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WORLD EXPERIENCE OF LEGISLATIVE REGULATION FOR LITHIUM-ION ELECTRIC VEHICLE BATTERIES CONSIDERING THEIR SECOND-LIFE APPLICATION IN POWER SECTOR

Abstract. *Understanding and incorporating global regulatory experiences and standards related to battery management is of greatest importance, particularly when considering the rapid evolution of the electric vehicle (EV) market and its implications for energy storage and sustainability. This is especially relevant for Ukraine, where the burgeoning secondary market for EVs and a keen interest in renewable energy sources underscore the need for proactive policy-making and standardization to address the challenges of battery second life and recycling. This article delves into the role of Electric Vehicle Lithium-Ion batteries within the ambit of the circular economy, underscoring the significance of legislative frameworks across the globe with a particular focus on European initiatives in light of Ukraine's EU integration ambitions. This encompasses extending battery life through recycling and repurposing, thereby ensuring both economic viability and minimal environmental footprint. The narrative outlines the varied legislative landscapes internationally, noting the differences in strategies from Asia's technological and safety emphasis to Europe's robust regulatory directives aimed at battery lifecycle management. In Europe, the drive towards sustainable battery utilization is marked by comprehensive policies like the EU Battery Directive and the emerging Regulation on Batteries and Waste Batteries, which set forth ambitious recycling targets and introduce innovative concepts like the battery passport. Drawing from this global overview, the article posits a set of recommendations for Ukraine, suggesting the development of extensive battery management legislation, adoption of European standards to smooth the path towards EU membership, investment in recycling infrastructures, fostering of public-private partnerships, and public awareness initiatives. These recommendations are designed to elevate Ukraine's position in the sustainability, promoting environmental stewardship and economic competitiveness. The growing importance of secondary lithium-ion batteries for electric vehicles in supporting and harmonizing renewable energy sources is emphasized, and accordingly, the need for adequate legislation and standardization to support a closed-loop economy.*
Keywords: Lithium-Ion Batteries, Second-Life Application, EV Battery Life Cycle, Circular Economy, Repurpose, Reuse, Recycling, Standards, Regulation, Legislation.

1. Introduction

The transition towards sustainable energy systems is a global priority, driven by the urgent need to address environmental challenges, mitigate climate change, and ensure energy security. In this context, the role of electric vehicles (EVs) and, more specifically, the potential of second-life EV batteries (SLBs), has gained significant attention [1, 2]. The global surge in EV adoption, fueled by a combination of regulatory pressure, tax incentives, direct consumer subsidies, and private-sector dynamics, underscores a shift towards sustainable transportation [3]. This transition is supported by improvements in EV range, reductions in price premiums, and the anticipated price/performance parity with Internal Combustion Engine vehicles within five to seven years [4]. This evolving landscape signifies the potential for a sharp increase in consumer demand for battery electric vehicles (BEVs), propelled by both supply-side beliefs in the inevitability of BEVs overtaking internal combustion engine (ICE) vehicles and demand-side factors like high oil prices and environmental concerns.

Electric vehicles have emerged as a one of key factors of the global strategy to reduce greenhouse gas emissions and decrease reliance on fossil fuels [5]. However, the environmental impact of EVs is not confined to their operation but extends to the lifecycle of their batteries. EV batteries, typically based on lithium-ion technology, offer high energy density and long service life but also pose challenges in terms of resource extraction, manufacturing emissions, and end-of-life management. As these batteries reach the end of their automotive life, typically when their capacity falls below 80 % of the original, they still possess substantial residual capacity that can be harnessed in secondary applications, particularly in the power sector [6].

The integration of second-life EV batteries into the power sector presents a compelling proposition to enhance the flexibility and resilience of energy systems, facilitate the integration of renewable energy sources, and contribute to circular economy principles [7–9]. This potential is grounded in several key motivations:

*Environmental Considerations***:** The repurposing of EV batteries supports waste reduction and resource efficiency by extending the useful life of valuable materials and components [10]. This approach not only diminishes the demand for raw materials, such as lithium, cobalt, and nickel, which have significant environmental and social footprints associated with their extraction but also reduces battery disposal challenges. Furthermore, by providing energy storage solutions, second-life batteries can enable a higher penetration of intermittent renewable energy sources, such as solar and wind, thereby contributing to the decarbonization of the power sector.

Economic Aspects: The use of second-life batteries in stationary storage applications offers an economically attractive proposition [11]. These batteries can be acquired at a lower cost compared to new batteries, making energy storage projects more financially viable and accelerating the return on investment. Additionally, the deployment of second-life batteries can contribute to energy cost savings and grid stabilization, offering economic benefits not only to energy providers but also to consumers and the broader economy.

*Technological Features***:** The technological advancements in battery diagnostics, refurbishment, and management systems are pivotal to unlocking the potential of second-life batteries [12]. Innovations in assessing battery health and performance, ensuring safety, and optimizing integration with energy systems are crucial for the effective and reliable use of repurposed batteries. Moreover, the development of smart grid technologies and demand response strategies further enhances the value proposition of second-life batteries by facilitating their integration into an increasingly digital and decentralized energy landscape.

In delving these dimensions, **this study aims** to provide a comprehensive understanding of the opportunities and challenges associated with the secondary use of EV batteries in the power sector. The analysis will encompass a review of current practices, regulatory frameworks, and market developments globally, with a particular focus on deriving insights and recommendations relevant to the Ukrainian context.

2. Methods and Materials

2.1. Lithium EV Batteries in Circular Economy

The evolution of sustainable transportation is intricately linked to the proliferation of EVs, a critical component in the global shift towards environmental sustainability. The transport sector, recognized as a significant contributor to global pollution levels, faces stringent CO_2 emission reduction targets set by the European Union (EU), aiming for a reduction of up to 37.5 % by the year 2030 [13]. The last decade has witnessed a remarkable surge in EV sales, fueled by a combination of supportive government policies, financial incentives such as consumer subsidies and emissions-linked vehicle taxation, alongside advancements in emission standards. This uptick in EV adoption has consequentially spurred an increased demand for electricity, potentially introducing new peak demand patterns that could challenge existing distribution networks. Conversely, EVs present a unique opportunity to serve as energy storage assets in the future through Vehicle to Grid (V2G) technologies [14, 15].

This growing fleet of EVs has precipitated a parallel increase in the volume of discarded EV batteries, necessitating effective recycling strategies. Typically retired after a 20 % decrease from their nominal capacity, these batteries still retain significant residual capacity that can be repurposed for secondary applications, such as stationary storage, underpinning the concept of second-life batteries (SLB). By 2030, as it is shown in Fig.1, it is anticipated that approximately 3.4 million end-of-life EV batteries will be available, collectively representing a staggering 953 GWh of battery capacity [16, 17]. Repurposing these batteries for stationary storage not only exemplifies efficient resource utilization by diminishing the materials required for new Lithium-ion (Li-ion) battery production but also mitigates environmental degradation, thereby fostering the principles of a circular economy.

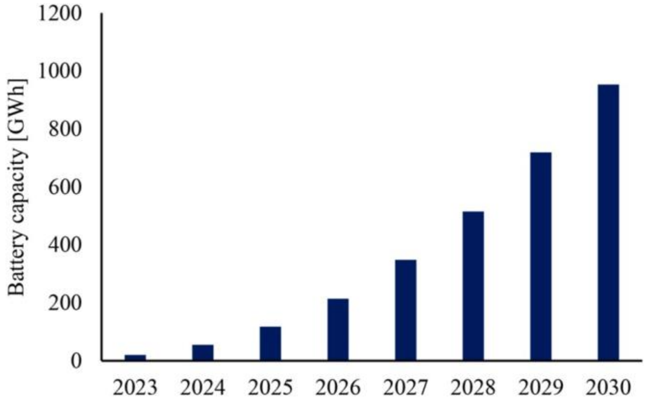

Figure 1. Forecasted global second-life battery capacity from 2023 to 2030 [17]

Furthermore, battery storage solutions have demonstrated their viability as short-term storage solutions, playing a pivotal role in grid stabilization amid fluctuating demand. EV fleets, when intelligently managed, can transform into dynamic storage systems, unlocking potential economic and energy savings and generating new revenue opportunities. Efficient energy management within these systems can facilitate various applications, including V2G, vehicle to building (V2B), or vehicle to home (V2H) scenarios. However, transitioning to SLB usage raises concerns about battery health and longevity [18].

Discarded batteries may experience capacity reduction or power degradation due to factors like cathode and anode degradation, high cycling rates, and inappropriate charging practices. These batteries undergo comprehensive health assessments, including screening, sorting, and testing, to determine their suitability for various applications, as shown in Fig. 2. SLBs could serve multiple purposes, from storing renewable energy for residential or commercial use to peak shaving in industrial settings, enhancing grid flexibility, stability, and facilitating the integration of renewable energy sources [19]. Additionally, these batteries could be aggregated into battery farms for electricity market trading or repurposed for vehicle propulsion, such as in forklifts and ferries, further promoting material resource efficiency and supporting the growth of a circular economy.

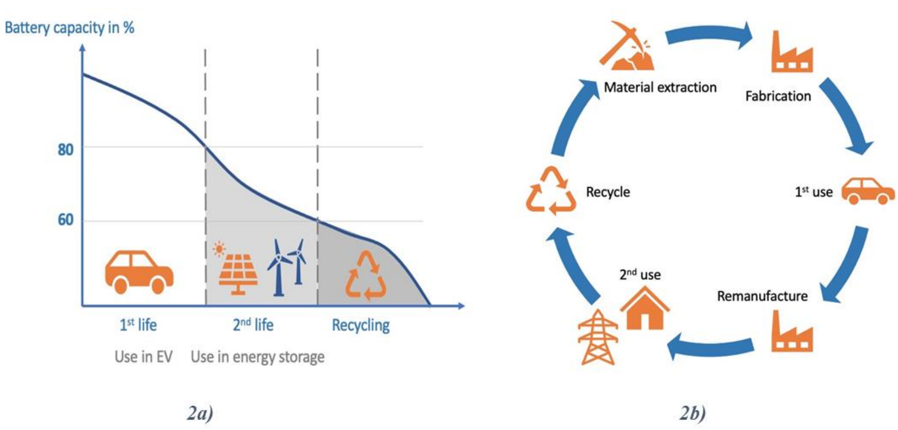

Figure 2. Circular Economy Framework for EV Batteries; 2a) EV Battery Life Range as a Function of Battery Capacity: 2b) EV Battery Life Cycle [19]

The integration of SLBs into the energy network represents a significant shift in the supply chain, with profound implications for the circular economy. This necessitates a broad expansion of SLB applications, beginning with the EV owner who transitions from a passive role to an active prosumer, thus contributing significantly to the sustainable development of energy consumption. Depending on their application, second-life batteries have the potential to last up to 30 years, further reinforcing the circular economy. The EU's Circular Economy Action Plan focuses on minimizing material wastage and promoting the longevity of resources within the economy, with particular attention to batteries and vehicles [20].

2.2. Terminology Uncertainties

The current body of legislation and technical standards reveals a significant lack of clarity and consensus on defining "second use." This ambiguity extends to several related terms, which remain vaguely interpreted within the scope of existing Battery Directives. Such terminological uncertainties, encompassing "second use," "reuse," "remanufacturing," "refurbishing," and "recycling," present substantial challenges for stakeholders in the industry, potentially complicating the management of EV batteries at their end of life [21–25].

The differentiation between "second use" and "reuse" warrants particular attention. "Reuse" often refers to employing EV batteries or their non-waste components for their originally intended purpose—mainly, powering EVs [21–23]. Another perspective on "reuse" considers it the straightforward application of a product without modifications [24], although this view does not account for the eventual application for which the battery is reused. This oversight is a departure from interpretations offered in Battery Directives, which suggest "reuse" implies employment for the original purpose.

Conversely, the Battery Directive provides a broader explanation, indicating "reuse" happens when a product is used for its initial intended function [24]. However, the clarity and consistency of definitions in battery directives are lacking, leading to confusion among sectors of industry and academia. To resolve these conflicts and promote a sustainable future for EV batteries, the Battery Directives should strive for legislative harmonization, adopting a uniform set of standards for end-of-life EV battery management.

"Remanufacturing" is described as a process primarily focused on cosmetic enhancements of a product, potentially with minimal functionality improvements [24]. The ambiguity surrounding what constitutes significant aesthetic improvement underscores the need for clear legislative guidance and standardization. In the context of EV batteries, remanufacturing's viability remains debatable, partly due to perceptions that remanufactured batteries may not meet the strict capacity specifications of new batteries.

The terms "repair" and "reconditioning" also exhibit a lack of clear distinction in the industry. "Repair" typically denotes the correction of specific malfunctions, whereas "reconditioning" involves modifying or replacing battery components to restore operational capacity [24, 25]. The absence of warranties common to new batteries in these processes highlights the necessity for legislative clarification. Defining these terms within Battery Directives, specifying the procedures that qualify as "repairing" or "reconditioning," and associating appropriate warranty levels could enhance standardization and consumer protection [21, 24].

"Remodeling" is defined as altering a battery's aesthetic aspects without enhancing its technical performance [24, 25]. Meanwhile, "recycling" involves extracting the battery's chemical components for use in new batteries or other products [25]. To clarify these processes, it's proposed to refine the definitions of "repair," "refurbishment," and "reconditioning," considering the product's warranty period and lifecycle to ensure legal framework alignment and maintain product safety and quality standards.

2.3. Legislative and Standards Framework for Second-Life EV Batteries

The rapid increase in EV adoption marks a crucial step towards reducing greenhouse gas emissions, aligning with global environmental preservation efforts. This trend elevates Lithium-Ion Batteries (LIBs) to the forefront as the preferred energy storage solution for EVs, thanks to their high energy density, durability, and low self-discharge rates. However, this surge in LIB usage also presents a significant environmental challenge at the end of their life cycle in EVs, necessitating effective end-of-life (EOL) management strategies. To address these challenges, the concept of repurposing spent EV batteries for secondary applications offers a promising solution. Such applications, requiring less stringent performance criteria compared to their initial use in EVs, not only extend the utility of these batteries but also contribute to environmental sustainability by minimizing waste. However, transitioning to this model requires overcoming several hurdles, including the higher likelihood of gas evolution in second-life batteries, which mandates rigorous testing and modifications to ensure safety in their new roles.

The legislative and technical framework for second-life batteries remains underdeveloped, lacking clear norms and guidelines for the safe and effective repurposing of EV batteries. The absence of well-defined standards, including terms like "second use," "reuse," "remanufacturing," "refurbishing," and "recycling," creates confusion and poses risks for the management of EV batteries at their EOL. Distinctions between these terms are crucial, with "reuse" typically referring to the employment of EV batteries or components for their original intended purpose without significant modifications.

US Regulatory Framework

The Inflation Reduction Act, made a significant pivot towards electric vehicle (EV) adoption through a federal tax incentive, underscoring a concerted move to solidify the domestic supply chain for lithium-ion EV batteries [26]. This legislative action, setting stringent conditions for the sourcing of critical minerals and battery components, marks a decisive step towards self-reliance, steering away from the existing dependency on international sources like China for battery materials. From a foreign perspective, the act's provisions for clean vehicle credits spotlight a proactive strategy to invigorate the U.S. automotive industry while addressing environmental concerns. The stipulation that by 2027, a substantial portion of the EV battery's critical minerals must be locally sourced or recycled within North America, escalates into a comprehensive requirement by 2029 for all battery components to be manufactured within the region [26]. This ambitious mandate not only challenges the current global distribution of mineral resources but also propels the U.S. towards a sustainable automotive future, potentially setting a global benchmark for environmental and economic policy in the EV sector.

Observations on the burgeoning infrastructure of recycling plants, particularly their strategic establishment in proximity to existing EV and battery production facilities, suggest a coherent ecosystem conducive to the circular economy. The projected capacity of these recycling plants (Fig. 3), significantly augmented by the announced expansions, indicates a robust readiness to address the recycling demands of the near future, reflecting a well-orchestrated response to the act's provisions.

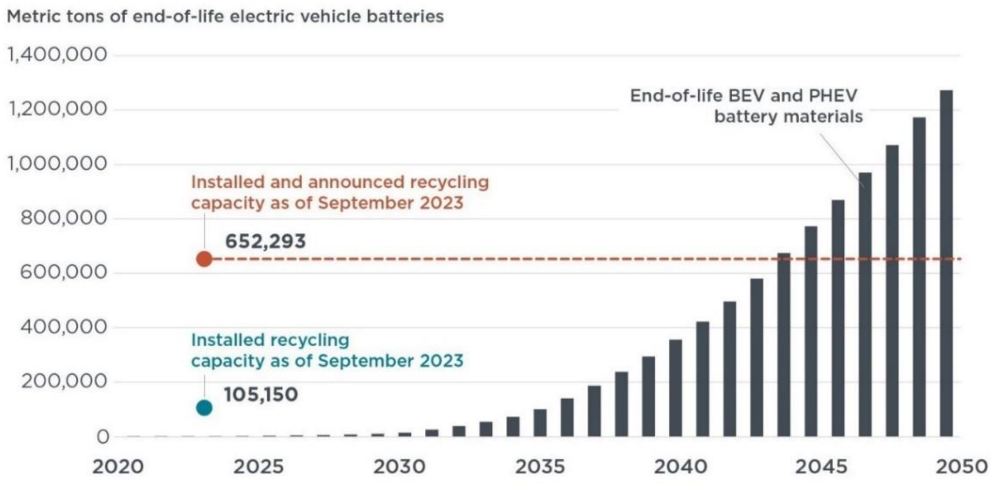

Figure 3. US Forecast of end-of-life BEV and plug-in hybrid electric vehicles (PHEV) battery materials towards 2050

In 1996, the United States implemented the 'Battery Act,' formally known as the Law for the Management of Rechargeable Batteries and Mercury-Containing Batteries [21]. This act delineates responsibilities for the disposal management of Nickel-Cadmium (Ni-Cd) and Small Sealed Lead Acid (SSLA) batteries, introducing specific requirements for labeling and recycling. However, it notably excludes Lithium-Ion Batteries (LIBs) and Nickel-Metal Hydride (NiMH) batteries from its regulatory purview, except in cases where these batteries contain hazardous heavy metals. This distinction underlines the need for ongoing legislative refinement to adequately address the diverse spectrum of battery technologies and their environmental and health ramifications, ensuring regulations keep pace with technological innovations.

LIBs, recognized for containing toxic components, fall under the Universal Waste Law's classification as hazardous waste. This classification obligates adherence to established protocols for their collection, treatment, and recycling to prevent improper disposal.

The regulatory landscape for second-life battery applications is complex and differs in local states (Table 1).

Table 1. Some policies and measures for batteries in USA [27]

Year	Regulation document	Outline
2006	California Cell Recycling Act	Establishing a system for collecting, recycling and proper legal disposal [28]
2010	New York rechargeable cell law	Providing free rechargeable batteries by manufacturer [29]
2014	Vermont main single-use cell law (Act 139)	Landfill of Ni-Cd and lead-acid batteries prohibition Subsidy collection and recycling of waste cells [30]
2018/2019	California AB-2832 Recycling: Lithium-Ion Assembly Bill 2832	Cost-efficient recycle or recovery of 100% waste LIBs Convening the Lithium-Ion Car Battery Recycling Advisory Group [31]
2022	The American Battery Materials Initiative Battery Safety Initiative for Electric Vehicles	First lithium-ion US battery recycling regulation Accelerating the development of the full end-to end battery supply chain
2023	Battery Safety Initiative for Electric Vehicles	Collecting and analyzing data related to EV batteries Investigating safety-related battery defects [32]

In 2019, the U.S. government initiated Recell, the country's first LIB recycling laboratory, led by Argonne National Laboratory [21]. This endeavor aims to bolster the recycling industry, enhance global competitiveness, and reduce reliance on imported raw materials for LIBs. Recell focuses on several key areas:

- Innovating recycling processes that permit the direct recycling of cathodes, enabling the reuse of recovered materials in batteries without costly reprocessing.
- Developing technologies to augment recycling profitability.
- Creating battery designs optimized for easier recycling and reuse.
- Employing computational tools for the modeling and validation of recycled batteries.

This legislative and developmental framework underscores a comprehensive approach to managing battery lifecycles, promoting environmental sustainability, and advancing the energy sector's infrastructure.

Asian Region: Policies of China, South Korea, and Japan

South Korea is distinguished by its stringent safety and recycling efficiency standards, highlighting innovative recycling methods. The country has implemented comprehensive safety protocols and cutting-edge technologies to ensure that battery recycling not only adheres to high safety standards but also achieves maximum efficiency. This approach reflects South Korea's commitment to sustainability and technological innovation in the battery recycling sector. South Korea stands out as an active participant in the second-life battery market, initiating a program in 2015 to support pilot projects using these batteries for stationary energy storage with backup capabilities [21, 33]. Alongside China, South Korea is a leading destination for recycling used batteries. In 2018, it was estimated that 69 % of the world’s recycled LIBs were processed in China, with South Korea accounting for 18.55 %. Contrary to the European model of producer responsibility, South Korean legislation under the Clean Air Law assigns the government the responsibility for battery recycling or reuse. The country is home to several enterprises, like Jeju Techno Park, which are engaged in pilot projects employing second-life batteries.

Japan concentrates on the legislative regulation of the collection and recycling of secondary batteries, promoting technologies that reduce environmental impact [21]. By implementing strict laws and regulations, Japan ensures that battery recycling processes are conducted responsibly and efficiently. The emphasis is on reducing the ecological footprint of battery disposal and recycling, thereby contributing to environmental conservation and sustainable development.

China has initiated strategic programs aimed at advancing battery recycling technologies and establishing guidelines for their utilization in secondary applications [21, 33, 34]. These initiatives are designed to streamline the recycling process, ensuring that batteries are reused in an environmentally sustainable and economically viable manner. The focus is on creating a circular economy for batteries, minimizing waste, and maximizing resource efficiency.

In China, the government is committed to overseeing the entire lifecycle of batteries, from production through to their eventual disposal, due to increasing amount of waste EV LIBs and new increment of EVs per year (Fig. 4).

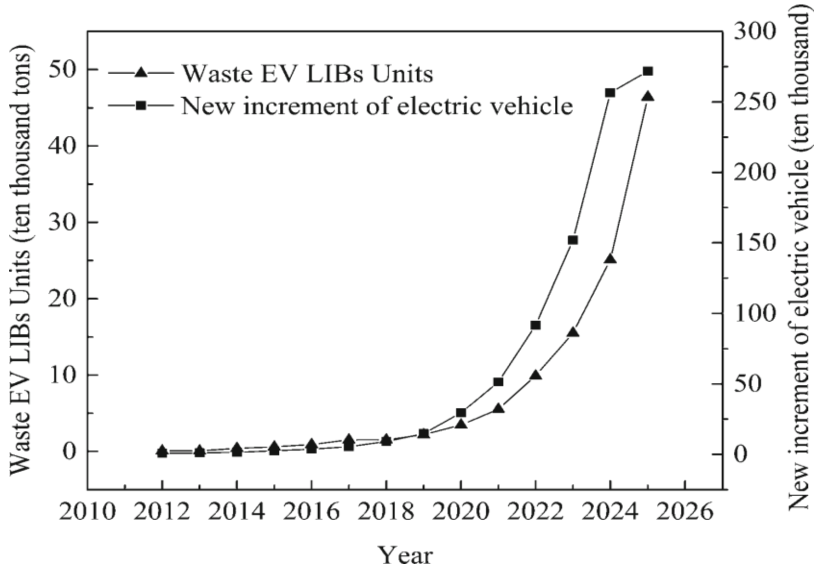

Figure 4. Increasing amount of waste EV LIBs and new increment of EVs in China [34]

In 2008, China introduced the Administrative Measures for the Prevention of Pollution (MAPP) [35] of electronic waste, implementing the producer responsibility principles to govern the disassembly, recycling, and disposal of electronic waste. Under MAPP, recycling operations require a government-issued operating license and must disclose information about hazardous components within batteries, including their composition, expected lifespan, and related environmental protection measures.

The Ministry of Industry in China has set forth regulations applying the Extended Producer Responsibility (EPR) concept to ensure electric vehicle (EV) manufacturers bear the responsibility for the collection, treatment, and disposal of batteries [21, 33]. EV manufacturers are required to set up service stations for the collection of used batteries, facilitating their storage and transfer to recycling facilities.

Battery manufacturers are tasked with automating and standardizing products to simplify disassembly and recycling processes [34]. Moreover, the government mandates battery manufacturers to equip EV producers with the necessary technical support for efficient battery storage and disposal. Research has explored various scenarios for the recycling process within the industry, analyzing the impact of government subsidies, the absence of subsidies, and the introduction of a reward and penalty system. The investigation categorizes policies into subsidies, punitive measures, and traceability, with subsidies promoting the shift from conventional to new energy vehicles, such as EVs, through financial incentives for buyers.

Punitive measures are designed to penalize battery or automobile manufacturers that fail to meet recycling and reuse targets or adhere to governmental policies [21, 34]. An example of this approach is the "Pilot Scheme for EV Battery Recycling System in Shenzhen," which sanctions companies that engage in fraudulent practices, withhold information, or neglect recycling duties. Traceability policies aim to monitor batteries throughout their lifecycle, ensuring accountability and supervision from production to disposal. Main policies and measures for batteries in China presented in Table 2.

Table 2. Some policies and measures for batteries in China [21]

Year	Regulation document	Outline
1957 (upd.in 1975, 1985, 2011 and 2015)	International transport of dangerous goods by road	Establishes requirements for the transportation of hazardous materials, including classification, packaging, labeling, and certification to minimize transport-related accidents.
1995 (upd. in 2015 and in 2016)	Law on the Prevention and Control of Environmental Pollution by Solid Wastes [36]	Enacted to mitigate pollution from solid waste, this law prohibits importing, dumping, and disposing of solid waste without a government-issued license.
2002 (updated in 2012)	Law on Clean Production Promotion	Focused on enhancing clean production, it provides financial incentives and possibly tax exemptions for small and medium-sized enterprises to adopt cleaner production methods.
2008	Waste Electrical and Electronic Equipment (WEEE) Pollution Prevention Administrative Measures (SEPA No. 40)	Aim to prevent pollution and health hazards from the disassembly, recycling, and disposal of electronic waste, demanding licensed operations for recycling activities.
2014	Interim Measures to Encourage the Purchase and Use of New Energy Vehicles in Shanghai	Offers financial incentives for recycling each EV battery, promoting the recycling industry.
2016	EV Battery Recycling Technology Policy [37]	Provides financial incentives to companies for second-use applications and material extraction, encouraging the development of recycling technologies.
2018	Circular Economy Promotion Law [38]	Aims to promote sustainable development by implementing a circular economy in companies, encouraging waste reduction, and efficient resource use, supported by fiscal and tax controls.
2018	Pilot Scheme for EV Battery Recycling System in Shenzhen	Introduces punitive measures for companies that fail to meet recycling obligations, aiming to enhance the recycling ecosystem's integrity.

This comprehensive legislative and regulatory framework in China underscores the nation's commitment to sustainable battery usage, recycling, and the broader objectives of environmental conservation and pollution prevention. Through these measures, China seeks to enhance the reuse of EV batteries, contributing to a more sustainable and responsible approach to electronic waste management.

European Union: From Battery Directive to Battery Passport

In the European Union (EU), concerted efforts are underway to streamline battery regulations and mitigate the environmental and societal impacts of batteries, culminating in the establishment of the Battery Directives. These directives mandate producers to oversee the collection and recycling of batteries, setting ambitious targets for collection rates and recycling efficiency across all battery types throughout Europe. Specifically, the European Battery Directives differentiate among portable, automotive, and industrial batteries, categorizing electric vehicle (EV) batteries as industrial, which diverges from the designation of "automotive" batteries as solely 12V lead-acid batteries used in EVs. This classification exempts EV manufacturers from the obligations of battery collection and recycling targets [21, 27, 33].

The directives necessitate battery manufacturers to retrieve and recycle used batteries, ensuring that EU Member States enforce measures allowing for the easy removal of batteries from EVs. Additionally, they require EV manufacturers to provide comprehensive information to EV owners regarding battery type, maintenance, safe removal, and disposal practices to prevent environmental and societal harm. While the directives permit batteries to be affixed permanently to EVs under specific conditions, such as product protection or when detachable batteries could compromise data integrity, performance, or safety, the overarching goal remains the conservation of resources and the reduction of waste.

EU Battery Regulation [39], entering into force in August 2023 and making the battery passport mandatory from February 2027, aims to enhance the sustainability, circularity, safety, and transparency of batteries across their entire lifecycle. This regulation, a component of the EU Green Deal [40], underscores the

EU's commitment to a sustainable circular economy and strategic action on batteries, marking a pivotal reform in the internal market by introducing the first digital product passport for batteries.

The Battery Passport serves as a linchpin in the EU Green Deal, harmonizing with both the Circular Economy [41] and Strategic Action Plans on Batteries [42] (Fig. 5).

This regulation, emerging as a groundbreaking reform within the EU's internal market, addresses the entire lifecycle of batteries and institutes the first digital product passport. The regulation, while broadly welcomed by stakeholders, has highlighted the necessity for addressing remaining challenges. It envisions the battery passport not only as a tool for regulatory compliance but as a potential harbinger of added value, contingent upon conditions beyond mere regulatory stipulations. The Battery Passport, as envisioned, aims to usher in an era of transparency and awareness, facilitating a pivot towards a circular economy and establishing a competitive and level playing field. It promises significant value across the entire value chain, from mining to end-users, by ensuring that all stakeholders are informed and can make decisions based on comprehensive data. The electronic record that the battery passport represents will encapsulate a detailed dossier of information gathered throughout the battery's lifecycle, with specifications laid out in Article 77 of the EU Battery Regulation [40]. Main policies and measures for batteries in EU presented in Table 3.

Table 3. Policies an measures for batteries in EU [27, 40, 43]

Year	Regulation document	Outline
2000	Instruction 2000/53/EC	Dismantling, recycling vehicles
2006	Directive 2006/66/EC [44]	Definition minimum collection objective, recycling objective and recycling rate Outspreading producer duty for cell producers and importers
2012	Instruction 2012/19/EC on WEEE [45]	WEEE action according to the rule of prevention, restoring and safety disposal
2013	Instruction 2013/56/EU	Limit the usage of Cd and Hg in portable cells
2016	Instruction (06/66/EC) [46]	Recycling rate of spent cells from 25 % up to 45 %
2018	Instruction 2018/851 [47]	Recommendation circular economy Achieving collection efficiency and recovery rate
2021	Fit for 55 [48]	Net reduction in greenhouse gas emissions surpassing the intermediate target of 55 % by 2030
2022	Batteries: deal on new EU rules for design, production [49]	Collection targets are set at 45 % by 2023, 63 % by 2027 and 73 % by 2030 for portable batteries, and at 51 % by 2028 and 61 % by 2031 for LMT
2023	Battery Regulation [39]	Provides a legal framework aiming to promote sustainability, circularity, ensure safety and improve transparency

Following the Battery Directive 2006/66/EC, the recycling process must achieve a minimum efficiency of 50 % for the materials used in LIBs and nickel-metal hydride batteries, with higher thresholds set for nickel-cadmium (75 %) and lead-acid (65 %) batteries [44]. To further advance the sustainability and circularity of battery usage, the European Commission introduced a new regulation in December 2020, known as the "Proposal for a Regulation on Batteries (PRB)," integrated into the Battery Directive [33]. This groundbreaking regulation establishes comprehensive collection and recycling targets, labeling requirements, and directives for the removal of batteries from vehicles. It notably prohibits the sale of batteries containing hazardous substances and encompasses all battery types, irrespective of their chemical composition, size, or design.

The PRB mandates the declaration of the recycled content of certain chemicals in batteries by January 2027, setting ambitious recycling targets for cobalt, lead, lithium, and nickel to increase significantly by 2035 [21, 33]. This initiative represents a significant step in promoting battery sustainability, safety, transparency, and the transition to a circular economy, ensuring that batteries entering the European market meet stringent safety and environmental standards.

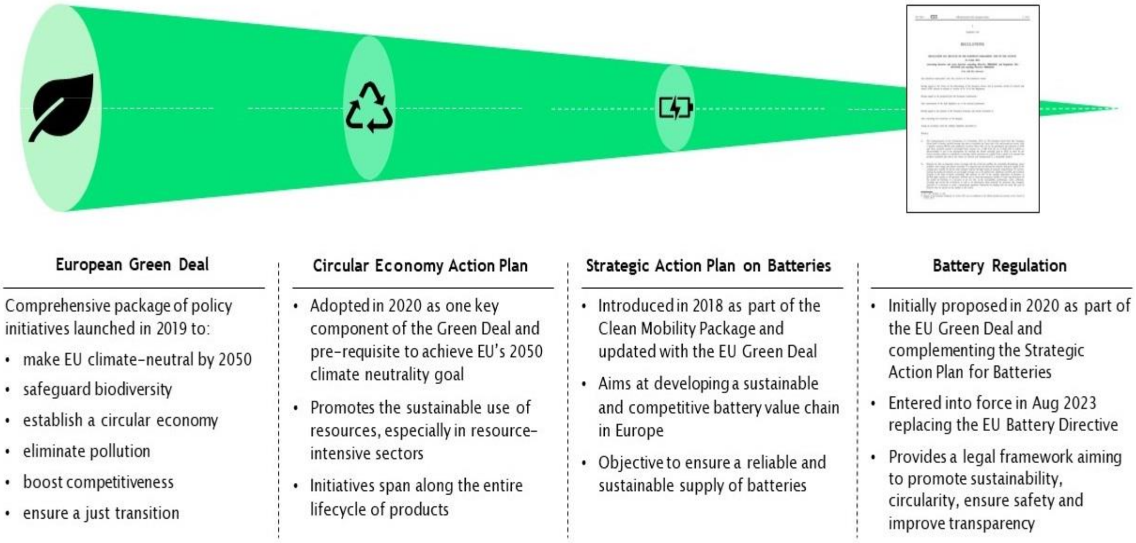

Figure 5. The 2023 Battery Regulation as a part of the EU Green Deal: complementing both the Circular Economy and Strategic Action Plans on Batteries [50]

EU Battery Regulation mandates a comprehensive data attribute set for the battery passport, as detailed in various articles and annexes, and groups these data attributes into seven clusters for a structured approach [39]. The guidance on content requirements aims not just at compliance but at promoting sustainability and circularity, addressing the entire battery value chain and suggesting a framework for the systematic collection and management of battery data. It outlines specific responsibilities for economic operators and delineates a framework for access and data management, underscoring the regulation's role in promoting a sustainable, circular, and low-carbon future.

This regulation was met with broad support from various stakeholders, although it was recognized that further challenges need to be addressed. The battery passport, as a novel digital product passport (DPP) in the EU, exemplifies a significant instrument for advancing the European Twin Transition by providing transparency, facilitating the shift to a circular economy, and establishing a level playing field across the battery value chain. This innovative approach aims to unlock significant value, offering comprehensive lifecycle information to ensure regulatory compliance, and foster sustainability and circularity in the rapidly evolving battery industry.

Initiatives in Other Regions

India

India is at a critical juncture in its journey toward sustainable energy, focusing on integrating second-life lithium batteries for energy storage. This aligns with the ambitious goal of a 4 GWh Battery Energy Storage Systems (BESS) project by 2030, highlighting the benefits of sustainable resource management and a circular economy [51]. The government's commitment is evident in the National Framework 2023, promoting advanced energy storage, including second-life batteries, with substantial financial backing. This approach supports India's renewable energy targets and offers economic growth opportunities through investment in the second-life battery sector.

Africa

Africa, with many regions facing extreme poverty, views electricity as a key driver for economic development. The continent's frequent power outages highlight the potential benefits of integrating second-life batteries into systems to enhance energy reliability and availability. Initiatives such as the Faraday Battery Challenge project assess the economic feasibility of using second-life batteries in energy storage systems combined with photovoltaic setups for households in Kenya, aiming to bolster local energy infrastructure and support regional development [33].

Australia

The regulation of lithium battery installation in Australian and New Zealand RVs is detailed in the AS/NZS3001.2:2022 standard, effective from November 2023 [52]. It encompasses lithium battery minimum specifications, safety approvals, monitoring, and installation requirements like exclusion zones and venting. Specifically, it mandates a battery management safety system for each lithium-ion battery, adhering to AS IEC 62619, to safeguard against damage and ensure safe operation under normal and misuse conditions, emphasizing the importance of comprehensive certification for both battery cells and the battery management system.

Latin America

Latin American countries possess a detailed framework for solid waste management, yet face challenges in collecting and recycling EV batteries, leading to approximately 55 % of battery waste ending up in landfills. While nations like Brazil, Chile, Colombia, Paraguay, and Peru have established regulations for recycling lead-acid batteries, the recycling of LIBs remains a significant hurdle due to the absence of appropriate industrial facilities [21, 33]. Consequently, EV batteries are often exported to Europe and the USA for processing. Despite these obstacles, there is a keen interest across the region to adopt principles of producer responsibility and to establish e-waste collection and recycling programs. Given the vast territories and favorable conditions for alternative energy sources like photovoltaics and wind power in countries like Brazil, business models that combine second-life batteries with renewable energy systems present promising and economically viable opportunities for the region.

3. Results and Discussions

Battery Regulation in Ukraine: Main Aspects and Future Tasks

In Ukraine, the development of energy storage system regulations is encapsulated in Law 2046-IX, effective from February 15, 2022 [53]. It focuses on fostering energy storage technologies, defining "energy storage" as the capture of electrical energy for deferred use, its conversion into other forms for storage, and its re-conversion into electrical energy for output into the grid. The law aims to enhance grid reliability, enable economic benefits through strategic energy purchasing and selling, and provide balancing services in the electricity market. It also addresses environmental concerns by minimizing imbalances for renewable energy producers. Amendments to the "Electricity Market Law" regulate energy storage activities, including licensing requirements.

Furthermore, Ukrainian legislation mandates the safe disposal and recycling of batteries and accumulators due to their hazardous waste classification, containing toxic elements like cadmium, mercury, lead, and dangerous electrolytes. The "Waste Law" [54] governs waste formation, collection, sorting, transport, storage, treatment, recycling, and disposal, ensuring environmental safety and human health protection. The "Chemical Power Sources" specifically regulates the disposal and recycling of batteries over 7 Ah, detailing responsibilities for usage, collection, and utilization, including an ecological tax on users of chemical power sources.

Despite these regulations, there's a noticeable gap in comprehensive policies for the recycling and second-life application of batteries, highlighting a need for detailed guidelines on recycling standards, second-life usage certifications, and incentives for recycling industries to align with global practices and further promote a circular economy.

How European Battery Regulation impacts Ukraine

The European Union's regulatory framework on batteries and the introduction of a battery passport represent significant strides toward ensuring that batteries are sustainable, safe, and circular throughout their life cycle. For Ukraine, a country with a rapidly growing secondary market for EVs and an increasing focus on renewable energy sources, these developments have far-reaching implications. This analysis explores how the European battery regulation and battery passport system might impact Ukraine, outlining potential consequences and necessary actions.

1) Adoption of Best Practices in Battery Lifecycle Management: With the EU setting stringent standards for battery production, use, recycling, and second-life applications, Ukrainian businesses and regulators might be prompted to adopt similar best practices to align with European norms. Ukraine could proactively adopt parts of the EU's battery regulation framework, especially concerning sustainability and recycling standards, to facilitate smoother trade relations and technological transfers with the EU.

2) Enhanced Focus on Sustainability and Circular Economy: The EU's focus on circular economy practices in battery management underscores the need for Ukraine to consider environmental impacts across the battery lifecycle. Development of national regulations and incentives for the adoption of circular economy principles in battery use, including measures to encourage battery reuse and recycling.

3) Consequences and Actions Related to the Battery Passport System: The battery passport system will enhance traceability and transparency for batteries in the EU market. Implementing systems to track and report on battery health, usage, and recycling history, aligning with the battery passport requirements.

4) Need for Technical and Regulatory Infrastructure: The successful implementation of a battery passport system in Ukraine will require significant investments in technical and regulatory infrastructure. Investing in technology and training for monitoring and certifying battery life cycles, as well as developing legal and regulatory frameworks that support the system's requirements.

5) Broader Implications for Ukraine: To maintain and enhance its trade relations with the EU, Ukraine may need to align its battery production and recycling standards with those of the EU, which could involve substantial regulatory and industry shifts. The EU's regulation encourages the development of battery recycling facilities and second-life applications. Ukraine could seize this as an opportunity to invest in these sectors, promoting environmental sustainability and creating new business models. For Ukrainian businesses operating in or with the EU, understanding and complying with the new regulations will be crucial. This may require closer collaboration between Ukrainian authorities, businesses, and European partners to ensure seamless integration of the standards.

Thus, the European Battery Regulation and the introduction of the battery passport system present both challenges and opportunities for Ukraine. Proactive engagement, investment in necessary infrastructure, and alignment with EU standards will be key for Ukraine to leverage these developments, promoting sustainable energy and circular economy practices within its borders.

Challenges and tasks in the legislative framework for repurposing EV batteries in Ukraine

In Ukraine, the burgeoning secondary market for EVs is a testament to the country's growing commitment to sustainable transportation as well as development of Microgrids [55, 56], RES [57–61], distributed generation [62–64], Smart Grids [65–68] and Circular Economy principles [69, 70]. However, this rapid adoption also brings to the forefront the imminent challenges associated with the second life and recycling of EV batteries. Given the pace at which the EV market is expanding, Ukraine is likely to face these challenges sooner than some other nations, emphasizing the urgent need for comprehensive legislative support and standardization.

The development of a robust legislative framework is crucial to address the complexities surrounding the reuse and recycling of EV batteries. This framework should encompass challenges and tasks as shown in Fig. 6.

Ownership and Liability: Clear definitions around the ownership of EV batteries at the end of their first life, including liability for recycling and repurposing.

Health and Safety Standards: Regulations ensuring that second-life battery applications meet strict safety and performance criteria to protect consumers and the environment.

Recycling Protocols: Guidelines for the efficient and environmentally friendly recycling of batteries, minimizing waste and promoting the recovery of valuable materials.

Standardization in Battery Assessment: Creating unified methods for evaluating the state of health of used EV batteries, facilitating their safe and effective repurposing.

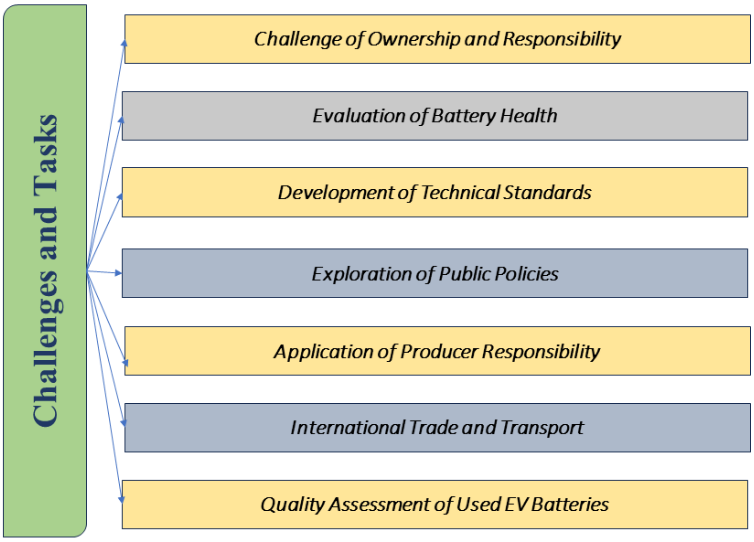

Figure 6. Main challenges and tasks for future battery regulation in Ukraine

Interoperability: Ensuring that repurposed batteries can be easily integrated into various energy storage systems, enhancing their utility and market value.

Quality Assurance: Implementing standards for the performance and longevity of second-life batteries, fostering trust and reliability among consumers and investors.

Ukraine's well-developed secondary EV market accelerates the urgency to address these legislative and standardization needs. Without prompt action, the country risks encountering significant obstacles in managing the lifecycle of EV batteries, potentially hindering its progress towards sustainable energy goals. Therefore, it's imperative for stakeholders across the industry, including policymakers, manufacturers, and recycling entities, to collaborate on developing a cohesive strategy. This approach will not only solve the immediate challenges of battery second life and recycling but also position Ukraine as a leader in sustainable transportation and energy storage solutions on the global stage.

The integration of SLBs into the power sector offers a multifaceted solution to environmental, economic, and technological challenges in achieving sustainable power systems. However, realizing their full potential necessitates comprehensive legal and regulatory support tailored to the unique aspects of SLBs. Legislation should address the entire lifecycle of EV batteries, from initial use through to repurposing and recycling, promoting practices that ensure environmental safety, economic viability, and technological efficiency.

For effective integration, laws and standards must encourage the repurposing of EV batteries through incentives and subsidies for projects utilizing SLBs, define clear standards for the assessment, refurbishment, and certification of SLBs to ensure their safety and reliability, foster innovation and investment in SLB technologies and business models through supportive policies and funding mechanisms.

By addressing these legal and regulatory needs, governments can facilitate the sustainable integration of SLBs into the energy ecosystem, enhancing the resilience and sustainability of power systems worldwide. For Ukraine, aligning with such standards, especially those emerging within the EU, could significantly bolster its aspirations for energy sustainability and European integration, setting a precedent for environmental stewardship and technological innovation.

4. Conclusions

This article has delved the evolving landscape of EV Li-ion batteries within the circular economy, highlighting the significant legislative initiatives across different countries and drawing special attention to the developments within Europe, given Ukraine's aspirations towards European Union (EU) membership. Based on these discussions, recommendations for Ukraine are outlined, considering the key challenges and standards identified.

EV Li-ion batteries represent a pivotal component of the circular economy, serving as a crucial link between renewable energy utilization and sustainable transportation. The transition towards a circular model for EV batteries involves not only extending their lifecycle through repurposing and recycling but also ensuring that such processes are economically viable and environmentally sound. This shift is essential for mitigating the environmental impact associated with battery production and disposal, fostering a sustainable automotive industry.

Globally, legislative initiatives addressing the recycling and second-life applications of EV batteries vary significantly. While countries like China, South Korea, and Japan have introduced comprehensive programs focusing on recycling technologies, safety standards, and environmental protection, the approaches differ in scope and emphasis. China's strategic programs for battery technology development, South Korea's focus on safety and recycling efficiency, and Japan's regulatory framework for collection and recycling demonstrate diverse strategies to manage battery lifecycle and environmental impact.

In Europe, the push towards sustainable battery management is characterized by robust regulatory frameworks such as the EU Battery Directive and the proposed Regulation on Batteries and Waste Batteries. These initiatives aim to establish stringent collection targets, enhance recycling efficiencies, and promote the safe disposal of batteries. The introduction of the battery passport under the new EU Battery Regulation exemplifies Europe's commitment to transparency, sustainability, and the circular economy. For Ukraine, aligning with these European standards presents an opportunity to integrate into a broader sustainable framework, enhancing environmental stewardship and economic competitiveness. Considering the global and European legislative landscape, the list of recommendations are proposed for Ukraine, such as to develop comprehensive legislation, to adopt European Standards, to invest in recycling infrastructure as well as to promote public-private partnerships.

In conclusion, as the global shift towards electrified transportation accelerates, adopting a circular economy model for EV Li-ion batteries becomes imperative. For Ukraine, leveraging legislative examples from around the world, especially Europe, and implementing tailored recommendations can foster environmental sustainability, economic growth, and closer alignment with EU standards and practices.

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СВІТОВИЙ ДОСВІД ЗАКОНОДАВЧОГО РЕГУЛЮВАННЯ ЩОДО ЛІТІЙ-ІОННИХ БАТАРЕЙ ЕЛЕКТРОМОБІЛІВ З УРАХУВАННЯМ ЇХ ВТОРИННОГО ЗАСТОСУВАННЯ В ЕНЕРГЕТИЧНОМУ СЕКТОРІ

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Анотація. *Розуміння та врахування глобального регуляторного досвіду та стандартів, пов'язаних з управлінням акумуляторами, має першорядне значення, особливо при розгляді швидкої еволюції ринку електромобілів (EV) та її наслідків для зберігання енергії та сталого розвитку. Це особливо актуально для України, де зростаючий вторинний ринок електромобілів та жвавий інтерес до відновлюваних джерел енергії підкреслюють необхідність проактивного формування політики та стандартизації для вирішення проблем, пов'язаних із вторинним терміном служби акумуляторів та їх переробкою. У цій статті розглянуто роль літій-іонних акумуляторів для електромобілів у контексті економіки замкненого циклу, підкреслено важливість законодавчої бази в усьому світі з особливим акцентом на європейських ініціативах у світлі інтеграційних амбіцій України до ЄС. Це включає в себе продовження терміну служби акумуляторів за рахунок переробки та повторного використання, тим самим забезпечуючи як економічну життєздатність, так і мінімальний вплив на навколишнє середовище. Оглянуто різноманітні законодавчі підходи на міжнародному рівні, відзначено відмінності в стратегіях від акценту на технологіях і безпеці в Азії до надійних регуляторних директив Європи, спрямованих на управління життєвим циклом акумуляторів. У Європі прагнення до сталого використання акумуляторів відзначається всеосяжною політикою, такою як Директива ЄС про акумулятори та новий Регламент про батареї та відпрацьовані батареї, які встановлюють амбітні цілі переробки та впроваджують інноваційні концепції, такі як паспорт акумулятора. На основі даного огляду представлено низку рекомендацій для України, які пропонують розробити широке законодавство про управління акумуляторами, прийняти європейські стандарти для спрощення шляху до членства в ЄС, інвестувати в інфраструктуру переробки, сприяти державно-приватному партнерству та ініціативам з підвищення обізнаності громадськості. Ці рекомендації покликані підвищити позиції України в секторі сталого розвитку, сприяючи дотриманню екологічних принципів та економічній конкурентоспроможності. Підкреслено зростаюче значення вторинних літій-іонних акумуляторів електромобілів у підтримці та гармонізації відновлюваних джерел енергії та, відповідно, необхідність адекватного законодавства та стандартизації для підтримки економіки замкненого циклу*.

Ключові слова: літій-іонні батареї, вторинне застосування, життєвий цикл акумуляторів електромобілів, циркулярна економіка, перепрофілювання, повторне використання, переробка, стандарти, регулювання, законодавство.

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