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THE LOGISTICAL CHALLENGES OF MANAGING HAZARDOUS WASTE FROM THE BATTERY INDUSTRY IN HUNGARY

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Abstract: *Thanks to its 'Opening to the East' industrial policy, launched in 2016, Hungary has grown to become Europe's fourth-largest manufacturer of lithium-ion cells. Through this explosive industrial expansion, comprising 44 priority investments, the country's production capacity could exceed 200 GWh by 2030. However, the volume of hazardous waste generated is increasing in direct proportion to production volumes. Due to the high scrap rate and the significant specific environmental impact of battery production, tens of thousands of tonnes of toxic, flammable and explosive by-products require professional handling, storage and disposal each year. By analysing primary regulatory data and domestic case studies (Göd, Komárom, Szigetszentmiklós, Abasár, Iklad), this article highlights that current domestic reverse logistics practices are ad hoc in nature, the regulatory environment is highly fragmented, and regulatory action is often inconsistent. To ensure sustainable and safe operations, the article proposes the introduction of a new, Seveso-compliant, multimodal and digitised inverse logistics methodology, which fully integrates the requirements of Regulations (EU) 2023/1542 [1] and (EU) 2024/1157 [2].*

Key words: *hazardous waste, battery industry, logistics challenges.*

1. INTRODUCTION

Hungary's economic and industrial policy took a marked turn after 2016. The strategic objective became the establishment of high value-added, energy-intensive, high-tech industries - particularly battery manufacturing. According to official data from the Hungarian Investment Promotion Agency (HIPA), a total of 44 battery industry projects received significant state support between 2016 and 2022, with a combined net investment value of €15.2 billion [3]. The geopolitical reality behind these mega-investments is also clearly set out in the European Union's Critical Raw Materials Act (2023): the European continent suffers from a drastic dependence on raw materials. Currently, Europe sources 86% of the lithium and 78% of the cobalt essential for manufacturing from global markets. Given this exposure, Hungary is becoming a kind of production bridgehead through foreign direct investment (FDI) from the East.

The peak of the domestic investment boom is marked by six giga projects, which are significant even on a European scale (Table I).

According to the consensus in the international literature, the volume of waste generated during production on this scale cannot be regarded as a marginal factor. Based on the research by Hayagan et al. [4], the normal production scrap rate is substantial, ranging between 5% and 30%. This is also supported by the Fraunhofer FFB [5]. Institute's paper entitled 'Mastering Ramp-up of Battery Production', which highlights that during the ramp-up phase of production, the scrap rate remains stable at around 15–30%. For a single large factory of

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this kind, this loss could amount to as much as €900,000 in financial damage on a daily basis. According to Transport & Environment's [6] analysis entitled 'From waste to value: the potential for battery recycling in Europe', the proper recycling of manufacturing waste could cover around 14% of Europe's lithium demand by 2030 – provided that the necessary infrastructure and logistics are in place for processing. At present, this infrastructure is lacking everywhere.

Table I.

Giga projects in the last years worldwide

Project	Investor	Country	Investment (billion €)	Investment (billion HUF)	Capacity/ Product	Jobs
CATL	Contemporary Amperex Technology Co., Limited (CATL)	China	7.34	2,900	100 GWh/year, NMC 811 technology	9,000
SK On	SK On (a subsidiary of SK Innovation)	South Korea	2.05	691	30 GWh/year, NMC technology	3,000
Huayou	Zhejiang Huayou Cobalt	China	1.5	520	100 kt cathode (NMC precursor)	1,000
Eve Energy	Eve Energy (a subsidiary of Farasis Energy)	China	1.2	400	20 GWh/year, LFP/NMC technology	2,000
Samsung SDI	Samsung SDI	South Korea	1.1	367	30 GWh/year, NMC technology	2,500
W-Scope	W-Scope (a subsidiary of Mitsui & Co. and UACJ)	Japan	0.9	300	Separator foils	500
Total	-	-	**14.09**	**4,178**	-	**18,000**

2. WASTE-SPECIFIC CHARACTERISTICS OF LITHIUM-ION CELL MANUFACTURING

The manufacture of lithium-ion batteries is currently an extremely complex, multi-stage heavy industrial process that generates numerous hazardous by-products and waste. The by-products and waste generated during these processes are classified as strictly hazardous waste under Decree 72/2013. (VIII. 27.) VM [7] and the European Waste Catalogue, and exceed the hazard level of conventional industrial waste. The specific environmental impact of production is striking in itself: producing 1 kWh of cell capacity requires 30–35 kWh of energy, 10,000 g of carbon dioxide equivalent emissions, and 0.5 kg of NMP (solvent) [8]. The chemical risks associated with the main waste streams are also significant, as they require special handling not only during production but at every stage of the logistics chain - from collection to processing.

N-methyl-2-pyrrolidone (NMP) is the primary solvent used in the production of cathode slurry; due to its reproductive toxicity (H361), it is also included on the REACH SVHC (Substances of Very High Concern) list [9]. Its vapour pressure at 20 °C is 0.3 hPa, resulting in rapid evaporation; furthermore, it is absorbed extremely quickly and efficiently through human skin, creating an immediate life-threatening situation. Electrolyte residues (e.g. lithium hexafluorophosphate) are found dissolved in various organic carbonates. The greatest risk is that, upon contact with moisture in the air or water, they immediately release hydrogen fluoride gas. This substance is extremely corrosive; inhalation can be fatal even at low concentrations [10]. The black dust is a fine powder produced during the mechanical crushing or grinding of defective, physically damaged or aged cells. It is a complex metal mixture containing high concentrations of nickel, cobalt and manganese. Nickel is a carcinogen (IARC Group 2B) [11], whilst manganese is highly neurotoxic and can cause damage to the nervous system. These hazardous substances require special handling not only during production but at every stage of the reverse logistics chain. To establish a safe logistics chain, it is essential to have a precise understanding of the chemical risks associated with the main waste streams, as well as to apply appropriate packaging, transport and storage solutions.

3. A CRITICAL ANALYSIS OF DOMESTIC LOGISTICS PRACTICES

The situation in Hungary is characterised by the latent tension between explosive industrial growth and a regulatory and infrastructural framework that is entirely unprepared for it. Reverse logistics processes are not characterised by preventive, scientifically and professionally sound planning, but rather by ad hoc, ongoing and spontaneous crisis management born of necessity.

Official inspections and investigative reports have recently uncovered numerous incidents in Hungary that seriously endanger the safety of the population and the environment:

- In Abasár in 2023, 1,700 tonnes of hazardous battery industry waste were illegally dumped; the barrels were labelled with false information to mislead the authorities.
- In Iklad, leaking barrels containing defective lithium-ion cells and Black Mass were identified, having been stockpiled without a permit.
- Meanwhile, at the SungEel Hitech Hungary Kft. plant in Szigetszentmiklós, fires and explosions had become a regular occurrence; two workers lost their lives in an accident, highlighting a complete lack of technological discipline and proper material handling, as well as staggering irresponsibility.

The case studies highlight the weakest links in the system: the exploitation of legal loopholes, the fragmentation of the regulatory environment, the inconsistency of regulatory action, and the complete lack of professional and legal preparedness among hauliers and subcontractors. Current practice entails not only safety risks, but also environmental and macroeconomic risks. In the case of international transfers, the notification procedures mandated by Regulation (EU) 2024/1157 [2] are consistently omitted, and the majority of hauliers do not hold the specific waste management permits at all.

4. THE NEED FOR AND DESIGN OF A NEW, INTEGRATED REVERSE LOGISTICS METHODOLOGY

The situation that has developed in Hungary is truly dramatic and unsustainable [12].

A modern, environmentally conscious industry in the heart of Europe cannot be built on illegal landfills or spontaneous, ad hoc solutions. It is inevitable that a complex reverse logistics chain, based on engineering and scientific principles, must be established, the paradigm of which is that scrap and waste are not ‘rubbish’ but critical secondary raw materials, the return of which to the economy is the fundamental principle of the circular model.

4.1. Network optimisation and modelling approaches

The design of an inverse logistics network cannot be random or based purely on intuition. Scientifically grounded modelling – such as mixed-integer linear programming (MILP) – enables logistics decisions to be made in an objective, data-driven manner. The research by Wang et al. (2020): Optimal design of electric vehicle battery recycling network' [13] also confirms that MILP models are capable of simultaneously optimising costs, environmental impact and safety risks, whilst taking into account capacity constraints, time constraints, safety regulations and the legal framework. In the domestic context, however, further research is needed to ensure that the models take into account domestic specifics: the potential and capacity of the rail network, the location of populated areas, urban planning, the significant constraints and shortcomings of the existing infrastructure, and the methods for complying with Seveso-compliant safety regulations. Optimisation is not just about minimising costs, but also about ensuring environmental and social sustainability. Multi-objective optimisation - where environmental protection and safety are priorities alongside economic efficiency - requires the development of complex mathematical and simulation models based on real-world data and supplemented by sensitivity analyses. Before practical implementation, pilot projects are required where the models can be tested in a real-world environment and validated under current domestic conditions. Phased scaling is then possible: following a successful pilot project, the solution can be rolled out across the whole country, with continuous refinement taking into account real-world operational experience.

4.2. Innovative packaging technology and safety approaches

Hazardous substances generated during the manufacture and processing of lithium-ion batteries - particularly NMP and electrolyte residues - pose an extremely high risk. In my view, traditional drum storage is inadequate for modern safety requirements, as it cannot prevent chemical reactions, leaks or thermal runaway.

There is therefore a need to introduce innovative, UN-certified, smart packaging technologies capable of addressing the aspects of chemical stability, thermal management and the detection of hazardous gases. These solutions can significantly improve not only safety but also cost-effectiveness, reducing transport costs and the risk of accidents. However, before selecting specific technological solutions, detailed research and testing are required to determine the most suitable materials, structures and monitoring systems.

The proposed solution would involve the use of double-walled containers equipped with passive fire protection and integrated IoT sensors. These sensors can monitor temperature, pressure, gas concentration and movement in real time, automatically triggering an alarm in the event of a hazardous incident (e.g. thermal runaway).

4.3. A paradigm shift in multimodal transport

The transport of hazardous waste within the country currently relies almost exclusively on road transport (ADR), which entails a number of drawbacks. The introduction of a multimodal transport model – particularly one that makes rail transport the backbone of the system – could significantly improve safety, cost-effectiveness and sustainability. The limitations of road transport are evident: high accident risk, significant environmental impact, public safety risks and limited capacity. The advantages of rail transport, meanwhile, are clear: it operates on dedicated tracks, offers high capacity, produces lower carbon dioxide emissions and is more easily traceable. However, planning a multimodal transport network is a complex task that requires detailed modelling of the domestic rail infrastructure, the location of terminals and container depots, and the optimisation of transport routes. These issues can be addressed within the framework of separate research projects, drawing on both domestic and international expertise.

4.4. Transparency and traceability

Digitalisation is a fundamental prerequisite for transparency, traceability and security in the reverse logistics chain. The integration of the Battery Passport system, which has been made mandatory by the European Union, and digital waste management systems enables the entire life cycle of hazardous waste to be tracked. The Battery Passport documents the entire life cycle of batteries: from the mining of raw materials through to manufacturing, use and recycling. This system can currently be implemented using QR codes or RFID tags, and blockchain-based storage ensures that the data is protected against tampering. The Digital Waste Management System (DIWASS), meanwhile, ensures comprehensive tracking of the transport, storage and processing of hazardous waste. This system is closed, subject to state supervision, and features IoT integration. The Real-Time Monitoring System (VIMOR) ensures the monitoring of the physical condition of hazardous waste through the cooperation of sensors installed in containers and the central monitoring system.

4.5. Designation of strategic regional terminals

The current ad hoc storage practices are unsustainable and pose a safety risk.

There is a need for a network of strategically located, Seveso-compliant, multimodal collection and transhipment terminals that function not only as storage facilities but also as logistics hubs. The terminals' function is not only the temporary storage of waste, but also its collection, transhipment and onward transport. These terminals will be built in four key regions:

- Northern Transdanubia (Komárom, Ács): Collection of waste from the Northern Transdanubia industrial corridor (Huayou, Samsung SDI).
- Central Hungary (the wider Budapest area): A central logistics hub, optimising national transit.
- Eastern Hungary (Debrecen, Nyíregyháza): Primary hub for the largest gigaprojects in Eastern Hungary (CATL, Eve Energy, W-Scope).
- South Transdanubia (Kaposvár, Siófok): Covering the potential future industrial capacities of the South Transdanubia region.

4.6. Proposals for regulatory and institutional reform

Technological and logistical innovations can only become effective if the legal and institutional framework is properly consolidated. The current regulatory environment is fragmented and inconsistent, which hinders the efficient operation of the reverse logistics chain.

4.7. Uniform regulation and waste classification system

Under current practice, the classification of hazardous waste takes place at county level, resulting in significant discrepancies and unpredictability. A central ministerial decree is needed to make the use of specific EWC codes for waste from the battery industry mandatory and to prevent reclassification into incorrect or less stringent categories. The introduction of digital classification tools is also essential, as these will assist in the automated classification of waste and reduce legal uncertainty.

4.8. Accreditation system

Ensuring that logistics service providers possess the necessary professional competence and safety preparedness is essential for the safe management of hazardous waste. There is therefore a need for a rigorous, independent, national accreditation system that guarantees operators have the necessary professional expertise, licences and safety systems in place.

4.9. Integrated concession system

Responsibility for the management of hazardous waste is currently divided among several operators (manufacturers, transporters, processors), which makes coordination and monitoring difficult. An integrated concession system is needed to manage the collection, transport, storage and processing of hazardous waste in a unified manner.

5. Summary

From a logistics and industrial policy perspective, Hungary is on the cusp of a critical transitional period. The explosive expansion of battery manufacturing capacity, driven by foreign direct investment (FDI) from the East – thanks to the CATL, SK On, Huayou, Eve Energy, Samsung SDI and W-Scope – could lead to the generation of 50,000–80,000 tonnes of hazardous battery waste annually by 2030, according to my calculations. This volume poses not only logistical challenges, but also environmental, social and economic challenges and risks. The current waste management system, which is often characterised by spontaneous reverse logistics, is burdened by numerous structural problems. With the further expansion of battery production, the volume of industrial hazardous waste could increase significantly, resulting in serious logistical, environmental and social challenges. To address these issues, it is of paramount importance to develop and proactively apply a scientifically grounded, integrated and digitally supported methodology for inverse logistics. A system based on optimisation models – such as MILP approaches – could provide the means for the safe, traceable and sustainable management of hazardous waste streams, thereby contributing to strengthening Hungary's competitive and sustainable role in the European battery value chain.

Statement on the use of artificial intelligence: During the preparation of this manuscript, artificial intelligence (AI)-based tools were used exclusively to support the analysis of the literature, as well as for the translation and linguistic stylisation of texts produced by the authors. The professional content, analyses, interpretations and conclusions of this article are based entirely on the authors' own work.

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