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Second Life of E-Truck Batteries for Sustainable Logistics

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About Smart Freight Centre
Smart Freight Centre is an international non-profit organization focused on reducing greenhouse gas emissions from freight transportation. Smart Freight Centre's vision is an efficient and zero emission global logistics sector. Smart Freight Centre's mission is to collaborate with the organization's global partners to quantify impacts, identify solutions, and propagate logistics decarbonization strategies. Smart Freight Centre's goal is to guide the global logistics industry in tracking and reducing the industry's greenhouse gas emissions by one billion tonnes by 2030 and to reach zero emissions by 2050 or earlier, consistent with a 1.5°C future.

About Cenex Nederland
Cenex Nederland (Cenex NL) is an independent, not-for-profit Consultancy and Research Technology Organisation based in Amsterdam, the Netherlands. They work with and for governments, industry, and academia on finding solutions in Zero Emissions Mobility, Energy Infrastructure and Circular Mobility.

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BESS: Battery Energy Storage Systems

BMS: Battery Management System

E-Truck: Electric Truck

EV: Electric Vehicle

ELSA: Energy Local Storage Advanced System

EoFL: End of First Life

EPR: Extended Producer Responsibility

GHG: Greenhouse Gas

GWh: Gigawatt hour

HDV: Heavy-Duty Vehicles

IRENA: International Renewable Energy Agency

Kg: Kilogram

kW: Kilowatt

LFP: Lithium Iron Phosphate

Li-S: Lithium Sulphur

LiB: Lithium-ion Battery

MWh: MegaWatt hour

NCA: Nickel Cobalt Aluminium

NMC: Nickel Manganese Cobalt

OEM: Original Equipment Manufacturer

RUL: Remaining Useful Life

SLB: Second-Life Battery

SLBESS: Second Life Battery Energy Storage System

SoC: State of Charge

SoH: State of Health

TCO: Total Cost of Ownership

TWh: Terawatt hour

Executive Summary

The road freight sector in the European Union (EU) is witnessing a surge in the adoption of electric trucks (e-trucks), with sales of heavy-duty vehicles tripling. Batteries are crucial component for decarbonizing the transport sector, yet they constitute up to 40% of the total cost of ownership (TCO) of e-trucks and 40% of the greenhouse gas (GHG) emissions in e-truck production. Additionally, their manufacturing is associated with social sustainability issues. Moreover, these batteries typically reach the end of first life (EoFL) in e-truck applications when their capacity drops to 80%. For shippers and fleet owners aiming for a sustainable and economical transition in the freight transport sector, it is essential to maximize the potential of these batteries. After their first life in e-truck applications, these batteries still retain significant residual value, making their secondary use an increasingly important consideration.

This study aims to provide a comprehensive overview of the reuse and repurposing of EoFL batteries of e-trucks. Section 1 delves into the landscape of battery technology in heavy duty e-trucks, emphasizing on the lifecycle of e-truck batteries. Section 2 begins by defining the concepts of battery reuse and repurposing. It outlines the anticipated market demand for second life batteries (SLB) and highlights the benefits of their secondary use. The section also explains how to assess and prepare these batteries for their second life, provides real-world examples of second life applications, and showcases innovative business models that leverage the value of these batteries. Section 0 evaluates the impact of SLBs from e-truck on road freight electrification from both a practical and strategic perspective. Section 3 provides an overview of the technical and economic challenges of using batteries in second life application. Additionally, the section presents a brief overview of the regulatory landscape for reuse and repurposing of EoFL batteries in EU. Finally, the study presents recommendations for policy makers and the logistic sector to facilitate the development of SLB ecosystem and capitalize on its benefits.

The study provides the following high-level findings:

Different battery chemistries used in heavy-duty e-trucks have varying impacts on usability in their second life. LFP (Lithium Iron Phosphate) and NMC (Nickel Manganese Cobalt) battery chemistries dominate the heavy-duty e-truck market in the EU. LFP batteries are more advantageous for second life applications due to their longer battery life. Additionally, LFP batteries have greater safety against thermal risks, making them safer for deployment in second life applications comparatively.

Stationary storage and the mobility sector contribute to the majority of demand for lithium-ion batteries, presenting an opportunity for shippers and fleet owners. Global demand for batteries stands at 4.3 terawatt hours (TWh) for mobility applications and 421 gigawatt hours (GWh) for stationary applications. This presents a significant opportunity for shippers and fleet owners to reuse or repurpose electric vehicle (EV) batteries for second life applications in these markets. It is projected that by 2030, the supply of SLB for stationary applications could exceed 200 GWh annually, representing a market valued at $30 billion globally.

SLBs offer reduced TCO and provide a stable, sustainable and economical charging infrastructure for shippers and fleet owners. SLBs could reduce costs for end-users by approximately 42% compared to new batteries. Therefore, EoFL e-truck batteries with significant residual capacity can be reused in less demanding mobile applications, drastically reducing TCO. Additionally, repurposing EoFL e-truck batteries for stationary applications at charging depots could reduce the capital cost of the charging system by approximately 25%. This would allow a large fleet of e-trucks to charge simultaneously at depots, minimizing the cost and time required for network reinforcements. Furthermore, SLBs will boost the deployed storage capacities on energy networks beyond what is achievable with new batteries, enhancing renewable energy deployment and reducing energy costs and emissions related to charging activities.

The feasibility of reusing or repurposing EoFL e-truck batteries depends on various technical and economic factors. Several technical challenges need to be considered when choosing second life options for EoFL e-truck batteries. These include battery heterogeneity, remaining useful life (RUL) prediction, unique safety and battery management system (BMS) requirements for different second life applications, and the complexities of the disassembly and repurposing process. On the economic side, the benefits of reusing or repurposing EoFL e-truck batteries depend on the cost of repurposing, the cost of new batteries, and its lifespan in second life applications. The cost gap between repurposed batteries and the declining cost of new batteries should be significantly large to justify the investment.

There is a lack of maturity in standards for battery durability, safety, information accessibility, and collection and refurbishment targets. Several regulatory gaps related to the battery second life ecosystem exist in the EU, hindering the feasibility of second life options for EoFL e-truck batteries. Information about the technical characteristics, state of health, and operation history of batteries is currently not easily accessible until the implementation of the EU battery passport in 2027. To support the economic feasibility of battery reuse, it is crucial to standardize state-of-health (SoH) metrics to inform decisions on second life applications. Moreover, mandatory battery durability requirements are significant to incentivize the production of long-lasting batteries and support second life usage. Defining safety standards for reuse and repurposing is crucial to reducing the associated risks. Lastly, defining collection and refurbishment targets will prevent unwarranted disposal and ensure batteries are used to their maximum potential.

The study further provides recommendations to enable shippers and fleet owners to maximize the potential of these EoFL e-truck batteries:

Mandatory Battery Passport in Procurement Criteria: When procuring e-trucks, it is essential to ensure that the e-truck batteries come with a digital battery passport, making this a mandatory procurement requirement. Although the EU battery regulations mandate digital battery passports only from 2027, making this a mandatory requirement now will help shippers and fleet owners ease the repurposing process later, making it safe and cost-effective to deploy these batteries for the right second life application.

Collaboration with Battery Reuse or Repurposing Companies and Knowledge Partners: Shippers and fleet owners should actively collaborate with reputable battery reuse or repurposing companies to gain a thorough understanding of their specific needs and operational requirements. This collaboration is essential for several reasons:

- **Customized Solutions**: By working closely with battery repurposers, shippers and fleet owners can ensure that the repurposing solutions are tailored to their operational demands and performance expectations, maximizing economic and environmental benefits.
- **Optimized Battery Life**: Collaboration allows for better tracking and management of battery health, ensuring that repurposed batteries are used efficiently and effectively, thereby extending their lifecycle.
- **Regulatory Compliance**: Collaborating with experienced repurposers ensures that all regulatory requirements are met, minimizing legal risks and ensuring compliance with environmental and safety standards.

Partnerships with knowledge partners can provide valuable insights into technology, market dynamics, and best practices, ensuring informed decision-making. These collaborations are instrumental in successfully running pilot projects for deploying EoFL e-truck batteries in secondary applications.

Glossary

Battery: Battery refers to any device delivering electrical energy generated by direct conversion of chemical energy, having internal or external storage, and consisting of one or more non-rechargeable or rechargeable battery cells, modules or of packs.

Battery Energy Storage Systems: A battery energy storage system, is a type of energy storage system that uses a group of rechargeable batteries to store electrical energy from renewable and non-renewable sources for later use.

Battery Pack: Battery pack refers to any set of battery cells or modules that are connected together or encapsulated within an outer casing, to form a complete unit.

Charge/Discharge Rate: Charge/discharge rate refers to the speed at which energy is either stored into or drawn from a battery.

Circularity/Circular Economy/Circular Value Chain: Circular economy is a system where materials never become waste and nature is regenerated. In a circular economy, products and materials are kept in circulation through processes like maintenance, reuse, repurpose, remanufacture, recycling, and composting.

Depth of Cycles/Depth of Discharge: Depth of discharge or depth of battery cycles refers to the percentage of a battery's capacity that has been discharged relative to its maximum capacity. In other words, it measures how much of the total energy stored in the battery has been used during a single discharge cycle.

End of First Life: The End of First Life of an electric vehicle battery refers to the point at which the battery can no longer meet the performance requirements for its initial application, such as powering a vehicle. This typically occurs when the battery's capacity has degraded significantly, meaning it can store and deliver much less energy than when it was new.

Recycling: Recycling refers to the systematic process of collecting, sorting, dismantling, and recovering valuable materials from used batteries.

Remaining Useful Life: The remaining useful life of an electric vehicle battery refers to the estimated duration before the battery's capacity declines to a point (below 70-80% of original capacity) where it no longer meets the vehicle's operational needs.

Repurposer: Repurposer refers to an entity or organization that takes used batteries from electric vehicles, refurbishes and reconfigures them for a second life application.

Residual Capacity: Residual capacity of a battery refers to the amount of charge it can still hold and deliver compared to its original capacity when it was new. It is a measure of how much usable energy the battery can store and provide after being used for a period of time.

State of Charge: The state of charge of a battery is defined as the ratio between the available capacity and the reference capacity, which is the maximum capacity that can be withdrawn from the fully charged battery.

State of Health: The state of health of an electric vehicle battery refers to its current condition and performance compared to its original state when it was new.

Stated Policies Scenario: The Stated Policies Scenario (STEPS) reflects existing policies and measures, as well as firm policy ambitions and objectives that have been legislated by governments.

Thermal Runaway: Thermal runaway is a condition where an increase in temperature within the battery can lead to further heat generation, potentially resulting in an uncontrollable chain reaction that can cause overheating, fire, or explosion.

Thermal Runaway Propagation Resistance: Thermal runaway propagation resistance refers to the ability of a battery to prevent the rapid spread of thermal runaway once it has been initiated in one part of the battery cell or pack.

Total Cost of Ownership: The TCO provides a way to calculate, and then fairly compare, the costs of owning and operating a vehicle over a period of time. It combines information on purchase costs, ongoing costs such as fueling/charging and maintenance, as well as financing.

Volumetric Energy Density: Volumetric energy density of a battery refers to the amount of energy it can store per unit volume. In simpler terms, it measures how much energy a battery can hold relative to its size or volume.

1 Introduction

As shippers and fleet owners transition to electric trucks (e-trucks), effectively managing batteries at the end of their first life (EoFL) becomes essential, with different battery technologies affecting both EoFL options and performance in e-trucks.

The increasing adoption of e-trucks driven by stringent policies is expected to transform the logistics and transportation industries. The heavy-duty e-truck market share has seen a threefold rise from around 0.3% in 2022 to nearly 0.9% share of all new heavy-duty trucks sold in 2023 (ICCT 2024). As shippers and fleet owners transition to e-trucks, a new aspect emerges: the management of e-truck batteries once their capacity for vehicular use diminishes. Typically, these batteries retain significant energy storage capabilities, making their secondary use a topic of growing interest. This study explores the potential for repurposing e-truck batteries, examining the second life battery (SLB) ecosystem, opportunities, challenges, relevant policies and impacts on shippers and fleet owners. It begins with an overview of the current and the future state of battery technology and discusses the EoFL of e-truck batteries, setting the stage for understanding their second life potential.

Battery Technology in E-trucks

Battery e-trucks are designed with a large rechargeable battery pack as the primary energy source along with an electric motor, inverter, battery charger, controller and charging cable (SEAI 2024). The battery packs consist of multiple individual cells configured to store the energy which powers the truck's electric motors (Milence 2023).

Over the years, rapid advancements in Lithium-ion Battery (LiB) technology have established them as the preferred choice for e-truck applications due to their higher energy density, improved safety, extended service life, rapid charging capabilities, and minimal self-discharge (Pesaran 2023; Basma et al. 2021).

However, LiB performance and energy efficiency can vary based on battery cell chemistry, cell format, and cell-to-battery-pack packaging. The different chemistries come with trade-offs in weight, capacity, performance, fast charging capability, packaging, and recyclability, while the different cell formats—prismatic, pouch, and cylindrical—impact the volumetric energy density, packing efficiency, and safety, particularly in terms of thermal runaway propagation resistance.

In freight vehicles, battery energy density is crucial as it directly impacts maximum payload, transport volume and vehicle range (Basma et al. 2021). Freight vehicles are typically used more intensively than light duty vehicles and are operated under harsher conditions. To meet these requirements, freight vehicles need battery packs capable of withstanding high-power discharges and a longer cycle life. To take advantage of ultra-fast charging during long-haul trips, batteries need to be capable of withstanding high thermal stresses (Abhyankar et al. 2022). Factors such as battery pack cost, charge/discharge rates, and safety are critical considerations in selecting the appropriate battery chemistry for commercial vehicles (Volta Foundation 2024).

Current LiB Chemistries used in Heavy-Duty E-Trucks

Currently, both Lithium Iron Phosphate (LFP) and high-nickel chemistries like Nickel Manganese Cobalt (NMC) and Nickel Cobalt Aluminum (NCA) are being installed in heavy-duty e-trucks (Basma et al. 2021). Amongst these, LFPs & NMCs dominate the heavy-duty e-truck markets in Europe (ICCT 2024). OEMs prefer varying LiB chemistries for heavy duty e-truck applications to capitalize on their specific advantages which are highlighted below:

- **Lithium Iron Phosphate:** LFP battery chemistries have higher durability enabling higher charge/discharge rates compared to NMC batteries. In addition, LFP batteries have significant cost advantage due to their lack of cobalt. While LFP batteries have lower energy density compared to NMCs, they are less prone to fire related accidents. Moreover, LFPs have the highest battery life cycle comparatively making them more suitable for use in second life (Basma et al. 2021). LFP chemistry is widely used in e-trucks manufactured by Daimler and DAF (Daimler Trucks 2022; DAF 2024).

- **Lithium Nickel Manganese Cobalt:** NMC batteries have the highest energy density comparatively making it the preferred choice of battery chemistry for heavy duty e-truck manufacturers like Volvo, Scania, MAN and Renault. However, this chemistry offers a lower cycle life compared to LFP as seen in the Figure 1 (Basma et al. 2021).
- **Lithium Nickel Cobalt Aluminum:** NCA batteries deliver higher energy density compared to LFP batteries at the same time provides excellent fast charging capability making it suitable for e-truck manufacturer Volvo (SAE 2024). However, they have the highest safety concerns comparatively.

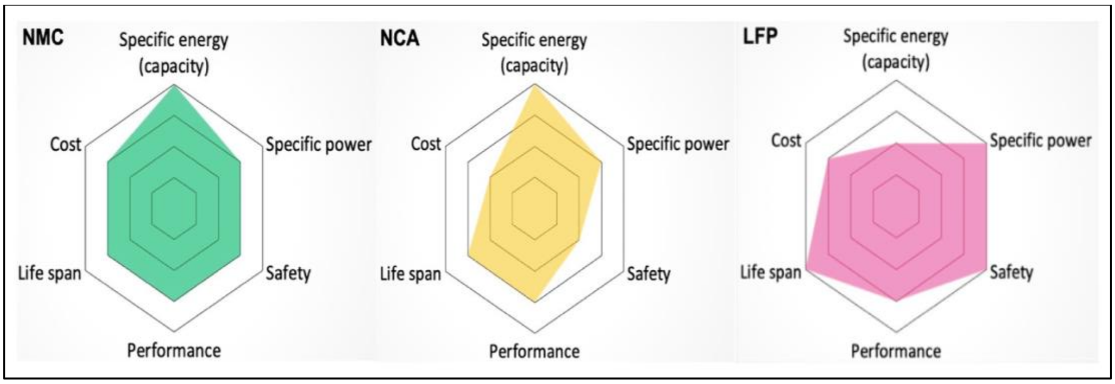

Figure 1: Comparison of different types of LiB chemistries used in e-trucks (Miao et al. 2019).

Potential Battery Chemistry in Heavy-Duty E-Trucks

Lithium-sulfur (Li-S) batteries and solid-state batteries (SSB) are few of the potential battery chemistries that may be used in heavy-duty e-trucks in the future (SAE 2024).

- **Lithium Sulphur Batteries:** These batteries have higher energy densities (up to 500 Wh/kg), approximately double that of LFPs and NMCs, presenting potential for heavy-duty e-truck applications. Challenges such as shorter cycle life and reduced performance in cold temperatures currently limit their commercial viability (SAE 2024; Volta Foundation 2024).
- **Solid State Batteries:** These batteries have increased operating temperature range, increased battery safety and energy densities and cycle life compared to LiB chemistries. However, this battery chemistry may have various technological challenges such as the scale-up of material production, compatibilities between components, as well as production challenges. Furthermore, the initial SSB costs may be higher compared to the current LiB battery technologies (Fraunhofer ISI 2022).

End of First Life of E-truck Batteries

Subjected to extreme operating temperatures and changing charge/discharge rates, LiBs in e-truck applications degrade drastically during the first five years of operation and are designed for over a decade of useful life in most cases (European Commission 2023b; Zhu et al. 2021). Typically, these batteries reach their EoFL in e-truck application as soon as its remaining usable capacity drops to 80% of its original capacity (Zhu et al. 2021). Yet, prior to recycling, these batteries can live a second life (as shown in Figure 2), even when they no longer meet EV performance standards but are still able to perform sufficiently to serve less-demanding applications, such as stationary energy-storage services. These batteries can support renewable energy integration, provide backup power, and enhance grid stability (Hassan et al. 2023). For shippers and fleet owners, this presents an opportunity to extract additional value from their e-truck investments. By extending the economic lifetime of the batteries, second life use of batteries lowers their overall lifecycle costs. If the battery materials are recycled and return to the economy at the end of second life, this also contributes to a circular battery economy, as shown in Figure 2.

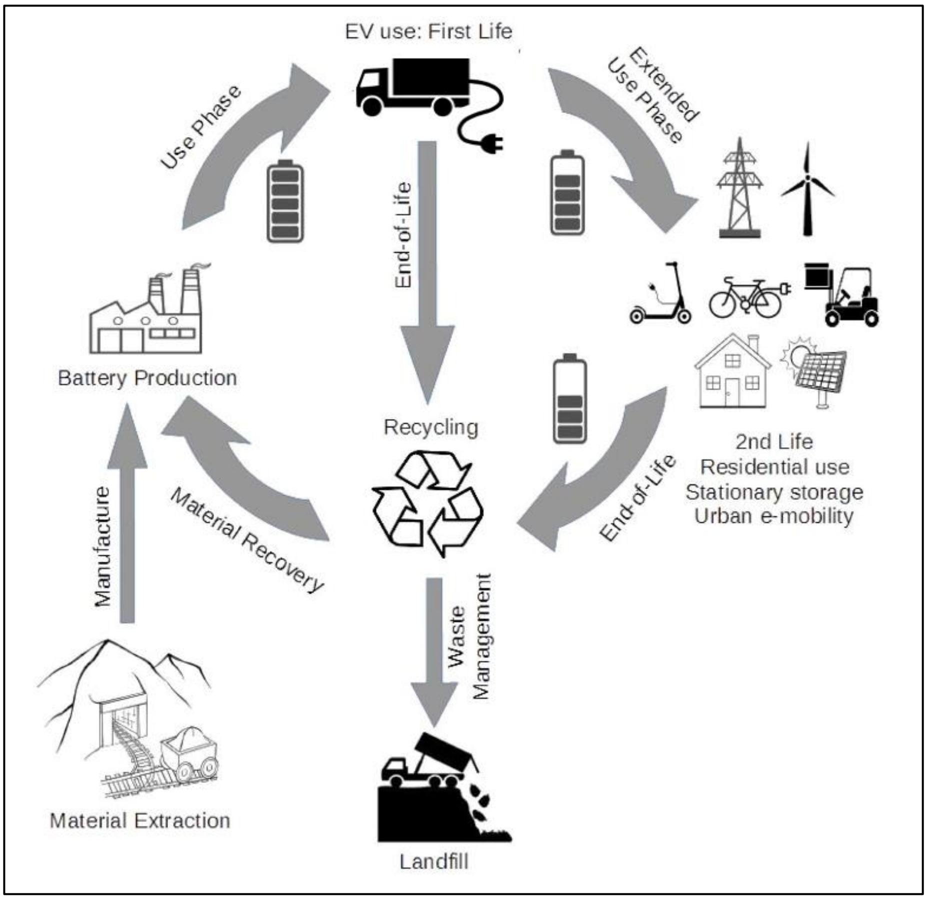

Figure 2: Lifecycle of an e-truck battery (Kotak et al. 2021).

Given the high investment costs needed for battery electric vehicles, options for reducing lifetime costs like SLB applications are crucial. The next section outlines the concept of battery reuse and repurposing, highlighting the anticipated market demand for SLBs and their benefits. It details the assessment and preparation processes for second life use, provides real-world examples, and showcases innovative business models leveraging the value of these batteries.

2 Second Life Batteries: A Comprehensive Overview

Several pilots have demonstrated the substantial opportunity for shippers and fleet owners to deploy EoFL e-truck batteries in diverse second-life applications, due to its significant economic, environmental, and social sustainability benefits.

The market for battery electric trucks is expected to expand to 31% of sales share in 2035 under the stated policy scenario, driven by recent emissions standards in the EU (IEA 2024). The anticipated increase in adoption will significantly boost the demand for electric truck batteries. Global demand for LiB's is projected to rise from about 700 GWh in 2022 to approximately 4.7 TWh by 2030, with mobility applications accounting for around 4,300 GWh (McKinsey & Company 2023). To meet this growing demand sustainably, the industry must transition from a linear approach to adopting circular value chain strategies, such as extending battery lifespan (battery second life) and recycling (providing secondary materials), as illustrated in Figure 3.

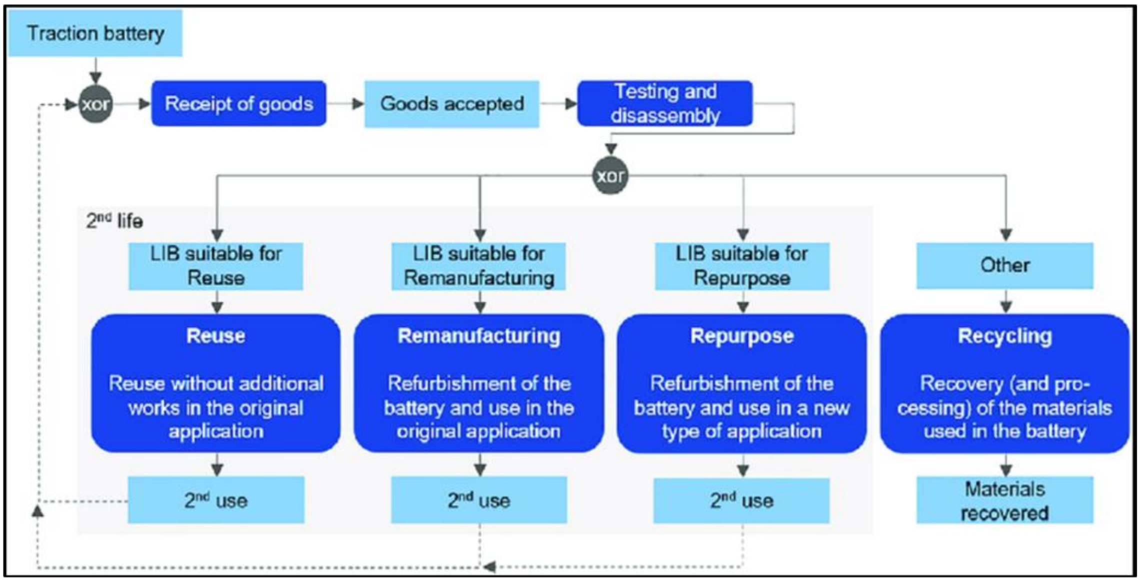

Figure 3: End of Life options for e-truck batteries (Börner et al. 2022).

EU Battery Regulation 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, sets targets for recycling used EV batteries. However, utilizing these batteries for second life applications before recycling has emerged as a viable and advantageous option, as these batteries still retain about 70-80% of their original capacity (Zhu et al. 2021). Employing EoFL e-truck batteries in second life applications can extend their use phase, delaying recycling and preventing unnecessary disposal.

The concept of SLB involves remanufacturing, repurposing, and reusing batteries after their primary use in EVs:

- **Reuse:** Reuse refers to any operation by which products or components that are not waste are used again for the same purpose for which they were conceived (European Commission 2024).

- **Remanufacturing:** Remanufacturing refers to any technical operation on a used battery that includes the disassembly and evaluation of all its battery cells and modules and the use of a certain number of battery cells and modules that are new, used or recovered from waste, or other battery components, to restore the battery capacity to at least 90 % of the original rated capacity, and where the state of health (SoH) of all individual battery cells does not differ more than 3 % between cells, and results in the battery being used for the same purpose or application as the one for which the battery was originally designed (European Commission 2023a).
- **Repurposing:** Repurposing involves any operation that results in a battery, that is not a waste battery, or parts thereof being used for a purpose or application other than that for which the battery was originally designed (European Commission 2023a).

Market Overview

Global battery demand is projected to reach 4.7 TWh by 2030, with the mobility sector constituting the highest demand, as illustrated in the accompanying . This surge in demand presents a significant opportunity for reusing or repurposing EoFL e-truck batteries for mobility applications.

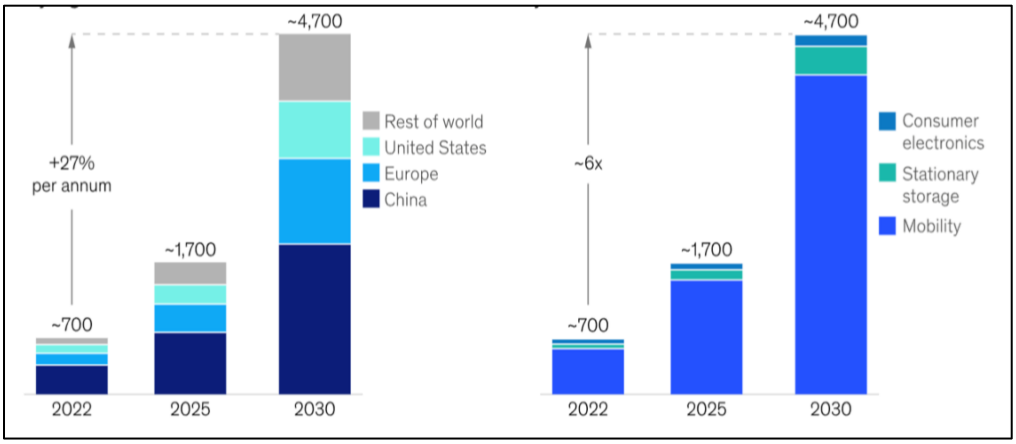

Figure 4: Global LiB demand in GWh (McKinsey & Company 2023).

Furthermore, the figure indicates that stationary storage is the second-largest sector for LiB demand. According to the International Renewable Energy Agency (IRENA), the total installed capacity of stationary batteries is expected to reach 421 GWh by 2030 (Gyalai-Korpos et al. 2020). With the rapid increase in EV adoption and the anticipated accelerated growth over the next decade, it is projected that by 2030, the supply of SLB for stationary applications could exceed 200 GWh annually, representing a market valued at $30 billion globally (McKinsey & Company 2019). The potential for repurposed e-truck batteries for second-life applications is substantial, especially since the primary markets for EVs such as China, the United States, and the EU align with regions where stationary storage demand is projected to be highest.

Benefits of a Second Life Battery Ecosystem

Once batteries reach the EoFL in e-truck applications, they can still contain up to 80% of their original capacity. Utilizing these batteries in second life applications offers significant benefits.

Reduced Total Cost of Ownership: The high initial purchase cost of e-trucks, primarily due to the expensive LiBs (around 40% of the total cost), creates a substantial price gap between e-trucks and internal combustion trucks (König et al. 2021). Reusing EoFL e-truck batteries in second life applications can reduce battery costs and, consequently, e-truck prices (Chirumalla et al. 2023). Studies suggest that SLBs could reduce costs for end-users by approximately 42%

compared to new batteries (elementenergy 2019). Additionally, repurposing batteries can generate additional revenue and lower the overall cost of operating EVs when used to support charging activities, thus reducing the TCO of e-trucks (WRI 2023).

Reduced Greenhouse Gas Emissions (GHG): Batteries are a significant component of e-trucks, accounting for 40%-60% of the GHG emissions from e-truck manufacturing (McKinsey & Company 2023). Extending the life of EoFL e-truck batteries through second life concepts can mitigate their environmental impact by avoiding the need for new battery manufacturing and the associated raw material extraction (Philippot et al. 2022). This extension in battery lifespan could range from 7 to 10 years, reducing the need for new batteries. Researchers estimate that up to 2031, SLB systems could prevent approximately 0.7-1.2 kilotons of battery-related waste, and circumvent 28-90 kilotons of CO2 emissions by recovering renewable energy (European Commission 2023b).

Enhanced Social Sustainability: The extraction and supply of raw materials for e-truck batteries, such as lithium, cobalt, and nickel, are unevenly distributed globally and are associated with mitigable social sustainability risks (Steckelberg et al. 2023). These include child labor, forced labor, unsafe working conditions, violations of indigenous rights and labor laws and several other governance issues (European Commission 2023a). Reusing or repurposing EoFL e-truck batteries can significantly reduce the need for raw material extraction for new battery manufacturing, thereby minimizing the associated social sustainability impacts and supply chain risks. Additionally, the industry and supply chain created around battery repurposing are expected to generate additional jobs and revenues, amounting to approximately $79 million by 2030 (elementenergy 2019).

Preparation and Assessment of End-of-Life EV Batteries for Second-Life Applications

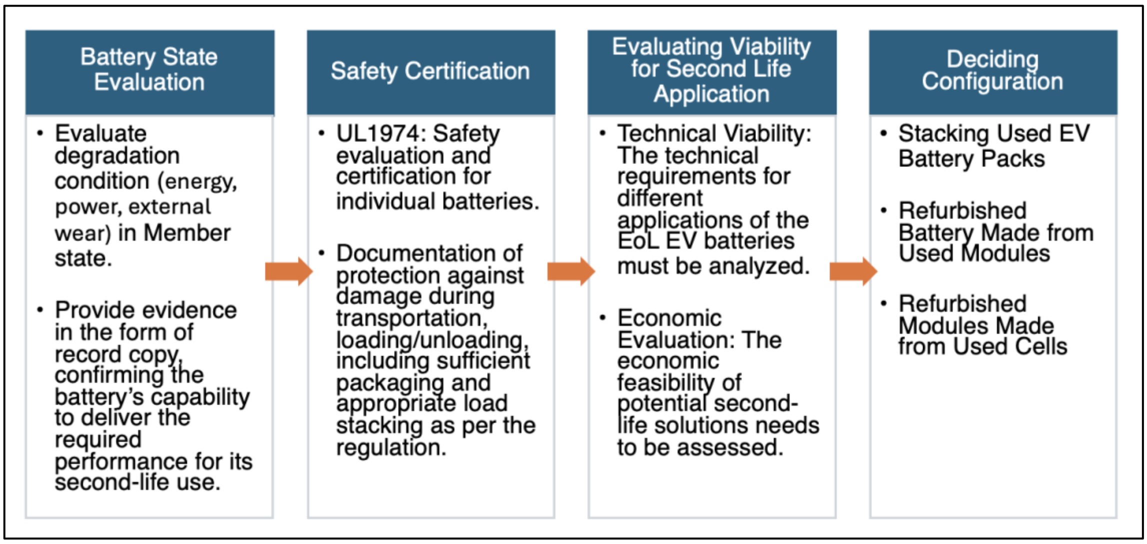

Figure 5: Steps for battery reuse or repurposing (European Commission 2023a; Michelini et al. 2023).

Before EoFL e-truck batteries can be reused or repurposed for second-life applications, they must undergo a thorough assessment and preparation process. In the EU, battery holders must comply with Article 73 of the Battery Regulation 2023/1542 concerning batteries and waste batteries, highlighting the preparatory steps prior to reuse or repurposing. The process includes several critical steps as shown in Figure 5:. Additionally, international standards IEC 63330-1:2024 (published as of 24th June 2024) provides basic requirements and a procedure to evaluate the performance and safety of used batteries and battery systems and provide general requirements for application of repurposed batteries (IEC 2024).

Consideration of different battery configurations when deciding on the appropriate second life application is an important part of the battery assessment process post its EoFL in e-truck application. The different SLB configurations are highlighted below (Montes et al. 2022):

- **Stacking Used EV Battery Packs:** This involves connecting multiple EoFL battery packs with minimal modifications, for applications requiring more energy than a single battery pack can provide.
- **Refurbished Battery Made from Used Modules:** This involves disassembling the battery pack to the module level, inspecting the exterior of the modules, conducting characterization tests, certifying that the modules meet second-life standards, and integrating them into a new battery pack for the intended application.
- **Refurbished Modules Made from Used Cells:** This involves disassembling battery packs to the cell level, and these cells are then repacked into new modules and battery systems. This approach is particularly valuable when pack or module dimensions are not suitable for the intended application.

Typical Applications of Second Life Batteries

The selection of the preferred second-life application for EoFL e-truck batteries is influenced by various factors. Detailed information about the battery's history (such as battery health, residual capacity, internal resistance, number of cycles, depth of cycles, etc.) and battery chemistry is crucial. Additionally, the size of storage systems (number of battery packs needed) as well as safety and reliability requirements are important considerations. The typical uses of EoFL e-truck batteries are outlined below (Michelini et al., 2023):

Stationary Category: The primary category for second-life applications of EoFL EV batteries is in stationary settings, where the battery remains in a fixed location during its operational cycle. Unlike mobile or semi-stationary applications, stationary applications are not subject to strict weight and volume constraints and face a lower risk of mechanical abuse. This can result in relatively less stringent safety requirements. Key stationary applications for EoFL e-truck batteries include:

- **Peak Shaving:** Managing demand quickly for short periods to prevent spikes in consumption.
- **Load Shifting/Demand Shifting:** Shifting electricity consumption from peak to off-peak hours to level out demand and reduce peak loads.
- **Buffer Storage:** Using EV batteries as buffer storage at charging stations which allows self-consumption of renewable energy.
- **Ancillary Services:** Providing supportive services such as frequency regulation to help maintain grid balance by adjusting consumption or production.
- **Wholesale Market Arbitrage:** Utility-scale energy storage for trading electricity on the spot market by selling energy during high demand and buying during off-peak hours.

Semi-Stationary Category: Second-life applications where batteries are not intended to operate while moving but are expected to be relocated frequently fall under the semi-stationary category. For example:

- **Mobile Power Supply:** Power generators or stations used to provide electricity in remote locations and automotive mobile charging stations.

Mobile Category: Mobile applications involve batteries that are expected to move during use. Due to relatively lower range and battery capacity requirements SLBs can be suitable for:

- **Micro Mobility:** Applications such as e-bikes, e-scooters, and e-3 wheelers.
- **Industrial Vehicles:** Applications such as forklifts, automated guided vehicles, and transport trolleys.
- **Commercial Vehicles:** Short-range EVs.

Second Life Battery Pilot Projects

Several pilots, in collaboration with repurposers, have been initiated and announced, focusing on repurposing EoFL e-truck batteries for stationary storage applications. The examples listed below illustrate this:

- **Einride** has repurposed batteries from its fleet of heavy-duty vehicles into second-life battery energy storage systems (SLBESS) installed at the Einride Smartcharger Station in Rosersberg, near Stockholm, Sweden. These batteries, EoFL from trucks used to transport goods in Europe, perform functions such as peak shaving, load shifting, and energy arbitrage (Einride 2024).
- **Volvo Trucks** has collaborated with Connected Energy to repurpose batteries for developing SLBESS, installing high-powered charge points in Enfield and Carlisle, United Kingdom. Project experiences report that the SLBBESS developed, named 'E-STOR', is often a more affordable alternative to costly grid infrastructure upgrades. The E-STOR systems provide sufficient power to support high-capacity charging points: 350kW and five 22kW electric car chargers in Enfield, and a 150kW truck charge point and two 22kW electric car chargers in Carlisle (Connected Energy 2024; Volvo 2024).
- **MAN** is currently exploring the use of SLBs in stationary storage systems in collaboration with the University of Kassel. They are investigating the potential of using EoFL battery packs as buffer storage or in another vehicle, utilizing approximately 120 truck battery packs with an energy content of 18.6 kWh per pack. These packs originated from MAN's first field trial with battery-electric distribution trucks in Austria, which began in 2018 and lasted three years (MAN 2024; Sustainable Bus 2022).
- **Daimler Truck North America** has partnered with Nuvation Energy to pilot a SLBESS using EoFL batteries from Daimler's fleet. These systems are designed to assist in charging, peak shaving, backup storage, and microgrid scenarios (Daimler Truck North America 2024).

Due to the limited adoption of e-trucks (only 0.9% of all new heavy trucks sold), most projects involving the repurposing of batteries at their EoFL currently focus on passenger vehicles.

- An early proof-of-concept example was the EU-funded **ELSA (Energy Local Storage Advanced System) project**, where vehicle original equipment manufacturers (OEMs) Renault and Nissan collaborated to use SLBs from the Nissan Leaf and Renault Kangoo ZE for stationary applications. These batteries provided various storage services at six pilot sites, including peak shaving, smoothing solar photovoltaic power generation, primary frequency services, and reactive power compensation (ELSA 2018).
- Another notable project was the **Johan Cruijff Arena** in Amsterdam, where stationary batteries were integrated into the stadium's energy system to manage high power demand peaks during football matches. About 40% of the batteries in the 3MWp-2.8 MWh battery system were second-hand Nissan Leaf batteries. Combined with a solar photovoltaic array and diesel generators, these batteries provided peak shaving, backup power, frequency services, and surplus solar energy storage (Warmerdam 2020).

Business Models Enabling EoFL Battery Use

Batteries constitute approximately 40% of the total value of e-trucks. Additionally, as previously mentioned, these batteries maintain significant residual value after their initial use in e-truck applications. Recognizing these facts, new business models have emerged to finance these vehicles over their lifetime and address the challenges of high initial purchase costs. We cover a few business models here.

Battery Leasing: An example of battery leasing is the Caledonia bus depot in Glasgow, Scotland, where a single company (Hitachi) provides comprehensive support for the initial deployment of the buses. This support includes telematics, smart charging software, and on-site decarbonization solutions, such as solar energy generation and stationary battery storage. This arrangement offers fleet operators a single point of contact with a technology provider, enabling them to extend the first life of the battery, assess its SoH at EoFL, and repurpose it for second life use within the depot (First Bus & Hitachi, 2021).

OEM Buyback: The vehicle OEMs, which have the most detailed knowledge about the battery materials and manufacture are expected to play a key role in their use in second life. A model pioneered by Nissan and Sumimoto through their Japanese joint venture, 4R, offers to buy the batteries of vehicle users back from them, creating a closed loop circular model. These batteries at the end-of-first life are graded and sorted. Depending on their grade, they are reused in vehicles like forklifts, grid storage and home storage. Since these repurposed batteries last for another 10 to 15 years, the batteries have competitive market value (Nissan Motor Corporation 2021).

3rd Party Purchase: An alternative to the OEM purchasing the battery back from the vehicle user is a business model where a 3rd party collectively performs this task for all OEMs. An example is the company Spiers New Technologies, based in Oklahoma, USA who in the year 2021 worked with EV batteries from General Motors, Ford, Nissan, Volkswagen, Audi, Toyota, Volvo, Porsche. Similar to the OEM buyback business model, the 3rd party purchasing the batteries grades them for use in a second life.

As the market for similar services are evolving, EoFL batteries are expected to have resale value beyond their utility to fleet owners or operators for energy management at depots. Vehicle OEMs are anticipated to play a role in creating these markets. Additionally, the use of third-party software for battery analytics, diagnostics, and SoH estimation is emerging as a key enabler of increased transparency in the battery ecosystem facilitating reuse and repurposing.

The following section presents economic cases of SLBs in stationary storage applications highlighting its impact on road freight electrification making the above business models viable.

3 Impact on Road Freight Electrification

SLBs facilitate road freight electrification by demonstrating a clear economic case to support charging infrastructure, thereby making the business models outlined in chapter 2 viable.

Insufficient charging infrastructure in terms of required energy and power output to support the operation of large fleet, is one of the significant challenges the road freight sector is facing while transitioning to e-HDVs. The emerging second life market for EoFL e-truck batteries offers significant benefits to road freight electrification by addressing these issues to a certain extent. This section presents case studies demonstrating clear economic cases for deploying EoFL e-truck batteries in second life application, leading to a positive impact on road freight electrification.

Electricity Distribution Support at Charging Depots

Distribution support involves using battery energy storage systems (BESS) to provide support during significant increases in peak demand, which can occur due to concentrated loads at e-truck depots or charging hubs. The BESS can enable energy storage (including from renewable sources) allowing for dynamic increase in capacity through the “charge at trough, discharge at peak” method.

When SLBESS instead of new batteries are deployed to provide distribution support for charging infrastructure, a capital cost reduction for the distribution support system is observed. A capital cost reduction of around 25% for an operating duration of about 2hrs and 35% for an operating duration of about 6hrs is observed. The reduction in the capital cost increases with increase in the duration for which the BESS is operated as depicted in the Figure 6: Capital cost reduction (%) of distribution support system for charging, using SLBs (elementenergy 2019)..

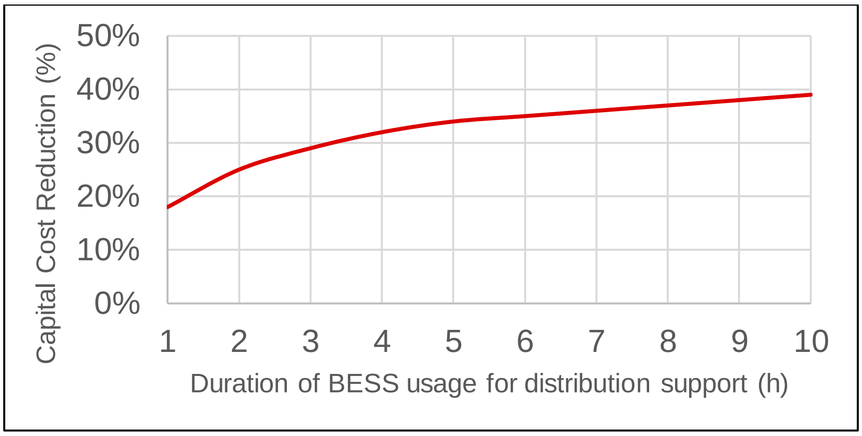

Figure 6: Capital cost reduction (%) of distribution support system for charging, using SLBs (elementenergy 2019).

Replace Peaking Plants with SLBESS

Peaking plants are often inefficient thermal power plants that operate primarily during peak demand periods. Since they supply power only occasionally, their electricity commands a much higher price per kilowatt-hour than base load power. BESS can be used to replace these power plants and address the required demand.

Three levels of deployment were tested, each a combination of power and energy stored.

It was observed that when BESS was used to replace traditional peaking plants a total savings was observed (fuel saving and savings due to avoided investment in peak capacity). However, the net savings started to reduce beyond a certain level of deployment due to the cost of BESS. Interestingly, when SLBESS were used, their lower cost allowed greater levels of deployment that is still economically viable as seen in the Figure 7: Comparison of net savings for various deployment levels of SLBs (elementenergy 2019)..

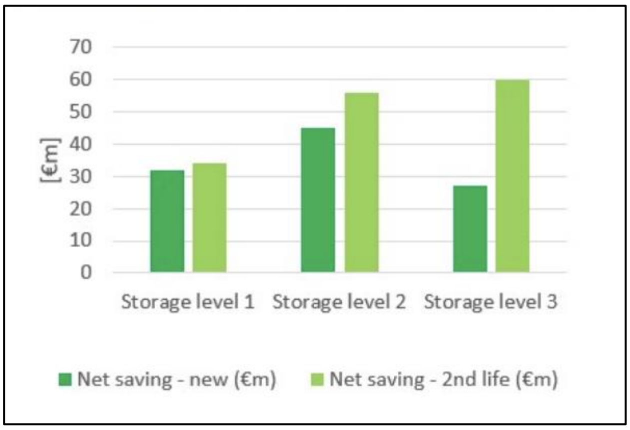

Figure 7: Comparison of net savings for various deployment levels of SLBs (elementenergy 2019).

Benefits for Road Freight Electrification

SLBs demonstrate a clear economic case which can be observed from the above two applications. These economic cases conclude several benefits for actors involved in road freight electrification which are highlighted below:

Vehicle fleets typically recharge overnight at depots. Transitioning to 100% fleet electrification could result in most e-trucks recharging simultaneously, creating a substantial localized electricity demand that might exceed existing network capabilities. Deploying SLBESS for distribution support at charging hubs or depots can reduce or avoid the need for deploying network reinforcements (which is time consuming) to handle such large, concentrated loads. Additionally, deploying SLBBESS to replace peaking power plants supports higher levels of economic grid battery deployment during peak demand periods.

These applications lower the substantial network costs for fleet operators and grid operators respectively, at the same time ensuring adequate energy and power output is delivered, thus facilitating road freight electrification. The reduction in network costs translates to lower costs associated with charging activities, further reducing the TCO of e-trucks.

In addition to the economic benefits from the above-mentioned applications, SLBESS can generate additional revenue by providing ancillary or balancing services to transmission system operators and by engaging in energy price arbitrage, thereby reducing net energy costs.

Furthermore, SLBESS allows the integration of local networks with renewable energy sources and the replacement of traditional peaking plants with renewable sources. This leads to a reduction in GHG emissions from charging activities and makes energy available at a lower cost, further reducing the TCO of e-trucks.

In conclusion, the residual value of EoFL e-truck batteries can be effectively utilized through second-life applications to support road freight electrification. This approach is particularly beneficial for larger batteries, such as those used in trucks or buses, because their residual value has a more significant impact on the TCO comparatively (Lebeau et al. 2019).

However, before deploying EoFL e-truck batteries in second-life applications, it is crucial to thoroughly understand the technical and economic challenges and, regulatory landscape, which are detailed in the next section.

4 Challenges and Regulatory Landscape

The design of current battery packs and systems, declining gap between cost of new battery and SLBs and underdeveloped regulations present significant challenges that must be considered when choosing battery reuse or repurposing as EoFL options e-truck batteries.

The battery second life strategies offer a hopeful path towards improving both the economic feasibility and environmental impact of electric trucks. Nevertheless, there are several technical and economic challenges and regulatory gaps to their successful use in second life applications which are highlighted in this section. The section also presents a few regulatory recommendations to facilitate the reuse and repurposing practices.

Technical Challenges and Regulatory Gaps

There are various technical challenges and regulatory gaps that impact the economic viability of deploying EoFL battery packs in second life applications. These challenges span across various steps in the process of battery reuse or repurposing.

The initial step involves collecting EoFL e-truck batteries. The EU currently lacks specific collection and refurbishment targets and a traceability mechanism for EoFL e-truck batteries, which would ensure these batteries are used to their full potential before recycling and prevent unwarranted disposal. Additionally, the trend towards structurally integrated battery designs complicates the removal process for reuse or repurposing, raises safety concerns, and increases the costs of removal and collection (Johannisson 2023).

Upon collection, the batteries undergo inspection to assess various technical parameters. However, the lack of readily available information on battery design, chemistry, SoH, and usage history necessitates costly tests and limits process optimization (Lih et al. 2012). Furthermore, the absence of uniform SoH estimation methods and EoFL decision-making criteria complicates safe decision-making regarding whether a battery should be recycled or repurposed and for what application.

Battery packs differ significantly in size, chemistry, and format to meet specific applications, resulting from a lack of standardization. This heterogeneity increases the complexity of the disassembly process, making it labor-intensive and potentially raising the overall cost of battery reuse or repurposing (Gu et al. 2023; Mckinsey & Company 2019). Additionally, many modules and cells are not designed for easy disassembly, further complicating repurposing efforts (ICCT 2023).

Following disassembly, the modules and cells need to be sorted and regrouped based on their performance capabilities for specific second-life applications. Challenges in this step include the lack of indicators, algorithms, certification, and standards for sorting and regrouping cells and modules (pack classification, cell grading, pack recombination, and comprehensive inspection and verification procedures) based on performance metrics (Meegoda et al. 2024). This further complicates the process and increases refurbishment costs.

Finally, placing these refurbished batteries in appropriate second-life applications poses its own challenges. The battery management systems used in automotive applications are often unsuitable for second-life applications, necessitating adapted control strategies to stabilize power output and prevent overheating. This includes designing specialized energy, thermal, and safety management systems tailored for second-use applications (Argonne National Laboratory 2020). Additionally, equalization strategies must be developed to address the increased inconsistencies in the electrochemical behavior of individual cells or modules expected during second-life usage. Advanced fault-diagnosis algorithms are also essential to enhance safety by detecting potential issues such as internal short circuits (ICCT 2023).

Economic Challenges

The economic feasibility of battery reuse/repurposing depends on various factors, such as the selling price of new and end-of-life batteries and their lifespan in secondary applications.

The above technical challenges and regulatory gaps increase the complexity and cost of repurposing EoFL battery packs thereby posing an economic feasibility challenge. Meanwhile, advancements in electrification have led to significant cost reductions in new LiBs. Bloomberg New Energy Finance (2022) reported an 80% decrease in the global average price of new LiBs from 2013 to 2021. This substantial cost reduction drives the adoption of electric trucks and renewable energy storage solutions. However, it also challenges the SLB market to find ways to lower the cost of repurposing to justify the performance limitations of SLBs compared to new batteries. Economies of scale and optimized battery reuse processes might help EoFL batteries stay price competitive (ICCT 2023).

Many operators prefer using these batteries to maximize runtime in specific applications, which often results in the battery being either discharged to a very low SoC or charged to a high SoC. This practice negatively impacts the battery's lifespan in second-life applications, reducing its economic feasibility compared to new batteries (Mathews et al. 2020). To address this, various companies such as Volytica, Twaice, and Voltaiq, offer battery analytics software that monitors battery technical parameters over its operational lifetime. This software enables operators to optimize battery performance, thereby paving way for higher battery life. The analysis of collected data allows for rapid diagnostics, corrective maintenance, predictive maintenance, and transparent insight into the battery's operational history and state of health at any given moment.

Regulatory Landscape

There are a few regulatory measures set in the EU that facilitate cost effective EoFL e-truck battery reuse and repurposing in the near future. Additionally, this study provides several recommendations for governments to consider that might address the above challenges and accelerate the reuse and repurposing practices for EoFL e-truck batteries.

Significance of EU Battery Passport

Battery passports have emerged as a means to increase standardized information and transparency of information sharing across the battery value chain. In effect, each battery should have labels and QR codes detailing:

- required information on their capacity, material use and origins, performance, durability, negative events, such as accidents;
- required periodically recorded information on the operating environmental conditions, including temperature, and on the SoC; and
- required guidelines for collection at EoFL and carbon footprint.

These parameters help a repurposer assess the remaining useful life, and other relevant battery parameters necessary to estimate the residual value of EoFL e-truck batteries. This, therefore, helps facilitate the reuse and repurposing of these batteries in the right secondary application. In the EU, the Battery Regulation 2023/1542 mandates battery passports for EVs from 2027 onwards. For batteries which are subject to processes to prepare them for reuse, repurpose or remanufacturing, a new passport will need to be linked to the original battery (European Commission 2023a).

Extended Producer Responsibility for Batteries

Batteries are also subject to the principle of extended producer responsibility (EPR) in several geographies, including the EU, India, South Korea, Brazil and several states in the US (Rufino Júnior et al. 2024; CPCB 2022) that would eliminate unwarranted disposal of these EoFL batteries. Based on this principle, the producers of batteries and the producers of products that include a battery are responsible for the waste management of batteries that enter the market as a result of their activities, extending to the financing of collection and recycling. Economic operators placing on the market a battery that results from preparation for re-use, repurposing or remanufacturing operations are also subjected to the EPR principles.

Regulatory Recommendations

Incentivizing Domestic Capacity for Battery Reuse and Repurposing: Governments should enhance domestic capacity for reuse and repurposing by developing incentive programs, creating supportive tax and trade provisions, and fostering public-private partnerships to accelerate the second life markets like The Battery Materials Processing Grants in the USA. This grant makes more than $3 billion available to state and local governments, for-profit and non-profit entities, and national laboratories to support domestic capacity for the reuse and recycling of batteries through project demonstration and other uses (U.S Department of Energy 2024)**.**

Create a Framework to Ensure that EoFL Batteries are Handled Responsibly and Used to Maximum Potential: Several countries including the EU have mandated EPR, that make manufacturers responsible for the collection of EoFL batteries to prevent unwarranted disposal. However, to implement these regulations successfully, collection and refurbishment targets and traceability mechanism are crucial. For instance, in China, the government established a traceability management platform in 2018 to track electric vehicle batteries throughout their lifetime, whereas India's regulation on Battery Waste Management 2022 states collection and refurbishment targets for EoFL EV batteries (Battery Waste Management Rules, 2022; ICCT 2021).

Establishing Performance and Durability Standards for New Batteries: Governments should mandate battery durability requirements incentivizing the production of long-lasting batteries to enhance their lifespan and safety throughout their usage, making them more suitable for second life applications. Example of such a standard is the Advanced Clean Cars II rule in California that states by model year 2031, individual vehicle battery packs are warranted to maintain 75% of their energy for eight years or 100,000 miles (CARB 2022). This will build confidence amongst the users to further invest in reused or repurposed EoFL batteries.

Standardization of Battery Health Metrics: Governments should further standardize SoH metrics to maintain a uniformity in test result for SoH of EoFL e-truck batteries thereby helps in informing the best decisions for second-life applications.

5 Conclusions

The adoption of heavy-duty e-trucks in the EU has increased threefold, from nearly 0.3% in 2022 to 0.9% of all new heavy-duty trucks sold in 2023, with projections reaching 31% by 2035. These trucks primarily utilize LFP and NMC battery chemistries due to their advantages in energy density, lifecycle, charge/discharge rate, and thermal resistance compared to other chemistries. A significant portion of these batteries are expected to retain 70-80% of their original capacity at the EoFL in e-truck applications.

To maximize the use of these EoFL e-truck batteries, the SLB concept—encompassing reuse and repurposing—has emerged as a viable option. LFP batteries, in particular, are well-suited for second life due to their longer battery life compared to NMC batteries. Shippers and fleet owners are expected to achieve considerable economic, environmental, and social sustainability benefits by deploying EoFL e-truck batteries in second life applications.

The substantial expected demand for LiBs in mobility and stationary energy storage presents a significant opportunity for reusing or repurposing EoFL e-truck batteries. Deploying EoFL batteries in stationary storage applications to provide charging support has a positive impact on road freight electrification. Actors benefit from deploying SLBs, in terms of reduced cost of charging e-trucks thereby reducing the TCO of e-trucks as well as reduced costs associated with charging infrastructure upgrades. This would allow a large fleet of e-trucks to charge simultaneously at depots, minimizing the large time delays associated with network reinforcements. It also enables the use of renewable energy, thereby lowering GHG emissions from charging activities.

However, technical and economic challenges remain while choosing reuse or repurposing as an EoFL option for e-truck batteries. These challenges include battery technology heterogeneity, lack of means to accurately estimate remaining useful battery life, complex disassembly processes, and the need for robust BMS. These issues need to be addressed to make SLBs economically viable and establish the SLB markets. Additionally, the declining cost of new battery packs for e-trucks makes it essential for reuse and repurposing costs to be price-competitive. The EU's requirement for a digital battery passport from 2027, with other regions expected to follow with similar regulations, is anticipated to make repurposing more cost-effective by addressing current technical challenges related to data sharing. Moreover, specific regulatory measures such as standards for battery durability and performance, estimating battery health metrics, collection and refurbishment targets, and financial support from the government would greatly enhance the SLB markets, making EoFL batteries economically viable for second-life applications.

As the relevant stakeholders address these challenges, logistic actors can also play a crucial role in enabling reuse and repurposing of EoFL e-truck batteries. This study provides a few recommendations that shippers and fleet owners can incorporate to obtain the benefits through SLB concepts:

Recommendations for Logistics Sector

Mandatory Battery Passport in Procurement Criteria: When procuring e-trucks, it is essential to ensure that the e-truck batteries come with a digital battery passport, making this a mandatory procurement requirement. Although the EU battery regulations mandate digital battery passports only from 2027, making this a mandatory requirement now will help shippers and fleet owners ease the repurposing process later, making it safe and cost-effective to deploy these batteries for the right second life application.

Collaboration with Battery Reuse or Repurposing Companies and Knowledge Partners: Shippers and fleet owners should actively collaborate with reputable battery reuse or repurposing companies to gain a thorough understanding of their specific needs and operational requirements. This collaboration is essential for several reasons:

- **Customized Solutions**: By working closely with battery repurposers, shippers and fleet owners can ensure that the repurposing solutions are tailored to their operational demands and performance expectations, maximizing economic and environmental benefits.
- **Optimized Battery Life**: Collaboration allows for better tracking and management of battery health, ensuring that repurposed batteries are used efficiently and effectively, thereby extending their lifecycle.
- **Regulatory Compliance**: Collaborating with experienced repurposers ensures that all regulatory requirements are met, minimizing legal risks and ensuring compliance with environmental and safety standards.

Partnerships with knowledge partners can provide valuable insights into technology, market dynamics, and best practices, ensuring informed decision-making. These collaborations are instrumental in successfully running pilot projects for deploying EoFL e-truck batteries in secondary applications.

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