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Review

Towards to Battery Digital Passport: Reviewing Regulations and Standards for Second-Life Batteries

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Abstract: Greenhouse gas emissions from transportation harm the environment. In response to these environmental concerns, numerous countries encourage the adoption of electric vehicles (EVs) as a more environmentally friendly option than traditional gasoline-powered vehicles. Advances in battery technology have made batteries an alternative solution for energy storage in stationary applications and for electric mobility. Reduced lithium-ion batteries (LIBs) production costs due to economies of scale, electrode material and cell design developments, and manufacturing process improvements have driven this success. This trend is expected to increase the number of LIBs on the market that may be discarded in the environment at the end of their useful life if more sustainable alternatives are not technologically mature. This coming environmental concern can be mitigated by collecting wasted EV batteries, reconfiguring them, and reusing them for applications with less stringent weight, performance, and size requirements. This method would extend battery life and reduce environmental effects. The present work investigates the main regulatory structures of the second-life battery industry that require rules, technical standards, and laws. To achieve this objective, a systematic review was carried out following a strict protocol that includes identifying relevant studies, extracting data and information, evaluating, and summarizing information. This paper explains the primary rules and technical standards governing the second-life battery business. The findings highlight the need for universities, research institutions, and government agencies to evaluate the second-life battery industry objectively. This would enable the creation of new technological regulations and laws for this burgeoning industry.

Keywords: second use; reuse; lithium-ion batteries; second-life batteries; standards; technical standards; regulations; battery passport; legislation; circular economy

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Citation: Rufino Júnior, C.A.; Riva Sanseverino, E.; Gallo, P.; Koch, D.; Diel, S.; Walter, G.; Trilla, L.; Ferreira, V.J.; Pérez, G.B.; Kotak, Y.; et al. Towards to Battery Digital Passport: Reviewing Regulations and Standards for Second-Life Batteries. *Batteries* **2024**, *10*, 115. https://doi.org/10.3390/batteries10040115

Academic Editor: Claudio Gerbaldi

Received: 8 June 2023
Revised: 4 March 2024
Accepted: 20 March 2024
Published: 26 March 2024

1. Introduction

In recent years, the automotive industry has observed a growing interest in electric vehicles (EVs) as an alternative to replacing conventional vehicles with internal combustion engines, primarily due to their potential to reduce greenhouse gas emissions and mitigate the effects of climate change. This interest has been driven by developments in EV technology, including battery performance, power electronics, and motor efficiency. In addition, government policies and incentives designed to promote the adoption of low-emission vehicles have contributed to the expansion of the market for EVs.

The ability of EVs to reduce CO_2 emissions depends on the source of electricity used to power them, with electricity from renewable sources, such as solar or wind, offering the most significant environmental benefit [1]. Therefore, the increasing adoption of this type of vehicle is motivated—among other factors—by the need to decarbonize the energy transportation sector and is associated with the decrease in the cost of lithium-ion batteries (LIBs) [2–5].

Batteries face an inevitable reduction in their efficiency and storage capacity over time, directly affecting their energy production capacity [6–8]. Due to reduced battery capacity, Original Equipment Manufacturer (OEM) recommendations for EVs generally suggest replacing the battery when its capacity is reduced to about 70–80% of its rated capacity.

Due to reduced battery capacity, OEM recommendations for EVs generally suggest replacing the battery when its capacity is reduced to about 70–80% of nominal capacity [9–11]. Upon reaching the end of their useful life, these batteries no longer meet three critical performance metrics: energy transfer rate efficiency, which impacts the vehicle's acceleration, the time required for a complete recharge, and the maximum distance that the vehicle can travel on a single charge, significantly limiting its functionality and effectiveness [11].

After reaching the end of their useful life in EVs, batteries can be placed into a secondary application through reuse [12–15], reassembled [16], recycled [5,17–19], or disposed of in landfills. Notably, batteries contain heavy and toxic elements that pose significant hazards to environmental integrity and human health, such as cadmium (Cd), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn). Due to the potential for soil contamination and the heightened environmental impact, landfill disposal is deemed unacceptable [20].

Recycling is an alternative technique for these problems that involves extracting the chemical components from batteries. However, given the current level of technological maturity, this process remains prohibitively expensive, implying that substantial technological improvements are required to improve its economic feasibility [12,21].

In this context, reusing batteries becomes an alternative to postponing the recycling phase. For example, the second-life batteries can be used in less demanding grid applications such as peak shaving, frequency regulation, voltage regulation, charging stations for EVs, and short-range cars (e.g., trucks and golf carts) [12,22,23].

Second-life batteries have a competitive price, performance, and service life compared to other battery technologies, such as lead–acid batteries used in stationary applications [10,12,24]. The battery cost is approximately 50% of the EV cost, which makes the battery the most expensive component of this type of vehicle [25–28]. Therefore, reducing the initial cost of batteries through reuse can make the price of EVs more commercially competitive and increase the penetration of EVs in the market. The potential of second-life batteries to reduce the price of new batteries lies in the ability of this product to reduce the need for new materials associated with battery production costs, including mining, refining, and manufacturing. Furthermore, reusing batteries extends the value extracted from the battery, which can spread the manufacturing cost over a more extended period and applications. Consequently, the cost per use will be reduced [29].

The market for reused batteries is relatively new and has been driven by the development of new policies and strategies developed by government agencies. Policies that encourage the reuse of batteries are essential to reduce the uncertainties in this market and may occur through federal and state tax credits, discounts, and other financial support. Therefore, the legislation impacts the construction of business models, and each aspect is essential when considering the technical and economic feasibility of the second use, reuse, and recycling of batteries [29,30].

Currently, several nations lack the necessary infrastructure to carry out battery recycling processes. These countries may not have the necessary technological components, financial resources, or logistical capacity to recycle many batteries. Therefore, these nations should not export their waste batteries to other regions with recycling capacity [31].

It is essential to mention that the translocation strategy, despite being seen as a short-term contingency measure for small companies to manage large amounts of battery waste, is prohibited in most countries. Furthermore, this solution is not economically viable for larger quantities in the medium and long term. This lack of sustainability results from the high transportation costs, the present stage of development of specialized recycling companies, and the immaturity of the recycling process itself [32]. Moreover, due to the hazardous nature of this type of waste, the transportation of second-life batteries requires special precautions. Multiple jurisdictions prohibit the exportation of such electronic devices to prevent developing nations from becoming significant electronic waste dumping grounds [33].

It is essential to mention that legislation and technical standards focusing on second-life batteries are limited. Despite the growing number of public policies, regulations, and technical standards proposed in recent years, there are still some questions in the literature that require attention:

1. Who will own the batteries at the end of their life?
2. What test procedures can be performed to diagnose the State of Health (SoH) and ensure the quality of second-life batteries?
3. What technical standards exist and can be applied to second-life batteries?
4. What public policies encouraging the second-life battery market have been adopted in the European Union (EU), the United States of America (USA), and China?
5. Can the principle of producer responsibility be applied to second-life batteries? Is it possible to transfer ownership of the batteries to third parties, and if so, under what circumstances?
6. Can second-life batteries be imported/exported?
7. Is there a possibility of transporting batteries between countries? If so, under what conditions?

To answer these questions, the present work aims to analyze the similarities between the technical standards proposed in the world and the need to elaborate or adapt new standards and harmonize the existing standards in different countries. This work also investigates possible regulatory and legislative barriers for the second-life battery market at the European and international levels.

2. Concepts and Definitions

Batteries are difficult to regulate due to their heterogeneous composition, which includes a variety of chemistries, sizes, and applications. Thus, the absence of precise and common terminologies can cause more than one understanding, which results in inconsistent practices in managing, recycling, and disposing of materials.

Many countries and economic blocs have legislation on battery waste disposal that can be ambiguous due to unclear terminology. These ambiguities can cause conflicts of interest between different stakeholders, including manufacturers, recyclers, regulators and the public.

Therefore, this section discusses the main ambiguities that exist in the legislation of many countries or economic blocs that can cause conflicts of interest and must be clarified in order to prevent end-of-life batteries from being discarded in inappropriate places, environmental accidents and inefficient recycling. The following key terms and concepts are described in the following sections to facilitate a comprehensive understanding of the analysis of existing regulations and standards and suggest adjustments and harmonization efforts.

2.1. Understanding Regulations, Directives, and Standards in the Battery Industry

Regulations are legally enforceable directives established by governmental or regulatory bodies to ensure safety, reliability, and compliance. Technical standards are detailed documents outlining specifications for products, services, processes, materials, and systems to ensure quality, interoperability, and safety. Familiarity with these terms is crucial for understanding the legal and operational frameworks within which second-life batteries operate. Laws in Europe are established in the form of regulations or directives. Regulations, which are mandatory, consist of rules governing procedural details or orders issued by the government and enforced by law. In addition, a 'directive' outlines a specific objective, similar to a regulation, but unlike regulations, it does not prescribe a specific method for achieving its goals. Instead, it grants individual member states the autonomy to determine the most suitable mechanisms and establish the necessary national legal instruments. This autonomy inevitably results in varying execution strategies among member states, even when working towards a common goal. The battery industry relies on these rules to ensure interoperability between products and services, a crucial aspect of innovation and competitiveness in the global market.

On the other hand, standards are technical guidelines that establish quality, safety, and effectiveness benchmarks. Standards can constitute barriers that restrict companies from entering the market and can also protect the interests of industries in the sector. In contrast, standards can promote harmonization and market integration of companies, uniform production methodologies, and extensive adoption of sustainable production methods. As with the GB standards, China is the only country with legal relevance and immediate application. In some other countries, legal standards only have legal relevance when referenced in legislation, as in the EU when referenced in a regulation or directive [34].

In turn, the accepted industry guidelines reflect the accumulated experience of professionals and specialists in each industry. The accepted industry synthesizes best practices, which are crucial to avoiding common mistakes and optimizing processes. Without understanding these guidelines, companies can waste resources or even put customers at risk. Political frameworks delineate the future that political entities aspire to or anticipate, owing to their visionary nature. Entities that fail to comprehend these frameworks may fail to seize opportunities for strategic alignment or exploit political incentives.

Lastly, administrative provisions are instrumental. Administrative provisions translate laws into practical actions, ensuring they are applied consistently and fairly. Without understanding these provisions, an organization may inadvertently find itself out of favor. Figure 1 summarizes the definition of laws, technical regulations, federal norms, and standards.

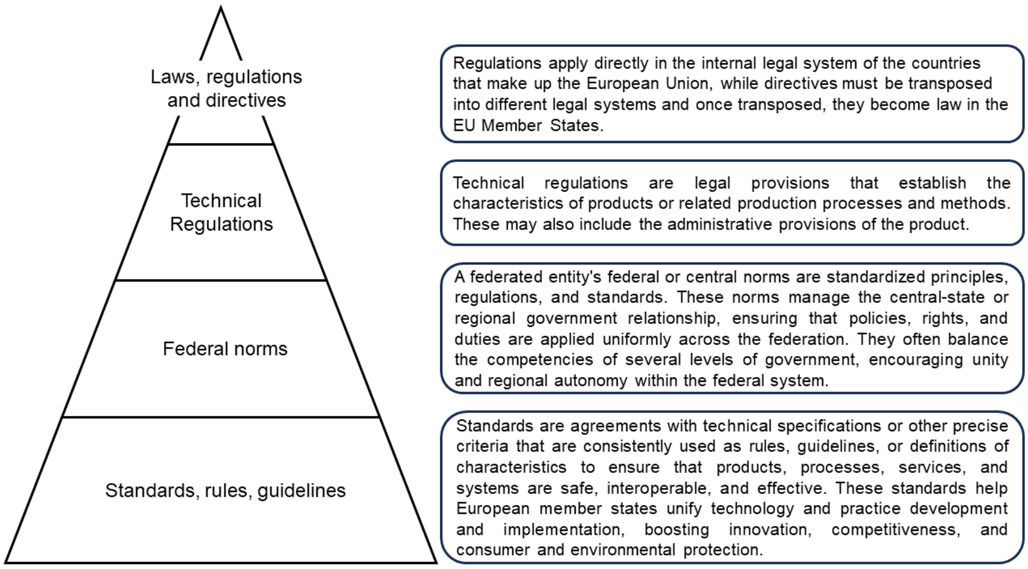

Figure 1. Definition of laws, technical regulations, federal norms, and standards.

2.2. Ambiguities in Defining and Managing End-of-Life EV Batteries

The literature contains several legislations and technical standards that do not present a definitive and precise interpretation of the word "*second use*". Therefore, there is still a precise definition of this specific term in the legislation and technical standards of several countries. The lack of clearly defined terms such as "*reuse*", "*second use*", "*refurbishing*", and "*recycling*" can create significant challenges for industry stakeholders and compromise the future management of end-of-life batteries.

According to the literature, distinguishing between "*second use*" and "*reuse*" is very important. The term "*reuse*" is commonly interpreted as a procedure in which EV batteries or non-waste components are used for their original intended function, namely EV operation [35,36]. Another definition of "*reuse*" described in [37] summarizes the concept as "*the straightforward application of a product with no modifications*". The definition described in [37] differs from the view offered in the Battery Directive. The authors neglect to consider the end application for which the battery will be utilized.

In contrast, the Battery Directive provides a more extensive explanation, indicating that "*reuse*" occurs when the product is deployed for its original purpose. Moreover, second use, also known as second life, refers to repurposing a product or its components for a different purpose, application, function, or setting [38]. However, it is crucial to note that the definitions presented in the battery directives are unclear and often confused by industry and academia sectors. Misinterpretation of the terms "*reuse*" and "*second use*" may lead a manufacturer to believe that "*reuse*" involves retrofitting a new EV with a used battery without the necessary certifications, upgrades, or checks. If an unforeseen incident occurs, such action could expose the vehicle to legal liability and compromise safety. Therefore, the Battery Directives must include a legislative alignment toward a uniform set of standards relevant to end-of-life EV battery management to alleviate industry conflicts and ensure a sustainable future for these batteries.

The concept of "*remanufacturing*" has been explained as follows in [39]: "*The largely aesthetic improvement of a product, which may involve making it look like new, with limited functionality improvements*". However, it is not clear what is considered a significant aesthetic improvement of the product. The typical market scenario for remanufactured EV batteries includes a one-year warranty from the remanufacturing entity. Remanufacturing may be a viable option for batteries with diminished capacity. However, the feasibility of this procedure for automotive batteries is questionable, according to the available literature [37]. This is primarily due to the perception that remanufactured batteries may not meet the exact capacity specifications of brand-new batteries. If suppliers or recycling firms lack comprehension of the necessary specifications for *"remanufacturing"*, there is a risk of improper execution of the process, producing substandard or hazardous goods. In remanufacturing processes, it is essential to consider the need for legislative guidance and standardization. Without a clearly defined legal framework, the safety and quality of remanufactured batteries may vary. Therefore, establishing standards and protocols for remanufacturing, perhaps as part of the Battery Directives, could assure dependable, safe, and sustainable products while promoting resource conservation and waste reduction.

Within the scope of the EU Battery Regulation, the term "*remanufacturing*" is defined as processes aimed at restoring the energy capacity of batteries to a minimum level of 90% of their original nominal capacity. Additionally, it is established that the health status of each battery cell must be uniform, with a maximum variation of 3% allowed between cells, allowing the battery to be reused both for its original purposes and for alternative applications. This process requires the disassembly and careful analysis of all battery modules and cells and the incorporation of new, used, or recovered cells and modules or other components to reconstitute the battery's functional capacity. Although the EU Battery Regulation has provided advances in the conceptualization of "remanufacturing", current legislation lacks clarity regarding the specific operations necessary to restore batteries effectively. Furthermore, new performance, durability, and safety criteria must be considered. Legislation could provide specific details on what data must be recorded in the battery passport and whether the battery passport must be linked to the battery passport of the original product or whether a new battery passport must be provided. The Ecodesign for Sustainable Product Regulation (ESPR) [40] suggests that the battery placed on the market after the remanufacturing process must have a commercial guarantee [41]. However, the EU battery regulation and the ESPR do not define the minimum warranty period for a remanufactured battery [41].

There is terminological ambiguity between the terms "*repair*" and "*reconditioning*" in the industrial sector. According to existing literature, "*repair*" is typically defined as the correction of one or more malfunctions, whereas "*reconditioning*" refers to the modification or alteration of individual battery components to restore the battery's operational capacity [37,39]. In both procedures, however, the assurance typically associated with a new battery, such as a warranty, is typically absent.

The concept of "*repair*", as defined in reference [40], is characterized by the restoration of defective products or discarded materials to a state that meets the requirements for intended use, as elucidated in [41]. In [41], the authors broaden the interpretation of the term "*repair*" to include, in the context of used batteries, the preparation for reuse, as well as the application of batteries that do not classify as waste, for reuse purposes, implying different considerations for registration in the battery passport. However, the need for a more precise and comprehensive definition of the criteria that determine a battery's suitability for its intended use is highlighted. Such specification is vital to establish clear guidelines that regulate the conditions under which batteries can be considered suitable for repair, aiming for their effective and safe reintegration into use cycles. The absence of detailed criteria presents a challenge for implementing consistent repair practices and evaluating the compliance of repaired batteries with the performance and safety standards required for their reuse.

If, in the context of LIBs, "*repair*" is interpreted as simply correcting a specific defect, such as replacing a faulty cell, while "*refurbishment*" refers to a broader process, such as replacing multiple cells, cleaning the electrolyte and updating the battery management system, and "*reconditioning*" involves a complete restoration of the battery so that it reaches nearly its original capacity and performs like a new unit, you can see how the confusion between these terms can create problems. If a customer ships an EV battery expecting a complete "*recondition*" but receives a battery that has only undergone a specific "*repair*", this discrepancy can result in customer dissatisfaction and impact quality and cost expectations. Likewise, a supplier that believes it is merely "*repairing*" a specific battery cell may be surprised when the customer expects a "*reconditioned*" battery with performance close to that of a new one. Furthermore, clarity is needed regarding when new certification must be provided for the product after the "*repair*", "*refurbishment*", and "*reconditioning*" process.

The legislative framework could benefit from clarifications regarding the ambiguity of these terms. It is essential to establish a clear, standardized definition within the relevant Battery Directives that outlines the criteria for each process, possibly outlining what procedures constitute "*repairing*" or "*reconditioning*" and what warranty levels, if any, should be associated with each. It is essential to define who is responsible for collecting and for a defect in the battery if this product is remanufactured or refurbished and returned to the market. Lack of clarity can lead to disputes over warranty responsibilities between original manufacturers and remanufacturing companies. Furthermore, customers, manufacturers, and remanufacturing companies should provide the minimum warranty time. The lack of clarity can lead to disputes between OEMs and remanufacturing companies over who provides the warranty. These legislative details could reduce confusion and improve industry-wide standardization, ensuring stronger consumer protections and safety regulations.

"*Remodeling*" is just changing the aesthetic characteristics of the battery without improving the product's technical aspects. Recycling refers to mining the chemical components of the battery and inserting these chemical components in the process of making a new battery or other product [37,39].

In [37], the authors propose improved definitions of the terms "repair", "*Refurbishment*" and "*reconditioning*", which are presented in [39]. In [37], the authors state that it is necessary to consider the product warranty period and its useful life. To complement the definition of these terms, the authors proposed a new definition for "*remanufacturing*", "*refurbishment*", and "*reconditioning*", stating that for the product to be classified according to these terms, it is necessary to consider the warranty period and the useful life and therefore, the product must be outside the warranty period or have reached the end of its useful life. A misinterpretation of the terms "*remanufacturing*", "*refurbishing*", and "*reconditioning*" can lead to inadequate cost-cutting or insufficient renovation efforts, compromising quality or safety.

The process of disassembling that is inherent to '*remanufacturing*', '*refurbishment*', or '*reconditioning*' the batteries by third parties can expose the industrial secrets of products and, to maintain the confidentiality of the company's data and know-how, the battery manufacturers avoid and are resistant to allowing other parties to disassemble their product. Most battery manufacturers prefer '*reuse*' or '*second use*' over '*remanufacturing*' since disassembling and opening batteries mean higher cost, time, and energy consumption. According to Directive 2012/19/EU [36], Member States must ensure the removal and disassembly of EV batteries without imposing obstacles or delay and at a reasonable cost. However, this rule becomes mandatory if this fact puts the product's industrial secrets at risk. Battery manufacturers are also motivated to standardize their modules to facilitate recycling and reuse.

EV batteries are intricate and sophisticated products that may encompass proprietary production knowledge. If unauthorized third parties engage in the "*remanufacturing*" or "*reconditioning*" of batteries, there exists a genuine potential for the disclosure of proprietary information and product tampering. Furthermore, the erroneous reassembly of batteries by these third parties may give rise to concerns regarding safety, reliability, and performance. The necessity of dismantling and disassembling EV batteries is contingent upon the potential compromise of trade secrets. The absence of a precise differentiation between the processes of "*disassembly for recycling*" and "*remanufacturing*" can potentially give rise to legal and regulatory disputes.

Battery manufacturers can be encouraged to establish a standardized approach for their modules to streamline recycling and reuse processes. Nevertheless, in the absence of a clear definition of the term "*reuse*" in the context of "*reconditioning*" or "*remanufacturing*", there is a potential for inconsistencies in performance and anticipated lifespan.

Moreover, there are uncertainties about how replacing battery components can affect the patent monopoly and expose the product's industrial know-how. Replacement of battery components can occur in three ways [37]:

1. Replacement of battery components and reinsertion of these components in the module with a warranty equal to the time remaining for the battery to reach its useful lifetime established in the warranty. For example, if the battery fails after three years of operation in the EV, the battery may have its defective components replaced and reinserted in the EV with a 5-year warranty (a total of 8 years, which is the warranty that manufacturers are expected to provide for the operation of batteries in EVs).
2. Another possibility is the replacement of components and reinsertion of the battery in the EV but with the warranty of a new battery (it is expected to be around eight years). For example, after three years of operation in the EV, there is a battery failure, and it is necessary to repair it, defective components can be replaced, and the battery can be reinserted into EVs. However, in the case of an 8-year warranty, the 3 years that the battery operated in the EV can be disregarded.
3. Another possible scenario is using components from two or more batteries to form a battery that will be reinserted into the EV. For example, the battery in an EV fails, and the manufacturer uses components from another battery or several other batteries to replace the defective component of the defective battery.

However, there is uncertainty in all these scenarios because it is challenging to distinguish remanufacturing from making a "new battery" and whether the industrial secrets of that battery were exposed through data access and the battery's electronic circuit [37].

The Battery Directive 2006/66/EC [42] defines the "producer" of batteries as being "*the person in a Member State who supplies or makes available to third-party batteries or accumulators (including those incorporated into appliances or vehicles) within the territory of that Member State for the first time on a professional basis*". The directive clarifies the roles and responsibilities within the battery manufacturing and distribution supply chain. Suppose a battery manufacturer or domestic importer transfers a battery to a retail entity. The retail entity is deemed to be the battery's initial market introducer. Following the stipulations of this Directive, the retailer has deemed the producer and is thus held responsible for the ultimate destination of the battery.

Another definition for the term "producer" is defined in Article 2 of Directive 2011/83/-EU as "any manufacturer, importer or distributor or other natural or legal person who sells which, regardless of the sales technique used, including through distance contracts" [41]. This directive establishes the legal framework for the responsibility associated with positioning batteries on the market and their eventual disposal. The Battery Directives must provide explicit roles and responsibilities to prevent ambiguity and ensure the proper management, recovery, and recycling of spent batteries. This can ensure that all supply chain participants, including manufacturers, importers, and retailers, adhere to regulations intended to promote environmental sustainability and efficient resource management.

Depending on the business model adopted by a company, "*ownership*" and "*user*" of a battery may not coincide. This scenario may occur if the battery is still under warranty or if the battery is provided as a service as opposed to a commodity. In the latter scenario, the battery or vehicle manufacturer may assess rental fees based on parameters such as total distance travelled or duration of use.

When batteries are provided as a service, the battery may be owned by the battery manufacturer, the automotive manufacturer, or a car rental company. Therefore, the end user is typically the renter of the vehicle. However, it is essential to observe that in this context, the end user is merely a consumer of the service and does not own the battery. This model adds a layer of complexity to battery lifecycle management and must be considered when developing and implementing regulations and standards about battery usage and disposal.

Therefore, all existing waste legislation must harmonize terms and definitions. To achieve this harmonization, legislative, and regulatory bodies must collaborate with industry and subject matter experts to establish precise definitions of terms that cover technical and practical dimensions, including warranty, expected useful life, and degree of modification. It is imperative to conduct public consultations and training to identify potential ambiguities and verify the viability and comprehensibility of proposed interpretations. Finally, legislation and standards must be reviewed and revised to satisfy the sector's expectations.

3. Methodology

To enable the exploration, discussion, and comparison of current legislation and standards, a systematic review was carried out, adopting the following methodology: (i) identifying relevant research studies, (ii) selectively filtering these studies, (iii) evaluating and summarizing the most pertinent information gleaned from these studies, (iv) categorizing and consolidating analogous information, and (v) comparing and extracting pertinent data. This methodical approach ensures a thorough and objective analysis, facilitating an informed comprehension of applicable legislation and standards. This approach is illustrated in Figure 2.

The first stage of the study involved formulating a strict protocol about the work's purpose, i.e., formulating the research questions. The keywords, article selection criteria, and databases in which the papers will be searched are defined in this phase. The papers were located by executing the following strings in the database search engines: Scopus, Google Scholar, Web of Science, PUBMED, IEEE, MDPI, Elsevier, Scielo, Science Direct, and Oxford Press Journal. In these databases, strings were executed to find papers for the systematic review. The strings executed were as follows: "*legislation* AND *second-life batteries*", "*extended producer responsibility* AND *lithium-ion batteries*", "*recycling* AND *EV batteries*", "*reuse* AND *EV batteries*", "*battery recycling*", and "*EV standards*".

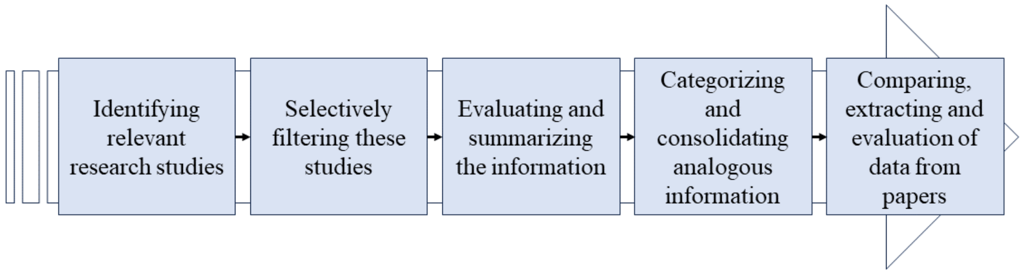

Figure 2. Flowchart of the methodology adopted in this paper.

After identifying the studies based on the predefined keywords, the next stage involved choosing and filtering them. The authors established specific criteria for inclusion and exclusion to conduct a systematic review focusing on identifying and discussing the fundamental technical standards, legislation, and regulations. Table 1 presents the criteria for including and excluding works in this review.

Table 1. Inclusion and exclusion protocol.

Inclusion	Exclusion
The paper deals with legislation on EV batteries.	The authors did not have access to the full text.
The paper deals with legislation and technical standards for reusing and recycling automotive batteries.	The paper does not discuss technical standards and legislation for batteries.
The paper describes testing and monitoring techniques for EV batteries.	The paper was not written in English.

Source: Prepared by authors.

After filtering and carefully selecting the papers, an analysis was carried out with the aim of extracting relevant information from the selected papers. A study of the number of publications throughout the year was used as a research parameter in this systematic review and provides an overview of the research field (see Figure 3). Note that the number of publications addressing legislation and technical standards for second-life batteries in the paper title and abstract is limited. Furthermore, there is an even smaller number of publications that deeply analyze the definitions and technical details that the standards of different countries have not yet clarified. Despite this, the number of publications in this area is growing, which shows the community's interest and the need for studies that discuss the gray areas of each topic and compare the legislation of different countries. Therefore, this reinforces the current importance of this paper.

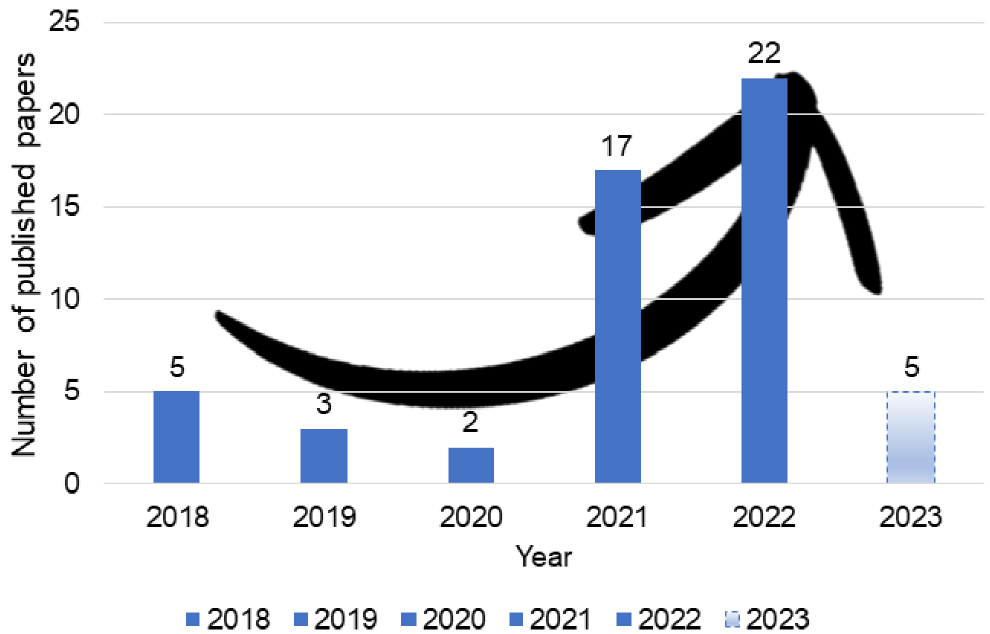

Figure 3. Number of publications over the years containing the words "second-life batteries" and "legislation" in the title, abstract, or keywords. Data extracted from Science Direct.

4. Legislation

EVs are set to solidify their market position further, and it is critical to develop government regulatory frameworks that oversee the battery industry and encourage the adoption of environmentally friendly and safe modes of transport. Such public policies could lead the industry toward more sustainable practices while promoting the wider acceptance and advancement of EVs, significantly contributing to reducing greenhouse gas emissions and mitigating climate change. These public policies must be effective, and the industrial sector, universities, and government agencies must participate in preparing them. Universities are neutral entities that can educate the public on the advantages of purchasing second-life batteries, the procedures for operating energy storage systems constructed with second-life batteries, and the operating standards necessary to ensure the expected security of second-life storage systems.

Cooperation across the entire ecosystem of the second-life battery market is critical to making it feasible for industries to implement automotive battery reuse business models and be responsible for generating innovation and new jobs by reusing EV batteries. The implementation of a circular economy in companies can be achieved using components until resources are depleted, and this may be possible through the reuse of batteries and/or the use of valuable battery components, which is possible with recycling. Recycling complements the closed-loop cycle of this product, recovering the chemical components of the battery and feeding back the loop of the product's life cycle.

For companies to enter the second-life battery market, they must know the legislation, as it may be a barrier to their business. The legislation of a particular country or region can promote the insertion of new companies when it is less stringent and can limit the attraction of new market players compared to when it is more stringent. Therefore, the legislation may enable or restrict the entry of used EV batteries into the market. New legislation or adaptations of existing legislation should be proposed to reduce market uncertainties, making it more transparent and safer for players to invest in the technological development of their processes and promoting the circular economy effectively [43].

Government, industry, academics, and society are alarmed by the rising number of EV sales because it is anticipated that the number of batteries reaching the end of their useful life will rise. Public policies must incentivize businesses to search out methods to manage LIBs that have ended their useful lives. These public policies are also necessary to prevent developing nations from becoming electronic waste dumps and to ensure that no "missing" or "orphaned" batteries are disposed of in inappropriate locations [44].

Strict regulatory standards are established to ensure that second-life batteries derived from depleted EV batteries function at their utmost potential, maintain a consistent performance standard, and avoid inadvertently causing environmental pollution. The lack of adherence to these regulations could give rise to several potential hazards. To begin with, the inconsistent quality and performance of second-life batteries may cause businesses and consumers to lose faith in them. Safety may be jeopardized without standardized benchmarks, potentially leading to catastrophic incidents such as fires or leakage. Moreover, without regulatory measures, batteries might be disposed of prematurely, which would be morally objectionable, worsen the e-waste crisis, and nullify the environmental advantages associated with battery reuse.

In addition, regulations furnish sectors with a methodical framework to conform to optimal methodologies following safety, efficiency, and ecological sustainability. By clearly understanding the performance metrics, recycling procedures, and expected safety measures, businesses can innovate while maintaining compliance and competitiveness. A suitably regulated market can also cultivate consumer confidence by guaranteeing that the second-life batteries they acquire adhere to precise criteria for safety and performance. Furthermore, regulations can prevent the deterioration of natural habitats and lessen the carbon footprint associated with battery production and disposal by establishing rigorous environmental standards. Therefore, although EVs represent a groundbreaking transition towards environmentally friendly transportation, strict regulatory oversight is necessary to ensure that the sustainability of their batteries persists beyond the vehicle's initial use, fostering a genuinely circular economy throughout the battery's lifecycle.

Therefore, in summary, the lack of concrete legislation has three main risks and challenges that affect the sustainability and efficiency of the battery supply chain. Firstly, there is a significant upward trend in the costs of raw materials essential for the production of batteries, highlighting, for example, a 410% increase in the price of lithium in 2022 compared to 2020 [45,46]. This phenomenon calls into question the stability of the battery supply chain, especially considering the limited production capacity of raw materials in certain countries or economic blocks, such as Europe. This situation highlights the urgent need for a regulatory framework that ensures the continued availability and economic accessibility of these critical inputs [45].

Additionally, intensifying competition in the sector requires companies to adopt strategies to safeguard their supply chain and battery market share. The absence of clear and comprehensive legal guidelines can result in unbalanced market practices, harming the sector's equitable and sustainable development [45].

Finally, the legislative gap contributes to the worsening of environmental impacts and increases the risks associated with safety in second-life battery applications. The implementation of specific regulations for the management, recycling and reuse of batteries is crucial to minimize environmental risks and ensure the operational safety of these systems. The development of legislation focused not only on the production and initial use of batteries but also on their extended useful life is imperative to promote a sustainable life cycle for these components essential to the energy transition [45].

Legislation is required to ensure that new and used automobile batteries introduced into the market meet performance and safety requirements in primary and secondary EV applications. Several non-governmental groups have led in developing technical standards to facilitate and regulate the use of batteries in EVs and their future life. The International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO), the International Society of Automotive Engineers (SAE), the European Committee for Standardization (ECS), and the European Committee for Electrotechnical Standardization (CENELEC) are among these non-governmental organizations. Furthermore, several national organizations, such as the British Standards Institution (BSI) and the Japanese Industrial Standards Committee (JISC), are involved in the formulation of these standards [47]. This collaborative effort in standardization initiatives aims to provide a high battery performance and safety level, boosting consumer confidence and facilitating EV adoption. Furthermore, these standards are crucial in formulating and implementing important legislation to control the battery business.

Although the standards proposed by various organizations are not legally binding or mandatory for battery and EV manufacturers to comply with, the regulations are constituted as national legal standards, are enforceable by law, and are promulgated by government authorities. These regulations outline the technical and safety requirements of EVs and their batteries.

According to the manufacturers' claims, batteries validated per these regulations should function as expected until the end of their useful life. However, numerous fires originating from electrical equipment and battery-powered vehicles have been documented. The risk of such fire incidents is anticipated to increase for batteries that have been repurposed [48]. This highlights the significance of stringent safety standards and regulatory supervision for both new and used batteries, as well as the need for ongoing review and improvement of these standards and regulations to guarantee the highest levels of safety and performance.

For companies to access the second-life battery market, the risks of this new business must be mitigated. One of the main risks reported in the literature is the properties of the batteries. It is still being determined who will be in possession of the batteries when they reach the end of their useful life, and there is also no definition of who will be responsible for recycling the electrochemical waste of these batteries. This doubt may be more significant because the ownership of the battery can be transferred over its life cycle. After the battery is placed on the market during the warranty period, the battery may be owned by a specific company (X), a battery manufacturer, an automobile manufacturer, or a car rental company. A company (Y) can provide the battery warranty, and the responsibility for the correct battery use can be with a user (Z). In this case, there will be a chain of responsibility between each party, and one party may be penalized if they do not comply with some of the requirements signed in the contract.

The warranty period may be sufficient to cover the entire period that the EV battery is in operation. The OEM usually offers a warranty based on two criteria: battery life and mileage traveled. The battery life warranty provided by most manufacturers is eight years or more and is generally valid for up to 100,000 miles traveled (may vary depending on the manufacturer). There is a challenge for battery and automobile manufacturers who offer a product warranty because replacing a battery within the warranty period can range from USD 5000 to over USD 16,000. Therefore, battery manufacturers want to avoid having to change the battery during the warranty period, and to do so. They can take measures to monitor the battery from production to consumption [43].

Novel commercial strategies can be based on battery swapping, designed to ameliorate the prevalent 'range anxiety' among EV owners. In this business model, the EV owner drives the vehicle until the battery is depleted, which is analogous to conventional vehicles that use nonrenewable petroleum reaching a low fuel level. The owner then proceeds to a battery exchange facility, analogous to a gas station. The vehicle's depleted battery is replaced with a fully charged one at this location. This allows the battery proprietor to recharge the vehicle in less than 15 min, like refueling conventional fuel vehicles.

For this business model to operate without difficulties, the swapped batteries must be compatible with the vehicle, meet the exact specifications, be free of unauthorized modifications, and be subject to the same utilization conditions; they must be identical. If an identical match is impossible, a mechanism must be in place to compensate one party for receiving a defective battery [49]. This emphasizes the significance of standardization in battery design and specifications and may result in new regulations or guidelines governing the operation of battery swapping stations.

Legislation should address these different types of business models, which may be traditional or service-based. In the traditional business model, ownership of the battery is transferred to the EV owner and then returned to the OEM, making them responsible for reusing or recycling it. In service-based business models, the battery or car manufacturer rents the battery to a company or a customer and captures value by charging for battery usage according to the number of cycles and the mileage traveled. In this business model, the complexity of battery ownership is reduced because battery ownership remains with the battery manufacturer, automobile manufacturer, or car rental companies. Monitoring the battery during use is essential to prevent batteries from being used in EVs after reaching the "aging knee" or reaching the limit of 70 to 80% of the remaining charge. The owner of the EV must use the batteries by the terms of use of the batteries and follow the manufacturers' instructions so as not to prevent their reuse [37].

However, business models that offer batteries as a service are still not widely adopted by customers for various reasons, including a lack of promotion, a battery swapping platform, and a battery analytics platform [29,50]. Companies will choose a traditional or service-based business model according to each country's legislation, strategies, and customer acceptance criteria [37]. Furthermore, the battery as a service paradigm is more promising for company fleets, breaking the tight coupling between vehicles and their batteries. The choice of keeping the ownership of the batteries or outsourcing charging services is given to the fleet manager.

The principle of Extended Producer Responsibility (EPR) defines the responsibility for the battery. However, some countries still do not have the principle of EPR. Both battery and EV manufacturers are interested in the owner's returning batteries after vehicle use so they can reuse them in different secondary applications, increasing their revenue. There may be a conflict of interest between battery and automobile manufacturers because neither has an interest in conveying ownership of the battery to the other, thereby losing access to the profitable second-life battery market. However, the benefits of exploiting the second-life battery market can be shared among the actors if the battery's history is tracked and each actor is compensated in proportion to their contribution (for instance, a company that will incur costs associated with battery recycling will receive a higher value than a company that had a more negligible contribution). It is also possible for the owner of an EV to participate in the chain, receiving benefits for taking care of the temperature and battery charge, driving on roads with suitable conditions, not having aggressive behavior behind the wheel, and consequently preserving the battery's SoH. On the other hand, a user who stresses the battery during the first life may not receive benefits or be penalized for such potentially abusive behavior [23,37,48,51,52].

Transferring battery ownership from battery manufacturers to vehicle manufacturers can expose the product's industrial secrets in some cases, such as (i) if there is a need for data sharing, it is difficult to determine which battery data can be shared in a way that does not expose any competitive advantage of the company, and (ii) if the vehicle manufacturer can open the battery and undertake the reverse engineering process. Therefore, the transfer of ownership must be carried out with well-drafted contracts or on a secure data-sharing platform to avoid damage to the brand [50]. Accidents involving batteries can occur, so it can be challenging to determine whether the cause of the accident was the battery manufacturer or the vehicle manufacturer if there is no battery tracking throughout a supply chain [23,37,48,51,52].

In business models in which ownership of the second-life battery is transferred from the battery or vehicle manufacturer to a company responsible for constructing an energy storage system, that company must assume liability in the event of an accident [29]. Therefore, it is probable that the manufacturer of energy storage systems constructed with second-life batteries will require access to all battery data (e.g., temperature, currents) to know the battery's history and ensure that the battery will perform as expected in a second application. However, it may not be possible for battery or automobile manufacturers to transfer ownership of the batteries and disclose their data due to the risk of losing their expertise.

Conversely, the manufacturer of energy storage systems with second-life batteries must have sufficient knowledge and data to evaluate battery condition, performance, and quality. Suppose battery, vehicle, and energy storage system manufacturers collaborate and share trusted data on the batteries, each from their perspective. In that case, second-life battery applications will be simplified, as the battery manufacturer may have knowledge of the battery but be unaware of its behavior in a secondary application. On the other hand, manufacturers of energy storage systems know little about the specific phenomenon that occurs in these batteries and how to integrate batteries into secondary applications (stationary or mobile). For this reason, it is crucial to define technical standards for second-life batteries in order to conduct a comprehensive evaluation [53].

The players in the battery market must know the legislation so that, according to their responsibilities, they can elaborate and modify their business model with the aim of reusing batteries, optimizing their battery recycling process, and ensuring the proper disposal of components that cannot be recycled or reused [43].

Automakers are mandated by EU law to collect batteries at the end of their useful life [43]. If batteries become a new product, responsibility can be transferred [52]. In this instance, there are still unanswered questions regarding the remanufacturing of batteries and the modifications required for second-life batteries to become new products. For example, it is not clear whether simply replacing a defective cell makes the battery a new product. According to the principle of producers' responsibility, for second-life batteries to be classified as a new product, they must be used for a different purpose, perform a different function, and have a new brand before their ownership can be transmitted [21,54].

These general aims established by the Batteries Directive [42] are shared across the EU, but how each Member State will achieve these goals is subject to national law. As a result, it is possible that one Member State's recycling process or system may not be suitable for another Member State [43].

The battery guidelines do not classify batteries as hazardous waste. It is important to note that no universal criterion has been adopted to declare batteries as waste products. Consequently, batteries are classified as hazardous waste from the moment they are declared waste. They receive a set of stricter rules for handling, transporting, and treating this waste, which can prevent reuse and recycling. Currently, the last battery user is responsible for declaring this battery as waste regardless of the conditions in which these batteries are found. Therefore, standardizing criteria to classify EV batteries as waste is essential so that the EV owner does not declare the battery as waste and OEMs can collect it and reuse it in a less demanding application. In this case, the principle of producers' responsibility must be applied so that the ownership of the battery remains with the manufacturer even though the battery has had a lifetime of use in an EV [43]. In the EU, Directive 2008/98/EC allows for the transfer of batteries from one party that owns them to another so that batteries can be reused instead of being declared as waste.

Countries are expected to implement the concept of paying producers. That is, the producer will be responsible for paying to recycle the product inserted on the market. Public policies can implement the concept of reward/punishment, which consists of punishing the producer if recycling goals are not met or providing incentives for the producer if that producer reaches the established goals. It would be interesting if these public policies allowed producers who exceeded the recycling targets to negotiate their credits with other companies that did not reach their goal [20].

4.1. United States of America (USA)

The United States enacted the 'Battery Act' in 1996, officially known as the Law for the Management of Rechargeable Batteries and Mercury-Containing Batteries [55]. This legislation outlines the responsibilities associated with the waste management of nickel–cadmium (Ni-Cd) and small sealed lead acid (SSLA) batteries and mandates labeling and recycling protocols. Furthermore, this legislation also prohibits the sale of specific categories of batteries that contain mercury. Additionally, it mandates the Environmental Protection Agency (EPA) to develop and execute a comprehensive public education program. The primary objective of this project is to disseminate knowledge to consumers regarding the environmental hazards linked to the improper disposal of used batteries. Furthermore, it seeks to clarify the acceptable protocols for treating and managing these materials at the end of their lifespan.

However, this legal document does not include LIBs and nickel–metal hydride batteries (NiMH) within its scope of application. If they do not contain heavy metals, LIBs are not considered hazardous waste. Including such elements could harm the product's environmental balance and human health. This statement emphasizes that distinct regulatory frameworks govern various types of batteries. Consequently, legislation must continue to evolve to accurately reflect the variety of battery technologies and their respective environmental and health impacts. This ongoing adaptability will ensure that battery technology regulation remains robust, comprehensive, and in step with technological advancement.

LIBs are classified as hazardous waste because they have toxic components and are regulated by the Universal Waste Law, which makes it mandatory to comply with a set of rules and procedures for collection, treatment, and recycling to avoid inappropriate disposal of this type of waste.

Due to the complexity of the concessionaire's regulations, the use of batteries in a second application may be problematic. In addition to utility regulations, federal regulations do not offer grid energy storage facilities any incentives. However, the Federal Energy Regulatory Commission (FERC) [56] approved Order FERC 784 in 2013, recognizing energy storage as a generating resource and allowing financial incentives to be directed to energy storage facilities, thereby encouraging the network connection of energy storage systems [57].

Similarly, Order FERC 792 represented a significant advancement by allowing energy storage facilities to connect to the network because they are qualified energy sources. However, a business model that presents renewable energy storage as the primary resource capable of altering the structure of electricity markets is still required [23].

In 2019, the government of the USA launched the first US Department of Energy (DOE) LIBs recycling laboratory, named Recell, led by Argonne National Laboratory (ANL), to boost recycling industries and make them globally competitive by reducing the country's dependence on buying foreign raw materials for LIBs. This laboratory has a focus on four areas as a priority:

- Recycling processes that enable the direct recycling of the cathode so that the recovered materials are reinserted into batteries, avoiding expensive reprocessing processes;
- Development of recycling technologies that increase company revenue;
- Development of new battery designs that facilitate recycling and reuse;
- Computational tools for modeling and validating recycled batteries.

The California legislature implemented the Electronic Waste Recycling Act (EWRA) in 2003, which is currently documented in the California Public Resources Code Sections 42460 through 42486. The legislation mentioned above was designed to establish a comprehensive framework to mitigate the financial burden associated with the appropriate collection and recycling of specific categories of electronic waste. The legislation focuses explicitly on the final stage of covered electronic devices (CEDs), encompassing various video display products like televisions and computer monitors. These products may include cathode ray tubes (CRTs), liquid crystal displays (LCDs), and plasma displays [32,58,59].

The funding model implemented by the Environmental Waste Recycling Agency (EWRA) involves the imposition of an Advanced Recycling Fee (ARF) during the retail sale of new consumer electronic devices. The fees that have been accumulated are transferred to the Electronic Waste Recovery and Recycling Account, overseen by the state. The legislation has implemented a financial framework that ensures consumers are not directly charged with recycling eligible devices. This approach serves to incentivize responsible disposal practices among consumers [32,58,59].

Furthermore, the legislation establishes rigorous guidelines for entities engaged in the electronic waste recovery process. In order to mitigate environmental impacts and minimize potential hazards associated with electronic waste components such as lead, mercury, and cadmium, collectors, recyclers, and manufacturers must adhere to stringent standards about the appropriate handling, management, and disposal of e-waste [32,58,59].

According to a recent report from an analysis of US supply chains, the US battery supply chain is at risk because the country cannot source all materials domestically at this time. Additionally, this report emphasized the necessity for public policies that increase domestic investment and decrease reliance on low-cost raw material imports from foreign suppliers [31].

The California State Assembly also passed House Bill No. 2832, which created an advisory group led by the California Environmental Protection Agency, the Department of Toxic Substances Control, and the Department of Resource Recycling and Recovery. Other interested parties, the environmental community, automobile dismantlers, and public and private representatives engaged in the production, collection, processing, and recycling of EVBs comprise the membership. This group proposed policies about recycling and reusing EoL EV batteries to achieve a maximum of 100% [60]. The advisory group recommended implementing the producer responsibility principle and a vehicle exchange and protection policy to define responsibility for out-of-warranty batteries [31]. In this proposed producer responsibility principle, the car manufacturer manages batteries at the end of their first useful life, including transportation and recycling costs and documenting proper disposal [61].

This policy stipulates that batteries must be removed from operational vehicles for reuse, second life, or recycling. Additionally, a validation and monitoring model for management must be implemented. When the battery is returned, the deposit paid by the customer for the replacement battery is refunded [61].

The EVs that are obtained by an automotive recycler or dismantler at the end of their life cycle: The individual or entity engaged in the process of vehicle dismantling or recycling assumes the responsibility of reutilizing, renovating, extending the lifespan, or engaging in recycling activities about batteries that have reached the end of their operational life. In the final stages of their lifecycle, EVs are not typically obtained by auto dismantlers or recyclers. The responsibility for properly dismantling the vehicle and appropriately reusing, refurbishing, repurposing, or recycling the battery lies with the vehicle manufacturer [61].

Despite the advisory group's suggestion, the United States does not have a broad producer requirement for EV batteries, so the party responsible for paying the cost of transportation is contract-specific rather than dictated by policy. This issue could potentially present a challenge in the future, as batteries that are no longer covered by warranty may be disassembled by small automobile dismantlers, scrap recyclers, or private repair facilities. These entities may face difficulties in terms of transportation costs, which could hinder the proper disposal of the batteries or deter them from acquiring the vehicle initially [31,62].

In the study presented in [63], the authors projected a spectrum of diverse circularity potentials for several critical materials in the United States by 2040. The range of these estimations for nickel is 35% to 69%, cobalt is 35% to 93%, lithium is 35% to 68%, and manganese is 29% to 69%. Additionally, aluminum showed potential circularity values ranging from 34% to 64%. In [64], the projected worldwide circularity potentials for the year 2050 were determined, indicating that lithium is expected to range from over 30% to 50%, cobalt from 40% to 70%, and nickel from 30% to 55%. The results in references [51,52] exhibit significant spread due to the inherent difficulties associated with predicting future market distributions of cathodes, sales predictions, and the allocation of batteries for second-life utilization. While circularity forecasts offer valuable insights, their primary emphasis lies on the number of resources that may be accessed, with limited consideration given to the economic viability and practical recovery rates involved in the collecting and processing stages. Establishing a more precise and practical understanding of the possibility for near-term circularity is crucial to effectively guide policy discussions and progress [47].

In the US, there is no regulation at the federal level, but each state implements an electronic waste management program, most of which have the principle of EPR. In the US, there is no regulation at the federal level, but each state implements an electronic waste management program, most of which follow the principles of EPR [32,58,59]. In these states, producers are required to internalize the costs of handling, recycling, and safely disposing of batteries [32].

4.2. South Korea

South Korea is a promising market for second-life batteries, and in 2015, a program was started to promote pilot projects that apply second-life batteries as a stationary energy provider with a backup function. Furthermore, South Korea and China are the countries that receive the most used batteries for recycling. According to [2], it is estimated that in 2018, about 69% of the LIBs recycled worldwide were recycled in China, and 18.55% were recycled in South Korea.

South Korea occupies a prominent position in battery production, with several renowned battery manufacturers such as LG Energy Solution, Samsung SDI and SK ON having their headquarters in this country. This factor not only underlines South Korea's technological capability and advanced infrastructure in the domain of battery production but also reflects its critical role in the global supply chain of battery components, driving innovation and sustainable development in the energy storage sector. South Korean legislation classifies used batteries as waste, which considerably increases the price of transportation and, consequently, the price of the energy storage system built with second-life batteries.

South Korea formulated a public policy called the Waste Management Act in 1986 to avoid social problems caused by poor waste management resulting from economic growth. In 1986, the Waste Management Law classified waste into different categories and assigned someone responsible for each type of waste. Later, in 1992, the Economy Promotion and Resource Recycling Law (APSRR) in South Korea introduced the concept of Deposit Refund (DRS). In this system, producers paid deposits to a state fund that returned the recycled quantity. Although these public policies have meant an important advance for waste recycling in South Korea, some categories of waste have not reached a significant level of recycling [65].

The main reason for the inefficiency of the DRS policy was that the battery recycling infrastructure in South Korea was non-existent and producers did not have the capacity to recycle or recover the products. Therefore, in 2002, the EPR policy was implemented by the government, and the volume of recycled products increased considerably [66]. The EPR establishes binding targets for the collection of primary batteries and fines in cases of non-compliance with these targets [66].

However, unlike other countries or economic regions, such as Europe, which apply producers' responsibility, in South Korea, the Clean Air law states that the government is responsible for recycling or reusing batteries. Experts suggest that the responsibility for second-life batteries and recycling should be attributed to companies, given that the government does not have the capacity to reuse, treat, and recycle waste batteries [45]. Additionally, business models focusing on reuse and recycling must be developed to enable the reuse and recycling of batteries [45].

4.3. Africa

Africa is a continent that has numerous places where people live in extreme poverty, and electricity can contribute to the region's economic development. In Africa, blackouts and brownouts are also common; therefore, integrating second-life batteries into systems that increase the reliability and availability of energy can be promising for the country's development.

There are some projects like the Faraday Battery Challenge project that investigate economic viability and have implemented an energy storage system built with second-life batteries integrated with photovoltaic systems for homes in Kenya.

4.4. Latin America

Latin American countries have great potential for the use of EVs. However, countries still face challenges in managing end-of-life batteries. Additionally, countries do not have adequate infrastructure for the collection and recycling of EV batteries. The lack of adequate structure for battery treatment can make the country susceptible to having its end-of-life batteries disposed of in inappropriate locations [67].

Countries like Brazil, Chile, Colombia, Costa Rica, Paraguay, and Peru have regulations, and some countries have industries that recycle lead–acid batteries. However, the limited capacity of these countries to recycle a large volume of batteries may make it necessary to export end-of-life batteries to be treated in other countries, which can be a serious problem from a legislative point of view.

In the context of environmental management and sustainability, Latin American countries are faced with a significant challenge related to the import of electronic waste, such as batteries, often masked under the pretense of reuse. This problem is exacerbated by insufficient regulation and border control, allowing the entry of substantial amounts of electronic waste under the pretext of being reusable products. The lack of effective regulation, which clearly distinguishes truly reusable electronic products from electronic waste, makes inspection difficult and provides an environment conducive to the practice of irregular imports of waste batteries. Consequently, it makes the EPR program ineffective [68].

Despite the infrastructure challenges these countries face, there is a desire for these countries to implement the principle of producer responsibility, e-waste collection programs, and battery reuse that work more effectively in practice. Some Latin American countries, such as Brazil, have extensive territory and a favorable climate for deploying alternative energies such as photovoltaics and wind, and, therefore, business models that connect second-life batteries in parallel with renewable energy systems can be promising and economically viable.

The National Solid Waste Policy (NSWP) of Brazil, which was enacted in Law No. 12.305/2010 [69], enforces the principle of producer and importer responsibility [70,71]. This law determines shared responsibility for the life cycle of products involving producers, traders, importers, and consumers. This law aims to establish a set of actions, procedures, and means designed to enable the collection and return of waste to the business sector for reuse, in its cycle or other production cycles, or to other environmentally appropriate final destinations.

Under this legislation, Brazilian commercial establishments and authorized technical assistance networks that handle portable batteries, namely those made of lead–acid, nickel–cadmium, and mercury oxide, are legally mandated to accept the return of used batteries from consumers. Once collected, the responsibility for ensuring environmentally correct disposal or reuse lies with the producers and importers of these products. The NSWP, as stipulated by Law No. 12.305/2010, incorporates the concept of shared responsibility for product life cycles. In line with this principle, the NSWP mandates establishing a reverse logistics system for electronic devices. It is important to note that this system should function autonomously, separate from the public urban cleaning service [69].

4.5. Europe

Europe encounters considerable obstacles within its battery supply chain, with a conspicuous reliance on imported primary resources predominantly sourced from Asia. As a result of these circumstances, the European Union undertook a sequence of strategic endeavors aimed at bolstering the bloc's independence and competitiveness in the worldwide battery industry [72].

The European Commission established the European Battery Alliance (EBA) [73] in 2017. This ambitious consortium aims to foster collaboration among Member States, industry, and other relevant stakeholders to develop a sustainable, innovative, and resilient battery value chain in Europe. The mission of EBA extends beyond mere stimulation of innovation to include advanced recycling strategies and optimization of manufacturing processes. In 2018, the Strategic Action Plan for Batteries was unveiled due to this endeavor. This plan, which transcends being a simple road map, embodies an all-encompassing strategy to expedite research, innovation, and the mass production of competitive batteries. It remains committed to upholding rigorous performance and sustainability criteria [72].

The European Union's implementation of the Circular Economy Action Plan (CEAP) [74] signifies a significant departure from the conventional economic paradigm. In conclusion, the European Union's implementation of the CEAP signifies a paradigm shift away from the conventional economic approach. The CEAP accentuates the significance of recycling and reuse by designating batteries as one of the seven fundamental value chains. In doing so, it endeavors to diminish reliance on imports and advocate for advancing battery production that is both sustainable and ecologically responsible [72].

The economic and environmental issues associated with reliance on imports and premature battery disposal are mitigated by regulating the safety, efficiency, and competitiveness of second-life batteries through legislation and technical standards. By enacting legislation supporting the second-life battery market, Europe has the potential to significantly decrease its reliance on external energy sources while enhancing innovation, competitiveness, and sustainability within the battery sector [72].

Legislation and technical standards for battery reuse ensure that second-life batteries are safe, efficient, and competitive, addressing the economic and environmental challenges associated with dependence on imports and premature disposal of batteries. By promoting the second-life battery market through appropriate legislation, Europe can effectively reduce its external dependence while boosting innovation, competitiveness, and sustainability in the battery industry [72].

In the EU, there is an effort to unify and reduce the difference between battery laws and reduce the impacts of batteries on the environment and society, which is why the Battery Directives and other regulations are developed. An example was the approval of European Regulation (EU) 2019/631 [75], implemented by the European Union in April 2019, representing a significant measure to tackle automotive emissions. This regulatory framework sets forth the limits for carbon dioxide (CO_2) emissions in passenger cars and light commercial vehicles, with measurement units expressed in grams of CO_2 per kilometer [76]. The current standards, European Regulation (EU) 443/2009 [77] for cars and Regulation (EU) 510/2011 [78] for light commercial vehicles, are being replaced by new regulations that impose fleet-wide pollution limits. These new regulations will come into force in 2025 and 2030. Significantly, the European Union aims to achieve a 40% decrease in greenhouse gas emissions by 2030 while concurrently advocating for more outstanding market penetration of vehicles with zero- and low-emission capabilities [76].

According to the battery guidelines, the producer is responsible for collecting and recycling the batteries. The directives also set the collection targets and the level of efficiency of the recycling process that must be achieved for all types of batteries across Europe [42].

The principle that needs to be followed by battery manufacturers is that those who sell the batteries on the market for the first time are required to "take back" the batteries and are also required to treat and recycle the battery residue as well. Therefore, EU Member States must ensure that battery producers protect their products in a way that facilitates batteries to be easily removed from EVs and establish that EV producers are required to provide only information to EV owners about the type of battery, necessary care, how to remove batteries safely, how to return batteries, and what damage the improper disposal of batteries can cause to the environment and society. The battery guidelines provide that batteries can be permanently attached to the EV when the manufacturer needs to protect their product or when non-permanent battery attachment increases the risk of loss of data integrity, performance, continuity of supply, and safety of batteries [36].

According to the Battery Directive 2006/55/EC, at least 50% of the materials used in LIBs and nickel–metal hydride must be recycled, i.e., nickel–cadmium chemicals with a minimum rate of 75%, lead acid must be 65%, and the minimum efficiency for the recycling process of other types of batteries must be 50%, as well as for LIBs [42,79].

On 10 December 2020, the European Commission presented a new regulation entitled "Proposal for a Regulation on Batteries (PRB)" [80], which aims to ensure that batteries that are inserted in the European market from that date have adequate safety and sustainability. This regulation was incorporated into the Batteries Directive to establish targets for collecting and recycling batteries and the specifications for labeling and removing batteries from vehicles. This regulation also prohibits the sale of batteries that are composed of hazardous substances. An essential feature of this regulation is that it applies to all types of batteries, regardless of their chemical characteristics, size, and design [81].

The Battery Directive 2006/55/EC [82] also prohibits the use of mercury and the incineration and disposal of batteries classified as "industrial" and holds the producer responsible for all costs of the information campaign and the costs of collection, transportation, treatment, and recycling. In addition, battery producers and any third-party company acting on behalf of the battery producer cannot refuse to return used batteries regardless of chemistry and origin. In Europe, the battery directive specified in September 2012 that at least 25% of spent batteries should be collected, and in September 2016, that percentage increased to 45%. PRB established that the collection of portable batteries must reach at least 65% in 2025 and 70% in 2030 [80].

The significant policies that regulate the use, collection, treatment, and recycling of batteries in the EU are the Batteries Directive (Directive 2006/66/EC) [42], End of Life Vehicles Directive (Directive 2000/53/EC) [83], Regulation for Registration, Evaluation, Authorization, and Restriction of Chemicals (Regulation (CE) 1907/2006 [84]).

Directive 2000/53/EC [83] was the first waste directive in the EU and addressed the end-of-life of automotive components, including batteries. This guideline introduced the concept of expanded producer responsibility and addressed aspects related to the vehicle's life cycle and treatment operations. This directive also prohibits the use of cadmium in batteries classified as "industrial", a category in which EV batteries are classified.

Directive 91/157/EEC [85] was established within the European Union as a disruptive legislative structure centered on batteries. It emphasized the appropriate disposal and retrieval of used batteries containing hazardous substances, including heavy metals. Directive 91/157/CE [85] established precise restrictions on the mercury concentration in alkaline manganese batteries, imposing a maximum threshold on the heavy metal's content to ensure the environment's safety and human health. Nevertheless, the directive encountered disapproval because of its limited reach, as it failed to address a broad spectrum of battery varieties, and the controls implemented could have been more specific and comprehensive [72,86].

Several EU countries have proposed policies to encourage second-life batteries in Europe. Directive 2006/66/EC [42] aims to mitigate the environmental impacts of batteries and accumulators by regulating collection, manufacture, and disposal. Directive 2006/66/EC established the following: (i) battery waste management standards, (ii) maximum amounts of some chemicals and metals in batteries, (iii) used battery collection rates, (iv) financial responsibility for programs, (v) the rules covering most stages of this legislation, including labeling, (vi) documentation and administrative matters, and (vii) the obligations of authorities, manufacturers, sellers, and importers.

Directive 2006/66/EC [42] states that EV battery manufacturers or third parties must establish collection schemes for discarded EV batteries that are not collected according to the schemes established by the directive and that all collected batteries must be recycled. This directive also establishes that EV batteries cannot be disposed of in landfills and must be recycled according to the established goals.

The principle of EPR requires producers to be physically and financially responsible for the entire life cycle of products and packaging, so they must have the resources to manage them through reuse, recycling, or energy production and can delegate them to third parties. In addition, EPR establishes that producers are responsible for the environmental impacts caused by their products. In this way, the government transfers responsibility for waste management to the producer through several directives, such as Directive 2006/66/EC [32,87,88].

Article 16 of Directive 2006/66/EC states that the 29 member states of the EU must finance the costs of collecting, treating, and recycling all industrial waste and automotive batteries. In many developing countries, such as Brazil, no regulation still makes battery producers responsible for their products. Therefore, a shared management system is adopted in which manufacturers, municipalities, and consumers share responsibility for managing electronic waste [32,87,88].

Directive 2006/66/EC and Directive 2000/53/EC established that a vehicle manufacturer is also considered a battery producer if it places the battery on the market in the car in a particular country on a professional basis. Directive 2008/98/EC defines using batteries only for the same purpose of their original applications. That is, it does not deal with the application of batteries in secondary applications. In addition, for reuse and recycling, there is the Environmental Sustainability of Lithium-Ion Battery Energy Storage Systems. Directive 2000/53/EC includes a warning that reuse means that end-of-life EV components should only be used for the same purpose, which also requires policies that aim to enable or encourage the use of second-life batteries in applications other than their first use [32,87,88].

Directive 2008/98/EC [35] presents the definitions of waste and recycling, as well as the concepts of waste management as the EPR. This legislation encourages the producer (battery manufacturer) to plan recycling and reuse from the product design stage. In addition, producers (manufacturers) are responsible for reducing environmental impacts and other damages that a battery generates at the end of its useful life.

Directive 2013/56/EU [89] replaces Directive 2006/66/EC and eliminates related exemptions for batteries and accumulators containing cadmium in cordless power tools. That directive also banned the use of mercury in all batteries and changed the batteries' market placement and removal capacity. According to the battery directives, the producer must retake the batteries without possibly refusing the return and cannot charge a fee to accept batteries classified as industrial. However, there is still no definition of who this "producer" would be.

In the EU, only one recycling company, Umicore, performs cathode recycling. Other initiatives exist in France with SNAM and Recupyl, Germany with Redux, and Switzerland with Batrec. However, these initiatives do not yet integrate these materials into producing new cathodes, feeding the production cycle [90].

According to this regulation, as of 1 January 2027, there must be a declaration of the amount of chemical components containing cobalt, lithium, lead, and nickel used in batteries that have been recycled. The legislation states that by 1 January 2027, companies must recycle at least 12% cobalt, 85% lead, 4% lithium, and 4% nickel obtained from batteries. These levels will be increased from 1 January 2035, when companies are expected to recycle 20% cobalt, 10% lithium, and 12% nickel [81].

A new regulatory framework (Regulation (EU) 2023/1542 [91]) for the battery sector has been implemented and came into force on 17 August 2023. Under this new regime, all manufacturers, producers, importers, and distributors of batteries available on the European market are now categorized as Economic Operators, subjecting them to a series of specific obligations and responsibilities.

This regulation applies to all batteries, from portable and ready-to-use battery modules to industrial batteries and batteries intended for EVs. Furthermore, it also applies to lead–acid batteries and starting, light, and ignition batteries (SLI), which are essential for providing energy for critical functions of vehicles and machinery, such as starting, lighting, and ignition. Light means of transport (LMT) batteries, including, but not limited to, electric bicycles, mopeds, and electric scooters, must also follow this regulation.

It is important to emphasize that the applicability of the regulation is independent of the geographic origin of the batteries or the raw materials used in their manufacture. This implies that regardless of whether batteries or their components are produced within or outside the boundaries of the European Union, they must comply with established guidelines. Specifically, Economic Operators must adopt and clearly communicate to suppliers and the public due diligence policies relating to the supply of cobalt, natural graphite, lithium, nickel, and other chemical compounds based on the listed raw materials in accordance with recognized international standards, such as the OECD Guidelines on Due Diligence and UN Guiding Principles on Business and Human Rights. From 2025, most batteries must have a digital battery passport. Digital battery passports will be applied to EV batteries, LMT batteries, and rechargeable industrial batteries over two kWh, which must have a "digital battery passport", with information about the battery model, the specific battery, and its use. All batteries must have labels and QR codes detailing their capacity, performance, durability, and chemical composition and must display the "separate collection" symbol.

A carbon footprint declaration and label must be provided for all EVs, LMTs, and rechargeable industrial batteries with a capacity greater than two kWh. In addition, the levels of recycled cobalt, lead, lithium, and nickel that are used in the production of the battery must be indicated. The European Commission will also evaluate, by 31 December 2023, extending the carbon footprint declaration requirement to portable batteries and the requirement for a maximum life cycle carbon footprint threshold to rechargeable industrial batteries with a capacity equal to or less than two kWh.

In addition to the carbon footprint label, all batteries must have the "CE" marking to demonstrate compliance with applicable EU health, safety, and environmental protection standards. The labeling of batteries included in a device must be affixed directly to the device in a clearly visible and legible manner. This marks a change from current practice in the EU and Germany, for example, where labeling is applied to the battery rather than the whole device. Labeling and information requirements will apply until 2026. However, QR codes will not need to be implemented until 2027.

The regulation aims to ensure that batteries are subject to separate, high-quality recycling. For example, a late council amendment provides for EV battery management systems (BMSs) to include a software reset function in case economic operators carrying out preparation for the reuse, repurposing, or remanufacturing of EV batteries need to load different BMS software. This may cause certain risks, such as cybersecurity reasons. Consequently, the regulation stipulates that should the BMS software's reset function be employed; the original battery manufacturer shall not be held liable for any breach of safety or functionality of the battery that can be attributed to the BMS software loaded after the battery was introduced to the market.

The regulation sets ambitious targets for each battery type:

- A collection rate of 45 percent by the end of 2023, 63 percent by the end of 2027, and 73 percent by the end of 2030 for portable batteries;
- A collection rate of 51 percent by the end of 2028 and 61 percent by the end of 2031 for LMT batteries.

The regulation also maintains a total prohibition on landfilling waste batteries. All waste batteries—including LMT, EV, SLI, and industrial batteries—must be collected by Economic Operators free of charge for end users, regardless of the nature, chemical composition, state, brand, or origin of the waste battery in question, and established mandatory minimum levels of recycled content for reuse in new industrial, SLI, and EV batteries: 6 percent for lithium and nickel, 16 percent for cobalt, and 85 percent for lead. Each battery must specify the amount of recycled content it contains.

By the end of 2023, the commission will assess the feasibility and potential benefits of establishing deposit return systems for batteries, particularly for general-purpose portable batteries.

The regulation also imposes obligations on end users:

- End-users must dispose of waste batteries separately from other waste streams at a designated separate collection point set up by the producer;

- To improve manageability, the regulation requires end users to be able to remove and replace all portable batteries from the device for which they are used. An independent professional must replace LMT batteries. Economic Operators will have 42 months from the regulation's entry into force to adapt the design of their products to this new requirement.

Within the technical and scientific scope, the regulation aims to boost innovation and sustainability in the battery sector, promoting manufacturing practices that minimize environmental impact and promote the circular economy. This involves optimizing production processes to increase energy efficiency, reducing the use of harmful and rare materials, and implementing advanced recycling methods to recover valuable materials from discarded batteries. These obligations include maintaining detailed records and providing accurate information about batteries' composition, origin, and final destination, thus facilitating oversight and regulatory compliance. These measures aim to make the battery sector more transparent.

An important factor defined in Articles 77 and 78 of Regulation (EU) 2023/1542 [91] specifies economic operators' responsibilities regarding battery management. The regulation specifies that the economic operator is responsible for assigning a unique identifier to the battery. Furthermore, the economic operator must record the data in the battery passport. Furthermore, the economic operator must ensure that the information contained in the passport is accurate, complete, and up to date with the data included in the battery passport.

This implies that the economic operator of the battery is responsible for the battery during periods when the battery is in use and when the economic operator does not directly own the battery or does not have direct control over the battery. Responsibility for the battery can be transferred in two scenarios: (i) when it is subject to reuse, repurposing, or remanufacturing and (ii) when the battery status is changed to "waste". Batteries, when subject to reuse, are considered a new product. Therefore, a new battery passport must be provided for these batteries. However, it is not yet clear whether the passport applied to second-life batteries should be linked to the first-life passport.

Once batteries are classified as "waste", the need to issue a new battery passport is eliminated. Moreover, the responsibility for battery disposal is transferred to the producer, an organization responsible for producer responsibility, or a waste management operator.

A conflict of interest may arise from the ambiguity in determining liability after classifying the battery as waste in a scenario where the EV owner disassembles the battery and returns the EV to the OEM. After this, the OEM sends the battery for recycling. In Article 61, the Battery Regulation suggests that the OEM is responsible for changing the battery status to waste in this scenario. However, it is unclear under what conditions the producer can transfer responsibility to an organization responsible for producer responsibility (if appointed by the OEM), a waste management operator, or have one of these actors as a substitute. Another possible conflict of interest in cases of transfer of responsibility for the battery is if the responsibility for the accuracy, integrity, and updating of battery passport data also lies with the economic operator.

This ambiguity can lead to an evasion of responsibility, where producers or OEMs may attempt to transfer their disposal obligations to third-party entities without ensuring that they have the appropriate infrastructure or capacity to manage the waste sustainably. Additionally, a lack of regulatory clarity can result in inconsistencies in battery waste management, potentially harming recycling efforts and environmental sustainability. Therefore, the regulation must be refined to clearly define the criteria and processes for transferring responsibility to mitigate conflicts of interest and ensure the effective and responsible management of discarded batteries.

Although the regulation requires the implementation of the battery passport by 2023, there is still a lack of clear definition of what data can be implemented and what the use cases for this passport are [92]. There is still a lack of information about what mandatory data companies must provide to ensure the sustainability and circularity of batteries [92].

Furthermore, it is not clear what data must be provided on a mandatory basis to prevent tax evasion and battery tampering. Other data may be provided voluntarily for developing a digital twin or validating projects in the early stages of development.

A study on battery labels should be conducted to understand which technologies can be adapted to monitor batteries in real time. Furthermore, smart labels could contribute to the rapid identification of battery material composition to increase sorting efficiency and facilitate the collection of batteries [92]. It is not yet clear what criteria will be adopted to define the performance and durability of batteries.

Performance and durability criteria are relevant to define the minimum acceptable criteria for first and second-life batteries to be marketed in Europe. SoH and RUL are essential metrics for determining battery quality warranty time and making strategic decisions, such as knowing the ideal maintenance time and whether it is more viable to reuse or recycle the battery directly.

The legislation in Article 14 establishes that battery manufacturers must provide access and relevant data to assess the battery's residual value and capacity for subsequent use. However, legislation relating to the risks of losing product know-how that companies may be subject to is unclear. Legislation must also be clear about at which level the RUL should be calculated. There are considerable differences when RUL is defined at the cell, module, and pack levels. The level of granularity regarding how the RUL should be provided will directly influence the second use of the batteries. In second-use scenarios, supply chain actors can benefit from module- and cell-level information, as distinct aging behaviors can be observed between individual units within a single battery. By having accurate RUL data relating to individual modules, a remanufacturer can decide which modules to recycle and which to remanufacture. Pack-level RUL information may also be appropriate to avoid duplicate testing in the supply chain and define battery resale value. On the other hand, accurate RUL prediction increases the cost associated with the BMS sensor and the development of models for cell-level RUL prediction. Furthermore, OEMs do not wish to share BMS data with the public, and therefore, legislation must ensure that OEMs do not lose their product and technology know-how.

Finally, although BMS generally contributes a marginal 4% to 5% increase to battery overhead, this amount does not sufficiently account for the additional time and engineering effort required to establish and authenticate sophisticated RUL estimation techniques. OEMs will encounter increasing challenges in complying with RUL reporting requirements while maintaining competitiveness in the global EV market. Therefore, keeping the requirements in their most basic form is advisable to promote extensive implementation of standardized RUL reporting criteria.

Through the United Nations Global Technical Regulations (GTRs) and the California Air Resources Board (CARB), the US recently implemented state-level legislation requiring battery SOH to be reported and accurate to within five percentage points by 2026. However, this legislation does not mention RUL as a metric to quantify battery durability [93]. Furthermore, in [93], the authors demonstrated that single-point SOH measurements cannot predict remaining useful life and that 5% SOH accuracy is insufficient to make reliable RUL predictions.

4.6. China

The Chinese government aims to manage batteries from the start of production to disposal. In this sense, the government enacted the Technical Policy on the Prevention of Pollution of Discarded Appliances and Electronic Products to reduce electronic waste and promote reuse and recycling. This policy aims to control the sources of pollution and product recycling, which means that the government is concerned with both the disposal of existing waste and the sources that generate this waste [94].

The technical policy on the Prevention of Pollution of Electronic Devices and Products aims to reduce, minimize, and encourage the reuse and recycling of electronic products through measures such as creating a fund to encourage the development of electronic waste recycling systems. By regulating the Recycling and Waste Disposal of Electrical and Electronic Equipment, China applies the producer responsibility principle, which gives the producer the responsibility to pay for the collection, labeling, and recycling of their product [95]. However, this policy does not yet implement procedures that facilitate the collection and logistics of electronic waste, such as batteries [96].

In 2008, China published Administrative Measures for the Prevention of Pollution (MAPP) of electronic waste that aims to apply the principles of producer responsibility and regulate the activities of disassembly, recycling, and disposal of electronic waste [94]. According to MAPP, recycling companies must have an operating license issued by the government and disclose what hazardous components are present in batteries, their composition, expected life, and environmental protection information.

The Ministry of Industry of China has implemented a set of rules that apply the concept of EPR to ensure that EV manufacturers are responsible for the collection, treatment, and disposal of batteries. In addition, EV manufacturers must establish service points, collect used batteries, and store and transfer batteries to recycling points.

Battery manufacturers are responsible for automating and standardizing the product, making them easy to disassemble and recycle. The Chinese government also obliges battery manufacturers to provide technical support to EV manufacturers to make battery storage and disposal possible. The work presented in [20] investigates the three possible scenarios for the industry to develop its recycling process. The authors investigated a scenario without government subsidies, with subsidies, and another scenario with implementing a reward and penalty mechanism. Policies were classified into three categories: subsidies, punitive, and traceability [17].

Subsidy policies are government incentives to replace conventional vehicles with vehicles that use new energy, such as EVs. An example of this type of policy is the “Provisional financial subsidy measures for demonstration and expansion of energy-saving vehicles and new energy vehicles in pilot cities,” which provides single fixed subsidies paid to vehicle buyers. Vehicles for personal use have not yet been included in the policy. Mention may also be made of the “Provisional financial subsidy measures for the private purchase of a new energy vehicle in pilot cities” and the “Management approach for the private purchase of battery EVs in Beijing (test implementation)” [20].

Punitive policies aim to punish battery or automobile manufacturers who fail to achieve battery reuse and recycling targets, including failure to implement government policies. An example of this type of policy is the “Pilot Scheme for EV Battery Recycling System in Shenzhen”, which proposes punishing companies that defraud, refuse to provide information, and/or fail to comply with recycling obligations. Finally, the traceability policy consists of policies that track, monitor, and supervise batteries throughout their life cycle in order to assign, among other things, those responsible for batteries during their life cycle [20]. Table 2 presents a summary of the primary laws that exist in China that can contribute to the reuse of EV batteries.

The safety of second-life batteries is a concern in different countries. The National Energy Administration stated in a Chinese policy document that it would ban “in principle” any new “large-scale” energy storage projects that use second-life batteries. This regulation was proposed after many safety incidents involving second-life batteries. However, the legislation is not clear about what it considers large-scale projects [97].

Table 2. Summary of the laws in China focusing on battery reuse and recycling.

Legislation	Year	Description
International transport of dangerous goods by road (in French, Accord européen relatif au transport international des marchandises Dangereuses par Route (ADR))	1957 (updated in 1975, 1985, 2011 and 2015).	ADR is an international agreement that aims to regulate the transport of dangerous goods to reduce the number of accidents caused by the transport of dangerous goods. This agreement defines dangerous goods' packaging, classification, labeling, and certification requirements. Dangerous goods are items and substances that are prohibited or that must be transported under specific conditions and are classified into nine classes, namely toxicity, corrosivity, flammability, and reactivity. This agreement changed on 21 August 1975 and became effective on 19 April 1985. The agreement still underwent changes and updates in 2011 and 2015.
Law on the Prevention and Control of Environmental Pollution by Solid Wastes	1995 (updated in 2015 and effective in 2016).	This law aims to prevent and control pollution by solid waste and, for that purpose, prohibits the import, dumping, and disposal of solid waste except for cases where the government issues a license.
Law on Clean Production Promotion	2002 (updated in 2012)	This law forces companies to improve their processes to promote clean production. This law provides funds for lime production and can reduce or exempt small and medium-sized companies from value-added taxes to promote clean production.
Waste Electrical and Electronic Equipment (WEEE) Pollution Prevention Administrative Measures (SEPA No. 40)	2008	These administrative measures aim to eliminate pollution and contamination relating to the disassembly, recycling, and disposal of electronic waste. These measures also present a scheme for licensing companies specializing in recycling electronic waste.
Interim Measures to Encourage the Purchase and Use of New Energy Vehicles in Shanghai	2014	The Shanghai municipal government provided financial incentives for recycling each EV battery. That incentive was 1000 RMB.
EV Battery Recycling Technology Policy	2015	Through this policy, the government aims to provide financial incentives for second-use companies and material extraction companies.
Circular Economy Promotion Law	2018	This law aims to promote the circular economy in companies, improve resource use efficiency, avoid environmental damage, and promote sustainable development. In order to achieve these objectives, this law implements a system of planning and statistical analysis of waste, and the current scenario implements fiscal and tax control and applies the EPR system. This law also provides tax incentives, monetary funds, loans, and credits to enable companies to implement the circular economy.
Pilot Scheme for EV Battery Recycling System in Shenzhen	2018	This public policy punishes industries that commit fraud or refuse to comply with recycling obligations. If the company does not fulfill its recycling obligations, its information will be inserted in the credit protection agencies.

Source: Prepared by authors.

China has implemented the principle of EPR and developed a robust framework to manage the life cycle of batteries. There are three models of battery recycling [98,99]. The first model is the guidance of the vehicle battery industry innovation alliance. In this model, government departments facilitate cooperation between different industrial actors and research institutes to encourage the use of batteries with residual capacity for energy storage systems applied to the supply of backup power and energy storage systems interconnected with energy storage systems, such as renewable energy generation and low-power mobile applications. The second model aims to promote cooperation between the upstream and downstream of the industrial chain. Vehicle manufacturers and battery manufacturers establish their own recycling systems to recycle the decommissioned batteries sold by them [98,99].

China proposed a national battery management platform, and one of the main functions of this platform is to collect information on the entire process of production, sale, use, scrapping, recycling, and use of batteries [98]. In China, the government has adopted a comprehensive regulatory approach to managing end-of-life EV batteries, implementing policies and standards to encourage safe and efficient reuse and recycling. The GB/T 34013-2017 [100] standard is a clear example of this regulation, establishing strict criteria for the dimensions and technical specifications of standardized power cells, modules, and battery cases for EVs. This standard defines parameters such as voltage, capacity, internal resistance, and physical dimensions of the cells, in addition to performance requirements for charging cycles and operating temperature. It facilitates interchangeability and standardization in the industry, promoting efficiency in battery production and remanufacturing.

The subsequent standard, GB/T 34014-2017 [101], is specifically targeted at the EV battery coding system. This standard describes in detail the coding method that must be used, structuring the identification code to include information such as battery manufacturer, the battery type, production date, and other relevant data. Coding is essential for maintaining the traceability of batteries throughout their useful life, which is crucial for safety, warranty management, and recall procedures, as well as for the effective selection and sorting of batteries for reuse or recycling.

In addition to the national standards mentioned, several associations led by large companies in the EV sector have established supplementary industry standards. For example, China's National Energy Administration (NEA), in collaboration with the China Electricity Council (CEC), has focused on effectively managing recycled batteries by defining procedures and standards for their collection, disassembly, and processing. The China Energy Storage Alliance (CNESA) collaborates in promoting energy storage standards that are vital for the integration of second-life batteries into renewable energy systems. Additionally, the China Association of Communications Enterprises (CACE) focuses on establishing standards for the communication and management of data related to EV batteries.

5. Discussion

5.1. Comprehensive Comparative Analysis by Region

Technical standards and legislation can help industries change their traditional economic model to the circular economy model. Public policies can help participants in the second-life battery market and companies focused on recycling to make decisions and develop viable business models. However, legislation and technical standards for both recycling and second-life batteries are still in their infancy and are insufficient to mitigate all risks in the EV battery business. There are doubts regarding the ownership of batteries and what responsibilities will be assigned to battery producers and owners throughout their life cycle. However, the primary areas involved in the EPR (a concept in which the manufacturers, producers, and importers of products take responsibility for the complete life cycle of their products, including social and environmental impact) are the responsibilities of those who design, produce, and sell goods in terms of the environmental and social consequences of their products, even after they have been sold and are no longer in use. Some key areas in which this concept applies are safety, testing and certifications, quality assurance, documentation and traceability, life cycle management, design for the environment, waste management and recycling, consumer awareness, regulatory compliance, collaboration with stakeholders, end-of-life planning, and continuous improvement. These responsibilities can vary depending on the jurisdiction and local regulations, though the objective of the responsible management of second-life batteries is to maximize value, minimize waste, and ensure that the circular economy is improvised, including solving environmental challenges.

Finally, it is important to highlight that in many countries, such as European countries, the EPR defines the operator as responsible for collecting and treating batteries. Therefore, the producer is responsible for the battery even when the batteries are under the direct control of the vehicle owner [41]. However, the responsibility for the battery remains with the producer who places the battery on the market. Therefore, battery tracking is important because it leads to greater transparency concerning the history of a battery. This is a challenge because there is still no specific legislation for second-life batteries in some regions, such as Latin America. The lack of clarity in legislation makes Latin America vulnerable to the transfer of waste batteries from one country to another and the disposal of batteries in inappropriate locations. Another challenge is when a company located in its country of origin places the battery on the market in another country and becomes the economic operator responsible for treating the battery in that country. In this case, the company often does not have adequate infrastructure to recycle the battery in that country, and the import of end-of-life batteries is prohibited in most cases under the Basel Convention. In South Korea, second-life batteries are considered waste and must be returned to the local government. It is still unclear how the government will manage many end-of-life batteries. Battery management is complex and even more difficult in countries that do not have legislation that implements EPR.

The EPR of batteries often includes provisions for the transfer of ownership, especially regarding responsibilities for end-of-life management and recycling. Some general principles are notification of transfer, continued producer responsibilities, information transfer, consumer education, collection and recycling infrastructure, joint responsibilities agreements, record keeping, and legal requirements. These aspects aim to reduce the gap in responsibilities and promote a more sustainable approach to product life cycles. China and Europe have led the way in drafting legislation and technical standards and have made significant progress. Among these policies, the major ones are the principle of EPR, and the leading technical standard for reusing batteries is UL 1974 [102]. Europe and China have clear targets for battery recycling, i.e., Europe established that 50% of the weight of batteries that reach the end of their useful life be recycled, and China considers the targets to be different according to the applied recycling process.

The EU has proposed several policy mechanisms to achieve a circular economy, including EPR, collection fees, material recovery rates, and emissions requirements. If the US does not implement similar requirements, battery and materials suppliers unwilling to reduce social and environmental impacts could shift their attention to sales in the US, while companies focused on a sustainable supply chain could focus their efforts on the EU. The harmonization of policies across regions could generate a global shift in the supply chain and production requirements, thereby positively decreasing regulatory uncertainty for manufacturers [31].

The study presented in [31] shows that recycling in China is less expensive than in the US, although domestic recycling in the US is still profitable in economies of scale. However, despite this, domestic recycling results in lower emissions due to reduced transport and a cleaner source of electricity. The raw materials for battery production are a risk to the supply chain of countries such as the United States and Europe because most raw materials originate from countries outside the United States and Europe.

With the current state of maturity in recycling processes, all batteries currently available cannot be recycled, and the industry will not be able to keep up with the growth of the battery market in the coming years. Despite this, some initiatives focus on stimulating a circular economy, such as the ReCell Center in the United States and the ReLib project in the United Kingdom [103]. From a market perspective, growth is expected to increase from USD 12.2 billion in 2025 to USD 18.1 in 2030, which means a growth of 8.2% from 2025 to 2030 in percentage terms [104]. The main reason for this growth is the increased demand for batteries, which is attributed to the increased sale of EVs [103].

Battery recycling is still in its infancy, and legislation can help stimulate the development of technical solutions and make the battery recycling process more efficient. Battery recycling legislation on cell labeling will help facilitate the efficient collection and sorting of batteries. Battery labeling can be undertaken in the form of serial numbers, QR codes, or RFID tags. However, some barriers still need to be overcome, such as sufficient battery collection infrastructure, high transportation costs, and safety concerns during storage and transportation [103]. The lack of standardization of battery chemistry is also a technological barrier. Lead–acid batteries have a standardized design in the USA and have few components, making this technology more accessible in terms of recycling [103].

A decentralized system for battery collection must be created so that supply chain actors share responsibilities and costs for battery collection. Furthermore, new efforts must be made to standardize batteries, making it easier to automate the disassembly process [103].

The California EWRA and the EU WEEE Directive aim to increase the recycling rate. However, it adopts the principle of "producer pays", establishing the responsibility of producers for the collection, treatment, recycling, and disposal of electronic waste. Therefore, in the EU, the producer is financially responsible for recycling. On the other hand, the California EWRA charges consumers a recycling fee when purchasing a new electronic device.

Despite concentrated efforts to harmonize public policies and legislation, there remains a disparity in the legislation established by different countries and economic blocs. The United States has a fragmented regulatory structure that relies on a combination of state and federal guidelines, which allows for greater flexibility and complicates enforceability. The EU defines producers as responsible for the collection, treatment, and recycling of batteries. However, the definition a producer is nebulous and can result in potential conflicts between stakeholders. For example, producers can be both battery and automobile manufacturers. The context needs to be better defined so that it is possible to know who will be responsible for collecting, reusing, and recycling a battery.

The EU's strict and detailed legislative framework contrasts the more flexible and variable American state-based approach, and both differ from China's centralized but less transparent system. Harmonizing these regulations would streamline global compliance and foster an international market that incentivizes the design of batteries with recycling in mind, leading to more sustainable battery lifecycle management.

Regarding technical standards focusing on second-life batteries, gaps remain to be filled. Several common points were identified in the legislation of several countries. However, some technical terms must be more transparent to avoid misinterpretation. The comparison between technical standards showed a trend regarding requirements regarding recovery rate and recycling efficiency in some countries. Canada has three states that require manufacturers to collect batteries, and the recycling rate is 50%. The recovery rate in the EU, as determined by legislation, is 45%, and the recycling efficiency is 50%. China and Japan encourage but do not require manufacturers to build recycling facilities. However, Japan requires recycling efficiency to be at least 30%. Australia does not have any laws requiring the collection and recycling of LIBs. In the United States, although some states prohibit the disposal of LIBs in landfills, there are still no strict standards. As a consequence of the lack of legislation, the US may face problems in the future as out-of-warranty batteries may be dismantled by small car dismantlers, scrap metal recyclers, or private repair facilities, for whom the cost of transportation may be a burden that discourages optimal elimination. Furthermore, end-of-life batteries may be disposed of in inappropriate locations if a recovery rate is not assigned.

Battery transport logistics must also be regulated on a regional, federal and international scale. This is important to mitigate the cost, accidents, and environmental impacts of transporting this dangerous commodity. The EU and China assign the producer, directly or through a third party, as responsible for collecting, sorting, storing, and transporting batteries. In the United States, the transportation of LIBs is regulated by the Department of Transportation (DOT) and is classified as a Class 9 hazardous material ("Miscellaneous"). Consequently, batteries sent for disposal are exempt from certain classification and packaging requirements but must be packaged to avoid short circuits, damage caused by movement or placement within the packaging, and accidental activation of the equipment. However, damaged or defective batteries are subject to stricter regulations.

The regulatory structure of countries and economic blocks directly impact the cost and greenhouse gas emissions during the transport of second-life batteries. Standard harmonization can reduce differences in regional transport costs and market uncertainty. Access to battery data will facilitate access to information about the health status of batteries and, consequently, will simplify the battery transport process. This will also increase battery safety once the battery's health status is known. The cost will be reduced because fewer batteries will be tested on-site. The classification of batteries as waste represents a risk to this market as this could imply additional costs, making this product economically unviable.

In the USA, the maritime transport of batteries can be carried out by third-party logistics companies that meet the requirements specified in federal and international regulations. However, the responsibility for packaging, marking, labeling, and completing documentation for dangerous goods regulations falls on the party shipping the goods and not on the logistics company transporting the battery.

Developing countries still face shortages of technical norms and standards and are lagging in implementing battery reuse and recycling. It is expected that the standards in these countries will be developed based on the standards that already exist in Europe, China, and the USA and that companies will import the technology to implement the reuse and recycling of batteries from developed countries.

With respect to the import/export of second-life batteries, the key points to keep an eye on are as follows: (i) international trade with logistics and transport regulations—as different countries might have their own specific regulations and restrictions regarding the transportation and handling of used batteries due to environmental and safety concerns and the organizations involved in the import/export of such batteries need to follow the international shipping regulations, including those set by the International Air Transport Association (IATA) and the International Maritime Dangerous Goods (IMDG) Code, and (ii) market dynamics—there is a strong influence by the demand for energy storage solutions, raw materials, and refurbished batteries in different regions, and key players, such as battery manufacturers, recyclers, and other stakeholders may participate in international trade to capitalize on opportunities in the second-life battery industry.

Batteries classified as waste are considered Class 9 miscellaneous hazardous materials. This classification makes the battery subject to the Basel Convention, which controls the international movement of hazardous waste and increases the cost of transporting this type of merchandise [105,106].

The Basel Convention is an international convention that sets precise regulations for the handling and moving of dangerous waste between countries. This agreement clearly forbids the export and cross-border transportation of hazardous waste without prior formal written approval from the importing and transit states. Consent guarantees that hazardous waste is managed and transported safely and responsibly, reducing environmental and public health hazards [105,106].

In a hypothetical scenario, a company located in country A wishes to export electronic waste, which is classified as dangerous due to the presence of heavy metals and toxic substances, for recycling in country B. Following the guidelines of the Basel Convention, the company must first request and receive written authorization from country B, in addition to any country through which the waste may transit. This authorization would ensure that country B has the capacity and adequate facilities to process electronic waste safely and environmentally soundly [105,106].

Still, on the Basel Convention, if a country prohibits the import of hazardous waste or other waste, all other signatory parties to this agreement must prohibit the export of hazardous waste. Bilateral, multilateral, or regional agreements may be concluded if they do not compromise the environmental management of waste required by the convention [105,106].

Therefore, after batteries are classified as waste, batteries can be transported only if (i) the exporting state possesses the technical capacity, necessary facilities, or suitable disposal sites to manage the waste in an environmentally and efficient manner. This ensures that the exporting state has evaluated its ability to handle the waste according to the convention's standards but opts for transboundary movement based on strategic, environmental, or economic reasons; (ii) the waste in question must be needed as a raw material for recycling or recovery industries within the importing state. This criterion supports the principle of a circular economy, encouraging the reuse and recycling of materials to reduce the demand for virgin resources, minimize waste, and support sustainable industrial practices; and (iii) the exporting and importing parties must establish an agreement on the movement of waste that aligns with the Basel Convention's objectives. This agreement ensures that both parties have mutually agreed upon the conditions and standards under which the waste will be managed, preventing any practices that could harm human health or the environment [105,106].

This information is important in a scenario where country A, with advanced technical capacity and facilities specialized in recycling lithium-ion batteries, exports used batteries to country B, which has a demand for materials recovered from these batteries for use in its industries manufacturing new batteries and electronic devices. In this example, the process occurs as follows [105,106]:

- Technical Capacity Assessment: Country A evaluates its technical capacity and concludes that, despite having recycling facilities, exporting to country B is strategically advantageous due to country B's specialization in recovery processes for specific materials and the existence of a significant demand for these recycled materials.
- Raw Material Need: Country B needs the recyclable materials contained in used batteries, such as lithium, cobalt, and nickel, for its rechargeable battery and electronics industries. The import of this waste supports the principle of the circular economy, minimizing the need to extract new resources and promoting sustainability.
- Bilateral agreement: Before the transfer, countries A and B establish a bilateral agreement, as required by the Basel Convention, detailing the terms of the import, including safety measures, recycling procedures, and environmental management plans. This agreement ensures that the movement of used batteries is carried out in a manner that protects human health and the environment.

If the company cannot transfer the battery to a country with adequate infrastructure for recycling, it must develop its own recycling infrastructure or, when legislation allows, hire third parties to carry out this task. With regard to the import of waste batteries in countries that are not signatories to the Basel Convention, this situation is more complex. Additionally, therefore, countries must develop more specific legislation for this scenario.

Therefore, since batteries are classified as waste, their transportation becomes complex, considering that transporters must request a specific license and receive authorizations from different parties involved to transport batteries. The complexity of this type of transport increases because one jurisdiction differs from another. Moreover, the vehicles used to transport the battery must be equipped with special handling equipment, and drivers must receive special training [105,106].

Some of the challenges associated with transporting these batteries between countries are as follows: (i) safety concerns: these types of batteries pose safety risks, including the potential for thermal runaway, leakage, or fire due to hazardous materials. Ensuring the safe transport of these batteries is a primary concern and may involve using specialized packaging, labeling, and handling procedures. (ii) Documentation and record maintenance: accurate documentation is vital for international transport, including records of battery specifications, safety data sheets, import/export permits, and other relevant documentation. Maintaining detailed records helps to ensure transparency and facilitates compliance with other regulatory requirements. (iii) Security issues: security concerns related to the transport of valuable or potentially hazardous materials, especially during transit through different countries, are crucial to prevent theft or unauthorized access. (iv) Technological compatibility: making sure that such batteries meet the technical specifications and standards of the destination country is an important factor for compliance as different countries may have multifarious standards and regulations for battery technologies. To resolve some of these challenges, stakeholders need to collaborate, including battery manufacturers, transporters, regulatory authorities, and environmental agencies. Developing standardized processes and international agreements can help streamline the import/export of second-life batteries while ensuring safety and regulation compliance.

The current scenario of economic crisis motivated by the by COVID-19 pandemic, associated with the implementation of the principle of producer responsibility in some countries and the emergence of new regulations, has motivated industries to seek cooperation to survive in an increasingly competitive market and achieve the goals of recovery, recycling, and reuse of EV batteries. There is still no definition of what modifications to used batteries are sufficient to consider them either remanufactured or new products. The definition of these parameters is fundamental to intellectual protection and the protection of industrial secrets relating to the product. Table 3 presents a comparison between the different regulations and standards that exist for recycling and reusing batteries.

In the transition towards a circular economy model, the regulatory landscape plays a crucial role in shaping industry standards and practices, particularly in the realm of EV battery recycling and second-life applications. Table 4 provides a comprehensive overview of the key similarities, differences, and gaps in legislation and technical standards across various jurisdictions, with a focus on the EPR concept. EPR mandates that producers, manufacturers, and importers bear the environmental and social consequences of their products throughout their lifecycle. The juxtaposes the regulatory approaches of major regions such as China, Europe, and the United States, highlighting their strategies towards battery ownership, recycling targets, and the implementation of technical standards like UL 1974 [102]. Additionally, it examines the impact of these regulations on the development of viable business models, the assignment of responsibilities throughout the battery lifecycle, and the overall effectiveness of recycling processes. By comparing legislative frameworks and technical requirements, Table 4 aims to elucidate the varying degrees of progress toward sustainable battery management and identify areas where harmonization could promote global compliance and encourage battery reuse and recycling.

Table 3. Summary of the principal regulations in the area of batteries in different regions of the world.

Status	China	Europe	USA	Japan	Korea	Africa	South America	India
Regulations on EV batteries for recycling	✓	The Battery Directive 2008/98/EC allowed batteries to be transferred from one party to another without being declared waste.	-	-	Clean Air Conservation was announced in 2004 and implemented in 2005 to monitor the pollution of cars with diesel emissions.	-	-	-
General Regulation on LIB Batteries	✓	✓	The USA has federal waste regulations that regulate batteries according to the status of each type of battery.	The Law on the Promotion of the Effective Use of Life Resources promotes the reduction of waste, reuse, and recycling of batteries.	-	-	-	-
Regulations on second-life batteries	✓	The Battery Directive 2008/98/EC allowed batteries to be transferred from one party to another without being declared waste.	-	-	Clean Air Conservation was announced in 2004 and implemented in 2005 to monitor the pollution of cars with diesel emissions.	-	-	-
EPR	✓	✓	✓	-	-	-	Some countries, such as Brazil, but not all countries in South America.	-
Recycling Efficiency Target	✓	-	-	-	-	-	-	-

Table 3. *Cont.*

Status	China	Europe	USA	Japan	Korea	Africa	South America	India
Leading players who are investing in second-life battery projects	The legislation establishes that the efficiency for recycling Ni, Co, and Mn must be 96% for the Hydrometallurgical process and 97% for the Pyrometallurgical recycling process to obtain nickel and rare earth.	The battery directive states that 50% of the total weight of batteries that reach the end of their useful life must be recycled.	-	-	-	-	-	-
Leading players who are investing in second-life battery projects	Yinlong Energy, Build Your Dream (BYD), GreatWall Power	Daimler GETEC/The Mobility House Remondis/EnBW (Germany), Renault (UK), Umicore (UK), Connected Energy (UK), Relectrify (Australia), Bosch (Alemanha), Siemens (Alemanha), Vattenfall (Germany), BMW (Germany), Audi (Germany), Volkswagen (Germany), Fortum (Finlândia), Acceleron (UK).	General Motors, ABB, Spires New Technologies Inc (SNT), Chevrolet, Florida Power and Light, FreeWire.	4R Energy, Honda, ITAsset Partners (ITAP), Mitsubishi, Nissan.	-	Eaton	-	-

Table 3. *Cont.*

Status	China	Europe	USA	Japan	Korea	Africa	South America	India
Major Recycle Associations of LIB	Waste Battery Recycling Committee China Battery Industry Association	European Battery Recycling Association and ReCharge	NAATBatt	Battery Association of Japan	Korea Battery Industry Association	The South African EV Association is still looking for viable projects for battery recycling.	-	-
Summary	Current policies aim to promote the reuse of batteries through recycling by encouraging advertising campaigns, transparency, and research and development projects. Policies focusing on recycling aim to improve the efficiency of the recycling process and process technologies.	The policies seek to enable the reuse and recycling of EV batteries. Europe has some industrial facilities with mature technology recycling processes, and EV manufacturers are aware of the benefits of battery reuse and recycling.	There is still no specific legislation for EV batteries. The main recycling laboratory is ReCall, led by Argonne Laboratory.	Japanese car manufacturers have proposed several battery recycling projects. The Electrical and Material Safety Act imposes a set of rules for LIBs. Japan had the first UL 1974 certified group, the joint venture (Sumitomo and Nissan) called 4R Energy.	South Korea still seeks, through projects in cooperation with universities, to have its first EV battery recycling facility.	-	South American countries still face problems managing lead acid batteries that reach the end of their useful life. The insertion of LIBs in the EV market will be a problem yet to be solved. No specific laws still regulate the recycling and reuse of this type of battery.	India also has no regulations that encourage the reuse and recycling of EV batteries.

Source: Prepared by authors. Note: ✓—Regulation has been implemented and "-" regulation has been not implemented.

Table 4. Comparative analysis of second-life battery market regulations across different regions.

Aspect/Region	USA	South Korea	Africa	Latin America	Europe	China	Similarities
Principle of Producer Responsibility	- Implemented at the state level with variations. - Focus on electronic waste management programs.	- Strongly implemented with DRS and EPR policy.	- Not widely implemented or in initial stages.	- Brazil stands out with the NSWP. - Other countries are developing or seeking to implement similar principles.	- Broad implementation with detailed regulations for batteries and electric vehicles. - Battery Directives establish producer responsibility for the collection, treatment and recycling of batteries.	- Robust closed-loop management system from production to disposal.	- EPR as a basic principle in all regions.
Incentives and Penalties	- Varies by state; incentives for energy storage, but without a unified approach to recycling penalties or incentives. - FERC orders recognize energy storage as a resource. - Incentives for energy storage connection to the grid.	- EPR establishes collection targets and fines for non-compliance, encouraging recycling. - Incentives for battery recycling.	- Lack of clear or implemented incentive and penalty structure.	- Inadequate infrastructure and a lack of clear regulation limit the effectiveness of potential incentives or penalties.	- Establishes clear collection and recycling efficiency objectives, with incentives for reuse and penalties for non-compliance. - Strict standards promote recycling and the circular economy. - Specific targets for recycling efficiencies.	- Incentives and mandates for battery manufacturers regarding recycling.	- Use of incentives and penalties for compliance.

Table 4. *Cont.*

Aspect/Region	USA	South Korea	Africa	Latin America	Europe	China	Similarities
Specific Regulations for Recycling and Reuse	- Battery Law, state regulations like EWRA in California.	- Focus on reuse and recycling, but gaps for second-life batteries.	- N/A	- Variety of national regulations, some lead–acid battery recycling initiatives.	- N/A	- N/A	- Variety of approaches focusing on recycling.
Differences	- Regulatory fragmentation between states. - The 'Battery Act' does not include LIBs and NiMH unless they contain heavy metals. - No specific incentives for second-life battery applications.	- Government responsibility for recycling, different from the more common producer responsibility model.	- N/A	- Regulatory diversity, with some countries advancing more than others. - Regulatory frameworks are less developed compared to Europe.	- Comprehensive and uniform approach across the EU. - Strong emphasis on circular economy and sustainability. - Regulations like the EU Battery Directive address battery life cycles.	- Specific regulations for second-life batteries are still developing.	- N/A

Table 4. *Cont.*

Aspect/Region	USA	South Korea	Africa	Latin America	Europe	China	Similarities
Identified Lacks	- Lack of clear incentives for battery reuse and state regulatory differences. - Need for specific regulations and standards for second-life batteries. - Economic incentives for second-life applications are lacking.	- Need for business models for reuse and recycling. - Standards for second-life performance and safety may need further development.	- Lack of comprehensive legislation on battery lifecycle management.	- Lack of regulations of LIBs, in particular, with focus on reuse and recycling. - Development of recycling infrastructure and incentives. - It is necessary to improve battery collection and recycling systems.	- Definition of responsibilities for second-life batteries. - Harmonization of standards for second-life batteries is ongoing. - Economic models for second-life battery applications need refinement.	- Need for clearer guidelines on repurposing and safety standards.	- Need for greater clarity and infrastructure.

Source: Prepared by authors. Note: The content of this table provides a broad overview and may not encompass all the intricacies of regulatory environments in each region. Specific regulations can differ greatly within regions, particularly in Africa, where regulatory maturity varies widely among countries. Additionally, these regulatory frameworks are rapidly evolving as the significance of battery lifecycle management is increasingly acknowledged on a global scale. "N/A"—Not available or not applicable.

5.2. Testing and Certification Standards for Second-Life Batteries: Ensuring Safety and Performance

Tests are essential to protect operators who often rely on battery specification sheets, and testing procedures prove that battery capacity values can differ by up to 20% from those specified on specification sheets. For this reason, the testing procedures need to be more assertive, increase reliability, and lower the risk of defects due to nonreal performance.

The development of new standards will ensure that batteries have satisfactory performance and safety. Second-life batteries need to be evaluated to determine whether they will perform and perform appropriately in a second application. For this, these batteries are subjected to a set of thermal and electrical tests that must be non-destructive, as well as being able to assess the main parameters of the batteries, among them, the SoH, State of Charge (SoC), voltage, and the current [30,48,107].

The UL 1974 [102] standard is a set of guidelines published in 2018 by Underwriters Laboratories (UL), a global safety certification company. This standard specifically focuses on the sorting, grading, and evaluation processes of battery packs, modules, cells, and electrochemical capacitors. These battery packs, modules, cells, and capacitors were originally configured and used for other purposes, such as EV propulsion, vehicle auxiliary power, and light electric rail applications [30]. Although this standard primarily focuses on reused lead–acid batteries, it also includes reused EV batteries and can increase customer confidence to enable second-life battery business models [30,48,107].

This standard is the first "manufacturing process" to ensure safety for remanufactured batteries in secondary applications. To assess the condition of the batteries, this procedure considers tracking charge and electric discharge rates. However, despite the publication of this standard, it is still challenging to identify and map all battery characteristics considering the different chemicals and variations in the design [30,48,107].

This protocol ranges from the batteries' classification and a visual assessment to the internal processes' audit process and the safety criteria necessary to guarantee the functioning of the companies responsible for reusing the batteries. To obtain UL 1974 [102] certification, reused batteries must also obtain UL 1973 [108] certification [61,109].

The UL 1974 [102] standard recommends that the following tests be carried out for the certification of batteries [61,109].

- Measurement of open-circuit voltage (OCV);
- Insulation test for high-input voltage;
- Capacity test;
- Measurement of internal resistance;
- Verification of BMS control algorithms and protective components;
- Test cycle discharge/charge;
- Self-discharge.

The UL 1974 [102] standard declared the expiration date of the batteries to be mandatory. This had not yet been specified in previous battery standards, and it is a challenge for battery manufacturers to estimate their lifetime because the charge status of the batteries is not 100%, and the lifetime of the batteries will depend on a wide variety of factors such as conditions of use and application. Although this new standard helps to classify the condition of reused batteries, it is still not enough to ensure that batteries maintain the OCV, but when in operation, the voltage drops, and they are short-circuited. It is also unclear whether this pattern is sufficient to predict battery failure.

Although the UL 1974 [102] standard offers detailed guidelines for the application of repurposed battery systems and systems employing repurposed modules, cells, and other components, it does not encompass the procedures involved in remanufacturing batteries, which are alternatively referred to as reconditioned or rebuilt batteries [30]. UL 1974 [102] states that no component of a battery system, including the battery casing, BMS, thermal regulation mechanisms, or any supplementary systems, is considered suitable for reuse after its lifespan specified by the manufacturer has expired [30].

The structural safety of batteries includes seven categories: casing, cells, spacing and thermal insulation, relays, fuses, BMSs, terminal blocks and cables, and circuit boards. The polymer material used in the casing must meet flame-resistance standards and pass different tests for impact, rupture, abnormal use, harsh conditions, and molding stress release deformation.

In addition to structural tests, performance tests must also be carried out to guarantee the performance of the batteries. Performance tests have four main objectives: (i) calibrate and validate battery aging models, (ii) investigate battery performance under different charging conditions and discharge profiles, (iii) investigate the mechanisms of the aging process and the durability of batteries over time, (iv) evaluate the level of battery self-discharge over time [110]. Table 5 shows the performance tests that must be carried out under UL 1974.

Table 5. Performance test items and descriptions.

Test	Test Method Description
OCV test	OCV must be measured at different levels of granularity: battery pack, system, modules, and cells must be measured. After that, the measured values of each cell must be compared with the module's total measured values must be compared with the battery and recorded. It must be rejected when the open circuit is lower than the secondary-use manufacturer's standards [102].
Incoming high-voltage insulation inspection	First, measure the battery's positive terminal and dead metal parts, then measure the negative terminal and dead metal parts of the minimum 60-s condition. The measured value should be at least 100 Q/V for DC and 500 Q/V for AC. Use 500 Q/V for measurement [102].
Capacity check	Secondary use manufacturers can specify standard procedures for inspection or follow the following method: first fully charge at room temperature, then let it stand for one to four hours, then discharge to the endpoint according to constant current or constant power, and record the discharge capacity. It must be rejected if the measured value is lower than the manufacturer's standard for secondary use [102].
Internal resistance check	Perform this check after the capacity check. The secondary use manufacturer can specify standard procedures for inspection or follow the following method: the item to be tested must be fully charged at room temperature, left to stand for thirty minutes to four hours, and discharged using a constant current (I_1) to 80~90% of the capacity. Then, use five times the current to instantaneously discharge for 1 to 10 s, record the voltage and current of these processes, and calculate using $R = (V_1 - V_2)/(I_2 - I_1)$. If the measured value is higher than the manufacturer's standard for secondary use, it must be rejected [102].

Table 5. *Cont.*

Test	Test Method Description
BMS control and protection component inspection	According to the results of cell, module, or battery pack disassembly, the relative self-discharge rates are measured, respectively. During the test, fully charge the item under test, then leave it at room temperature for at least one day, and measure the OCV for five minutes, one hour, and 24 h. If the measured value exceeds the manufacturer's standards for secondary use, it must be discarded [102].
Charge and discharge cycle test	The tested sample must be discharged and charged at least once at room temperature. If the possible temperature for secondary use is ≤ 0 °C, the ambient temperature should be at least ± 2 °C. During the charging and discharging process of the battery, the voltage, current, and temperature must be recorded. If the measured value exceeds the manufacturer's standard for secondary use, it must be rejected [102].
Self-discharge inspection	According to the results of cell, module, or battery pack disassembly, the relative self-discharge rates are measured, respectively. During the test, first fully charge the item under test, then leave it at room temperature for at least one day, and measure the OCV for five minutes, one hour, and 24 h. If the measured value exceeds the manufacturer's standards for secondary use, it must be discharged [102].

Source: Adapted from [111].

Innovation in the battery sector can be boosted using data. Data can be used to develop more sophisticated tools, parameterize data-driven and physics-based models, and develop models to evaluate the technical–economic feasibility of an application and its environmental impacts. To achieve this, a large amount of data must be collected, and the main obstacle is that companies do not want to risk their competitive advantage by sharing data. Several initiatives, such as Battery Genome and GAIA-X, have been proposed to encourage data sharing. The UL 1974 standard describes the data that must be collected from the BMS, as shown in Table 6.

Table 6. Useful data that can be read in BMS [102].

Project	Data
Capacity (Ah or Wh)	For the complete process, the measured capacity, along with total charging and discharging capacity, is measured [102].
Current	The maximum current exceeding the charging and discharging values during the process, the distribution of charging and discharging current during the process, as well as the maximum individual current surpassing the standard results [102].
Voltage (VDC)	For the complete process, the maximum, minimum, and average charging and discharging voltage are required [102].
Power (W)	Complete power distribution. Full module voltage distribution, minimum and maximum discharge voltage surpassing the standard values [102].

Table 6. *Cont.*

Project	Data
Remaining power (SOC) (%)	The maximum and minimum remaining power throughout the complete process, as well as the distribution of remaining power at the time of startup and shutdown [102].
Temperature (°C)	The maximum and minimum temperature values as well as the temperature distribution during completion. The maximum and minimum temperature of electronic components and sub-components in the complete process. The maximum voltage in the complete process [102].
Time (h)	The total time of the production, including the start, usage, and shutdown time. The complete charging, discharging, and balancing time. The complete period of over-voltage, under-voltage, over-high and low temperature and, over-current time during charging and discharging [102].
Internal resistance	Complete measured values [102].
Error message	The variety and quantity of the error messages [102].

Source: Adapted from [111].

In addition to the data that must be collected from the BMS, other data can be used to classify batteries. This is relevant in second-life scenarios because it is necessary to automate the process of sorting and grading batteries to reduce cost and time. Furthermore, the data can be used to extract relevant information that can avoid time-consuming testing. Table 7 summarizes the main data that need to be collected.

Table 7. Data to be collected during the initial screening process.

Areas for Data Collection	Collection of Data
Battery system	Manufacturer details along with production date, capacity, specifications (including structure and type), and instructions. Further information in relation to, user manual, cooling system, outage date and storage time, failure, abnormality, and maintenance records [102].
Module	Contains relevant information related to battery systems, such as manufacturer details, production date, capacity, component number, specifications, charge and discharge parameters, user manual, and structure and type [102].
Batteries	Like battery system and module, information such as manufacturer details, production date, weight and size, component number and marking, specifications, rated voltage and capacity, charge and discharge parameters, safety test data, expiration date, and internal structure (refer to IEEE 1625 [112] or IEEE 1725 [113]) [102].
BMS	Manufacturer details, production date, component number, specifications concerning current, voltage and temperature protection, transmission protocol, CAN bus signal architecture, electrical circuit diagram, components list and configuration, and calculation logic [102].

Table 7. *Cont.*

Areas for Data Collection	Collection of Data
Cooling system	Manufacturer details, production date, part number, specifications in relation to temperature, control, and flow, refrigerant substance: installation, operation, fault inspection, and maintenance [102].
Other systems	Manufacturer details, production date, component number, and specifications such as power capacity, dimensions, and usage parameters: installation, operation information on operation, troubleshooting, and maintenance records [102].

Source: Adapted from [111].

Batteries must also be evaluated for electrical, mechanical, and thermal abuse conditions. Electrical abuse testing exposes cells to overcharge, forced discharge, and external short-circuit scenarios [114]. These tests are intended to reproduce a battery safety incident caused by an electrical malfunction [115,116]. Table 8 presents the electrical tests that must be carried out for second-life batteries in accordance with UL 1974.

Table 8. Electric abuse tests to be performed on second-life batteries.

Test	Test Method Description
Overcharge protection test	Charge the Device Under Test (DUT) at the maximum charging rate (equivalent to at least 110% of the maximum rated charging voltage). Stop to protect the circuit. After completion, a charge and discharge cycle along with the withstand voltage test are performed. The DUT will be disqualified if it releases flammable and/or toxic gases, leaks, ruptures, burns, or explodes, and eventually fails in protection control [102].
External short circuit test	After the DUT is fully charged, use a resistor to connect the positive and negative electrodes for a short circuit, and then use the load discharge to generate a current discharge of 85~100% of the maximum value of the protector and discharge completely until the core temperature stabilizes and thereafter let it sit for 7 h. After that, undertake the pressure test. The DUT will be disqualified if it releases flammable and/or toxic gases, leaks, ruptures, burns or explodes and eventually fails protection control [102].
Overdischarge protection test	After the DUT is fully charged, use a constant current to discharge until 95% of the rated capacity of the passive protection device or the voltage or until temperature protection device is activated. Thereafter, a charge and discharge cycle is performed, and then a withstand voltage test is performed. The DUT will be disqualified if it releases flammable and/or toxic gases, leaks, ruptures, burns or explodes and eventually fails protection control [102].

Table 8. *Cont.*

Test	Test Method Description
Temperature and operation limit check test	After the DUT is discharged, it should be kept in a test box, adjusted to the maximum charging limit temperature, and the maximum discharging rate should be used to charge it fully. After that, adjust the maximum discharge limit temperature and use the maximum discharge rate. The above charge–discharge cycle is carried out five times. During this period, the sample's voltage, current, and temperature should not exceed the manufacturer's operating limits, and it should not rupture, leak, burn, or explode [102].
Unbalanced charging test	If the DUT is fully charged, but one of the cells or modules is completely discharged, then the remaining cells or modules are discharged up to 50% and then charged at the maximum charging rate. A charge and discharge cycle is performed, followed by the withstand voltage test. The DUT will be disqualified if it releases flammable and/or toxic gases, leaks, ruptures, burns, or explodes, and eventually fails in protection control [102].
Cooling/heating management system failure test	The DUT in the test chamber is completely discharged, the maximum operating temperature is adjusted, and it is kept on standby for 7 h. Thereafter, turn off the cooling/heating management system and fully charge it; then take it out, discharge it, and return it to the test chamber. After the tested DUT is fully charged, it is adjusted to the maximum operating temperature and kept on standby for 7 h, then the cooling/heating management system is disabled and then completely discharged. After completion, a charge and discharge cycle is performed, followed by the withstand voltage test. The DUT will be disqualified if it releases flammable and/or toxic gases, leaks, ruptures, burns or explodes and eventually fails protection control [102].
Electrical components test	If the fan is clogged, wrap the fan blades with paper such as toilet paper and let the fan run continuously for 7 h. There should not be any burning phenomenon noted on the paper. Leakage current: separated controllers must be tested for touch current, in accordance with UL 60950-120 [117]. Strain release: Use a pulling force of 156 N to pull the wire for one minute. No damage or joint displacement should occur, and the deformation of the joint should not exceed 2 mm [102].

Source: Adapted from [111].

Battery mechanical testing is performed with a focus on two fundamental objectives: (i) the calibration or validation of mechanical models and (ii) the investigation of the structural properties of the battery, characterized by their reaction to intense loads, including but not limited to fracture strain, tolerance to strain in short circuit scenarios, and peak force thresholds. Consequently, mechanical testing assesses the potential for battery failure and safety features. Although there are several standards for mechanical testing, such as ISO 12405 1-3 [118], SAE J 2464 [119], SAE J 2929 [120], QC/T 743 [121], UN/DOT 38.3 [122], and UM ECE R100 [123], UL 1973 [108] is the main standard that describes the tests, as described in Table 9.

Table 9. Mechanical tests of secondary utilization energy storage products.

Type of Tests	Description of Test Method
Static Test	Once the DUT is fully charged, apply static pressure of 250 ± 10N on the top, bottom and sides for five seconds. A charge and discharge cycle is performed, followed by the withstand voltage test. The DUT will be disqualified if it releases flammable and/or toxic gases, leaks, ruptures, burns or explodes and eventually fails in protection control [102].
Impact Test	After the DUT is fully charged, it should be hit with a steel ball (diameter of 50.8 mm and a weight of 535 g) from a height of 1.29 m at different angles, at least three times in total. A different sample can be used for each impact. After that, a charge and discharge cycle should be followed by the withstand voltage test. The DUT will be disqualified if it releases flammable and/or toxic gases, leaks, ruptures, burns, or explodes and eventually fails in protection control [102].
Drop Test	Once the DUT is fully charged, it is dropped directly on a cement floor. When the DUT weighs ≤ 7 kg, the drop height should be 100 cm; when the weight of the DUT is greater than 7 kg, the drop height should be 10 cm. The flat drop method should not be used if only one test is conducted. A charge and discharge cycle should be performed, followed by the withstand voltage test. The DUT will be disqualified if it releases flammable and/or toxic gases, leaks, ruptures, burns, or explodes and eventually fails in protection control [102].
Molding stress test	Once the DUT is fully charged, keep it in the test chamber and set the temperature to 10 °C, which is higher than the maximum operating temperature but not lower than 70 °C. Thereafter, a pressure test should be performed. The DUT will be counted as a failure if it leaks or breaks [102].
Pressure relief valve and Pressure test	Soak the DUT in mineral oil and then continue to increase the current for charging until bubbles appear in the pressure relief valve and the action is displayed. The DUT qualifies when the pressure is normal and there is no rupture or leakage is found [102].
Pressure Relief valve open	To qualify as a normal pressure relief valve, three pressure relief valves should be selected. The air should be gradually pressurized to determine the starting pressure. Then, the average value should be used to calculate the UL test results. It passes if the test result is 90~100% of the nominal value of the pressure relief valve starting to release [102].

Source: Adapted from [111].

The environmental testing of second-life batteries evaluates safety in order to reduce the risk of fire and explosions. To achieve this, batteries are tested under extreme temperatures, vibrations, and shocks to reduce the likelihood of failure and ensure adequate performance in extreme scenarios. Environmental tests are also performed to evaluate the durability and reliability of batteries under extreme conditions. Environmental test results are used to validate battery life requirements and define battery maintenance requirements [124].

Typically, these tests focus on studying the thermal stability and behavior of a battery under extreme temperatures, its mechanical durability under anti-sinusoidal shock, sinusoidal vibration, random vibration and impacts, its electrical performance under different environmental conditions and its chemical stability, including leaks or dangerous reactions. Several standards define the methods used to test battery performance. ISO 17546 [125] contains standards for evaluating the lifespan and environmental performance of batteries, whereas ISO 12405 [125] specifies test procedures for LIBs in electric cars. SAE International provides guidelines for automobile battery testing. MIL-STD-810G [126], a United States military standard, stresses testing equipment in the environment in which it will be utilized. UL 1642 [127] and UL 2054 [128] are standards for lithium batteries and household/commercial batteries, respectively. UN 38.3 [129] provides the testing criteria for transporting lithium batteries, while IEC 62133 [130] focuses on the safety of portable sealed secondary cells. Furthermore, organizations such as ABSL, NASA, Eaglepicher, Quallion, Mitsubishi, and GS YUASA establish standards for space applications, stressing exceptional reliability and safety in space. These standards are critical for manufacturers, engineers, and regulatory agencies to guarantee that batteries satisfy the appropriate safety, performance, and durability criteria [124]. Table 10 shows the environmental tests to be performed in order to validate second-life batteries.

Table 10. Environmental tests of secondary utilization energy storage products.

Project	Test Method Description
Hot and cold cycle test	Place the DUT in the test chamber, set it to 25 ± 5 °C, and leave it on standby position for 24 h. After 30 min, increase the temperature to 75 ± 2 °C, and keep it on standby for 6 h; then, after 30 min, let it cool down to 20 ± 2 °C, and leave it on standby for 2 h; then, leave it for 30 min to cool down to −40 ± 2 °C, and leave it on standby for 6 h; then, for another 30 min, increase the temperature to 20 ± 2 °C, and leave it to stand for 6 h, for a total of 9 cycles. Thereafter, perform a pressure test. The DUT will be disqualified if it releases flammable and/or toxic gases, leaks, ruptures, burns or explodes and eventually fails in protection control [102].
Humidity Resistance Test	According to the IP level test method specified in ANSI/IEC 60529 [131], a withstand voltage test is performed upon completion. If the sample ignites, releases flammable gases, releases toxic gases, suffers electrical shocks, leaks, ruptures, or fails protective controls, it does not comply with UL 1973 [102].
Salt Spray Tests	According to the standard environmental test method IEC 60068-2-52 [132], a withstand stress test is performed upon completion. If the sample explodes, releases flammable gas, releases toxic gas, suffers electric shock, leaks, ruptures, or failures in protective control, it will not be qualified. [102].
Internal flame exposure test	Fully load the sample, select a cell in the center of the interior, and then use heating or other methods to render it thermally ineffective. Note that the fault can be handled internally. It will be considered unqualified if combustion or explosion occurs [102].
External flame exposure test	Place the test sample on the top of the fuel container, 61 cm away from the fuel liquid level. Install a thermometer on the sample to monitor and record the burning time for 20 min. If no exposure occurs, you will be considered qualified [102].

Source: Adapted from [111].

Battery capacity testing is the most suitable technique for screening and classifying second-life batteries and is included in the UL1974 standard. However, this test is time-consuming, taking up to four hours per cell, and typically requires expensive equipment [133]. These tests can be expensive and make selling a product built with second-life batteries unfeasible.

The lack of standardization in battery disassembly processes is still a technical barrier to battery reuse. New technical standards need to establish criteria for battery module standardization to facilitate the disassembly of batteries at different levels of granularity (cell, module, and pack). These measures will prevent reusing batteries from being more expensive than buying a new one. An example of these measures is replacing the use of adhesives and welding with screws to facilitate the disassembly of batteries. This standardization will help automate the operations necessary for disassembling batteries. Automation reduces the occurrence of thermal runaway, short circuits, and electrolyte leakage compared to manual processes.

It is unclear how each country's legislation will address the fact that batteries from different manufacturers have different useful lifespans, sizes, shapes, configurations, and safety levels. Therefore, each battery may have a different disassembly and, consequently, a different level of environmental impact.

6. Conclusions

The comprehensive analysis of legislation and technical standards focusing on battery reuse and recycling underlines the urgent need for robust regulatory frameworks and international cooperation to address the environmental and economic challenges associated with the growing EV market. The results of this study offer critical insight into the complexities of the battery supply chain, the diverse legislative landscapes in different regions, and the innovative business models emerging in the industry. It highlights the indispensable role of government regulation in steering industry toward sustainability, the potential for second-life batteries to contribute significantly to energy storage solutions, and the need for global standards for battery recycling and reuse.

The results obtained emphasize the importance of EPR, innovative recycling technologies and the development of a circular economy. Analysis of legislative frameworks across jurisdictions offers valuable lessons on the effectiveness of different regulatory approaches in promoting battery reuse and recycling. Furthermore, new business models for second-life batteries must be developed to enable companies to enter this emerging market.

The comparison of regional regulations and the absence of specific standards for the reuse of LIBs reveals a potential market but also challenges. The early stage of battery recycling regulations significantly impacts the evolution of the circular economy within the EV battery industry. Europe and China are at the forefront, with clear legislative frameworks. At the same time, differences in approach, such as the EU's strict policies, the more flexible US system, and China's centralized but opaque practices, suggest that global harmonization could reduce uncertainty and promote sustainable battery design.

The lack of established technical norms, particularly in the UK and Europe, impedes the development of sustainable business models for LIBs, posing risks to safety, performance, and environmental responsibility. This regulatory gap affects investor confidence and consumer trust and jeopardizes environmental and human safety through unsustainable practices. Without comprehensive standards, the total value of LIBs throughout their lifecycle may not be realized, leading to economic inefficiencies and negative environmental impacts.

The main contribution of this study lies in the comprehensive examination of the EV battery ecosystem, including regulatory challenges, market dynamics, and technological barriers to recycling and second-life applications. It highlights the critical need for collaboration between stakeholders—governments, industries, and academic institutions—to develop standards and policies that facilitate sustainable battery lifecycle management.

However, the study also recognizes its limitations, particularly in the variability of legislative environments and the nascent state of recycling technologies. The diversity of regulations between countries and regions poses a challenge to the global harmonization of standards, while current technological limitations in battery recycling require further research and development.

Future research should focus on developing new safety standards for batteries, clarifying battery passport legislation, and investigating battery transport legislation. Additionally, new, more efficient and economical battery recycling technologies must be developed, and the environmental impact of such practices must be assessed. Additionally, new studies will investigate the potential for international agreements or frameworks to harmonize regulatory standards and facilitate global trade in second-life batteries and recycled materials. Finally, new efforts must be made to harmonize regulations at the European and international levels. This could facilitate consistent practices, reduce trade barriers, and promote innovation in the sector.

An action plan must be developed to create clear guidelines on battery ownership, recycling, and safety standards. New research should focus on reducing uncertainties in the second-life battery market, as well as promoting partnerships between different actors in the battery supply chain, including governments, industries, research institutions, and academia. These actions will be fundamental to promoting the safety, environmental protection, and economic viability of second-life batteries.

Author Contributions: H.Z., E.R.S., P.G. and H.-G.S. proposed the concept and supervised the work. They were responsible for project administration and funding acquisition. C.A.R.J. wrote the first draft of this manuscript. E.R.S., P.G., D.K., H.-G.S. and H.Z. co-wrote the manuscript. All authors participated in data analysis and manuscript discussion. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to thank the Total Energies company through ANP (Brazil's National Oil, Natural Gas, and Biofuels Agency), which funded part of this research. The authors would also like to thank the BloRin Project—"Blockchain for renewables decentralized management", PO FESR Sicilia 2014/2020—Action 1.1.5—identification code: SI_1_23074 CUP: G79J18000680007 for all the support given to the authors. This work was partly founded by the Bavarian Ministry of Economic Affairs, Regional Development, and Energy in the program BayVFP Digitalisierung, grant number DIK0384/02, and also partly funded by the German Academic Exchange Service in the project 2LIFEBAT, grant number 57680517.

Data Availability Statement: There are no data available in this work.

Acknowledgments: The authors thank Moura Batteries for the financial support, especially Gustavo Tinelli, Businesses Director.

Conflicts of Interest: The authors declare no conflicts of interest.

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