BATMAN
-Battery Life Cycle Management in Charging Networks

Public report

Project within FFI Circularity
Author Anna Costalonga, Sara Fallahi, Christoph Futter, Farnaz Goudarzi, Mats Johansson, Patricia van Loon, Louise Söderlind

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Fordonsstrategisk Forskning och Innovation

Content

FFI in short

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

For more information: www.ffisweden.se

1. Summary

This project explored the feasibility of reusing decommissioned Lithium Iron Phosphate (LFP) batteries from automotive applications, specifically for integration into a Battery Energy Storage System (BESS) and DC charging product tailored for electric trucks. This goal was driven by the increasing electrification of the logistics sector, which aims to reduce high CO2 emissions, but faces significant challenges related to infrastructure capacity and energy availability along transport routes.

Electric vehicle (EV) batteries are typically retired when their State of Health (SoH) drops to approximately 80%, a practice favouring safety, performance, and optimization. The project investigated how the remaining capacity could be utilized in a second-life application. The core focus was to analyse the environmental and economic impacts of these second-life batteries, alongside the operational challenges (logistics, production, and recommissioning).

The collaboration yielded significant findings:

- Technical Feasibility: The approach proved feasible. Taking batteries from an electric truck and refitting them into a BESS demonstrated similar performance compared to new battery cells.
- Economic Viability: A simulation model confirmed that the reuse of batteries offers an economical advantage, showing a payback period shorter than the remaining technical lifespan of the batteries in the second-life application.

However, the investigation also identified major hurdles, including risks associated with refitting batteries, high production costs, specific storage requirements, and, most significantly, uncertainties surrounding the legal responsibility for the battery cells once repurposed.

The project commenced in 2022 and concluded in December 2025. It was coordinated by Einride and included RISE, Chalmers, and Zpark Energy System as key participants.

The project encompassed two central focuses: the development of the BESS and DC charger, and the exploration of second-life battery utilization.

Zpark Energy System primarily focused on sub-goals 1 and 2 (Installation and Operation) and contributed to sub-goal 3 (Integration to logistics system). This work involved developing a BESS using both new battery cells and a comparison module built with second-life batteries. Zpark undertook the refitting and testing of the decommissioned modules, comparing their performance against new cells and identifying production challenges, risks, and costs. Einride supplied the decommissioned truck batteries and all relevant historical operational data, contributing directly to Work Package 2 (WP2).

Einride, Chalmers and RISE collaborated on Work Package 4 (WP4), developing an optimization model for battery use at a truck charging station. This model determines the optimal time for the battery to act as a charging buffer, participate in grid ancillary services, or perform time-shifting for arbitrage, ensuring a financially and operationally feasible solution.

The project successfully proved the technical and financial feasibility of using second-life LFP batteries for truck charging stations. However, this feasibility remains largely theoretical, with several missing steps preventing practical, large-scale reality:

- Supply Chain and Production: A full-scale production system encompassing the entire supply chain for battery delivery and processing was not considered. This leaves several unknowns regarding how such a process would be managed effectively.
- Chain of Trust and Regulation: Establishing the required chain of trust between the original battery manufacturer and the second-life application producer is currently unclear, non-transparent, and difficult to establish.
- Regulatory Gaps: Current regulations are missing and need to be implemented to secure and facilitate the processes required for large-scale, safe, and efficient battery reuse.

2. Sammanfattning på svenska

Transportsektorn står för nästan en tredjedel av Sveriges klimatutsläpp, där tunga fordon är en betydande del. Projektet BATMAN (Battery Life Cycle Management in Charging Networks) inleddes för att undersöka potentialen i att återanvända uttjänta litiumjärnfosfatbatterier (**LFP**) från tunga ellastbilar. När batterier i elfordon når cirka 80% av sin ursprungliga kapacitet (State of Health, SoH) anses de ofta vara uttjänta för fordonstillämpningar. Projektets huvudsyfte var att utforska om dessa batterier kan få ett ”andra liv” som stationära energilager (BESS) kopplade till laddinfrastruktur.

Projektet har genomförts av Einride, RISE, Chalmers och Zpark Energy System mellan 2022 och 2025. Arbetet skedde i flera faser:

- Proof of Concept (PoC): Ett första system byggdes i en container med 32 kWh lagringskapacitet för att bygga kunskap kring termiskt beteende och säkerhet.
- Fullskalig installation: Under 2024 utvecklades ett system med 450 kWh kapacitet som integrerades med en DC-snabbladdare, vilket möjliggjorde samtidig laddning av två fordon.
- Tester av begagnade batterier: Projektet utvärderade tre nivåer av återanvändning: hela batteripack, moduler eller enskilda celler. Man valde att fokusera på

modulnivå. Testerna visade att de använda cellerna presterade likvärdigt med nya LFP-celler vad gäller temperatur och prestanda.

En central del av projektet var att utveckla en simuleringsmodell för att utvärdera lönsamheten. Resultaten visar att:

- Ekonomisk fördel: Återanvändning av batterier är ekonomiskt fördelaktigt, med en återbetalningstid som understiger batteriernas kvarvarande tekniska livslängd.
- Intäktsströmmar: Systemet kan generera värde genom arbitrage (utnyttja elprisvariationer), kapning av effekttoppar och deltagande i nätvänliga stödtjänster som frekvensreglering.
- Cirkularitet: LFP-celler är särskilt intressanta för återanvändning då deras materialvärde vid återvinning är relativt lågt (ca 9$/kWh jämfört med 25$ för NMC-celler), vilket gör det miljömässigt och ekonomiskt motiverat att förlänga deras brukstid.

Trots de positiva resultaten betonar rapporten flera betydande hinder för storskalig implementering:

1. Regulatoriska gap: Det råder stor osäkerhet kring juridiskt ansvar och certifiering när batterier byter användningsområde. Vem bär ansvaret om en begagnad cell fallerar?
2. Produktionskostnader: Att montera isär och rekonditionera batterier kräver specialverktyg och strikta säkerhetsprotokoll, vilket driver upp kostnaderna.
3. Tekniska osäkerheter: Begagnade batterier har ofta olika laddningsstatus (SoC), vilket kan kräva balansering som tar flera veckor. Dessutom saknas ofta transparens i dataöverföringen mellan originaltillverkare och tredjepartsutvecklare.

Projektet bevisar att ett andra liv för batterier är tekniskt möjligt och ekonomiskt lovande. För att gå från teori till praktik krävs dock nya affärsmodeller, tydligare reglering och tekniska lösningar som ”batteripass” för att säkerställa spårbarhet och förtroende i hela värdekedjan.

3. Background

The transport sector accounts for close to a third of climate emissions in Sweden today and emissions from heavy transport (vehicles above 3.5 tonnes) account for about a third of the climate emissions of road traffic. In total, this means that trucks and buses account for about 6.5 percent of Swedish climate emissions[1]. Powerful measures are needed to reduce emissions, and electrification is an important part of this work. Fortunately, the electrification of the transport industry has accelerated in the last couple of years. A large reason for this development is the rapid development of the batteries. However, the batteries are and will be a significant part of the cost of a BEV and from a sustainability and economic perspective it is important that the batteries are utilized in a smart way in order to optimize their lifetime. But even if the batteries are well managed to extend their lifetime, there will come a time when they are too degraded to be used in vehicles.

Once the batteries are too degraded to be used in vehicles there is a possibility to reuse the batteries from electric vehicles in other applications and create a second life for the batteries, before they eventually are recycled. Given that the numbers of batteries will increase exponentially in the coming years, the supply market for this will be huge. Forecasts point to aggregated capacities of up to 200 GWh for second-life batteries worth over $30 billion by 2030[2]. Also, from a sustainability perspective it is, given the limited resources of the raw materials used, important that the batteries are used as long as possible before they are recycled. The ambient conditions in stationary applications can be much better controlled to maximize the residual lifetime of the cells.

The applications for decommissioned batteries from BEVs are often believed to be stationary and include: microgrids, smart grids, backups for renewable electricity production and frequency control[3]. However, there are still many uncertainties related to the second life of batteries from electric vehicles, both related to business models and to the application and its systemic effects. In the domain of heavy-duty vehicles (trucks/buses), second application usage of batteries that are decommissioned from the vehicles is especially important since LFP-type cells (Lithium Iron Phosphate) are often the chemistry of choice. While their properties are well suited for the vehicle segment, and their adoption helps reducing demand on NMC (Nickel Manganese Cobalt)/NCA (Lithium nickel cobalt aluminium oxide) cells needed in the passenger vehicle sector, they are not particularly attractive for recycling: The material value as of today is only about 9$/kWh, as compared to 25$ in NMC-type cells[4]. However, at the battery end of life, the battery materials must re-enter the industrial value chain to fulfil the promise of a circular economy. Although, this doesn't mean that all materials need to remain in the battery domain. Especially in the case of LFP cells, this is an interesting problem since they consist

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[1] Fossilfritt Sverige, Färdplan för fossilfri konkurrenskraft: Fordonsindustrin – tunga fordon, https://fossilfrittsverige.se/wp-content/uploads/2020/09/Fardplan_Tunga-fordon.pdf (2020).
[2] Shahjalal, Mohammad, et al. ”A review on second-life of Li-ion batteries: Prospects, challenges, and issues.” Energy (2021).
[3] Shahjalal, Mohammad, et al. ”A review on second-life of Li-ion batteries: Prospects, challenges, and issues.” Energy (2021).
[4] Holland, A. Jiao, Na: “End-Of-Life Electric Vehicle Batteries: Recycling or Second-Life?” IDTechEx report (2020).

of cheap and abundant materials - here, the energetic effort for separation and purification must be carefully weighed against the environmental and economic benefits.

Energy storage systems and their role in charging infrastructure is an emerging field and the possibility to use second life batteries in this application needs to be further explored. However, real-world data on the load profiles of a charging station backed by second-life batteries is scarce/unavailable. Apart from the technical possibilities, batteries connected to vehicle charging infrastructure will potentially spawn second and third order effects that will impact the entire transportation system beyond the obvious short term energy storage solution. Compared to passenger vehicles, trucks require high charging power that can easily exceed local grid capacity. Reliable storage capacity that is added to the grid has many overall benefits, including levelling effects and elimination of peak capacity requirements, which are considered in the proposed project. A key unique feature of this project is that the batteries will remain within the same "ecosystem" since they are taken from the trucks that serve the same logistics operation as the proposed chargers. This practice will help to mitigate the issue of having batteries with severe variations in their state-of-health (SOH), which often impedes the usage of second-life batteries. This is possible because the trucks are managed through a fleet operating system and the battery health status is always accurately known.

4. Purpose, research questions and method

The purpose of this project was to explore and demonstrate the potential benefits and challenges with using decommissioned LFP vehicle batteries as an energy storage system connected to a charger for heavy duty electric trucks. The project aimed at exploring the following areas:

- *Systemic economic and environmental effects* - From a life cycle perspective, when should the battery be taken out of its first life? Under which circumstances should it be reused and under which circumstances should it be recycled?
- *Logistical benefits and challenges* - How could an energy storage system be used to optimise the overall planning of the operations of a fleet of heavy-duty electric vehicles, i.e., when is it optimal to charge and with how much power? Will it be possible to leverage the availability of extra energy storage to gain operational advantages?
- *Financial benefits and challenges* - Will it be possible to use the battery storage to lower the energy cost by reducing the use of the grid when the energy price is high? Also, while not used for charging, capacity could potentially be used for grid support services.
- *Technological challenges* - Which development is necessary in order to use decommissioned LFP batteries as energy storage connected to a charging station?

Would it be possible to use an energy storage system both as a "curve-flattener" and "booster"? What is the appropriate energy capacity for the desired application?

A mixed integer linear programming cost minimization was defined to optimize the use of the decommissioned LFP batteries acting as energy and power buffer for charging the electric trucks and providing ancillary services in the form of frequency containment reserve for disturbances (FCR-D). This was then combined with a cost-benefit model to assess when it will be economically viable to install decommissioned truck batteries at a truck charging station. The model assessed if a new, decommissioned, or no battery should be connected to the truck-charging station by comparing the costs and benefits of the three distinct scenarios. The break-even point was assessed to determine how long the battery should be in operations at the truck charging station to have higher financial benefits than costs.

5. Objective

The goals of the project were to install, operate, integrate and analyse a solution for second life use of batteries in a heavy truck transportation system:

Goal 1: Installation - Install and operate at least one DC charger in connection to a stationary battery storage consisting of used electric vehicle batteries. This includes:

- Check feasibility of technical performance using second life LFP batteries from heavy duty electric trucks in the use case of DC charging.
- Investigate in which form the second life batteries bring best performance vs cost ratio, whole battery assemblies, disassembled to battery modules or disassembled to individual cells.

Variables to analyse related to this goal is:

- Cost for different methods to transfer batteries from truck to stationary application

Goal 2: Operation - Exploration of use cases for the 2ndlife stationary battery systems. This goal include analysis around:

- Business potential of using second life batteries in a charging infrastructure to boost power from the grid to DC charger(s) compared to other use of the battery capacity, e.g., grid services. This could potentially reduce the need for a larger grid connection and speed up the process of building a high-power charging network.
- The potential of using the added storage capacity to add more fluctuating green energy would further accelerate the transition to a sustainable transport system.

- Exploration of grid ancillary services - Which features are suitable for a second life battery system and what other benefits can be achieved with battery energy storage system to help improve the electric infrastructure?

Variables to analyse related to this goal are:

- How much does different ancillary services cost in terms of battery degradation?
- What revenue streams can be expected from using the battery for ancillary services?
- Potential reduction of grid installation costs and time
- How much can lead times for grid connection be reduced due to lower power demand?
- How much can the cost per kWh be reduced with peak shaving?

Goal 3: Integration - interaction between logistics platform for vehicle operation/delivery of goods and charging system with stationary battery. This includes analysis of:

- What are the requirements that the vehicle operation has on the charging infrastructure?
- How predictable are the charging schedules?
- How far in advance is it possible to know when a charging event will take place? - How far in advance should a charging event be scheduled?
- How sensitive are vehicle operations to variations in charging power/charging time?
- In which scenario is it feasible/not feasible to use a stationary battery storage to boost DC charging?

Goal 4: Analysis - Life cycle analysis by looking at system effects focused on business and environmental aspects. This includes:

- Assessing the economics of batteries with a system perspective in mind
- Analysing the yield of having the battery in the stationary application and in the different scenarios
- Study life cycle cost and environmental impact of batteries, both with and without a 2ndlife use case.
- Analyse the impact of recycling/disposal at various points in time.

Variables to analyse related to this goal are:

- What is the ideal cut-off SOH when the battery is transferred from first to second life
- Quantification of the monetary value of one unit of energy cycled through the battery in logistics operations. It is assumed that this will vary over the lifetime of the battery (i.e. the yield is higher from 100%-90% SOH than between 80% to 70% SOH, because of e.g. reduced power capability etc.)

- At what point of SOH are the batteries not feasible to use any more. Battery ageing/degradation effects beyond the “usual” EOL-state of health are hard to predict and differ widely between different Li-Ion cell types

6. Results and deliverables

The project successfully demonstrated the feasibility of using decommissioned LFP batteries as energy storage for heavy-duty EV charging. It achieved its main purpose by generating valuable insights into battery reuse, including modelling and theoretical analyses of cost structures, financial potential, and impacts. The work also fully accomplished the life cycle and system-level analysis, resulting in a complete simulation model that evaluates economic consequences of second-life battery use.

The project aligned well with FFI’s goals by demonstrating how second-life LFP batteries can support a fossil-free and efficient road transport system. By showing that reused batteries can contribute to lower emissions, compared to using a new battery, and reduced grid demands, the project supports broader societal acceptance of sustainable charging solutions. Collaboration between industry and research partners strengthened innovation and knowledge in battery repurposing, charging infrastructure, and system modelling. The project also highlighted needs related to regulations and future business models, contributing to FFI’s aim of developing competencies, frameworks, and infrastructure for sustainable transport. The project was fully aligned with the FFI Circularity sub-program, as its core focus, extending battery life through reuse, directly supports reduced climate and environmental impact across the vehicle and battery value chain.

During the project, we worked in stages to develop a battery storage system and its integration with a DC fast charger. The process began with a proof of concept (PoC) and then advanced into a development phase aimed at transforming the PoC into a functional Product.

The initial phase focused solely on the battery storage solution without an integrated DC charger. The PoC was built using used LFP 40Ah cells, which had not previously been used in automotive applications. Installed in an 8-foot outdoor container, the system operated on a 16A grid connection and provided 32 kWh of energy storage with 32 kW peak power (60 minutes). This phase was essential for building knowledge around battery management, thermal behaviour, safety routines, and operational procedures.

The subsequent development phase expanded the system by integrating a third-party DC charger from Alpitronic and a payment terminal from Codab. This work resulted in a full system delivery in Q1 2024. The upgraded installation featured a 125A grid connection, 85 kW connection power, and a significantly larger storage capacity of 450 kWh. The system offered 600 kW peak power (10 minutes), 450 kW (45 minutes), and 250 kW continuous, and enabled simultaneous charging of two vehicles. For this product, new LFP 280Ah cells were used. In the final part of the project, the focus shifted to the development of an in-house DC charger. Delivery of the complete integrated product is planned for Q1 2026.

The second focus of the project was to investigate the possibility of reusing Einride's decommissioned truck batteries as stationary energy storage. This work was carried out after completing the first energy-storage prototype and before transitioning into the development phase. The batteries were delivered in the same configuration as used in the trucks, including the original modules and battery control electronics (BRC). Receiving the packs in this form provided valuable insight into what a practical refitting process would require. Based on this, we evaluated three potential levels of reuse: whole battery assembly, battery module, or individual battery cells.

Below is a summary of the advantages and disadvantages of each approach:

	Pro's	Con's
Whole battery assembly	• Does not require any disassembly, lower cost and no risk for the production personnel • Cheaper adaptation: only requires HW to connect the assembly to the rest of the energy storage	• Packaging is not ideal – Might take more space than necessary • Unknown state of batteries: data monitoring is limited by the current electronics • Storage issues
Battery modules	• Easy to be refitted in another packaging • Easier to balance in case of different SoC • Easier access to data/monitoring due to custom electronics	• Need for disassembly: Risk for production personnel • Higher adaptation cost: Purchasing and design of HW to refit
Individual cells	• Even higher degrees of freedom for battery module customization • Better handling of cell status	• Need to disassembly: Risk for production personnel but also need of specific tooling • Battery modules are now assembled in a way that is not feasible to disassemble (poles are welded) • Even higher production costs

After all these considerations, we opted for the second approach and disassemble the batteries at battery module level. Three of these modules were then refitted in a similar packaging for battery module. After a series of charging and discharging we noticed that the battery cells showed similar performances and temperature ranges as the other LFP cells we used. The test concluded that the used cells are theoretically a good alternative to newly produced batteries, but they come with uncertainties on their remaining life span and some extra costs.

This process showed some technical challenges:

- Refitting costs of electronics are high: These costs are both production (work force) costs and material costs. The safety risk that comes with disassembling batteries require protocols and way of working that are in line with requirements for the work safety. This might mean two people working at the same time and therefore higher costs. The costs are to some extent dependent on the volume processed.
- Refitting might also come with need for extra tools for either remove the welding, if refitting at cell level, or for heavy lifting.
- The state of charge of used batteries is not like new cell and therefore the refitted modules could contain cells with different state of charge. This requires balancing which can take up to weeks in worst case.

The decision of not continuing with the decommissioned battery for the full product was then discarded as it was not possible to do a re-certification process without manufacturer responsibilities on the cells.

The cost-benefit model analysed the full life cycle costs of repurposing and installing the BESS (from dismantling to final recycling). The BESS generates benefits through varying electricity prices (arbitrage), reducing peak power charges, and providing ancillary services (frequency regulation). The data showed economic feasibility for this type of solution. However, this feasibility is highly sensitive to external factors, including frequency regulation prices, spot market electricity prices, and the specific load profile of the charging station.

While the technical and financial model proves viability, the project highlights that the solution is currently hindered by non-technical factors. A full-scale supply chain for battery decommissioning and refitting was not considered, leaving many unknowns about practical implementation. Establishing a clear, transparent, and legally sound “chain of trust” from the original manufacturer to the second-life producer remains a significant hurdle. New regulations must be implemented to facilitate a secure, scalable, and standardized process for the circular flow of batteries into second applications.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	
Be passed on to other advanced technological development projects		
Be passed on to product development projects		
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

The project results are disseminated through the following activities:

- Poster presentation and pitch, Swedish Electromobility Center Road to the Future conference, 27 August 2025 – Gothenburg.
- Webinar Swedish Electromobility Center Theme (4) Environment and Society, "BATMAN: Battery Lifecycle Management in Charging Networks" 17 November 2025, online.
- Euroma: "Decommissioned electric truck batteries as energy storage systems for truck-charging stations – a feasibility study. Van Loon, P., Johansson, M., Goudarzi, F., Futter, C., Fallahi, S. 13-18 June 2025, Milano, Italy.

7.2 Publications

- Euroma: "Decommissioned electric truck batteries as energy storage systems for truck-charging stations – a feasibility study. Van Loon, P., Johansson, M., Goudarzi, F., Futter, C., Fallahi, S. 13-18 June 2025, Milano, Italy. See Attachment.

8. Conclusions and future research

The project confirmed the theoretical feasibility of reusing decommissioned LFP batteries for EV charging applications, as well as for other stationary energy storage use cases. From a technical and system-level perspective, second-life batteries can deliver meaningful performance and benefits. However, the project also highlighted a significant gap between theoretical feasibility and practical, economically viable implementation for companies and investors. Safe, standardized, and cost-efficient production and refitting methods are not yet sufficiently defined, and the lack of clear regulations, certification pathways, and responsibility frameworks remains a major barrier. Optimizing battery life-cycle use requires stronger connections between actors supplying second-life batteries and those developing suitable applications.

Looking ahead, future research faces substantial uncertainty due to evolving regulatory landscapes and emerging requirements related to battery identity and traceability, such as battery passports. At the same time, these developments create opportunities for new actors, business models, and value-chain roles focused on battery reuse, lifecycle optimization, and circular energy systems.

9. Participating parties and contact persons

Einride AB
Louise Söderlind
Public Funding and Policy Manager
Louise.soderlind@einride.tech

Chalmers University of Technology
Patricia van Loon
Associate Professor, Supply and Operations Management
Patricia.van.loon@chalmers.se

Zpark Energy System AB
Anna Costalonga
Project leader
Anna.costalonga@grepit.se

Research Institutes of Sweden AB
Sara Fallahi
Director Strategic Research, Prototyping Societies
Sara.fallahi@ri.se