Battery Cluster Reverse Logistics Challenges

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Abstract — **This paper explores three primary strategies that enhance not only the deployment of battery technologies through scalability and interchangeability but also examine their significant impact on reverse logistics flows. It delves into the critical role of modular battery design, advocating for the standardization of battery size, capacity, and the integration of blockchain technology in Battery Management Systems (BMS) to ensure traceability and security. Furthermore, the study will reveal specific conditions under which the cost of Going-To-Market (GTM) strategies can align with or equal the expenses associated with battery reverse logistics, offering insights into cost-effective and sustainable battery lifecycle management.**

Keywords—fixed battery, swappable battery, blockchain, secondary usage, recycling, logistics, sustainability

I. INTRODUCTION

The onset of climate change has catalysed significant technological shifts, paralleling historical milestones such as the advent of the steam engine, electricity, and nuclear energy. In response, the European Union's Green Deal [1] commits to an unprecedented technological transition, highlighting the urgency of adopting renewable energy sources and enhancing energy efficiency across various sectors, including transportation and household energy consumption.

This paper focuses on the deployment of battery technologies, particularly examining the scalability and interchangeability of integral batteries versus swappable/modular solutions in automotive and household applications. Despite the burgeoning market for battery electric vehicles (BEVs) and home solar electric systems (HSES), which remains under 2% saturated, the lifecycle management of batteries presents complex challenges in reverse logistics and recycling, exacerbated by the nascent state of lithium battery recycling technologies [2].

We delve into the regulatory landscape governing the transport and recycling of batteries, underscoring the critical role of safety and cost-efficiency in reverse logistics. The paper argues for the standardization of Battery Management Systems (BMS) and the adoption of blockchain technology to enhance traceability and security in the battery lifecycle. By examining the conditions under which the costs of market entry and reverse logistics converge, this study contributes to the discourse on sustainable battery technology deployment and lifecycle management, aiming to inform both policy and practice in the evolving energy landscape.

The life expectancy of the present rechargeable dry batteries based on the clusters of 18650 or equivalent battery type is supposed to be between 800-1200 cycles or 8-12 years [3]. While the stamina of the battery blocks assisted by the mass production and hands on experience objectively improve [4], the present technology cannot by-pass the physics-based life expectancy.

The conservative sources indicate, traditional processing of the Lead based 6/12V batteries, where the mass automobilism eventually trained the recycling, results in up to 99+% of the battery materials recovery: the sulfuric acid, the lead are used completely, the residuals come from plastic partitions and encasement [5]. Lithium based battery recycling, however, is still at early stages and the estimates suggest anything from pessimistic 1% [6]: *"Despite the growing attention and the development of various lithium recycling technologies, less than 1 percent of lithium is recycled currently"*) to optimistic 50% [7]. The methods still evolve to meet the expected boom of the used battery inflow [8] and besides the physical disassembly process standardization, more and more attention is also focused on:

a) BMS standardization – to unify the logic "Fit4Use" or "reprocess".

b) Blockchain seal the BMS transaction in order to make the battery life mapping credible for further trade or alternative/ secondary use.

Unlike the Lead batteries, Lithium has lower density of individual cub-compounds making it more difficult to extract, hence, we cannot expect the 99% extraction can be reached soon [9].

While the "Go2Market" processes spread seamlessly with business and prosperity forced around the Green Deal, the reverse flow beginning with the warranty and RMA, continuing with the service failures and ending with the used equipment recycling efforts remain hidden. Nevertheless, the reverse logistics of the integrated or swappable battery packs used for BEV (battery powered electric vehicles)/ PHEV (plug-in hybrid electric vehicle), HSES (Home Solar Electric System), Server UPS (Uninterruptible Power Supply), in general, any battery cluster using the set of Li-Ion/ Li-Pol cells, generates reprocessing costs, half of which is reportedly related to logistics [10].

Moreover, all domestic and international shipments containing lithium batteries (fresh or used) are subject to transport regulations on hazardous goods listed below. While the "Go-to-Market" (GTM) is mimicking the existing production-to-distribution paths with all its nuances, where numerous studies have been performed [11] and the critical factor is the **customer satisfaction**, the reverse logistics is driven by slightly different set of requests and the principal guideline is the **cost while satisfying the requirements of the regulators and overall safety** criteria.

The danger of transport is reflected in its EWC (European Waste Catalogue) categorisation and specific requests for both fresh and used battery material regulation of dangerous goods, which can be located in ADR (Transport of Hazardous Materials for Ground Transport), IMDG (International Maritime Dangerous Goods for Maritime Transport), and IATA (International Air Transport Association for Air Transport).

Unlike a common cargo, the waste battery materials shall always prepare alternative routes and alternative processing plants, in-transit temperature monitoring avoiding the fire risk, safety stops allowing to solve emergencies related to the nature of the transported cargo.

From the present level of 5.2billion USD in 2021 and 6.5 billion USD in 2022, the battery recycling market is estimated to reach the value of 35 billion USD by 2031 [12] and it is not reaching its peak by then. BEV and HSES sales in large scale begun around 2020; the mass related waste can be expected after 8-10 years of service – in 2031 we might see the beginning of the inflow.

While the fresh battery logistics accents the speed/ End-to-End (E2E) turn-around-time (TAT) and security of the GTM product, enforces manipulation and operation by skilled personnel only and the costs are hidden in the GTM product price, the cornerstone of reverse logistics is the safety and cost, because there is no nominal customer willing to pay for the waste product, the density of the logistics is relatively low and also the insurance cost is relatively high. (Volkswagen internal materials/ standards + RFI/ RFQ docs, subject to NDA).

II. SPECIFICS OF BATTERY LOGISTICS

The logistics involved in the battery life cycle play a crucial role in ensuring the efficiency, sustainability, and cost-effectiveness of the entire process. Effective logistics management based on two main pillars (standardization and subsidiarity) is capable of improving the economy of the battery lifespan.

A. *Standardization*

Back in 1984 Panasonic developed the etalon of the rechargeable battery cells which soon became the standard adopted by variety of emerging manufacturers. This type also became a basic building block for the battery packs/ clusters regardless the underlying technology – Li-Ion or any other, the 18650 cell simply defined the size standard accompanied with the minimal 3.7V charge. Furthermore, the cell allowed for Battery Management System (BMS) deployment allowing to monitor the battery health, performance and influence of aging.

Still, the basic 18650 cell construction (and convenient size) allows creation of the modular clusters for variety of application. The recent green technology imperative made it (together with similar cells like 21700 or the new constructions such as LiFePol4 prism cells) a basic building block of the battery packs suitable for electromobility and house appliances harnessing (preferably) the Green energy or traditional energy for the consumer emission-free use.

Following the logic of the standard vs. embedded battery, the devices with the embedded (proprietary) batteries are by definition consumer goods not intended to survive the moral aging of the products, i.e. one-off/ single use consumer product (e.g. Disposable cameras of the past). The charging battery certainly extends the lifespan of such a device, nevertheless, the product with such power solution is expected to be disposed of when the battery is no longer capable of powering the device up. The products with expected longer lifespan tend to use not only rechargeable but also replaceable power source [13] (the recent unhealthy development e.g. in the area of cell phones is being challenged, but the fact is the cell phone age faster than the battery in them; BEVs or home battery with the solution life expectancy of 20+ years are contradicting the idea/ trend).

The same as any portable power source that became a standard [14] the Li-Ion/ Li-Pol battery and its clusters became subject of further studies following its real-life use. Unlike the existing AAA or AA batteries (typically containing the electrolyte, and hence being “wet”), the standard Lithium based battery does not contain any liquid, is “dry” by definition – and, therefore, is considered safer. Neither the proclaimed safety prevented the 18650 cell from being eventually removed from air transport (IATA recommendations evolve since 2001 on the lithium battery subject), latest [15] and being watched in any other means of transport (Ocean, Rail or Road) [16].

B. *Subsidiarity*

Properly distributed testing centres with the equipment allowing the BMS testing/ Blockchain sealing, collection centres with equipment capable of basic disassy and repurposing the batteries (including the BMS and Blockchain alteration to serve the new purpose), recycling centres for the waste batteries to be converted to raw battery-grade materials – all this infrastructure can mitigate the burden of reverse logistics.

The biggest logistic costs incur in case of C2C (customer to customer)/ E2E (end to end) trade. Modern economy realized that the principle of distributed bulk can achieve the best \$/kg ratio. That is why the long-haul traffic between continents requires the biggest transportation capacities (e.g. Antonov An-225 Mryia, HMM Algeciras) and consequently the largest operable unit became a container – allowing for the multimodal transportation (ship container can be quickly converted to a truck or train, container can be quickly distributed in the form of pallets and boxes). Such practical scalability of the transportation batches enables the groupage of the batches with the same denominator: continent – country – wholesaler/distributor – customer.

The aim of the paper is to study challenges linked to reverse logistics of the battery clusters. To proceed with the topic, we defined three research objectives:

1. Propose battery lifecycle model respecting standardization and subsidiarity premise.
2. Map the areas where costs are generated in Reverse logistics and compare them with GTM costs.
3. Identify possible cost mitigating solutions and apply them to the defined case study.

III. MATERIALS AND METHODS

In the initial phase of our study, we conducted a review of literature and industry standards related to battery technologies and their lifecycles. The synthesis of this information served as the foundation for the development of a battery lifecycle framework. To illustrate the practical application and complexity of reverse battery logistics, we identified a relevant case study within the field. Then we applied our developed battery lifecycle framework to analyse the case study with the aim to reveal hidden costs of battery reprocessing. In the next step we compared costs and requirements for GTM and reverse battery logistics.

IV. REVERSE BATTERY LOGISTICS: CASE STUDY EXAMPLE

The real-life business case provided for this study shows us that the recycling efforts of one of the central UK repositories for the used batteries is amounting 250 tons of 3 homogenous separated materials (spec below) to be processed in the Central Europe (Poland or the Czech Republic)

Standards of the material categorized under EWC [17].

TABLE I. BATTERY WASTE SAMPLE

Category	EWC Code	Notes	Packaging	Qty per month
Dry (Cathode + Cells w/o)	16 03 03*	• Cathode Powder • Cathode Cake • Electrode Cathode – Sheet • Stacked electrode • Cell w/o electrolyte (Dry cell)	All materials are packaged in sealed polyethylene bags and bags in 1m3 cardboard boxes and transported on pallets with 1 box per pallet. Avg pallet weight: ~700 kg	130tons/ ~ 185 pallets
Wet (Cells and Modules)	16 03 03*	• Cell with electrolyte (UN3480) • Battery Modules (UN3480)	All materials packed in 205 litre drums (UN certified) surrounded by vermiculite and transported on pallets with 4 drums per pallet (shrink wrapped). Avg pallet weight:~1100 kg	25tons/ ~23 pallets
t/Anode + Foils/tabs	16 03 04	• Electrode Anode – Sheet • Al foil • Cu foil • Al Tab • Cu Tab	All packed in sealed polyethylene bags and bags in 1m3 cardboard box and transported on pallets with 1 box per pallet. Avg pallet weight:~500 kg	110tons/ ~220 pallets

EWC code 160303 = inorganic wastes containing hazardous substances
EWC code 160304 = other inorganic wastes containing hazardous substances

The substances require new approach in logistics services. This common case will require:

- Transport services, including selecting appropriate carriers which can transport waste in accordance with applicable Law, including Law related to cross-border shipments of waste (meeting the requirements regarding permits, policies insurance, ADR, registers, including but not limited to export licensing, forwarding, duty, forwarder fees, taxes, filing of export declarations/ other required by Law documents)
- The service provider will have a document confirming the company's entry in the register as a waste carrier in the language of the country in which it intends to provide services.
- Freight forwarding services, meeting legal requirements for the forwarder.

The material follows the steps of battery failing to satisfy its primary and/ or alternative use, it passed the functional disassembly, and might pass also the shred, mechanical and magnetic separation to be fit for hydrolysis/ pyrolysis processing. At this stage the material is, therefore, semi-homogenous as specified above and in a sense in the best possible form for transport. At this mid-stage, the separates are still not in their pure form of e.g. lithium, copper, aluminium – but in the form of compounds depending on their original battery construction. Following the well mastered “wet” Lead-Acid battery pattern, the logistics logic attempts to clone any working process in Li-Ion/ Li-Pol “dry” batteries, where the recovery rates are still at their infancy. It also satisfies the requirement of economic collection and reverse distribution in homogenous bulk of 3 types (**Table 1**).

V. RESULTS

The first research objective considered proposal of battery lifecycle model respecting standardization and subsidiarity premise. The framework of our study is determined by three readily identified logistics points. The **Figure 1** will help us understand their respective locations.

The “yellow star 1” is positioned at the cell manufacturer – the production is supported with either fresh or recycled material with the battery grade lithium, hence, it is at the birth point of the Li-Ion/ Li-Pol cell path to market.

The “yellow star 3” is positioned at the customer point; preferably at the moment, the battery is considered no longer fit for its primary use, based on BMS/ Blockchain data.

Both these points are clearly defined, their logistics qualities (raw material on one side and finished product at the end of its life) are also easily determined.

The “yellow star 2” is one of the neuralgic points of the battery reverse logistics process; we demonstrated the complexity of the logistics problem which is unknown to the fresh battery logistic path in the Case-Study example.

The reason why no other logistics point on the Figure 1 is defined as sensitive stems from the fact that although the “Customer – Fit4Use” connection works with the nominal battery shape and function, it is subject to battery regulation and the price for logistics service is calculated in the “normal use” scheme. The path from hydrolysis/ pyrolysis onwards already works with the battery grade material and the risks of burning and chemical contamination are limited to the levels of pristine raw material; the logistics is already performed in homogenous bulk.

Our model comprises with GTM market requirements (which is behaving as a clear “push” from the reverse logistics perspective – reverse logistics of the used batteries has no option to limit the inflow, it is expected to simply respect it) and the requirements of the recycling technologies and/or capacities installed to convert the waste to the recycled raw materials.

At this stage, we are ready to compare the requirements accompanying the GTM logistics flow with the Reverse Battery logistics flow.

The sub segment of the **Figure 1** describing the Global/ Regional/ Local transport involves the principle of subsidiarity:

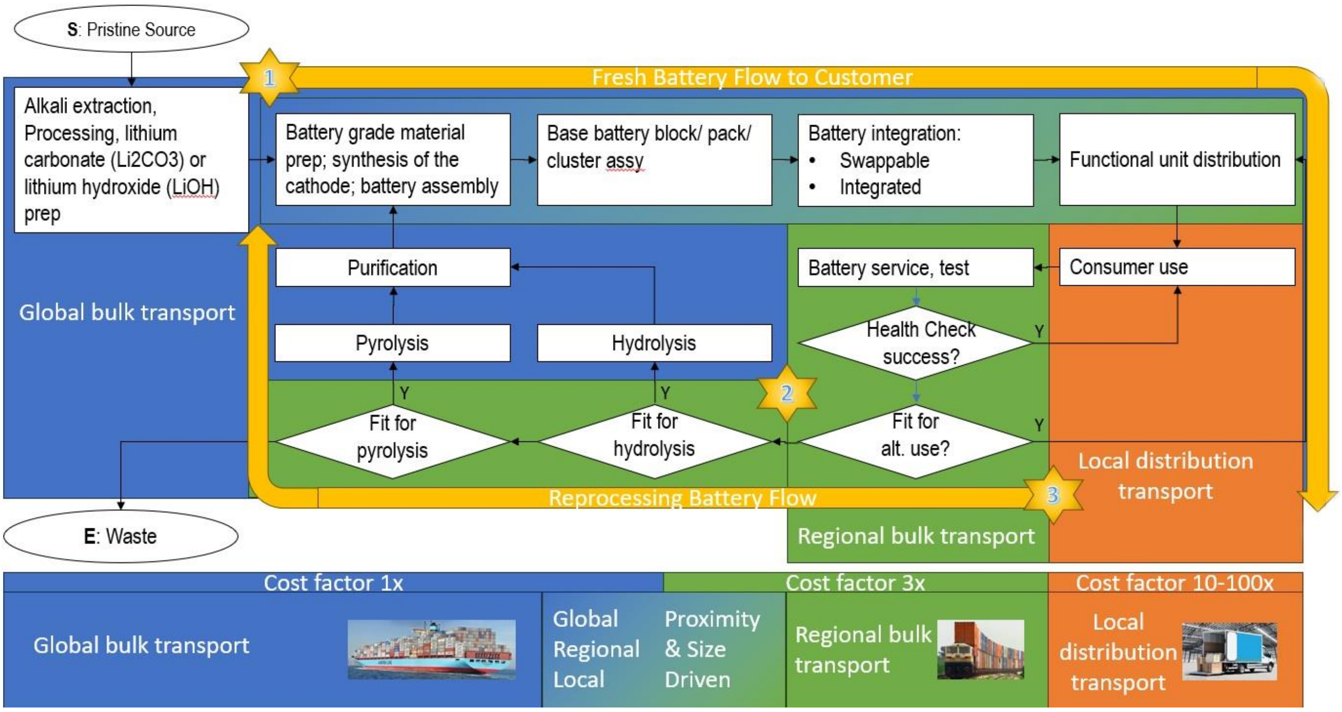

Fig. 1. Battery life from mining via customer use to re-use/ re-processing

The large bulk cargo allowing economy of scale (great transportation density) will deliver the best ratio of $ per kg and it is an excellent B2B logistics tool on the corporate level. The pre-processed materials (as outlined in the case study) are transported in 1.1t pallets, 800l drums per pallet or 500kg per pallet. For the calculation we will disregard pallet height and respecting the nature of the transported cargo, we shall consider one level of pallets on a truck with **average weight of 620kg per pallet** (130+25+110t)/ (185+23+220pallets).

TABLE II. COMPARISON OF THE COSTS [18], [19]

Means of transport	**Cost EUR/ pallet/ km**	**Pallets [kg] to transport**	**Cost EUR/ kg**	**Index**
Truck/ Trailer/ Boat International [18]	1.42 EUR one way/ 3.22 EUR return	10pallets/ 6200kg	0.00023	1.00
Small Truck/ Van (3.5t)	0.9 EUR	2pallets/ 1240kg	0.00073	3.17
Collection Taxi (1.5t)	1.5 EUR	1 pallet 620kg	0.00242	10.56
Courier (1.2t) [19]	15 EUR	1 pallet 620kg	0.02419	105.63

As we can see in **Table 2**, regardless GTM or reverse logistics, the individual transport is 10-100x more expensive than a bulk transport (disregarding the ADR nature of the product), hence it is advisable to limit the individual non-consolidated transport as much as possible. **If we are to equal the GTM and reverse logistics costs, the distance to the nearest BEV or HSES shop and the distance to the nearest collection point must be equal**, as the individual mode of transport is the most inefficient (cost) as ineffective (process) for the society.

The growing flow of the fresh lithium products and consequently lithium-content wastes will trigger the growing number of regulations. The same as the standards being developed in the GTM battery flow, the presently underestimated reverse path (with expectable ramp up following the GTM +6-10 years of the expected life span) will shortly witness the regulation extending present standards (ADR, IMDS, etc.)

The aim of the recycling infrastructure installation (presently decided by the private investors, i.e. recycling companies) might/shall be co-defined by the government, local authorities and Public-Private Partnership (PPP) in order to be able to cope with the size and scope of the future expected inflow of the lithium battery wastes in order to mitigate the problem of individual transportation costs as much as possible.

The idea expressed at **Figure 1** requires the reverse logistics to behave the same in the same region size regardless different parameters of the merchandise utilizing the logistics process, i.e. on the way back group the used batteries in the regionally appropriate central points (limiting the need of individual transports with the low density), where the economy of scale justifies creation of collection points for used batteries, test stations for the failing units, creation of disassy capacities and capabilities in order to prepare the homogenous material for safer transport, on the larger scale prepare the infrastructure for pre-processing of the "waste batteries" through hydrolysis/ pyrolysis and finally for processing the sorted waste materials to the level of battery grade materials. Battery life from mining via customer use to re-use/ re-processing

GTM AND REVERSE LOGISTICS: KEY DIFFERENCES AND SIMILARITIES

Manufacturing vs. Collection Costs: The initial manufacturing costs for batteries include raw materials, production, and assembly, whereas reverse logistics primarily deals with the costs associated with collecting used or defective batteries for recycling or disposal – sensible distribution of central collection points is needed.

TABLE III. BATTERY WASTE SAMPLE

Factor	**Battery GTM Logistics [To: Customer]**	**Reverse Battery Logistics [From: Customer]**
Accuracy	✓	✓
Competition	✓	
Compliance	✓	✓
Comply with regulations	✓	✓
Cost	✓	✓
Customer Experience	✓	
Demand Forecasting	✓	
Efficiency	✓	✓
Flexibility	✓	✓
Inventory Holding	✓	✓
Processing & Handling	✓	✓
Reliability	✓	✓
Responsiveness	✓	
Restocking/Refurbishing		✓
Scalability	✓	✓
Seasonality	✓	
Security/ Safety (*)	✓	✓
Speed	✓	
Sustainability	✓	✓
System and Technology	✓	✓
Transportation	✓	✓
Visibility	✓	✓
Waste Disposal		✓

Transportation Costs: Both processes incur transportation costs, but the context differs. GTM logistics focuses on efficient distribution to customers, while reverse logistics emphasizes the cost-effective return of products from customers – and the logistics cost optimization is key to efficient collection.

Warehousing vs. Processing/Handling Costs: While GTM logistics involves warehousing costs for storing products before sale, reverse logistics faces processing and handling costs for sorting, safety inspecting, and processing returned items.

Distribution vs. Restocking/Refurbishing Costs: GTM logistics includes the costs of distributing products to various sales channels, whereas reverse logistics incurs costs in refurbishing or repackaging goods for resale or recycling process (grinding, separation, purification, smelting or chemical separation).

Inventory Costs: Both processes deal with inventory costs, but reverse logistics also has to manage the holding costs of returned items until they can be processed with special safety care namely when the product is non-homogenous.

Packaging vs. Disposal Costs: Initial packaging costs are a concern in GTM logistics, aiming to protect the product and enhance its appeal, while reverse logistics must consider the costs of disposing of products that cannot be refurbished or recycled. While the packaging of the fresh product must primarily protect the cargo (functional battery), the principal function of the battery recycled material packaging is to protect the environment.

Regulatory Compliance: Both processes must navigate regulatory compliance, but the focus may differ. GTM logistics deals with compliance related to product safety and distribution, whereas reverse logistics must also consider environmental regulations related to disposal and recycling.

Marketing and Sales vs. System and Technology Costs: GTM logistics includes the costs associated with marketing and selling the product, which is not a direct concern in reverse logistics. Instead, reverse logistics may incur significant costs in systems and technology for tracking and processing returns.

Customer Service vs. Loss of Value: Customer service costs are part of maintaining customer satisfaction and facilitating sales in GTM logistics. In contrast, reverse logistics must account for the loss of value in returned products, affecting the overall cost recovery.

Besides the above description of the similarities and differences between GTM and reverse flow, **Table 3** outlines all known aspects of the logistics in both directions.

In fact, each of the named aspects is affecting both flows, the tick and colours are only stressing where we can expect further growth of interest (authorities and public).

For example, the field “Comply with regulations” wants to stress the fact that the GTM is already reaching its production zenith closely followed by the corresponding regulation, while reverse logistics can only benefit from present regulations set up for the secondary/ alternative battery use and will need to develop when the expected growth in the traffic flow materializes.

Another nice example with similar connotation is at the field “Cost” – although the logistics cost for battery lithium materials is extremely important in both directions, the GTM side can project the cost into the battery solution or even the finished application price. Relevant studies [10] estimate that the logistics might consume up to 50% of the E2E solution cost – unless optimized.

As of February 2024, the EU regulatory framework for batteries comes into power [20] replacing the original Battery directive from 2006 [21]. The expected standardization and optimization of the recycling process will be assisted by all these regulations. While the standardization within a region or even on the WW scale tends to help the economy of scale, the optimization often clashes with the enforced regulations namely in EU where very stringent requirements often directly contradict any business-driven attempts in the field of optimization.

VI. DISCUSSION

If we are to improve battery clusters life management substantially, we shall follow the pattern of present battery standards. Even the large battery packs shall have (per a defined block):

- Standard **size/ shape** (to fit the EV or household application)
- Standard **weight** allowing the legal manipulation (i.e. 15kg per such swappable battery)
- Standard **capacity** (e.g. 15kg block can accommodate 333 batteries of 18650 type in serial or in parallel set up; used in series, it can theoretically deliver 333x3.7V=1323V)
- Standard **connectors** allowing to use the clusters in serial or parallel applications.
- Standard **BMS and PoA Blockchain logic** (namely for the service and disposal purposes)

Such standards allow use in variety of appliances and their efficient use after the battery is no longer fit for its primary use. Standardized BMS with the blockchain seal supports the credibility of the solution during the service but can also deliver the critical information when the pack is no longer fit for the primary use. The process is starting with the individual manufacturers [22], but the general standards would allow the re-processing/ re-purposing while mitigating the additional logistics costs.

Even the inevitable logistics would benefit from standardization; BMS can deliver the information about techno used, charge and health status of the battery and hence allows grouping of the batteries and consequently can arrange for the homogenous material storage and transport.

The additional benefit of the standards can be seen in standardized processing (besides automated logistics, it could be testing lines, manipulation/ conveyors, disassy processing lines, onboarding/ moving/ outsourcing the technology, etc.). Besides, the nominal logistics cost related to transportation and on-the-way manipulation might be greatly optimized.

The healthy and GTM verified principle of subsidiarity shall be maintained also in the reverse flow; the standardized battery shall be returned to the distribution centre capable of the battery BMS verification – and based on the received data, move the battery cluster to the regional centre preparing the material for the return.

Once the flow of the fresh batteries balances the flow of the disposed batteries, the transportation capacities can be further optimized – or the regions can decide to build the infrastructure for the used battery processing: repurposing (2nd life is greatly assisted by the standardization), hydrolysis or/and pyrolysis.

VII. ACKNOWLEDGEMENT

The paper has been completed with the kind support of SGS_2024_017 project, Students grant competition of the University of Pardubice.

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