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From Regulation to Practice: Exploring conceptual policy pathways for EV battery circularity in Europe

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ABSTRACT

With the rapid development of the electric vehicle (EV) industry, the large-scale retirement of batteries has introduced multiple environmental risks and challenges to industrial sustainability. Smart circular business models (SCBMs) utilizing 10R circular strategies (i.e., Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover) present a promising solution. However, the success of implementing such strategies, policies and regulations is considered the core support factor.

This study combines a review of regulatory frameworks with semi-structured interviews in the Swedish EV battery ecosystem to explore the key challenges in implementing the 10R strategies under the Battery regulation. Finally, it identified four interrelated pillars that shaped battery circularity: (1) policies and regulations, (2) digital technologies, (3) business models and economics, and (4) organizational and behavioral management. These pillars illustrate how various dimensions intersect to influence the implementation of 10R strategies for EV batteries.

This study contributes to both theory and practice by offering a conceptual policy pathway for translating the 10R strategies to actionable strategies. It provides guidance for Europe policymakers and industry actors to build a digitally empowered, regulations-supported, and standardized circular battery ecosystem.

Keywords: policy and regulations, digital technologies, 10R strategies, organization and behavior management.

NOMENCLATURE

Abbreviations	
CE	Circular Economy
EV	*Electric vehicle*
DPP	Digital Product Passport

1. INTRODUCTION

Due to the rapid increase in EV battery consumption and the growing importance of environmental considerations, developing circular strategies for EV batteries that maximize resource recovery rates, minimize environmental impacts, and ensure supply chain resilience are considered crucial. The 10R strategies are a CE framework built around “Refuse”, “Rethink”,” Reduce”,” Reuse”,” Repair”,” Refurbish”,” Remanufacture”,” Repurpose”, “Recycle”, and “Recover” [1]. They are applied to support EV batteries’ circularity and sustainability. However, the implementation of these strategies is influenced by the changing technological and regulatory environment, particularly the development of new battery technologies [2]. As a frontrunner in sustainability policy, the European Union (EU) has developed systematic regulations to promote battery circularity [3]. The new EU Battery Regulation directly aligns with the 10R circular strategy, including reuse, repurposing, and recycling [4]. However, the practical implementation of such policies remains challenging in reality. This tension arises from the balance of financial viability, standardisation of safety and environmental regulations, data sharing issues, and technological uncertainties, etc. [4-6].

This study aims to understand the perspectives of relevant actors on the implementation of circular strategies for EV batteries, with the objective of identifying the key issues that have the largest effect on implementing the 10Rs in industrial processes. The concept of policy pathway refers to the structured progression of policy instruments and actions that guide systemic transitions [8]. In this paper, it is defined as the interconnected mechanisms through which regulations, economic incentives, digital technologies, and organisational practices influence the realisation of circular strategies. It explores how the policies and regulations shape the implementation of 10R strategies for EV battery circularity in Europe from the perspective of actors in the Swedish EV battery ecosystem. It also provides a brief comparison of relevant policies in the US and China and discusses briefly what the European Union (EU) can learn from these countries. The research question (RQ) is formulated as follows:

RQ: What are the key issues for the successful implementation of the 10R circular strategies under the EU battery regulation?

2. THEORETICAL BACKGROUND

2.1 Circular Economy and the 10R Circular Strategies

A circular economy (CE) is defined as a sustainable development strategy that aims to reduce waste and promote resource circularity [9]. In academia, the discussion of CE has expanded from the "3Rs" (Recycle, Repair, Reuse) to the 10Rs framework, which provides a broader scope for corporate innovation and sustainable development [1]. The 10R framework provides a systematic structure for companies and policymakers to understand ways to maximise resource use at all stages of the product life cycle [10]. However, the effective implementation of circular strategies relies on policy support, clear accountability mechanisms and financial incentives, which leads businesses to circular development [4, 6].

2.2 Regulations and Polices for Battery Circularity

The EU began regulating the sustainability aspects of batteries as early as 1991 [11]. The 2006 Battery Directive introduced a more comprehensive regulatory framework for the collection and recycling of batteries, although it primarily targeted the waste phase of the battery's lifetime. Over time, it has become evident that the Directive was implemented differently across different EU Member States, and that recycling markets have not functioned effectively [12]. Therefore, the European Commission proposed a new Battery Regulation (NBR), aiming to provide a more comprehensive legislative framework for batteries, with more ambitious sustainability objectives, notably through the integration of CE principles into battery rules and the introduction of due diligence requirements [13].

The 2023 EU Battery Regulation [14] is the most comprehensive battery law ever adopted and is considered the 'blueprint' for the EU's new generation of product laws. It contains several interesting legislative innovations for EVs (See Table 1).

The US has a very different approach towards sustainability policies for EVs [15]. The Inflation Reduction Act [16] and the Clean Vehicle Credit Provisions support US-based recycling and de-choosing minerals from certain jurisdictions. Several federal initiatives and funding schemes have also been employed to support US recycling efforts and innovations. Several States in the US have adopted producer responsibility laws and other initiatives. Generally, the US approach favors innovation and flexibility, compared to the EU approach, which aims for more regulated and standardized practices [15].

China has been gradually introducing policies on EV batteries since 2012. From 2021 several regulations related to battery circularity have been either approved or promulgated. The "Action Plan for Improving the Recycling and Utilisation System of New Energy Vehicle Power Batteries" aims for "*strengthening battery whole-life-cycle management, removing bottlenecks, and building a safe, standardised battery circularity system via digital technologies, ensuring traceability across battery production, sales, dismantling, and reuse*"[17]. Efforts should be made to "*expedite the development and revision of standards for green design and product carbon footprint calculation for power batteries, guiding recycling and utilization through these standards*". The Chinese standard "GB 38031-2025 - Safety Requirements for Power Storage Batteries for Electric Vehicles" is the world's first standard that requires batteries to prevent fire and explosion even after internal thermal runaway occurs [18]. Regarding recycling, China classifies black mass, as non-waste, whereas the EU classifies it as hazardous waste [19]. Additionally, China is considering importing EoL batteries. It may lead to new regulations in the future [20]. There are emerging signs that China will take the lead in setting some standards for batteries. One example concerns its standard for EV battery safety, which is the most stringent in the world. It is believed that Chinese OEMs will be better positioned to comply with the standard than many other OEMs [18].

Table 1. Legislative innovations for EVs (From NBR)

Type of requirement	Explanation
Labelling requirements	Mandatory labelling of certain parameters, such as QR codes that enables finding information about battery capacity and the amount of certain hazardous substances. Manufacturers must disclose information about the environmental and health impact of battery contents and safe end-of-life management.

Digital Battery Passport (DPPs)	The passport can provide information about issues like origin of minerals in battery components, manufacturing data, data on the battery's performance/usage/testing throughout its lifespan, and end-of-life management.
Support for repurposing and remanufacturing	The Regulation aims to support repurposing and remanufacturing, e.g. by mandating manufacturers to provide information about the battery to repurposes.
Recycled content obligations	New EVs put on the market must contain minimum levels of recycled content, for several materials.
Due diligence requirements	Corporations must adopt several supply chain practices, including setting due diligence policies and a system to support it, conduct risk assessments, and carry out third party verifications.

3. MATERIAL AND METHODS

This study employs an inductive approach and utilizes exploratory qualitative methods to investigate the topic [21]. The goal is to explain "How" and "Why" policies and regulations influence industrial practice, and to identify what the most important issues are for the key actors. This qualitative method is particularly effective for gaining a deeper understanding of complex social phenomena and the experiences of participants [22].

For empirical data collection, we conducted eleven interviews with key actors in the Swedish EV battery ecosystem (See Table 2). The questionnaire is designed based on literature reviews. The comparative approach in subsequent textual descriptions, numbers (e.g., "OEM 1," "OEM2," etc.) will be used to refer to them for greater clarity. Each actor is anonymized, which preserves confidentiality while making the analysis transparent.

For data analysis, we applied the reflective thematic analysis approach proposed by Braun and Clarke. This method is designed to identify, analyse, and report themes in data by 6 steps, which provides a flexible and easy-to-use approach to qualitative data analysis [23]. By following the steps strictly and initial coding, we identified multiple sub-themes and concluded four major themes. They are policies and regulations, business models and economics, digital technologies, and organisational and behavioural management.

Table 2. Interviewee companies and informant details

Actor Type	Core EV Business	Interviewee Roles	Duration (Hours)
OEM 1	Construction Equipment	Research Coordinator	2
OEM 1	Construction Equipment	Expert of EV Battery Safety	3.5
OEM 2	Vehicle and Equipment	Head of Circular development Asia	2
OEM 3	Mining Equipment	End-to-End Operations Director, Electrification Solutions	2
Technology Provider 1	Monitor Systems	Experts of IOT.	5
Technology Provider 2	System Distributor	Business Development Manager	4.15
Technology Provider 3	Cloud Computing Solutions	CEO, Chief Technology Officer	2
Technology Provider 4	EV Battery Trading Platform	Market Lead	0.8
Technology Provider 5	B2B Invoicing Solutions	Chief Products Officer	4
EV Operator	Public Transportation	Head of Technology and Innovation	2
EVB Manu. & Recycler	EV Battery Production and Recycling	Site Manager	19.5

4. RESULTS

After conducting a systematic thematic analysis of the interview data, this research inductively revealed four core themes: policies and regulations, digital technologies, business models and economics, and organizational and behavioral management. These themes illustrate how various dimensions intersect to influence the implementation of 10R strategies. Each theme highlights a distinct aspect of the emerging policy pathways and encompasses various sub-themes that address specific barriers and challenges related to the circularity of EV batteries.

- *Theme 1: Policies and Regulations*

Several interviewees (OEM1, OEM2, and the battery manufacturer and recycler) emphasized the importance of policy and regulation for battery circularity, as changes in regulations and policies could disrupt the implementation of battery circular strategies. Regulations such as the *EU Battery Regulation,* which primarily refer to **Digital Product Passports (DPPs)** and **Extended Producer Responsibility (EPR).** They outline the requirements for DPPs and establish targets for recycling and material recovery. These measures were described as Essential for enabling 10R strategies.

Actors emphasized that inconsistent **definitions** of terms and a lack of **standardisation** would increase the complexity of battery circularity. E.g., OEM2 mentioned "*Regulation and law should follow the same terminology. What is reuse, what is repair, and what is refurbishment? e.g., you take an old battery, repair it manually so that the old components are replaced with new ones. But it is refurbished. I think in regulations, it is a part of remanufacture*." The actor also mentioned, "*there is a lack of standardization in how regulatory needs are evaluated and tested in battery manufacturing and recycling*" (edited for clarity). Those increase the complexity for battery circularity, especially for multinational companies. Because regulations vary across jurisdictions. For instance, ambiguities in legal definitions of terms lead to confusion in compliance and business decisions. As the OEM safety expert and recycler site manager mentioned, "*these evolving definitions pose risks when a battery crosses borders*."

Due diligence obligations are proposed during the verification, compliance recording, procurement, and declaration of conformity processes. E.g., an OEM mentioned, "*We have a 5-step-framework and due diligence guidance for responsible supply chains of minerals*". ***Extended Producer Responsibility (EPR)*** *is important for battery circularity,* as several actors discussed. stating that "*EPR is the key,*" and "EPR should be functional." The actors also emphasised that EPR is closely linked to due diligence: "*In some cases, the producer might need to have the responsibility, and we will conduct the due diligence and confirm with the assessment…. Everything that needs to be produced is being properly made, and that's where conformity becomes relevant."* (edited for clarity).

The **DPPs** and the General Data Protection Regulation **(GDPR)** are described as both catalysts and barriers for battery circularity. OEMs' compliance teams are mapping and researching the types of information, such as state of health (SoH), repair history, and materials, that must accompany each battery. However, not all information will be made public due to privacy concerns and the sensitivity of data. Although the GDPR is designed to protect personal data, it can also hinder transparency by imposing strict limitations on data usage and sharing, which may conflict with EV battery circular strategies. As the recycler site manager stated, "W*hen they need to collect data from the EV battery, it conflicts with GDPR. since the data may give away drivers' daily lives and locations. etc."*

- *Theme 2: Business Models and Economics*

There are no obvious direct financial **subsidies** in Sweden for battery circularity. However, indirect funds, such as research funding, are provided. The research coordinator from OEM1 also mentioned, "The public procurement can be a kind of **incentive**. **Taxation** is regarded as a potential tool for promoting the circularity of batteries, although there is a lack of clear tax relief policies for their second-life utilisation. An OEM mentioned that the **change in international tariffs,** especially tariffs set by the US administration**,** will impact the risk associated with the battery business. "*It's very evident when it comes to trade restrictions that are discussed, especially now in the US, for example, when Trump became president, and a lot of uncertainty about what would happen.*" It makes risk assessment a standard procedure at the time of purchasing. And as mentioned, "*not only go for price, but really to see what the supply chain looks like*".

Notably, for the 10R strategies, some interviewees believe that second-life batteries can operate effectively without external incentives, while others argue that targeted regulations and financial incentives are crucial for facilitating the transition to circular business models and the gradual implementation of the 10R strategy from high-level to low-level. As the OEM1 mentioned, "*We need policies and initiatives that steer customers toward adopting circular business models and embracing circularity*" (edited for clarity).

- *Theme 3: Digital Technologies*

Most technology providers highlighted the enabling role of digital technologies for supporting 10R practices for EV batteries. **DPPs and blockchain technology** are integrated for tracing battery history. A technology provider explained that blockchain can ensure data integrity and auditability. Once the data of the battery is recorded, it cannot be tampered with, which will build trust among parties. Additionally, a distributed ledger means that no single company owns all the data. Instead, each authorised party can contribute and verify information. One interviewee mentioned that such transparency is invaluable for demonstrating compliance and facilitating the handovers of batteries between owners. **Homomorphic encryption technology** protects supply chain confidentiality and user privacy by enabling cross-party data verification without revealing plaintext. This helps meet the requirements of verifiability and data minimization under the EU Battery Regulation and GDPR. It completes compliance disclosure and auditing through hierarchical access without exposing original data. A technology provider explained an early-stage payment solution: "*We provide* ***automated carbon footprint calculation from e-invoices*** *and integrate it into companies' systems through APIs.*" This will promote the transparency of the ESG report.

The EU battery regulation and DPPs make data sharing mandatory by changing it from optional to compulsory for the industry, prompting companies to design batteries that support a second life. A common technical barrier, frequently cited by interviewees, is the lack of standardised data. One technology expert gave an example about measurement: some companies measure the SoH of batteries in terms of remaining capacity percentage, while others use total energy throughput. Thus, a common metric is needed so that everyone knows what is meant by 80% health. Without such alignment, digital systems will struggle to communicate.

- Theme 4: Organizational and Behavioral Management

Several actors reported that evolving and improving regulatory requirements force organizations to **reform and upgrade** their **organizational structures**. One interviewed OEM is forming a dedicated team to manage battery life cycles and integrating regulatory compliance into its work. However, internal conflicts may arise between the team of the traditional core business and the circular business.

More than one actor argues that it requires a battery alliance to facilitate standardization, at least at the EU level. Discussion about mining frequently focus on **Ethical sourcing and labor standards**. An actor claims, "*Due diligence is conducted to actively assess whether their supply chains are subject to irregularities.*"

The findings demonstrated that policies and regulations play a dominant role in implementing the 10R framework. It also relies on the interconnection of business models and economics, digital technologies, and organisational and behavioural management. Those four themes serve as key pillars in shaping conceptual policy pathways for battery circularity.

5. DISCUSSION

This study indicates that the regulation of EV batteries can be understood through four interlinked pillars, including internal and external factors. First, regulations and policies set the rules of the circular game. These include standards, targets, and reporting duties, which the battery actor must follow. Second, the economic and business factors provide the market feedback as a responder, who provide feedback to policymakers by revealing how Incentives, taxation, subsidies, and other factors influence market formulation. Third, as the enabler, digital technologies provide the enabling infrastructure for policy implementation. They enable traceability and compliance by facilitating the sharing of data and monitoring. Policies changes also trigger the development of digital technologies, such as DPPs. Finally, organisational and behavioural practices ensure institutional adaptation, which are supportive factors for battery circularity. Seen together, these four pillars form a pathway that works synergistically for battery circularity (see in Figure 1).

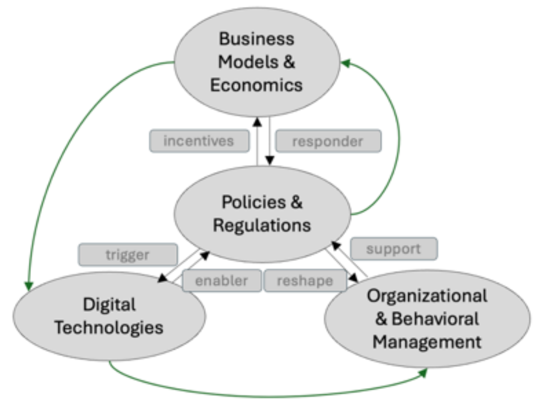

Figure 1. The conceptual policy pathway for EV battery circularity in Europe

Building on the four pillars, it is interesting to make a comparative analysis among the EU, the US and China. For the EU, the NBR already introduced strong tools such as DPPs, EPR, and due diligence. However, the success of implementation depends on practical enablers, such as the definition of different Rs for EV battery, circular standardisation, and SoH metrics. Practically, a clear role definition and authority, compliance routines, and targeted training for technical and operational staff are also important to support such activities. The EU can learn from the US and Chinese policies as they can complement the EU's regulation-oriented approach. The elements of the US approach supporting innovation should be considered, and the Chinese standards related to safety and recycling should be carefully studied. A relevant concern is when the EU should aim to set its own standards, and when it should aim for international collaboration on standards.

At the same time, instruments such as public procurement, tax incentives, and tradable recycling obligations are still in their early stages. However, such policies are needed to support the transition. In the future, with the development of battery technologies, the cost of new batteries may be lower than that of second-life batteries, which could potentially discourage the adoption of battery circularity and cause the dysfunction of the 10R strategies. Regulation and policies may be a way to avoid the dysfunction of 10R strategies for EV batteries. However, Strict enforcement of the 10R hierarchy risk creates unintended effects. For example, overly strict regulations could incentivize informal or illegal recycling practices, which potentially give rise to the black market for used batteries or materials. Inspired by the flexibility of U.S. regulations and the structure of the Chinese regulatory system, the EU requires policies that combine diverse flexible incentives with consistent and stable frameworks. Finally, digital technologies support DPPs and other regulations. It enhances collaboration, transparency, and regulatory feasibility in the circular economy of EV batteries.

This study aims to contribute to Europe's transition towards sustainable and circular batteries, both theoretically by expanding the application of CE's 10R framework and practically by providing a reference for EU policymakers and industry.

6. CONCLUSIONS

This study examined actors' insights to identify key pathways influencing the implementation of SCBMs for EV batteries in the EU. Drawing on insights from actors in the Swedish EV battery ecosystem and a comparative review of US and Chinese policies, the study identified four interlinked pillars: policies and regulations, business models and economics, digital technologies, and organizational and behavioral management. However, the study focuses on the Swedish EV battery ecosystem, which may limit its broader applicability. Additionally, the qualitative research method may constrain the findings. Future research should expand the geographical scope and use quantitative validation to strengthen the proposed pathway.

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