accounted for in the Aftermarket approach. To ensure maximal accuracy, the authors suggest periodic revisions of this profit projection model, given that some forecasted data may undergo fluctuations over time.

Initially, the ESS approach was projected as the most lucrative. However, an intriguing turn of events occurs in 2042, when the Remanufacturing approach usurps the ESS in profit margins. The viability and sustained effectiveness of this approach play a pivotal role in its selection as the ultimate approach by both the authors and the company. However, the chief determining factor was its relative ease of implementation from the company's vantage point, especially when compared with the complexities associated with the ESS approach.

By considering each approach's potential, the company can make informed choices about the path to follow. The Remanufacturing approach appears to offer the greatest potential in terms of long-term profitability and market alignment, making it the recommended choice for the company. Nevertheless, the Aftermarket and ESS approaches should not be entirely overlooked, as they may still offer valuable insights and opportunities for the company's future growth and expansion.

This study set out to answer the research question: ‘What is the economic feasibility for second life use of Li-ion electric vehicle battery packs in the heavy-duty vehicle industry?’ Our findings indicate that the remanufacturing approach emerges as the most economically viable option, offering a robust return rate of 27.8 % over a 15-year period, followed by reusing for energy storage systems approach. This aligns well with the growing trends in the electric vehicle market and the reducing costs of Li-ion batteries. Thus, the results directly address the research question by assessing and comparing the economic feasibility of each circular approach.

6. Discussion

The implications of this study are both theoretically rich and practically applicable, rendering it a significant contribution to the realm of second life Li-ion battery utilization. The identified three-pronged circular approaches - remanufacturing, repurposing, and reusing - offer a fresh perspective, simultaneously providing viable solutions to environmental challenges and presenting substantial economic benefits.

This research amplifies the understanding of the second life approaches for Li-ion batteries, particularly the approach of remanufacturing. It underscores how this remanufacturing approach can be considered the most promising, given the imminent expansion of the EV market and the potential for reduced costs associated with Li-ion batteries. Additionally, the study draws attention to the intricate interconnections between EV market growth, EV manufacturers' involvement, the remanufacturing processes, and the strategic positioning of facilities in the life cycle of the battery. Furthermore, this study illuminates the potential barriers to the widespread implementation of the remanufacturing approach, including the absence of universally accepted regulations for battery circularity. It emphasizes the necessity of effective circular processes within each country, given the hazardous substances within batteries and their subsequent environmental impacts. A significant implication of this study is the advocacy for involving OEMs in the remanufacturing process due to their domain-specific expertise. This insight underscores the importance of adopting a more holistic and collaborative approach in the remanufacturing process to maximize its potential benefits.

6.1. Theoretical contributions

From this extensive study, the authors have identified the remanufacturing approach as the most promising among others. This limitation is further amplified by the dearth of available data on the subject (Ding et al., 2023). Nonetheless, there is an expectation of substantial growth in the EV market, as noted by Sanders (2017). This anticipated expansion, the authors argue, could pave the way for an increased wealth of data on remanufacturing processes.

A similar connection between the growth of the EV market and the amplified involvement of EV manufacturers in remanufacturing processes for EV battery packs has been suggested by Curry (2017). This collaboration would effectively extend the service life of these battery packs. In the context of the Remanufacturing approach, there are additional factors to consider, such as reverse logistics, recycling, and the strategic positioning of facilities (Ding et al., 2023).

At this juncture, the price of Li-ion batteries remains considerably high. Martinez-Laserna et al. (2018) point out that the price difference between EVs and non-electric vehicles can be largely attributed to the high costs associated with Li-ion batteries. Secondary use approaches have the potential to ameliorate this price difference (Govindan, 2022). The author also acknowledges the potential of remanufacturing batteries for a second life, as it promotes the reuse of materials instead of merely discarding them.

A key concern that currently plagues this area is the absence of universally accepted regulations pertaining to the circularity of batteries (Habib et al., 2023). Each country has its own set of regulations, leading to an overall ambiguity surrounding the circular process. The authors assert the necessity of developing efficient circular processes within each country, particularly considering the hazardous substances contained within batteries and their consequent environmental impact (Rajaeifar et al., 2022).

Reinhardt et al. (2019) postulate that circularity is currently an unprofitable venture due to the lack of well-defined circular process frameworks. As batteries pose a significant environmental hazard, the authors underline the urgency of creating these frameworks without delay. Scholars accentuate the potential for a well-structured circular process to minimize the environmental impact of battery life cycles (Zisopoulos et al., 2023). For effective remanufacturing processes to be established, battery packs must be securely transported between locations. While regulations for transportation differ based on country specific, a consistent necessity is the need for trained personnel to manage the transport due to potential risks (Chen et al., 2022; Tsvetkova et al., 2022).

While remanufacturing does necessitate a comprehensive cell exchange, there is still potential to repurpose used cells in alternate applications. Canals Casals et al. (2016) bring to light the challenges of this process, including the substantial effort and cost that battery dismantling requires. Research underscores the position of engaging Original Equipment Manufacturers in remanufacturing processes due to their specific expertise in this complex domain (Zheng et al., 2022). Consequently, the authors have incorporated Original Equipment Manufacturers in the mentioned approach.

To conclude, we underscore the imperative of second life approaches for Li-ion batteries, with a special focus on remanufacturing. This is in response to the rising demand for solutions that are both sustainable and cost-effective. The projected expansion of the EV market, coupled with the potential decline in battery prices, suggests that remanufacturing practices may become more widespread in the foreseeable future. Additionally, it is crucial that effective circular processes are developed within each country to manage the hazardous substances present in batteries and reduce their environmental impact appropriately. A collaborative approach, involving car manufacturers, Original Equipment Manufacturers, and other relevant stakeholders, is key to overcoming the challenges associated with battery dismantling and remanufacturing. As the remanufacturing market for Li-ion batteries continues to grow, a wealth of data and experience will become accessible, leading to improved processes and, ultimately, contributing to a more sustainable and circular economy.

6.2. Practical implications

The practical implications of this study are multifaceted and have great potential for a wide array of stakeholders within the EV and Li-ion battery industries. The articulation of three circularity approaches: remanufacturing, repurposing, and reusing, introduces new avenues for businesses, regulators, and practitioners in the sector.

6.2.1. Remanufacturing approach

Our research promotes the remanufacturing approach as the most promising, considering the continuous growth of the EV market and decreasing costs of Li-ion batteries. Companies in the EV sector can integrate this approach into their operations, thus extending the lifespan of their batteries, while simultaneously reducing the demand for raw materials and decreasing their environmental footprint. Such a paradigm shift can result in substantial cost savings for both manufacturers and consumers, due to a decrease in the initial costs of EVs, thus promoting a wider adoption of these vehicles.

6.2.2. Repurposing approach

Repurposing used batteries into smaller power units provides an opportunity for manufacturers and aftermarket businesses to explore and create new markets. The approach of converting a 20-kWh battery pack into a set of 11 starter batteries can expand the applications of used batteries beyond the confines of the automobile industry. This can be particularly beneficial to sectors where the storage and supply of energy in smaller units is crucial.

6.2.3. Reusing approach

By suggesting the direct reuse of the battery packs in large-scale ESS applications, the study provides a potential solution for energy storage providers and utility companies. Leveraging used batteries in such a manner could alleviate the environmental and financial burdens associated with the production of new batteries for energy storage. This approach offers a chance for energy storage solutions to become more economically viable and environmentally friendly, propelling the renewable energy sector further.

6.2.4. Regulatory implications

The study also contributes to the ongoing discussions around the regulatory framework surrounding the circularity of Li-ion batteries. The inconsistency of these regulations across different countries currently poses a significant challenge to the circular process. Policymakers should take note of the findings of this study and consider implementing universal standards and regulations for battery circularity. This will not only help in mitigating the environmental impact of used batteries but will also boost the efficiency of circular processes.

6.2.5. Collaboration

Lastly, the study emphasizes the crucial role of collaboration among different stakeholders involved in the battery life cycle. The engagement of OEMs is essential due to their specialized knowledge and expertise in battery manufacturing and remanufacturing. Thus, these collaborative efforts could pave the way for the creation of a more circular economy within the battery and EV industries.

The practical insights and approaches outlined in this study present a roadmap to creating sustainable, economically viable solutions for the ever-growing demand for EVs and Li-ion batteries. The widespread adoption of these approaches will undoubtedly contribute to the transition towards a more sustainable and circular economy in the heavy-duty vehicle industry.

7. Limitations and future research

While this study provides valuable insights into the economic feasibility of second life battery approaches, it is important to acknowledge its limitations. One of the most significant limitations is the absence of a sensitivity analysis. Given that our study relies on various assumptions, such as investment costs, projected profitability, and alignment with a company's existing resources, a sensitivity analysis would have been valuable for assessing the robustness of our findings. Another limitation is the focus on a single case study on a large manufacturing company in the heavy-duty vehicle industry. The manufacturing company is part of a large group, where other business areas such as trucks, buses, remanufacturing are in place. Hence, the proposed approaches and selection depends a lot on their company's competence, resources, and infrastructure. Careful consideration of these contextual factors would be useful in generalizable to other companies in similar or different sectors or even different types of electric vehicle batteries. Additionally, the study does not account for potential changes in regulatory frameworks that could impact the economic viability of second life battery approaches. Regulatory shifts could either facilitate or hinder the implementation of these approaches, thereby affecting their profitability.

Future research could address these limitations by conducting a sensitivity analysis to assess the impact of varying assumptions on the study's conclusions. Studies could also explore the applicability of our findings to other industries and battery types. Furthermore, research could investigate the influence of changing regulations on the economic feasibility of second life battery approaches.

8. Conclusions

This study aimed to assess the feasibility of three circular approaches for the second life of Li-ion batteries: remanufacturing, repurposing, and reusing. Our results indicate that each of these approaches has its own set of financial and sustainability implications, with remanufacturing emerging as the most promising in terms of long-term profitability and alignment with market trends.

From a financial standpoint, our results showed that the Remanufacturing approach could yield a robust return rate of 27.8 % over a 15-year period, with a total projected profit of 7.1 billion SEK by 2038. This was closely followed by the ESS approach, which had a return rate of 22 % and a projected profit of 8.7 billion SEK. The Aftermarket approach, while still profitable, lagged the other two in terms of return on investment.

Our discussion further elaborated on the theoretical and practical implications of these findings. The remanufacturing approach not only offers economic benefits but also contributes to environmental sustainability by extending the lifespan of batteries and reducing the demand for raw materials. This aligns with the growing need for sustainable solutions in the face of an expanding EV market and decreasing costs of Li-ion batteries. The study also highlighted the importance of collaboration among various stakeholders, including OEMs and policymakers, to address challenges such as the lack of universally accepted circularity regulations.

Considering these findings, we recommend the adoption of the remanufacturing approach as it offers the greatest potential for long-term profitability and environmental sustainability. However, the other two approaches—repurposing and reusing—should not be entirely dismissed, as they also offer valuable opportunities for specific market segments and can contribute to a more circular economy.

The study underscores the need for a multi-stakeholder approach to maximize the benefits of these circularity approaches. Policymakers should consider implementing universal standards for battery circularity, and businesses in the EV sector could benefit from integrating remanufacturing approaches into their operations.

In conclusion, our research provides a comprehensive analysis of the financial and sustainability aspects of second life approaches for Li-ion batteries. It offers actionable insights for businesses, policymakers, and academics, contributing to the ongoing efforts to make the battery and EV sectors more sustainable and economically viable. Future research should focus on the real-world implementation of these strategies to validate the financial models and sustainability metrics proposed in this study.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT 4.0 to enhance the English language proficiency and fluency of the manuscript. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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.

Acknowledgement

This work was supported by the RECREATE (Second Life Management of Electric Vehicle Batteries) funded by the Knowledge Foundation (KKS) in Sweden [1602, 2019]. In addition, the work was supported by the TRUST-SOS (Trusted Site Simulation) funded by the Vinnova FFI in Sweden [02551, 2021] and the Excellence in Production Research (XPRES), a government funded Strategic Research Area (SRA) within manufacturing engineering in Sweden [0219, 2016].

Appendix 1. Detailed overview of research sessions

Session No.	Type of interview	No. of participants	Role of participants	Main topics discussed	How session started	Duration
1	Unstructured	2	Executive, Engineer	Secondary use of batteries	Introduction of research goals	60 min
2	Unstructured	3	Engineers, Manager	Financial considerations	Briefing on objectives	45 min
3	Workshop	8	Executives, Managers	Recycling considerations	Agenda overview	120 min
4	Semi-structured	1	Engineer	Business models	Casual conversation	30 min
5	Semi-structured	3	Executive, Managers	Technical specifications	Explanation of topics	50 min
6	Workshop	6	Executives, Engineers	Investment scale	Introduction and ice-breaker	100 min
7	Unstructured	1	Manager	Market opportunities	Introduction of study	25 min
8	Semi-structured	3	Executive, Engineers	Safety protocols	Brief on study sims	55 min
9	Semi-structured	1	Engineer	Regulatory compliance	Casual chat	35 min
10	Semi-structured	2	Managers	Future sustainability plans	Explanation of objectives	40 min
11	Workshop	5	Managers, Engineers	Timelines for remanufacturing	Agenda presentation	90 min
12	Unstructured	2	Executive, Engineer	Cost considerations	Brief Introduction	60 min
13	Unstructured	2	Engineer, Manager	Profit calculations	Overview of study	48 min
14	Workshop	4	Managers	Environmental impacts	Quick ice-breaker	85 min
15	Unstructured	1	Manager	OEM considerations	Explanation of research	28 min
16	Semi-structured	3	Executive, Managers	Unit price range	Brief on topics to discuss	52 min
17	Workshop	5	Executives, Engineers	Recycling technologies	Welcome and introduction	95 min
18	Semi-structured	1	Engineer	Data gathering years	Simple introduction	33 min
19	Workshop	7	Executives, Managers, Engineers	Disposal methods	Opening remarks	110 min
20	Semi-structured	2	Manager, Engineer	Second-life utilization	Overview of research goals	47 min
21	Final workshop	8	Executives, Managers, Engineers	Overall opinions on concept	Opening and agenda	130 min

Appendix 2. Basic interview questions

Secondary use of batteries

- Is the organization the OEM, or will it be marketing the concept of secondary use?
- Do you see secondary applications for batteries as a viable option soon?
- What is the anticipated source for acquiring used EV batteries?
- What is your overall opinion on the concept of giving batteries a second life?
- What reference year should be used for gathering pertinent data on lithium-ion batteries?
- Should ideation focus on upscaling or downscaling the applications?
- Are there any technical specifications available for lithium-ion batteries intended for future secondary use?
- Do the proposed business models align with the idea of battery second-life utilization?

Financial and numerical considerations

- Is it possible to pinpoint the exact time frame within which an investment would yield positive returns?
- Does the proposed formula accurately represent both the total cost and expected profit?
- Is the unit price range of 60-80% for used EV lithium-ion battery packs reflective of your experience, or should the range be adjusted?
- What scale of investment is deemed reasonable for the different second-life battery concepts?
- What is the approximate cost per hour for remanufacturing batteries at the company's Swedish facility?
- Could you elaborate on the steps involved in the remanufacturing process?
- What are realistic timelines for remanufacturing and repurposing EV batteries?
- Over what period (in years) should calculations for total costs and profits be made?
- What should be the time scale for our line diagrams representing years?

Recycling considerations

- To what extent will the recycling process be detailed in the study?
- Is the organization actively recycling starter batteries, and if so, could you describe the procedure?
- What technologies or methods are currently being employed for the recycling of lithium-ion batteries?
- What percentage of materials from recycled batteries is repurposed or reused?
- Are there any challenges or bottlenecks experienced in the current recycling process?
- What are the environmental impacts associated with the recycling of lithium-ion batteries?
- How does the company comply with existing regulations and standards on battery recycling?
- Is there a plan to improve the efficiency and sustainability of the battery recycling process?
- Are partnerships with external organizations or third parties involved in the recycling process?
- What is the approximate cost associated with recycling a unit of lithium-ion battery?
- Are there any safety concerns or protocols that must be strictly adhered to during the recycling process?
- How does the organization handle the disposal of non-recyclable components?
- Are there any market opportunities for materials recovered from recycled batteries?

References

Ahmadi, Leila, Fowler, Michael, Young, Steven B., Fraser, Roydon A., Gaffney, Ben, Walker, Sean B., 2014. Energy efficiency of li-ion battery packs re-used in stationary power applications. Sustain. Energy Technol. Assess. 8, 9–17. https://doi.org/10.1016/j.seta.2014.06.006.

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 Climate Change 3, 100086. https://doi.org/10.1016/j.egycc.2022.100086.

Alonso-Villar, Albert, Davíðsdóttir, Brynhildur, Stefánsson, Hlynur, Ásgeirsson, Eyjólfur Ingi, Kristjánsson, Ragnar, 2022. Technical, economic, and environmental feasibility of alternative fuel heavy-duty vehicles in Iceland. J. Clean. Prod. 369, 133249 https://doi.org/10.1016/j.jclepro.2022.133249.

Bonsu, Nana O., 2020. Towards a circular and low-carbon economy: insights from the transitioning to electric vehicles and net zero economy. J. Clean. Prod. 256, 120659 https://doi.org/10.1016/j.jclepro.2020.120659.

Canals Casals, Lluc, García, Beatriz Amante, Benítez, Maria Margarita González, 2016. A Cost Analysis of Electric Vehicle Batteries Second Life Businesses, pp. 129–141.

Chen, Chao, Feng, Tao, Xiaoning, Gu, Yao, Baozhen, 2022. Investigating the effectiveness of COVID-19 pandemic countermeasures on the use of public transport: a case study of the Netherlands. Transp. Policy 117, 98–107. https://doi.org/10.1016/j.tranpol.2022.01.005.

Chirumalla, Koteshwar, Reyes, Lizbeth Guerrero, Toorajipour, Reza, 2022. Mapping a circular business opportunity in electric vehicle battery value chain: a multi-stakeholder framework to create a win–win–win situation. J. Bus. Res. 145, 569–582. https://doi.org/10.1016/j.jbusres.2022.02.070.

Colarullo, Linda, Thakur, Jagruti, 2022. Second-life EV batteries for stationary storage applications in local energy communities. Renew. Sust. Energ. Rev. 169, 112913 https://doi.org/10.1016/j.rser.2022.112913.

Curry, C., 2017. Lithium-ion Battery Costs and Market.

Ding, Lu, Wang, Tong, Chan, Paul W., 2023. Forward and reverse logistics for circular economy in construction: a systematic literature review. J. Clean. Prod. 388, 135981 https://doi.org/10.1016/j.jclepro.2023.135981.

Foster, Meaghan, Isely, Paul, Standridge, Charles Robert, Hasan, Md Mehedi, 2014. Feasibility assessment of remanufacturing, repurposing, and recycling of end of vehicle application lithium-ion batteries. J. Ind. Eng. Manag. 7 (3) https://doi.org/10.3926/jiem.939.

Frankel, D., Kane, Sean, Tryggestad, Christer, 2018. https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/the-new-rules-of-competition-in-energy-storage.

Frey, Daniel D., Herder, Paulien M., Wijnia, Ype, Subrahmanian, Eswaran, Katsikopoulos, Konstantinos, Clausing, Don P., 2009. The Pugh controlled convergence method: model-based evaluation and implications for design theory. Res. Eng. Des. 20 (1), 41–58. https://doi.org/10.1007/s00163-008-0056-z.

Govindan, Kannan, 2022. Tunneling the barriers of blockchain technology in remanufacturing for achieving sustainable development goals: a circular manufacturing perspective. Bus. Strateg. Environ. 31 (8), 3769–3785. https://doi.org/10.1002/bse.3031.

Habib, A.K.M., Ahasan, Mohammad Kamrul, Hasan, Ghassan F., Issa, Dalbir Singh, Islam, Shahnewaz, Ghazal, Taher M., 2023. Lithium-ion battery management system for electric vehicles: constraints, challenges, and recommendations. Batteries 9 (3), 152. https://doi.org/10.3390/batteries9030152.

Hantanasirisakul, Kanit, Sawangphruk, Montree, 2023. Sustainable reuse and recycling of spent Li-ion batteries from electric vehicles: chemical, environmental, and economical perspectives. Global Chall. 7 (4) https://doi.org/10.1002/gch2.202200212.

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.

Hesse, Holger, Schimpe, Michael, Kucevic, Daniel, Jossen, Andreas, 2017. Lithium-ion battery storage for the grid—a review of stationary battery storage system design tailored for applications in modern power grids. Energies 10 (12), 2107. https://doi.org/10.3390/en10122107.

International Energy Agency, 2021. Global EV Outlook 2021. Prospects for Electric Vehicle Deployment.

Jiao, N., 2019. Business Models for Second-life Electric Vehicle Battery Systems. University of Cambridge.

Kane, M., 2018. Tesla's ESS Australia, 2018-09-25. Retrieved May 16, 2023. https://insideevs.com/tesla-powerpack-australia-17-million-revenue/.

Knäble, David, de Quevedo, Esther, Puente, Clara Pérez-Cornejo, Baumgärtler, Thomas, 2022. The impact of the circular economy on sustainable development: a European panel data approach. Sustain. Prod. Consum. 34, 233–243. https://doi.org/10.1016/j.spc.2022.09.016.

Lai, Xin, Chen, Quanwei, Tang, Xiaopeng, Zhou, Yuanqiang, Gao, Furong, Guo, Yue, Bhagat, Rohit, Zheng, Yuejiu, 2022. Critical review of life cycle assessment of lithium-ion batteries for electric vehicles: a lifespan perspective. ETransportation 12, 100169. https://doi.org/10.1016/j.etran.2022.100169.

Marques, Pedro, Garcia, Rita, Kulay, Luiz, Freire, Fausto, 2019. Comparative life cycle assessment of lithium-ion batteries for electric vehicles addressing capacity fade. J. Clean. Prod. 229, 787–794. https://doi.org/10.1016/j.jclepro.2019.05.026.

Martinez-Laserna, E., Gandiaga, I., Sarasketa-Zabala, E., Badeda, J., Stroe, D.I., Swierczynski, M., Goikoetxea, A., 2018. Battery second life: hype, hope or reality? A critical review of the state of the art. Renew. Sust. Energ. Rev. 93, 701–718. https://doi.org/10.1016/j.rser.2018.04.035.

Mol, Carlo, O'Keefe, Michael, Brouwer, Arie, Suomela, Jussi, 2010. Trends and insight in heavy-duty vehicle electrification. World Electr. Veh. J. 4 (2), 307–318. https://doi.org/10.3390/wevj4020307.

Pelegov, Dmitry V., Chanaron, Jean-Jacques, 2022. Electric car market analysis using open data: sales, volatility assessment, and forecasting. Sustainability 15 (1), 399. https://doi.org/10.3390/su15010399.

Rahimi, Mohammad, 2021. Lithium-ion batteries: latest advances and prospects. Batteries 7 (1), 8. https://doi.org/10.3390/batteries7010008.

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.

Reinhardt, Robert, Christodoulou, Ioannis, Gassó-Domingo, Santiago, García, Beatriz Amante, 2019. Towards sustainable business models for electric vehicle battery second use: a critical review. J. Environ. Manag. 245, 432–446. https://doi.org/10.1016/j.jenvman.2019.05.095.

Rohr, Stephan, Wagner, Stephan, Baumann, Michael, Muller, Stefan, Lienkamp, Markus, 2017. A techno-economic analysis of end of life value chains for lithium-ion batteries from electric vehicles. In: 2017 Twelfth International Conference on Ecological Vehicles and Renewable Energies (EVER). IEEE, pp. 1–14.

Sanders, M., 2017. The Rechargeable Battery Market and Main Trends 2016–2025. In: 33rd Annual International Battery Seminar & Exhibit, pp. 1–98. Fort Lauderdale, FL, USA.

Sarker, Mushfiqur R., Pandzic, Hrvoje, Ortega-Vazquez, Miguel A., 2015. Optimal operation and services scheduling for an electric vehicle battery swapping station. IEEE Trans. Power Syst. 30 (2), 901–910. https://doi.org/10.1109/TPWRS.2014.2331560.

Sato, Fernando Enzo Kenta, Nakata, Toshihiko, 2019. Recoverability analysis of critical materials from electric vehicle lithium-ion batteries through a dynamic fleet-based approach for Japan. Sustainability 12 (1), 147. https://doi.org/10.3390/su12010147.

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. Consum. 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.

Tsvetkova, Anastasia, Kulkov, Ignat, Busquet, Caroline, Kao, Ping Jen, Kamargianni, Maria, 2022. Implications of COVID-19 pandemic on the governance of passenger mobility innovations in Europe. Transp. Res. Interdiscip. Perspect. 14 https://doi.org/10.1016/j.trip.2022.100581.

Yang, Zhijie, Huang, Haibo, Lin, Feng, 2022. Sustainable electric vehicle batteries for a sustainable world: perspectives on battery cathodes, environment, supply chain, manufacturing, life cycle, and policy. Adv. Energy Mater. 12 (26) https://doi.org/10.1002/aenm.202200383.

Zheng, Xiaochen, Jinzhi, Lu, Kiritsis, Dimitris, 2022. The emergence of cognitive digital twin: vision, challenges and opportunities. Int. J. Prod. Res. 60 (24), 7610–7632. https://doi.org/10.1080/00207543.2021.2014591.

Zisopoulos, Filippos K., Steuer, Benjamin, Abussafy, Ricardo, Toboso-Chavero, Susana, Liu, Zhaowen, Tong, Xin, Schraven, Daan, 2023. Informal recyclers as stakeholders in a circular economy. J. Clean. Prod. 415, 137894 https://doi.org/10.1016/j.jclepro.2023.137894.