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Research article

Eco-Design and Battery Regulation: Strategies for Sustainable Lifecycle Management

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Abstract

Addressing the urgent need for sustainable lifecycle management within the battery industry, the present study focuses on the implications and challenges posed by the European Union's Battery Regulation (EU) 2023/1542. A comprehensive eco-design framework is proposed, aimed at harmonizing battery design with the stringent requirements of the regulation, thereby fostering sustainable value chains development, promoting circularity, and mitigating lifecycle impacts. The methodology involves reviewing existing eco-design frameworks and analyzing the Battery Regulation's legislative details. The proposed framework fills critical gaps, focusing on responsible design from material extraction to end-of-life processing. It incorporates eco-design tools for various lifecycle stages, contributing to environmental footprint reduction and legislative compliance. Adaptable across battery applications, this versatile model can be applied to other regulated products, guiding stakeholders towards sustainable practices and industry-wide environmentally conscious production and disposal. Implementing this framework will significantly advance the shift towards cleaner and sustainable energy alternatives.

Keywords: Battery; Battery Regulation; Eco-design; Design for Sustainability; Lifecycle management; Theoretical Framework

1. INTRODUCTION

The battery is not a recent discovery in technology; however, over time, it has become an indispensable element in our daily lives. This is due to the incremental improvement in their performance, which has enabled us to have increasingly powerful handheld devices like smartphones. Furthermore, batteries are playing a crucial role in the green energy transition, facilitating the development of electric vehicles with satisfactory power and range capabilities. They have also proven essential for effectively storing energy generated from renewable sources, reducing dependence on the intermittency of natural events. According to estimates, the global battery market is projected to exceed a value of 400 billion dollars and reach a market size of 4.7 TWh by 2030, with 4.2 TWh specifically in the mobility sector (89.36%) and a growing rate higher than 30% per year (Fleischmann et al., 2023). Therefore, stakeholders in the market must adapt to these growing numbers while concurrently addressing the various challenges that arise throughout the battery lifecycle. These challenges encompass environmentally harmful upstream processes, such as resource extraction and manufacturing, which contribute to pollution and resource depletion (Bhuyan et al., 2022). Additionally, downstream challenges encompass inefficient recycling and disposal practices (Gianvincenzi et al., 2024), leading to the suboptimal utilization not only of valuable battery materials and the generation of waste but also the full potential of the battery. In fact, an Electric Vehicle (EV) battery is typically deemed at the end of its life when its capacity drops below 80%. Even though it might still be suitable for stationary storage or other applications, it is often destined for disposal (Casals et al., 2019). Recently, Europe has recognized the symbiotic relationship between the potential and challenges within the critical battery industry. In Q3 2023, the Battery Regulation (EU) 2023/1542 was introduced with the aim of establishing a

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sustainable internal market, regulating, for the first time, the entire product lifecycle from extraction to recycling and extending its influence beyond European borders. The set objectives are rigorous, necessitating not only market adaptation to growing demand but also compliance with European mandates.

One of the most impactful and immediately applicable approaches is eco-design, which has the capacity to preemptively address issues throughout the lifecycle during the design phase (Woidasky & Cetinkaya, 2021). In the context of eco-design and battery regulation, innovation is not limited to technological aspects but also encompasses educational and public policy dimensions (Mosconi et al., 2013). However, existing literature has highlighted a deficiency in eco-design frameworks and a complete absence of legislative integration within them. This paper aims to provide a comprehensive theoretical framework for battery eco-design, addressing the lacks identified in scientific literature and harnessing the potential of eco-design to meet the objectives outlined in the Battery Regulation. Following this brief introduction, the subsequent two sections will focus on the literature analysis of eco-design frameworks, highlighting their challenges and proposed solutions, and the analysis of the Battery Regulation and how eco-design can contribute to its fulfillment. The findings have been incorporated into the theoretical framework presented and discussed in the fourth section. Finally, the paper concludes with the summarizing remarks and future developments.

2. LITERATURE REVIEW

Eco-design is a branch of design that incorporates sustainability as a fundamental parameter in product development. One of the most comprehensive definitions comes from Charter and Tischner: “Sustainable solutions refer to products, services, hybrids, or system alterations aimed at minimizing adverse sustainability impacts and maximizing positive effects, encompassing economic, environmental, social, and ethical dimensions, throughout and beyond the life cycle of existing products or solutions, while meeting acceptable societal demands and needs." (Charter M, 2001).

In the domain of eco-design for batteries, a limited array of frameworks has emerged, primarily due to various compelling reasons. These are the salient challenges:

- Battery System Complexity: The intricate nature of battery systems, involving multiple components and various life cycle stages, presents substantial hurdles in pinpointing and mitigating all environmental impacts effectively (Rahlfs et al., 2021).
- Swift Technological Advancements: The rapid pace of evolution in battery technology necessitates continuous updates to maintain the relevance and accuracy of these frameworks (Malhotra et al., 2024).
- Lack of Metric Consensus: Discord over the metrics and indicators to be employed obstructs the development of standardized frameworks, creating a complex landscape for decision-makers grappling with numerous parameters (Koroma et al., 2022).
- Challenges in Life Cycle Assessment (LCA): Life Cycle Assessment, the cornerstone of eco-design, grapples with challenges such as the absence of standardized manufacturing databases, which can result in inaccurate Life Cycle Inventories and contradictory outcomes. Altering the functional unit (FU) can even reverse comparison results (Dolganova et al., 2020).

Notwithstanding these impediments, the literature has witnessed the emergence of various eco-design frameworks tailored for batteries, broadly categorized into two distinct types: comprehensive and partial frameworks.

Comprehensive Frameworks strive to holistically encompass environmental impacts throughout the entire battery life cycle. These frameworks employ a comprehensive set of indicators, tools, and methodologies to enhance the effectiveness and efficiency of end-of-life processes.

In contrast, Partial Frameworks narrow their focus to specific aspects, phases, or types of environmental impacts. These frameworks typically address isolated issues, such as assembly and disassembly (Pilley et al., 2018; Talens Peiró et al., 2017; Tornow et al., 2015), recycling (Mao et al., 2022), and second-use scenarios (Troussier et al., 2017).

In the first category, X. Zhang et al. (2020) introduced a systematic framework for eco-designing chemical products, albeit with some uncertainties in problem-solving and a limited ability to delineate the interconnections between the three pillars of sustainability. Conversely, C. Zhang et al. (2020) concentrated on Battery Electric Vehicles (BEVs) by employing a life cycle simulation (LCS) model and parameterized lifecycle inventory (P-LCI) within a highly intricate framework that primarily optimizes design for environmental impacts while sidelining social and economic considerations. In contrast, Zwolinski & Tichkiewitch (2019) developed an agile framework grounded in standardized methods for identifying Critical Project Life Cycle Parameters (CPLCPs), encompassing diverse facets, including economic considerations.

A distinct framework, projected by Sansa et al. (2019) embraced all three pillars of sustainability, incorporating fuzzy Analytic Network Process (ANP)-based multi-criteria decision-making. Their approach commences with constructing product design scenarios and comprehensively analyzing internal and external contexts and stakeholders.

In reviewing the literature on eco-design frameworks for batteries, it is also crucial to consider the broader market and policy context that shapes these frameworks (Mosconi, 2003). However, none of these existing solutions adequately address legislative aspects. To rectify this gap, a comprehensive eco-design framework is imperative, considering diverse factors, including a company's capabilities, battery performance, market trends, potential end-of-life scenarios in relation to the application domain, value chain requirements, and legislative constraints. In this current study, the authors aim to surmount these challenges by proposing an encompassing eco-design framework tailored to batteries. This comprehensive approach endeavors to provide guidance to companies seeking to minimize the environmental, economic, and social impacts of their battery products throughout the entire product life cycle.

3. METHODOLOGY: ECO-DESIGN FOR BATTERY REGULATION

The strategic significance of batteries has not escaped the attention of the European Commission, as underscored in the Green Deal Industrial Plan for the Net-Zero Age (COM(2023) 62 Final, 2023). This importance is primarily tied to sustainable development and prevailing industrial trends. Consequently, the regulatory framework governing batteries has undergone revision, aligning with the multidisciplinary approach outlined in the Circular Economy Action Plan – CEAP (COM (2020) 98 Final, 2020), which constitutes a pivotal component of the European Green Deal (COM(2019) 640 Final, 2019). The Commission has duly acknowledged the necessity for such regulation in order to repeal Directive 2006/66/EC. This step is aimed at fortifying the sustainability of the burgeoning battery value chain for electromobility and amplifying the circular potential of all batteries entering the EU market, positioning the EU as a formidable global player second only to China.

To achieve this, the Battery Regulation (EU)2023/1542, which came into effect on August 17, 2023, draws its legal basis from Article 114 TFEU, focusing on the establishment and operation of the internal market, rather than relying solely on Article 175 concerning environmental protection. This Battery Regulation marks the inaugural initiative under the new CEAP and represents the first Regulation built upon a lifecycle approach. The proposal is grounded on three primary objectives:

- Ensuring the establishment of an internal and sustainable battery market.
- Facilitating the circularity of batteries and their constituent materials.
- Mitigating the environmental and social impacts associated with battery lifecycle management.

The Regulation is set to impose ambitious thresholds across various dimensions in the short, medium, and long terms, encompassing limits on Carbon Footprint, recycling recovery, and efficiency. Additionally, a range of tools will be introduced, ranging from mandatory carbon footprint declarations to digital passports and due diligence requirements within the raw and secondary material supply chain. As previewed in the introductory section, Eco-design is poised to play a pivotal role in achieving these objectives. In the Table 1, the key points of the Battery Regulation are outlined, categorized according to the phases of the lifecycle. For practicality, the Use and Collection phases have been merged, and the End of Use phase encompasses refurbishing, remanufacturing, and second life aspects. Each phase is accompanied by one or more Eco-design tools with macro-examples to illustrate how they can contribute to achieving the objectives.

Table 1. Eco-Design Support to Battery Regulation

Lifecycle Stage	Regulation Goals	Eco-Design Approach
Extraction	Contribute to responsible sourcing, addressing methods of extraction and processing of raw materials by operators, including extra-EU countries, to mitigate environmental and social impacts.	Design for Sustainability (DFS) and Design for Recycling (DFR). Implementing a closed-loop supply chain for battery materials, design batteries to favouring recycling and use of secondary raw material reducing extraction activities.
Manufacturing	Hazardous substance restrictions, Carbon Footprint declarations by 2024, battery performance classes by 2026, and maximum CO2 thresholds by 2027. Also, mandate recycled content declarations (e.g., Lithium, Cobalt, Lead, Nickel) by 2027, with increasing recycled material requirements by 2030 and 2035. Ensure removability, replaceability, and safety standards.	Design for Manufacturing and Assembly (DFMA). Reducing the number of battery assembly steps, optimizing design for energy-efficient low-impacts production, and using recycled and non-hazardous materials in battery production.
Use and Collection	Minimum performance and durability requirements, collection targets for portable batteries, 100% EV battery collection by certified operators, alignment with Extended Producer Responsibility (EPR) requirements.	Design for Use Experience (DFUX). Design batteries for long-term use, ensuring they withstand environmental conditions, and creating user-friendly collection systems.
End-of-Use	Criteria and requirements for repurposing and remanufacturing, with a strong emphasis on prioritizing reuse within the waste hierarchy.	Design for Disassembly (DFD) and Design for Second Life (DFSL) to design the battery with modular components that can be easily disassembled and refurbished, such as the battery cells and modules, minimize the use of adhesives and other difficult-to-disassemble materials.
End-of-Life	Increasing recycling efficiency targets for Lead, Lithium, and other battery types by 2025 and 2030. Additionally, set recycling recovery targets for materials like Li, Co, Copper (Cu), Pb, and Ni by 2026 and 2030.	Design for Recycling (DFR) to minimize hazardous and non-recyclable materials, using standardized materials that are easy to separate and recycle during the end-of-life process.

Certainly, it is undeniable that all phases of the lifecycle can be impacted by design that is responsible, thoughtful, and holistic. In the subsequent section, the methodology for integrating these tools and considerations through a series of economic and engineering processes will be elucidated.

4. ECO-DESIGN FRAMEWORK FOR BATTERY

In this section, the proposed framework is detailed, characterized by its comprehensive nature as it encompasses all phases of the product life cycle, its collaborative approach as it actively involves the entire value chain, and its theoretical foundation, grounded in literature analysis and accumulated knowledge. The framework comprises five macro phases (Figure 1):

1. Internal Input Collection: During the initial phase, internal inputs are gathered, forming the foundational elements for battery design. These inputs encompass producer objectives and existing designs.

2. Stakeholder Engagement Across the Value Chain: The second phase focuses on identifying stakeholders throughout the entire value chain. These stakeholders play pivotal roles from extraction to recycling. Furthermore, among the stakeholders considered are also policymakers, who, through their legislation, already express their requirements, influencing the eco-design considerations.

3. Parameter Definition: During the third phase, technical solutions are identified for meeting the requirements of each stakeholder within the value chain and for addressing each element of the Battery Regulation.

4. Compatibility Analysis and Solution Formulation: The fourth phase identifies potential conflicts or synergies among parameters. Based on these insights, multiple design solutions are formulated.
5. Sustainability Assessment and Comparison: In the fifth and final phase, a thorough assessment and comparison of design solutions are conducted, encompassing economic, environmental, and social sustainability aspects facilitating informed decision-making in selecting the most suitable battery eco-design solution.

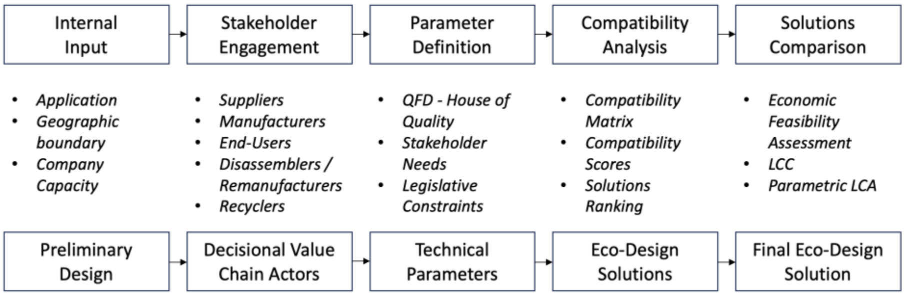

Figure 1. Eco-Design Framework Flowchart

To elucidate the multifaceted approach adopted in our eco-design framework for batteries, Table 2 provides a comprehensive overview of the key tools utilized throughout the process. This table outlines each tool's specific function, the rationale for its inclusion, and its unique contribution to tailoring the eco-design towards sustainability, compliance, and market needs. The subsequent sections will delve into how these tools are applied across the different phases of the framework, ensuring a holistic and effective design strategy.

Table 2. Adopted Tools in the Framework

Tool	Function	Rationale for Inclusion	Contribution
Market Segmentation Analysis	Utilizes statistical analysis and modelling to dissect the market into distinct groups based on consumer preferences, usage patterns, and demographic factors. (Weinstein, 2011, 2014)	Critical for identifying nuanced consumer demands in different segments, enabling precision in tailoring battery specifications such as energy density, charge rates, and lifecycle expectations to distinct market needs.	Facilitates the engineering of battery designs that precisely align with segment-specific requirements, enhancing application efficiency and market penetration. For instance, it enables the tailoring of battery chemistries and form factors to specific applications like high-energy-density for electric vehicles or high-power-density for portable electronics, guided by detailed market insights.
Competitive Landscape Assessment	Applies competitive intelligence frameworks and tools to analyse competitors' strategies, product offerings, and market positioning. (Hole et al., 2019)	Essential for identifying technological gaps and opportunities in the battery sector, enabling the development of innovative solutions that surpass existing market offerings in sustainability and performance.	Informs the strategic development of battery technologies and eco-design practices that establish competitive advantages, such as adopting cutting-edge materials science innovations or advanced manufacturing processes that reduce environmental impact while enhancing performance and cost-effectiveness.
SWOT Analysis	Conducts a systematic evaluation of internal and external factors affecting the eco-design project, leveraging engineering and business analysis techniques. (Olabi et al., 2023; Olabi, Abdelkareem, et al., 2022; Olabi, Wilberforce, et al., 2022)	Provides a comprehensive overview of the strengths to leverage, weaknesses to address, opportunities to capture, and threats to mitigate in the context of sustainable battery design and development.	Directs the eco-design process towards exploiting technical and market opportunities (e.g., emerging battery materials or recycling technologies) while addressing engineering challenges (e.g., thermal management, energy density) and regulatory constraints, ensuring a balanced approach to innovation that is both sustainable and viable.

Regulatory Environment Analysis	Reviews and interprets current and forthcoming regulations using legal and technical analysis to understand their impact on battery design and lifecycle management. (Halty et al., 2020)	Guarantees that battery designs not only meet current environmental and safety standards but are also forward compatible with anticipated regulatory changes, ensuring long-term viability.	Ensures the integration of compliance into the eco-design process, driving the adoption of battery technologies and materials that meet stringent environmental regulations, such as minimizing hazardous substance use and optimizing for end-of-life recyclability or reusability, thus embedding regulatory foresight into the engineering design process.
Quality Function Deployment (QFD)	Implements the House of Quality (HOQ) to systematically translate customer and stakeholder requirements into engineering specifications and technical features.(Halty et al., 2020; Sabaleuski et al., 2013)	Bridges the gap between market/stakeholder needs, regulatory requirements included, and technical solutions, ensuring that battery designs are aligned with both consumer expectations and regulatory requirements, emphasizing sustainability.	Facilitates a structured approach to integrating sustainability criteria into battery design parameters, such as material selection, energy efficiency, and lifecycle impact, ensuring that technical solutions are directly aligned with eco-design principles and stakeholder expectations. This methodical alignment enables the development of batteries optimized for both performance and environmental impact.
Compatibility Matrix	Utilizes systems engineering principles to assess the interoperability and synergistic potential of various technical solutions within the battery design. (Halty et al., 2020)	Essential for identifying optimal combinations of materials, technologies, and design approaches that together enhance the battery's overall sustainability and performance, while avoiding incompatible interactions.	Facilitates informed decision-making for battery manufacturers by highlighting material and technology combinations that enhance battery efficiency, safety, and recyclability. For example, it aids in selecting cathode and electrolyte pairs that maximize energy density while ensuring environmental compliance. This targeted approach streamlines the design process, aligning product development with eco-design goals and market expectations.
Economic Feasibility Assessment	Conducts detailed cost analysis using engineering economics principles to evaluate the cost-effectiveness of eco-design solutions across the battery lifecycle. (Makhdoomi & Askarzadeh, 2023; Yamujala et al., 2022)	Critical for ensuring that sustainable design solutions are economically viable, balancing the cost implications of eco-design choices with their environmental benefits to ensure market acceptance and commercial success.	Enables a comprehensive evaluation of the lifecycle costs associated with eco-design strategies, from raw material procurement through manufacturing, usage, and end-of-life processing. This assessment helps in making informed decisions that prioritize eco-design solutions offering the best value proposition, such as optimizing the design for manufacturing efficiency and end-of-life material recovery, thus ensuring that sustainability enhancements are also economically justified.
Life Cycle Assessment (LCA)	Employs quantitative environmental assessment methodologies to evaluate the impacts of a battery across its entire lifecycle, from cradle to grave. (Sankar et al., 2024; Setyoko et al., 2023)	Integral to understanding the full environmental footprint of battery designs, highlighting areas where engineering innovations can significantly reduce impact.	Informs the eco-design process by pinpointing specific stages in the battery lifecycle where environmental impacts can be minimized through technical innovations, such as adopting new materials with lower environmental footprints or improving energy efficiency during use. This comprehensive environmental profiling supports the development of batteries with minimized emissions, resource use, and waste generation, aligning technical decisions with environmental sustainability goals.
Life Cycle Costing (LCC)	Applies engineering cost analysis techniques to estimate the total cost of ownership of a battery, considering all phases from production to disposal. (Makhdoomi & Askarzadeh, 2023; Yamujala et al., 2022)	Essential for assessing the economic implications of eco-design choices, ensuring that sustainability measures are not only environmentally but also financially sustainable.	Supports the selection of eco-design solutions that are cost-effective over the battery's entire lifecycle, considering production costs, operational efficiencies, maintenance requirements, and end-of-life management. This holistic cost assessment aids in identifying design choices that, while environmentally beneficial, also offer cost savings or value

	enhancements to stakeholders, promoting the adoption of sustainable battery solutions that are financially viable.

The first phase involves the collection of internal inputs by the manufacturer, necessary for identifying a preliminary design or an existing design to be used as a design basis for development, along with potential actors within the value chain. Using various versatile techno-economic tools and methodologies, it is possible to systematically collect comprehensive information that helps in understanding market dynamics and aligning the company's capacity with market demands. These tools encompass Market Segmentation Analysis for identifying specific customer needs, Competitive Landscape Assessment to evaluate market competitors, SWOT Analysis to assess the organization's readiness, Customer Surveys and Feedback Analysis to gather direct customer insights, Market Trend Analysis to track industry trends, Business Capability Assessment to gauge internal capacities, and Regulatory Environment Analysis to understand the regulatory landscape affecting the industry. These tools collectively provide valuable insights regarding the product's application, the geographic boundary within which various life cycle stages will occur, and the company's capacity. Indeed, batteries manifest diverse performance parameters contingent upon their respective application domains. For example, batteries deployed within the realm of smartphones necessitate a pronounced emphasis on achieving high power density. This emphasis stems from the imperative requirement for smartphones to deliver rapid surges of power, particularly during resource-intensive application usage or voice communication. Conversely, batteries utilized in solar-powered outdoor lighting systems require a primary focus on attaining elevated energy density. This focus arises from the necessity to efficiently store and discharge energy, thereby enabling sustained and extended illumination, notably during nighttime hours. Furthermore, depending on the geographic boundary, laws, resources, and infrastructures will differ. Lastly, based on company capacities, production processes, the extent of internalization and externalization, and market objectives will fluctuate.

Building upon this information and the definition of a preliminary design, the second step concerns the identification of various actors within the value chain (suppliers, manufacturers, end-users, disassemblers, remanufacturers, and recyclers) operating within the geographic boundary and capable of successfully fulfilling all life cycle stages of the battery based on the preliminary design. These actors must be willing to actively participate in the third step, which involves the identification of technical parameters.

In this phase, the tool deemed most suitable for ensuring flexibility and accuracy is the Quality Function Deployment, using a revised agile House of Quality (HOQ) for each life cycle stage. The term "revised" is used because, instead of clients' needs in the strictest sense, the needs of various identified actors, broadly considered as users of the product, including policymakers with their legislation, have been incorporated. Each actor rates each need from 1 (not relevant) to 5 (indispensable). Regarding legislative elements included among the needs, they are weighted based on the active involvement of the battery to be produced and receive a weight of 5 if such regulation is in force and influences the battery, 3 if the regulation will come into effect before the end of the battery's productive life, and 1 if the regulation does not affect the battery or will come into effect after the battery's expected lifetime. The term "agile" is used because each HOQ is simplified, as shown in Figure 2, focusing on the aspects described above in the rows and technical solutions in the columns. The roof evaluates the compatibility level between various technical solutions. In the center, the degree of relationship between the technical solution and the value chain's needs is assessed, with values ranging from 0, where the solution does not contribute to fulfilling a need, to 9, where the solution completely resolves the issue. At the bottom, the results of each technical solution are evaluated through the product of the relationship degree and the weight of each need.

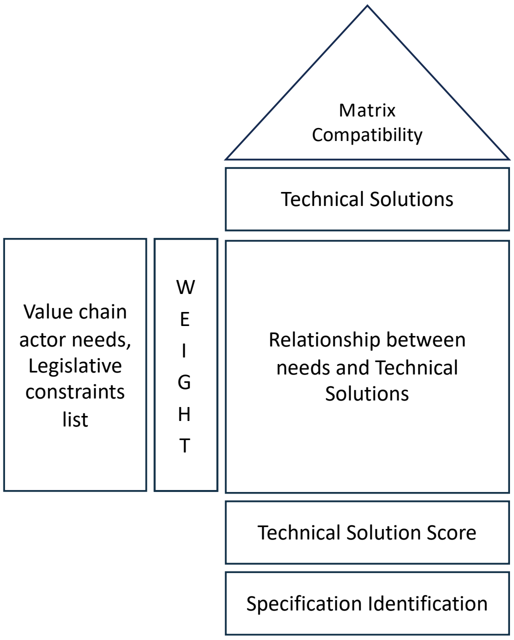

Figure 2. HOQ Structure

The technical parameters identified within each House of Quality (HOQ) will be compiled into a comprehensive Compatibility Matrix. This matrix serves as a tool to assess the level of compatibility among individual technical solutions, with each relationship evaluated on a scale ranging from 0 (indicating no compatibility) to 1 (indicating complete compatibility). Through this evaluation process, a spectrum of battery designs will be generated, which will subsequently undergo scrutiny in the final phase. These assessments will initially prioritize economic feasibility, primarily conducted through Life Cycle Costing analysis. Following this, an environmental evaluation will be carried out using Life Cycle Assessment. Based on the outcomes of these assessments, the manufacturer will be empowered to select the most optimal eco-design solution.

5. DISCUSSION

The framework outlined aims to provide a structured approach to eco-design in the battery industry, suggesting potential utility across various scenarios and regulatory frameworks. Recognizing its conceptual foundation, the necessity for empirical validation to substantiate its practical applicability and effectiveness is paramount. This process will engage industry stakeholders to bridge the gap between theoretical potential and real-world utility. Designed to be adaptable, the framework theoretically supports various stakeholders, from production to end-of-life management. Detailed plans for empirical testing are underway, focusing on collaborative pilots with industry stakeholders spanning production to end-of-life management. Feedback from these engagements will be instrumental in refining the framework, ensuring it meets the nuanced needs of the battery value chain. However, its real-world flexibility and impact, especially across different types of batteries and regulatory environments, require rigorous testing. The importance of collaborative efforts with industry stakeholders for refinement and empirical validation is emphasized, aiming to align with the diverse requirements of global markets and regulatory standards.

At the heart of the envisioned framework is its strategic alignment with the Battery Passport, a pivotal component introduced by the EU Battery Regulation (EU) 2023/1542 for comprehensive lifecycle data management. This digital tool, mandatory for batteries exceeding 2 kWh from February 18, 2027, encapsulates a wealth of information, from sustainability credentials to detailed battery health data, facilitating informed recycling and repurposing decisions. The framework, in its theoretical phase, seeks long-term goals to analyze this data for eco-design solutions, emphasizing a scientific approach to fulfill regulatory sustainability requirements through objective, data-driven methodologies. This integration is crucial for facilitating a seamless exchange of lifecycle data among stakeholders, enhancing transparency, circularity, and compliance with sustainability standards. By leveraging Artificial Intelligence (AI) and Machine Learning (ML), the framework not only enables the customization of outputs tailored to the specific needs of different stakeholders but also ensures the continuous optimization of lifecycle analyses. AI's role is instrumental in ensuring that the outputs are finely tuned to meet the varied requirements of manufacturers, recyclers, and policymakers, thereby transforming these stakeholders into both providers of input and beneficiaries of the system's outputs.

The inclusion of ML techniques further refines the process by dynamically improving the analysis based on accumulated data, enhancing the framework's efficiency and adaptability. The envisioned integration of AI and ML to customize outputs and optimize lifecycle analyses remains aspirational, pending rigorous validation. This future-focused approach underlines our commitment to grounding technological advancements in empirical evidence.

The collaborative dimension of the framework represents both its greatest strength and a notable challenge. Active engagement from all stakeholders across the battery value chain is crucial, from manufacturers to recyclers, policymakers, and end-users. Achieving a consensus among these diverse perspectives necessitates nuanced negotiation and alignment of interests. This collaborative effort is essential, recognizing that the achievement of sustainable eco-design objectives is not the purview of a single entity but a collective endeavor that spans the entire lifecycle of batteries. The framework's success hinges on this multifaceted participation, leveraging the unique insights and contributions of each stakeholder to foster innovation and drive eco-design forward. Such collaboration is pivotal in navigating the complexities of regulatory compliance, technological advancements, and market dynamics, aiming to create a cohesive strategy that aligns with the overarching goals of environmental sustainability and circular economy principles. To further incentivize stakeholder participation, the framework should propose the benefit of receiving tailored information in return for their engagement. This tailored approach ensures that stakeholders not only contribute to the eco-design process but also gain valuable insights specific to their needs, fostering a mutually beneficial relationship. Additionally, the integration of automated data collection processes could presents a compelling proposition, offering stakeholders enhanced services without the need for additional resources. This automation must streamline the data-sharing process, making participation more attractive by minimizing the burden on stakeholders while maximizing the utility of the information they receive.

The journey towards a fully integrated eco-design ecosystem faces challenges, including ensuring robust data security, engaging stakeholders effectively, and adapting to a wide array of battery types and use cases. These hurdles highlight the ongoing need for research and development, particularly in the fields of automated data integration, blockchain to ensure data integrity, and AI and ML for enhancing the precision and applicability of eco-design practices.

Acknowledging these complexities, future endeavors will concentrate on developing sophisticated solutions that address these challenges head-on. By doing so, the ambition is to foster a collaborative, technology-driven environment that not only advances the sustainability goals of the battery industry but also empowers all actors within the value chain through improved decision-making capabilities and innovative eco-design solutions.

6. CONCLUSIONS

The framework presented seeks to establish a novel, collaborative strategy for eco-design within the battery sector, responding directly to the deficiencies and challenges previously unaddressed in existing literature. It spans critical areas such as legislation, engineering, and economics, aiming to bridge these realms through a unified approach. Acknowledging the framework's conceptual stage, it is imperative to proceed with empirical validation to determine its efficacy in practical scenarios. Future directions involve refining the framework for real-world application, emphasizing the necessity of stakeholder cooperation across the battery value chain. This cooperation, while challenging due to the diversity of perspectives, is vital for fostering a consensus-driven approach to sustainable eco-design.

Concluding, this framework emerges as an exploratory proposal aimed at integrating eco-design within the battery industry, leveraging interdisciplinary principles to address sustainability challenges. Its advancement is contingent upon rigorous empirical validation to confirm its applicability and impact, signifying a methodical approach towards enhancing industry-wide sustainability practices through the synthesis of legislative, engineering, and economic insights.

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AUTHOR CONTRIBUTIONS

Mattia Gianvincenzi: conceptualization, methodology, investigation, writing— original draft preparation, visualization, writing— review and editing.

Marco Marconi: methodology, validation, writing— review and editing, supervision.

Enrico Maria Mosconi: conceptualization, validation, resources, writing— review and editing, supervision.

Francesco Tola: formal analysis, investigation, writing— original draft preparation.

Mariarita Tarantino: formal analysis, investigation, writing— original draft preparation.

DECLARATIONS

Competing interests The authors declare no competing interests.

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