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Introduction to the Battery Passport

1.1 Why the Battery Passport Matters

Global battery demand is skyrocketing, driven by the electrification of transport, expansion of renewable energy, and digital device proliferation. But behind this surge lies a critical challenge: batteries are resource-intensive, environmentally risky, and often built through opaque, fragmented supply chains.

The environmental costs of the rapid increase in battery manufacturing are already visible. Raw material extraction threatens ecosystems and human rights. Recycling rates are still low. And without lifecycle visibility, manufacturers, regulators, and consumers cannot assess compliance, safety, or sustainability; they are flying blind. This industry needs a solution that drives real sustainability.

Enter the Battery Passport. This digital tool creates a full traceable record of a battery's lifecycle from raw material sourcing to production, use, and end-of-life. By integrating identification data, material composition, performance metrics, and carbon footprint disclosures, the Battery Passport aims to bring transparency to one of the world's most complex and opaque product ecosystems.

At its core, the Battery Passport is about accountability. It empowers governments to enforce regulations. It helps companies meet ESG expectations. And it enables consumers and other stakeholders to make informed, ethical choices. By embedding lifecycle data into each battery, it lays the foundation for a circular battery economy where reuse, recycling, and sustainability are not afterthoughts but built-in features.

Global momentum is growing. The European Union will mandate Battery Passports for industrial and EV batteries starting in 2027. Initiatives like the GBA, backed by the World Economic Forum, are standardizing frameworks. Countries like China and South Korea are exploring their own models, with traceability and supply chain security as key motivators.

The Battery Passport arrives at a pivotal moment. Climate goals depend on scaling clean energy storage. Trade tensions hinge on access to critical minerals. And industries are under growing pressure to demonstrate real evidence of sustainable practices, not just promises. In this context, the Battery Passport is a tool that aims to be a strategic instrument for building a transparent, secure, and sustainable battery economy, expanding energy security, and empowering European governments to effectively manage their critical raw minerals supply chains (Figure 1.1).

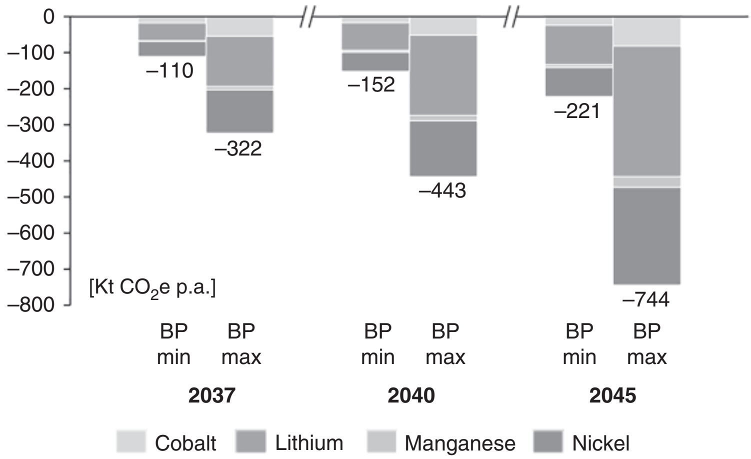

Figure 1.1 CO_2 reduction through primary materials avoided. Due to the additional secondary active materials available from reducing battery leakage, we estimate that **~220–740 kt CO_2 equivalents could be reduced each year** starting in 2045. *Source:* Battery Pass Consortium / Unlocking the Value of the EU Battery Passport. https://thebatterypass.eu/assets/images/value-assessment/pdf/2024_BatteryPassport_Value_Assessment_Synthesis.pdf (accessed 12 November 2025).

1.1.1 Urgency and Strategic Context

Batteries are central to the global transition toward a low-carbon economy, playing a vital role in achieving the ambitious targets of the Paris Agreement and other international climate goals [1]. As global demand accelerates due to electric vehicles (EVs), renewable energy storage, and digital technologies, the battery industry is expanding at breakneck speed.

This is not an abstract or far-off future problem. The speed of deployment is currently outpacing our ability to manage the environmental and social impacts. Without reliable oversight, the battery boom could undermine the very climate goals it is meant to support.

The Battery Passport is designed to help bridge the gap between the demand for batteries and our capacity to produce them responsibly, illuminating blind spots that current systems cannot. This set of digital tools helps users ensure that the materials, processes, and technologies used in battery production and recycling adhere to rigorous environmental standards. By tracking every stage of a battery's lifecycle, battery passports facilitate resource efficiency and align with environmental directives, propelling the global energy landscape toward sustainability and carbon neutrality [2].

Within the EU, the Battery Passport is set to become a mandatory component of the industry by 2027, reflecting the need for a standardized global framework to assess. By facilitating a circular battery value chain, the Battery Passport addresses the significant environmental and social challenges associated with resource-intensive battery production, positioning itself as an essential tool in the global energy transition [1, 3].

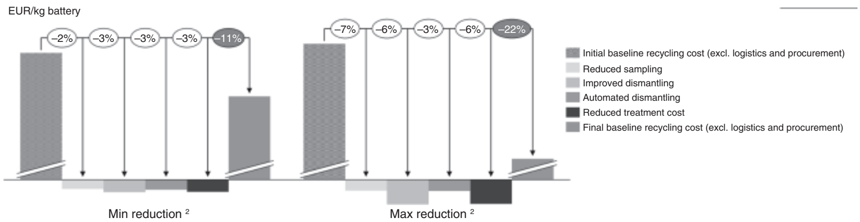

Figure 1.2 Example High-Nickel NMC (622) EV Battery; generic mechanical–hydrometallurgical recycling cost (excluding cost of logistics and procurement). Note that LFP battery recycling has different unit economics. However, the general pre-processing cost reduction levers could apply similarly. *Source:* Battery Pass Consortium / Unlocking the Value of the EU Battery Passport. https://thebatterypass.eu/assets/images/value-assessment/pdf/2024_BatteryPassport_Value_Assessment_Synthesis.pdf/last (accessed 12 November 2025).

Product passports and their consequences are becoming market expectations. They can bring trust in the market, enable smarter regulation, and drive alignment with a future that is low-carbon, circular, and accountable by design (Figure 1.2).

1.1.2 The Problem: Lifecycle Blind Spots and ESG Failures

Despite their growing importance, today's battery production systems operate with serious blind spots. Most supply chains are fragmented and opaque, making it difficult to track the origin of raw materials, monitor production impacts, or ensure ethical end-of-life practices. These gaps expose manufacturers, governments, and investors to significant ESG risks.

Without full lifecycle visibility, companies are more likely to rely on suppliers linked to environmental degradation, forced labor, or illegal mining. Manufacturers are often in the dark about these practices, and there is little incentive to avoid or divest from unethical suppliers due to the plausible deniability created by opaque supply chains. Recycling rates are low, and material recovery is inconsistent, undermining the circular economy goals batteries are meant to support. This lack of accountability poses ethical and environmental challenges, as well as real financial and regulatory consequences. Investors are increasingly divesting from companies that fall short of ESG benchmarks, while regulators are heightening scrutiny through laws that demand traceability and sustainable sourcing all over the world.

The battery industry faces serious challenges with opaque supply chains and limited oversight, especially in the sourcing of critical materials like cobalt and lithium, which are often linked to environmental harm and human rights violations. Stakeholders currently lack the data needed to trace these impacts or hold manufacturers accountable.

Today's battery systems operate in the dark: data is fragmented, supply chains are murky, and accountability is rare. This lack of transparency prevents manufacturers, regulators, and consumers from fully understanding the environmental and ethical costs tied to battery production. As a result, sustainability efforts are often reactive, inconsistent, and disconnected from real-world impacts (Figure 1.3).

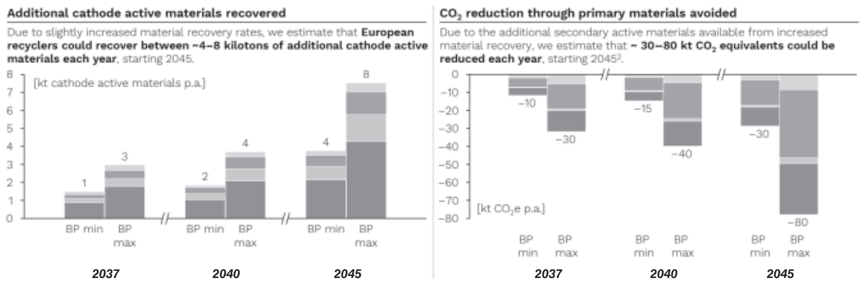

Figure 1.3 Additional cathode active materials recovered. Due to slightly increased material recovery rates, we estimate that **European recyclers could recover between ~4 and 8 kt of additional cathode active materials each year,** starting 2045. **CO_2 reduction through primary materials avoided.** Due to the additional secondary active materials available from increased material recovery, we estimate that ~**30–80 kt CO_2 equivalents could be reduced each year,** starting 2025. *Source:* Battery Pass Consortium / Unlocking the Value of the EU Battery Passport. https://thebatterypass.eu/assets/images/value-assessment/pdf/2024_BatteryPassport_Value_Assessment_Synthesis.pdf (accessed 12 November 2025).

1.1.3 The Solution: What the Battery Passport Delivers

As a part of the larger DPP system, the Battery Passport enables compliance with emerging global standards such as the European Union's Battery Regulation and the Ecodesign for Sustainable Products Regulation (ESPR), which aim to ensure traceability, transparency, and circularity in product systems.

By linking each battery to its full lifecycle profile, these passports collect and consolidate the data that matters to stakeholders. Manufacturers gain transparency throughout the supply chain, enabling better risk management and responsible sourcing. Regulators can monitor compliance with evolving environmental and social standards. And consumers receive clear, comparable information that supports informed, ethical purchasing decisions.

This tool transforms the battery from a black box into a traceable, accountable asset. It helps companies future-proof operations against ESG risk, meet market expectations, and actively contribute to decarbonization. In doing so, the Battery Passport accelerates the transition from linear consumption to a circular economy where sustainability is not a trade-off but a competitive advantage (Figure 1.4).

1.1.4 Momentum and Policy Alignment

The Battery Passport is becoming a fast-maturing global standard. Introduced by the GBA at the World Economic Forum, the Battery Passport proof of concept marked a turning point for how the battery industry approaches sustainability, compliance, and lifecycle transparency.

This initiative has garnered widespread support, receiving endorsements from influential global entities, including the G7, the European Union (EU), Canada, and the United States. Within the EU, the Battery Passport is set to become a mandatory

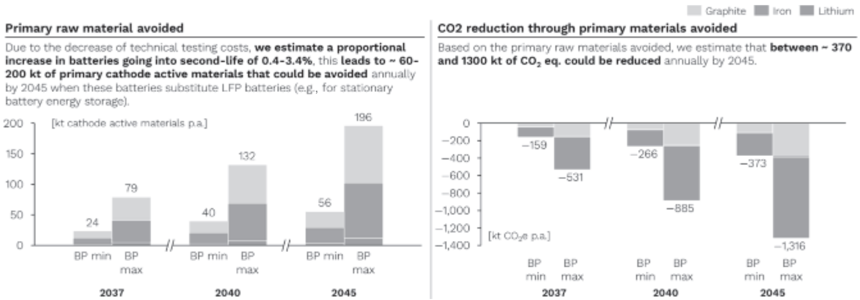

Figure 1.4 Primary raw material avoided. Due to the decrease of technical testing costs, **we estimate a proportional increase in batteries going into second life of 0.4–3.4%**; this **leads to ∼60–200 kt of primary cathode active materials that could be avoided** annually by 2045 when these batteries substitute LFP batteries (e.g., for stationary battery energy storage). **CO_2 reduction through primary materials avoided.** Based on the primary raw materials avoided, we estimate that **between ∼370 and 1300 kt of CO_2 eq. could be reduced** annually by 2045. *Source:* Battery Pass Consortium / Unlocking the Value of the EU Battery Passport. https://thebatterypass.eu/assets/images/value-assessment/pdf/2024_BatteryPassport_Value_Assessment_Synthesis.pdf (accessed 12 November 2025).

component of the industry in Europe by 2027, reflecting the need for standardized global frameworks to assess and ensure sustainability. By facilitating a circular battery value chain, the Battery Passport addresses the significant environmental and social challenges associated with resource-intensive battery production, positioning itself as an essential tool in the global energy transition [1, 3].

The policy momentum behind the Battery Passport is closely tied to the EU's Battery Regulation Amendment and the broader ESPR. These frameworks are designed to keep hazardous industrial waste out of the environment, improve material recovery, and push producers toward circular economy models. The Battery Passport plays a vital role in documenting extensive lifecycle data, from production to end-of-life management, ensuring regulatory compliance and building consumer trust in battery safety and sustainability standards [4].

To support this transformation, blockchain technology is playing an increasingly central role. It offers a tamper-proof, secure infrastructure for storing and verifying data across complex global supply chains. Supported by initiatives like HORIZON-CL5-2023-D2-02-03 under Horizon Europe, blockchain solutions enhance data interoperability, prevent duplication, and ensure low energy consumption, all while protecting sensitive information. These advancements establish the Battery Passport as a cornerstone of sustainable battery production and management [5].

With the push for transparency and traceability no longer confined to Europe, early adopters of the Battery Passport stand to gain significant advantages, from smoother compliance with emerging regulations to stronger ESG performance and competitive differentiation in sustainability-conscious markets. Countries like China and the United States are actively exploring their own frameworks for battery data governance, supply chain security, and sustainability enforcement. And as with other consumer standards, like the EU's mandate for USB-C charging ports, European regulation often sets the pace globally. Because the EU represents one of the world's largest consumer markets, manufacturers worldwide frequently align with its standards to maintain access. This creates a ripple effect: what starts as an EU requirement often becomes a de facto global norm. This convergence is accelerating, signaling the rise of a new international standard for product accountability.

1.1.5 The Bigger Picture: A Platform for Global Transformation

The Battery Passport is part of a shift in how the world approaches product sustainability, digital governance, and circular economy systems. Its adoption reflects a growing global consensus: to reach climate targets and protect finite resources, we need full lifecycle accountability embedded into every product we make and use.

The EU's ESPR, introduced in 2022, mandates the implementation of DPP across various product sectors. This regulation, which will affect a range of products from textiles to batteries, requires detailed lifecycle data, traceability, and environmental impact assessments, all aimed at ensuring better product management within a circular economy. The Battery Passport fits within this initiative, offering the necessary transparency and detailed data to support the sustainable and circular management of batteries [6].

A new digital infrastructure for sustainable industry, in which every product carries a verifiable record of its environmental and social impact, is emerging. Battery Passports, as an early example of this infrastructure, show how machine-readable data can drive compliance, inform consumers, and streamline global supply chains. They help align disparate stakeholders around shared sustainability metrics and provide a model for other sectors to follow.

Beyond the EU, the principles behind Battery Passports have an influence on global policy design. As major economies explore their own versions of DPPs, interoperability and cross-border standards will become essential. The integration of blockchain and secure data architectures ensures that this transformation is scalable and resilient, building trust into the foundation of trade, technology, and environmental governance.

The Battery Passport is proof that sustainability does not have to come at the expense of complexity but can thrive within it. The right tools can help rewire industrial systems to serve long-term planetary goals.

By establishing a framework for tracking, verifying, and sharing product-level sustainability data, it creates the foundation for a digital infrastructure that can be adapted across nearly every industry. From textiles to electronics to construction materials, the same principles of transparency, traceability, and lifecycle accountability can drive better environmental and social outcomes at scale. What begins with batteries could soon reshape how the entire global economy designs, regulates, and manages products. It is the start of a universal system for embedding accountability into the flow of trade, technology, and materials worldwide (Figure 1.5).

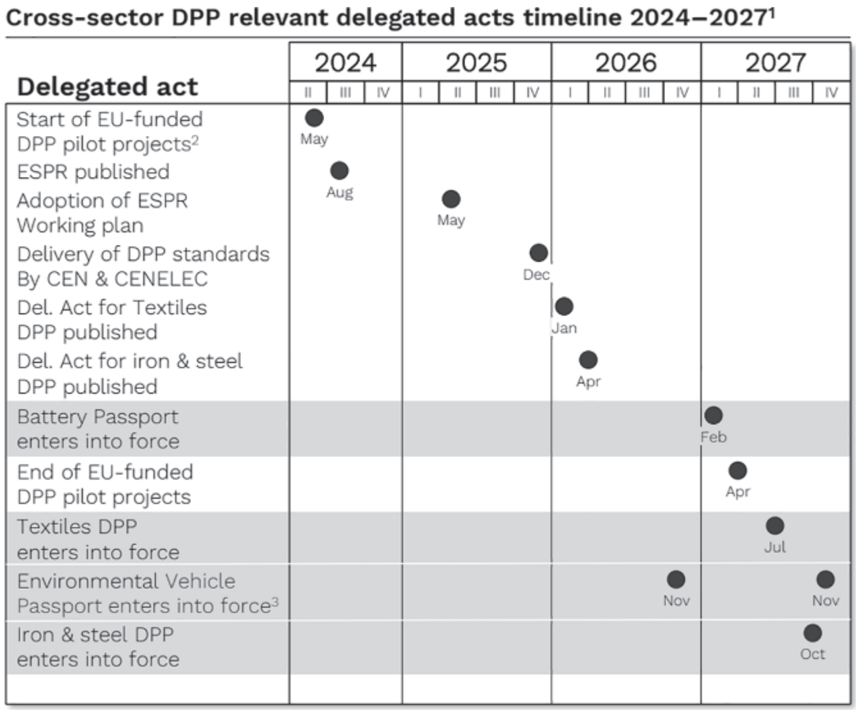

Figure 1.5 Cross-sector DPP relevant delegated acts timeline 2024–2027. *Source:* Adapted from BatteryPass.

1.2 What It Is and How It Works

1.2.1 Core Components

The Battery Passport is a digital record that captures the full lifecycle of a battery from raw material sourcing and manufacturing through use, reuse, and eventual disposal. It provides standardized, verified data that empowers stakeholders across the battery value chain to ensure safety, performance, sustainability, and regulatory compliance.

To make the data meaningful and actionable, the passport is built on seven essential components, grouped into three core categories (Figure 1.6).

1.2.1.1 Product Identity

This group establishes the unique identity and technical foundation of each battery unit.

Identification Data: Each battery is assigned unique identifiers, such as serial numbers and QR codes. These identifiers provide access to digital records and ensure traceability throughout the battery's lifecycle, enabling efficient tracking and management [7].

Manufacturing Information: Detailed records are maintained regarding the battery's production, including the place and date of manufacture, the manufacturer's identity, and physical characteristics such as the battery category

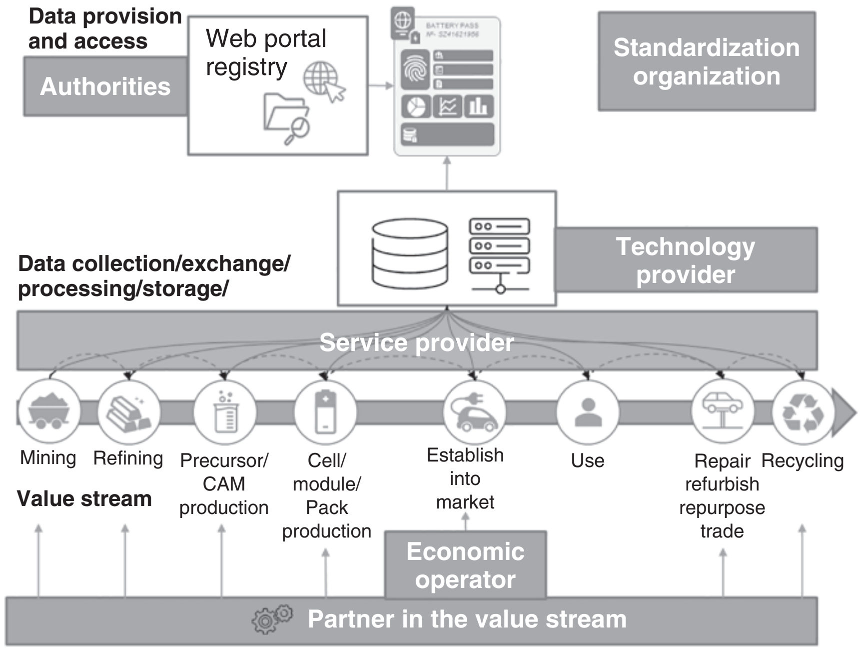

Figure 1.6 The EV battery value stream and the related targeted audience. *Source:* Adapted from Berger et al. [7].

and weight. This data is essential for understanding the production context and ensuring transparency in the supply chain [7].

Technical Specifications: The Battery Passport includes critical technical data, such as the battery type, capacity, energy density, and other performance-related metrics. This information helps determine the suitability of the battery for various applications and assess its performance characteristics [7] (Table 1.1).

1.2.1.2 Lifecycle and Performance

These components track real-world usage and assess environmental and safety standards throughout the battery's operational life.

Lifecycle Data: The passport provides detailed records of the battery's usage, including charging cycles, aging characteristics, and state of health. This information plays a pivotal role in assessing the battery's expected lifetime and efficiency, as well as guiding decisions on repurposing or recycling at the end of its life [4]. However, this should be understood as an objective of the Battery Passport framework rather than a guaranteed outcome, since its practical value will depend on still-evolving rules on access rights, update frequency, standardization of dynamic indicators, and the extent to which commercially sensitive use-phase data can be shared with second-life and recycling actors.

Sustainability and Safety Certifications: Compliance with environmental regulations and safety standards is comprehensively documented in the Battery Passport. Certifications indicate the carbon footprint and recycled content of the battery, offering valuable insights into its environmental impact [4].

Table 1.1 Required battery label data elements, standard sub-clauses, and EU Battery Regulation references.

Information to be displayed on the label	Subclause	BattReg reference
The carbon footprint and the carbon footprint performance class	6.2.4 Carbon footprint label; 6.3 Battery carbon footprint	Article 7(2) via Annex XIII (1c)
Information identifying the manufacturer; • name; • registered trade name or registered trademark; • postal address, indicating a single contact point; • web address, if available; • e-mail address, if available.	6.1.2.4 Manufacturer identifier and information	Article 13(1) via Annex VI Part A (1)
Information identifying the battery: • model identification; • batch or serial number; OR • product number; OR • element allowing identification.	6.1.2.2 Battery identifier	Article 13(1) via Annex VI Part A (2)
Battery category	6.1.3.5 Battery category	Article 13(1) via Annex VI Part A (2)
Place of manufacture geographical location	6.1.3.1 Manufacturing place	Article 13(1) via Annex VI Part A (3)
Date of manufacture (month and year)	6.1.3.2 Manufacturing date	Article 13(1) via Annex VI Part A (4)
Battery mass	6.1.3.6 Battery mass	Article 13(1) via Annex VI, Part A(5)
Capacity	67.2.2 Rated capacity	Article 13(1) via Annex VI, Part A(6)
Chemistry	6.5.2 Battery chemistry	Article 13(1) via Annex VI, Part A(7)
Hazardous substances present in the battery, other than mercury, cadmium, or lead	6.5.5 Hazardous substances	Article 13(1) via Annex VI, Part A(8)
Critical raw materials present in the battery in a concentration of more than 0.1% weight by weight	6.5.3 Critical raw materials	Article 13(1) via Annex VI, Part A(10)
Usable extinguishing agent	6.2.5 Extinguishing agent	Article 13(1) via Annex VI, Part A(9)
Symbol for separate collection	6.2.2 Separate collection symbol	Article 13(4) via Annex VI, Part B, Annex XIII (1q)
Symbol for elements	6.2.3 Symbols for cadmium and lead	Article 13(5)
QR Code	5.2.1 Access to Battery Passport information	Article 13(6) Annex VI, Part C
CE Marking	6.2.7 EU declaration of conformity	Article 20(1)

Source: DIN DKE SPEC 99100:2025-02 [8].

1.2.1.3 End-of-Life and Sustainability

This final group supports responsible disposal, materials recovery, and alignment with circular economy goals.

Material Composition: Details about the materials used in the cathode, anode, and electrolyte are documented in the passport. It also includes information about critical raw materials and any hazardous substances present. This component is particularly vital for recycling and sustainability efforts, as it supports informed decisions about resource recovery and environmental safety [7].

End-of-life Information: Guidelines for recycling or repurposing the battery are a crucial component of the passport. This section includes data on disassembly processes, the recyclability of individual components, and associated environmental considerations, ensuring responsible end-of-life management and promoting sustainability [4].

This architecture turns each battery into a transparent, data-rich asset. By unifying identity, usage, and disposal records in a single digital profile, the Battery Passport lays the foundation for smarter regulation, ethical sourcing, circularity, and climate accountability (Table 1.2).

1.2.2 System Functionality

The Battery Passport is a functional tool that enables visibility, accountability, and continuous improvement across the battery value chain. Its strength lies in how it operationalizes sustainability, turning complex lifecycle data into actionable insights for manufacturers, regulators, and consumers alike.

1.2.2.1 Traceability and Transparency

The Battery Passport provides visibility into the chemical and material composition of each battery. By specifying the general and detailed composition, hazardous

Table 1.2 Summary of core components.

Category	Component	Description
Product identity	Identification Data	Unique identifiers (e.g., serial number, QR code) for traceability.
	Manufacturing Information	Data on origin, manufacturer, production date, weight, and category.
	Technical Specifications	Key metrics like capacity, energy density, and battery type.
Lifecycle and performance	Lifecycle Data	Usage history, charging cycles, aging, and state of health.
	Sustainability and Safety	Certifications on carbon footprint, recycled content, and regulatory compliance.
End-of-life and sustainability	Material Composition	Details on materials, including critical and hazardous substances.
	End-of-Life Information	Recycling guidelines, disassembly data, and environmental considerations.

substances, components, and build, the passport facilitates recycling and reuse. Additionally, it includes data on the battery's carbon footprint, reflecting the environmental impact of production and use, as well as supply chain due diligence, ethical sourcing, and procurement practices. These features align with regulatory mandates requiring operators to publicly disclose their battery due diligence policies, further driving accountability and sustainability [9].

The lifecycle begins with manufacturing, where the Battery Passport offers unparalleled visibility into production processes. By documenting the materials used, carbon footprint, and supply chain practices, the passport enables stakeholders to identify opportunities to improve efficiency and sustainability. Manufacturers can use this data to refine operations and adopt greener production methods, while consumers can make more informed purchasing decisions. This level of visibility encourages demand for responsibly produced batteries, driving systemic improvements across the industry [9] (Figure 1.7).

1.2.2.2 Circularity and Resource Efficiency

Battery Passports play a pivotal role in advancing the circular economy, establishing a closed-loop system that minimizes waste and maximizes resource efficiency at every stage of the battery lifecycle [9]. The passport supports reuse, repurposing, and design-for-recyclability by providing verified, lifecycle-specific data that guides technical and commercial decision-making. It enables manufacturers to design with end-of-life in mind and allows recyclers to extract maximum value from recovered materials.

1.2.2.3 Policy Alignment and Consumer Empowerment

As major initiatives like the European Union's sustainable battery strategy and China's evolving regulatory frameworks gain traction, the Battery Passport promotes

Reporting to the commission: Regulatory requirements

Who reports to whom?	What needs to be reported?	Reporting timeline
Producers and waste management operators → the competent authorities *(Article 75(1)-(3), (7))*	Quantities of: • batteries first placed on the market, excluding batteries that left the Member States before being sold to end users • waste batteries collected and sent for preparation for re-use or for preparation for repurposing • collected waste exported to third countries for treatment, preparation for re-use, preparation for repurposing, or recycling • collected waste sent to treatment and recycling facilities • batteries collected, and the collection rate achieved by the producer or the waste operator	**6 months[1]**
Waste management operators (for treatment and recycling) → the competent authorities *(Article 75(5))*	Quantities of: • waste batteries received for treatment and recycling • waste batteries sent to preparation for re-use, preparation for repurposing, or the recycling process Information on recycling efficiency and on the amounts of materials recovered from waste batteries, as well as the destinations and final outcomes of the output fractions.	**6 months[1]**
Member States → Commission *(Article 76)*	Quantities of: • batteries first placed on the market • waste batteries collected and sent for preparation for re-use or for preparation for repurposing • batteries collected, and the collection rates achieved Values for the recycling efficiencies and material recovery efficiencies achieved	**18 months[1]**

Commission
- Data collected and reviewed by the commission
- A report assessing the organisation of the data drawn up six months after the first reporting of the data and then, every four years

Figure 1.7 Reporting to the commission: regulatory requirements. *Source:* Battery Passport Content Guidance / Battery Pass consortium.

consistent data standards across jurisdictions. These initiatives aim to standardize data collection and exchange, ensuring seamless integration across the entire battery lifecycle. This infrastructure redefines manufacturing and value creation processes to align with circular economy principles. By equipping consumers with actionable insights, the Battery Passport enables them to make environmentally conscious choices, reinforcing sustainable practices as a fundamental component of the battery industry [9].

1.2.2.4 Driving Innovation and Industry Transformation

Beyond compliance, the Battery Passport serves as a catalyst for innovation. As companies adapt to meet its data and sustainability standards, they are incentivized to develop longer-lasting, more recyclable, and higher-performing batteries. This accelerates research and development in battery technologies, supports competitive advantage, and fuels the next generation of energy storage solutions, impacting everything from consumer electronics to EVs and grid-scale storage.

1.2.2.5 Technical Infrastructure and Digital Backbone

The Battery Passport is powered by a layered digital infrastructure designed to ensure data integrity, accessibility, and interoperability across the battery lifecycle. Its architecture combines physical identifiers with secure, tamper-proof systems to manage sensitive information and support circular economy goals at scale. The passport functions as a digital twin of the physical battery, evolving in real-time as the product moves through its lifecycle.

1.2.2.6 Blockchain Backbone and Data Integrity

Blockchain could be used as the digital backbone of the Battery Passport, ensuring that all recorded data on sourcing, production, usage, and disposal is verifiable and cannot be altered retroactively, according to industry players like Minespider. This is especially important in supporting trust across a complex, multiactor value chain. Blockchain also enables decentralized verification of sustainability claims, which is critical as companies face increasing scrutiny over ESG performance.

1.2.2.7 Infrastructure for Interoperability and Expansion

The digital infrastructure supporting the Battery Passport is built for scalability. It integrates with wider systems like the EU's DPP framework and is designed to operate across jurisdictions. By adopting common standards and shared protocols, it enables seamless data exchange between manufacturers, governments, and recyclers. This foundation also opens the door for advanced capabilities, including real-time monitoring, artificial intelligence (AI)-enabled supply chain insights, and automated compliance reporting (Figure 1.8).

1.2.3 Regulatory and Governance Framework

The Battery Passport operates within a tightly defined regulatory ecosystem shaped primarily by the European Union. At the heart of this system is the EU Battery

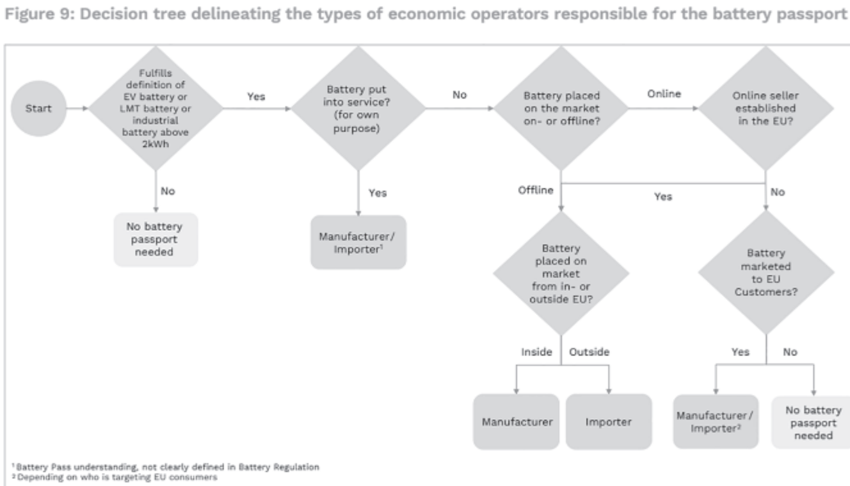

Figure 1.8 Decision tree delineating the types of economic operators responsible for the Battery Passport. *Source:* Battery Passport Content Guidance / Battery Pass consortium.

Regulation Amendment (to ensure a uniform and binding application of the new rules, the previous Directive 2006/66/EC was replaced with an actual regulation: European Regulation 2023/1542), which lays out detailed compliance obligations and performance benchmarks. The Battery Passport is part of this EU Battery Regulation Amendment, being a comprehensive framework designed to mitigate the environmental and social impacts of battery production. By, among others, focusing

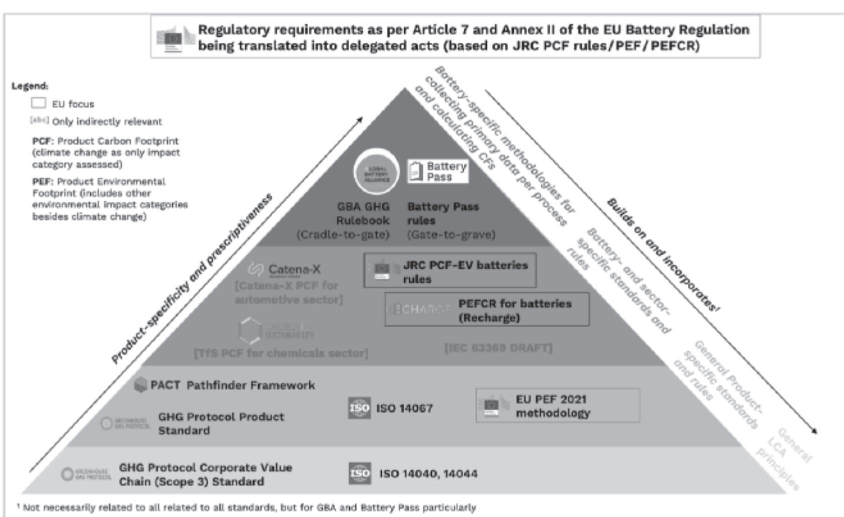

Figure 1.9 Regulatory requirements. *Source:* Batteries European Partnership Association (BEPA) [10].

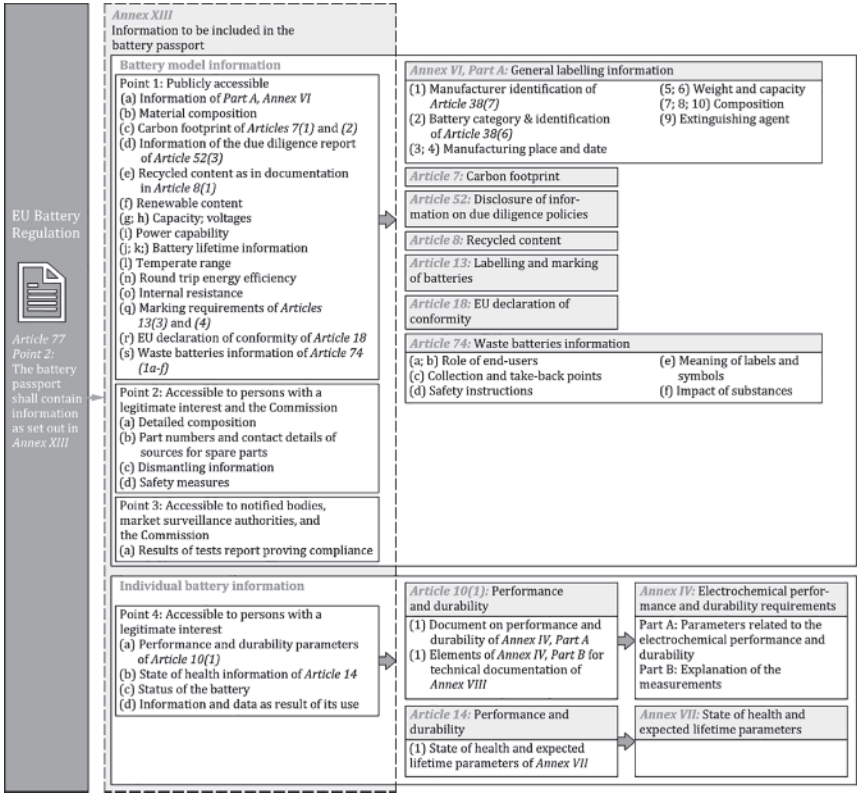

Figure 1.10 Battery Passport information flow in the battery regulation (DIN DKE SPEC 99100 [8]).

on reducing hazardous substances and enhancing recycling rates, the amendment reinforces the principles of a circular economy (Figures 1.9 and 1.10).

As a cornerstone of this initiative, the EU's Battery Regulation specifies rigorous content requirements for the passports. These include comprehensive data on general battery and manufacturer details, compliance certifications, carbon footprints, supply chain diligence, material composition, circularity metrics, resource efficiency, and durability standards. This regulation underscores the EU's commitment to fostering transparency and advancing circular value chains in battery manufacturing [11, 12].

1.3 Comprehensive Overview of the EU Battery Regulation (Regulation 2023/1542)

(Figures 1.11 and 1.12)

Within scope of battery passport

Battery Categories	Battery Definition and Use Cases	Battery Weight
Electric vehicle (EV) battery	• Provide electric power for the traction to hybrid or electric vehicles – of categories L (Regulation (EU) No 168/2013), if larger than 25 kg, or – of categories M, N or O (Regulation (EU) 2018/858)	> 25 kg (category L)
Light means of transport (LMT) battery	• Provide electric power for traction to wheeled vehicles that can be powered by an electric motor alone or by a combination of motor and human power including type-approved vehicles of category L (Regulation (EU) No 168/2013), e.g., e-bikes and e-scooters	≤ 25 kg
Industrial battery[1]	• Designed specifically for industrial uses or • Intended for industrial uses after being subject to preparation for repurposing or repurposing, **or** • Any other battery above 5 kg that is not an LMT, EV nor SLI battery • Industrial uses include, non-exhaustively (*Recital 15*): – industrial activities – communication infrastructure – agricultural activities – energy storage in private or domestic environments – generation and distribution of electric energy – traction in other transport vehicles including rail, waterborne and aviation transport or off-road machinery *Subcategory:* **Stationary battery energy storage system** – Industrial battery with internal storage – specifically designed to store and deliver electric energy from and into the grid or store and deliver electric energy to end-user, regardless of where and by whom this battery is being used	> 5 kg (if no other category applies)
SLI (starter, lighting, or ignition) battery	• Designed to supply electric power for starter, lighting, or ignition • May also be used for auxiliary or backup purposes in vehicles, other means of transport or machinery	-
Portable battery	• Not designed specifically for industrial uses • Neither an electric vehicle battery, nor a light means of transport battery, nor an SLI battery	≤ 5 kg
Portable battery of general use	• Rechargeable and non-rechargeable portable batteries specifically produced to be interoperable • Common formats: 4,5 Volts (3R12), button cell, D, C, AA, AAA, AAAA, A23, 9 Volts (PP3) • Providing traction to wheeled vehicles considered as toys (within Toy Safety Directive 2009/48/EC)	-

[1] Only industrial batteries above 2 kWh within scope of battery passport

Figure 1.11 Overview of battery category definitions. *Source:* Battery Pass Consortium [13] / Battery Pass Consortium.

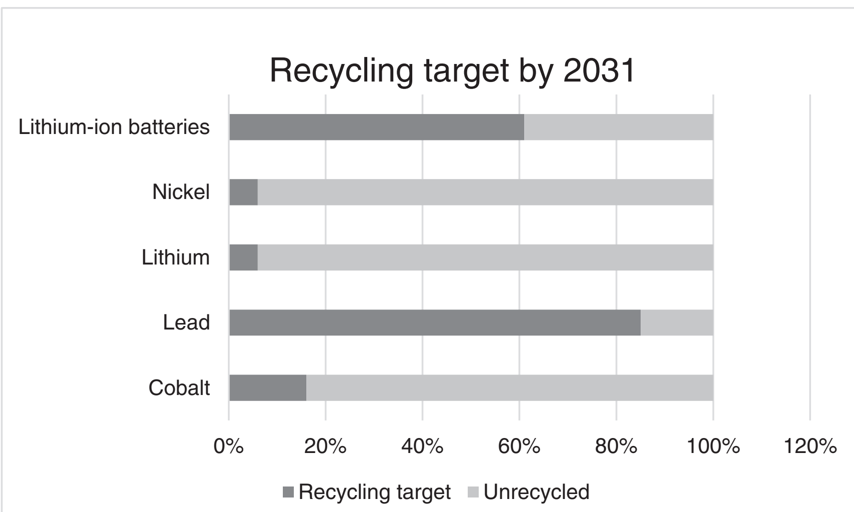

Figure 1.12 Recycling target by 2031.

Recycled Content Targets:

- By 2031, the following percentages of materials must be recovered from battery manufacturing waste or post-consumer waste:
  - Cobalt: 16%
  - Lead: 85%

  - Lithium: 6%
  - Nickel: 6%
- By 2036, these targets increase to:
  - Cobalt: 26%
  - Lead: 85%
  - Lithium: 12%
  - Nickel: 15%

Labeling and Collection Requirements:

- Every battery must clearly indicate the amount of recycled content it contains.
- For Light Means of Transport (LMT) batteries, the collection rate targets are:
  - 45% by 2028
  - 61% by 2031

End-of-life Management:

- There is a total prohibition on the landfilling of waste batteries.
- Economic operators are required to collect end-of-life batteries from end users free of charge.

1.3.1 Manufacturing Liability and Labeling

All EVs, LMT, and rechargeable industrial batteries with a capacity exceeding 2 kWh must include a carbon footprint declaration and label. This label should detail the recycled content of cobalt, lead, lithium, and nickel used in the battery's production. This information must also be accessible via a QR code by 2027.

Additionally, these batteries will require a digital Battery Passport. This passport will contain comprehensive information about the battery model, its intended use, and specific details such as capacity, performance, durability, chemistry, and its recycling collection symbol.

Restrictions on Hazardous Substances

- **Mercury:** The limit is set to no more than 0.0005% by weight.
- **Cadmium:** The limit is set to no more than 0.002% by weight.
- **Lead:** The limit is set to no more than 0.01% by weight in portable batteries by 18 August 2024.

A report will be submitted to the European Parliament and Council by 2027. This report may propose expanding the list of restricted substances to include other materials that are hazardous to human health or that hinder the recycling of safe and high-quality secondary raw materials in batteries.

4:34 p.m.

End Uses and Applications (Figure 1.13)

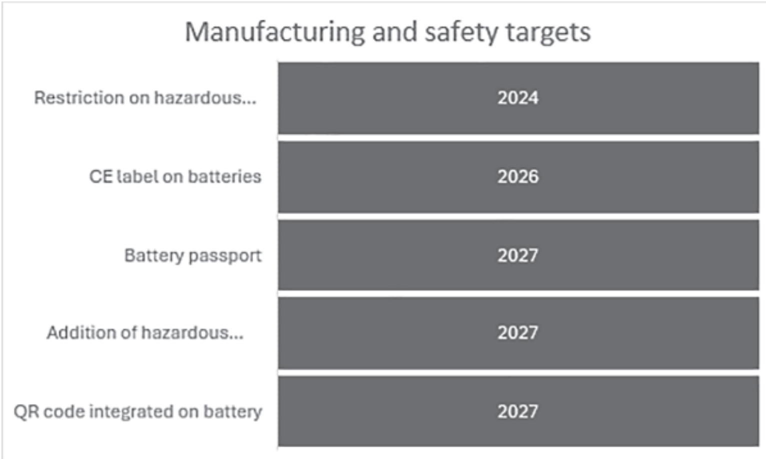

Figure 1.13 Manufacturing and safety targets.

1.3.2 End User Liability

By 2026, batteries must display the "CE" label to show compliance with EU health, safety, and environmental standards. These labels should be prominently placed on the entire device, not just the battery, and must also be accessible via a QR code by 2027.

Users are required to dispose of waste batteries separately from other types of waste.

LMT batteries need to be replaceable by an independent professional, with users having 42 months to adjust their product designs accordingly.

Additionally, Battery Management Systems (BMS) must include a software reset function to facilitate the installation of a different BMS for second-life or end-of-life use. Once this reset is performed, the original manufacturer will no longer be responsible for the battery.

1.3.3 Supply Chain Due Diligence (Updated Timeline)

Due diligence obligations, originally set for 2025, now apply from **18 August 2027**. These apply to any operator placing batteries on the market or putting them into service and cover raw materials such as cobalt, lithium, nickel, and natural graphite.

Requirements Include:

- Public due diligence policy (aligned with Organisation for Economic Co-operation and Development [OECD] and United Nations Guiding Principles on Business and Human Rights [UNGP] standards)
- Risk management systems
- Assessment and mitigation strategies
- Third-party audit by a notified body

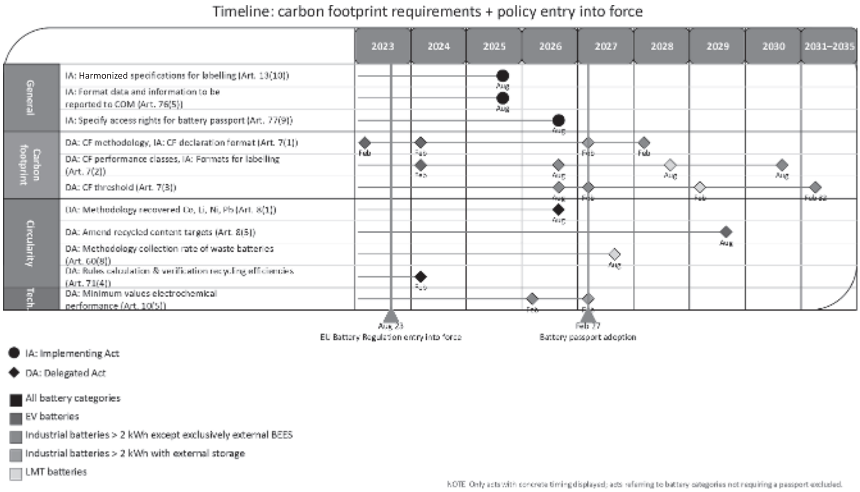

Figure 1.14 Timeline of some battery passport-related delegated and implementing acts following the Battery Regulation. Delegated and implementing acts scheduled by the battery regulation (DIN DKE SPEC 99100 [8]).

Key Changes:

- Threshold raised: Applies only to companies with >€150 million global annual turnover
- Reporting: Every three years starting in 2028
- EU guidance: Delayed to July 2026

Despite the delay, companies must be operationally ready before the 2027 enforcement deadline (Figure 1.14).

The new EU Battery Regulation introduces numerous changes affecting the entire battery lifecycle, including stricter requirements for manufacturing, usage, and recycling. Key aspects include:

- **New Battery Categories: In addition to existing battery types, new categories have been introduced, including batteries for light vehicles (e.g., e-bikes) and traction batteries for EVs.**
- **CO_2 Footprint: From 18 February 2025, manufacturers must disclose the carbon footprint of their batteries. By 2033, CO_2 limits will be introduced.**
- **Increased Collection Targets: The collection rate for portable batteries must rise to 73% by 2030. For light vehicle batteries, targets are 51% by 2028 and 61% by 2031.**
- **Minimum Recycled Content: From 2028, manufacturers must document the recycled material content in batteries. Minimum requirements for cobalt, lithium, nickel, and lead will apply from 2031.**

- **Battery Replaceability: From 2027, consumers must be able to remove and replace portable batteries themselves. Stricter replaceability rules also apply to other battery types.**
- **Extended Labeling Requirements: Batteries must feature QR codes containing essential information on capacity, durability, and recycling. From August 2025, labeling with the "Separate Collection" symbol will be mandatory.**
- **Digital Battery Passport: This will be mandatory for certain battery types from 2027 and will provide information on origin, CO_2 footprint, and material composition.**
- **New Due Diligence Obligations: Companies with revenue exceeding €40 million must implement additional supply chain monitoring measures.**

Battery Waste Management and Producer Responsibility
EPR is strengthened:

- Free battery take-back systems must be available to consumers.
- Distributors must collect used batteries on a **0:1 basis** (no purchase required).

Collection Targets:

- **Portable Batteries:**
  - 45% by 2023
  - 63% by 2027
  - 73% by 2030
- **LMT Batteries:**
  - 51% by 2028
  - 61% by 2031

SLI, industrial, and EV batteries do not have fixed collection targets but still require robust EPR systems.

1.3.4 Mandatory Recycling Efficiency and Recovery Targets

By **31 December 2027**, certified recycling facilities must meet minimum efficiency targets:

- **90%** for cobalt, copper, nickel, and lead
- **50%** for lithium

Recovered materials must be prioritized for reuse in the production of new EV, industrial, and Starting, Lighting, and Ignition (SLI) batteries supporting the EU's circular economy strategy.

1.3.5 Transition Timeline Through 2036

Although key obligations start between 2024 and 2028, the regulation's full scope will continue unfolding until **2036**. This phased implementation allows time for infrastructure development, regulatory clarity, and industry adaptation across all member states (Tables 1.3 and 1.4).

Table 1.3 EU Battery Regulation explained.

Regulated areas	Portable	LMT	SLI	Industrial	EV
CE conformity assessment of batteries based on sustainability[1] and safety[2] requirements	X	X	X	X	X
Supply chain due dilligence for raw materials; cobalt, natural graphite, lithium or nickel[3]	X	X	X	X	X
Battery passport for individual samples	-	X	-	X[4]	X
Removability and replaceability of batteries in products	X	X	-	-	-
Battery waste management	X	X	X	X	X

[1]Different sustainability requirements depending on the battery category
[2]Only applicable for stationary battery energy storage systems
[3]Does not apply to economic operators with a turnover of less than EUR 40 million
[4]Only applicable for industrial batteries > 2 kWh
Source: [14] / *Intertek Group plc.*

Table 1.4 EU Battery Regulation explained.

Article	Description	Portable	LMT	SLI	Industrial		EV
					≤2kWh	>2kWh	
6	Restriction of substances (Cd/Hg/Pb)	X/X/X	-/X/-	-/X/-	-/X/-		-/X/-
9-10	Performance and durability requirements	X[4]	X	-	-	X[2]	X
12	Safety of stationary battery energy storage systems	-	-	-	X[1]		-
13	Labelling, marking and information requirements	X	X	X	X		X
14	Information on the state of health and expected lifetime of batteries using a BMS	-	X[6]	-	X[1,6]		X[6]
7	Carbon footprint	-	X	-	-	X[3]	X
8	Recycled content (Co/Pb/Li/Ni)	-	X[5]	X[5]	-	X[3,5]	X[5]

[1]Only applicable for stationary battery energy storage systems
[2]Only applicable for rechargeable industrial batteries > 2 kWh
[3]Only applicable for industrial batteries > 2 kWh with internal storage
[4]Only applicable for portable batteries of general use, excluding button cells
[5]Only applicable if the active material in the electrodes contain Co, Pb, Li or Ni
[6]Only applicable if the battery includes a battery management system (BMS)
Source: Intertek [14].

Select either self-declaration (module A) or involving a notified body (module D1/G)

Mandatory notified body involvement (module D1/G)

1.3.5.1 What Are Producer Responsibility Organisations (PROs) Under EPR in Europe?

PROs *are approved organizations that act on behalf of multiple battery producers to fulfill their collective obligations under EPR laws. Their role is to implement practical and financial systems for the end-of-life management of batteries.*

Functions of PROs:

1) **Collect and Recycle Batteries**
   - Set up nationwide collection networks.
   - Organize take-back from retailers, public bodies, and private collection points.
   - Ensure environmentally sound recycling (compliant with Art. 70–71 of the EU regulation).
2) **Administrative and Legal Compliance**
   - Report battery volumes to authorities.
   - Monitor and report recycling performance.
   - Handle producers' registration and compliance paperwork.
3) **Financial Management**
   - Collect eco-contributions from producers.
   - Guarantee funding for the collection and treatment of waste batteries.
   - Maintain financial reserves and submit security deposits to protect against insolvency (Batt-EU-AnpG §9).
4) **Ecological Incentivization**
   - Design fee structures to reward recyclability, reusability, and lower environmental impact (Batt-EU-AnpG §10).
5) **Transparency and Public Reporting**
   - Publish annual data on collection rates, fees, ownership structure, and recyclers used (Batt-EU-AnpG §11 Abs. 6).

Who Must Join a PRO?

- **All battery producers** (including importers and online sellers) must either:
  1) Join an authorized PRO, or
  2) Fulfill all obligations individually, which is legally possible but logistically and financially difficult.

1.3.5.2 Role of PROs in the EPR Framework

They embody the EPR principle by shifting the responsibility and cost of waste management ***from taxpayers to producers****, ensuring that the environmental impact of batteries is accounted for across their lifecycle from production to disposal or reuse.*

1.3.5.3 Standards Evolution and Industry Guidance

The CIRPASS initiative, supported by Horizon Europe, contributed to defining key use cases and data requirements for the Battery Passport, helping align its development with real-world stakeholder needs [15].

1.3.6 Integration with DPPs and Global Frameworks

The Battery Passport is a foundational element of the European Union's broader strategy to embed sustainability, traceability, and circularity into product policy through DPPs. As part of the ESPR, DPPs will become mandatory for most product categories sold in the EU starting in 2024. The Battery Passport, with its lifecycle-wide data structure and secure digital integration, exemplifies how DPPs can deliver machine-readable, verifiable insights into product origins, composition, performance, and environmental impact [6].

To provide a comprehensive view of this shift, the EU's Circular Economy Action Plan (CEAP) includes several flagship policies that embed DPPs across industries. These include:

- **ESPR:** making DPPs the central vehicle for transparency on durability, repairability, and resource efficiency.
- **EU Battery Regulation (2026/2027):** requiring Battery Passports for EV and other batteries to ensure supply chain visibility and promote circularity.
- **CSRD and Green Claims Directive:** enabling companies to substantiate ESG claims using verified lifecycle data from DPPs.
- **Sector-specific rules** for textiles, construction, detergents, toys, and electronics, each of which will use DPPs to standardize sustainability reporting and improve product traceability [16].

The success of the Battery Passport is paving the way for this broader rollout. It demonstrates the value of standardized, interoperable digital infrastructure for managing complex product data across international supply chains. The Battery Passport's architecture, including secure blockchain integration, QR code linkage, and real-time updates, serves as a blueprint for other DPP applications.

Lessons learned from its implementation, particularly around data governance, stakeholder coordination, and technical scalability, are now shaping cross-sector standards. By anchoring DPPs in a common framework, the EU aims to streamline compliance, fight greenwashing, and drive innovation through transparent, accountable value chains.

In this way, the Battery Passport is a test case for a unified, data-driven future of sustainable production. As DPPs expand across sectors, the model pioneered by the Battery Passport will help harmonize environmental standards and enable a truly circular, cross-border product economy.

1.3.7 Driving Circularity and Sustainability

(Figure 1.15)

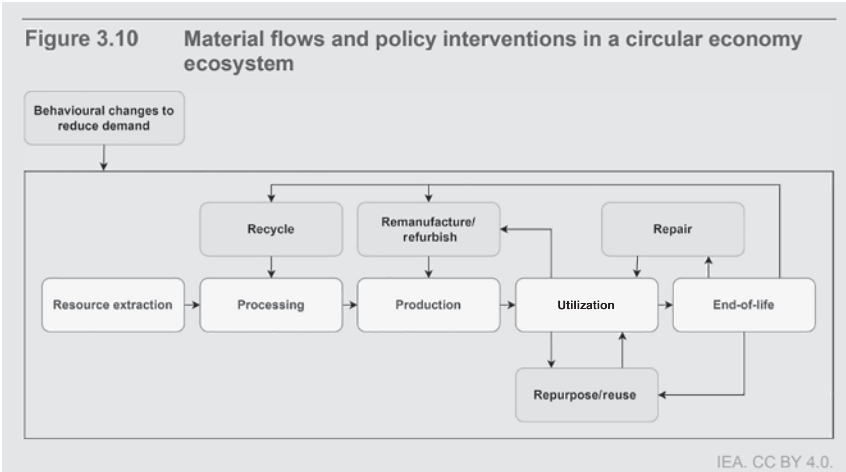

Figure 1.15 Material flows and policy interventions in a circular economy ecosystem. *Source:* Recycling of Critical Minerals / IEA / CC BY 4.0.

1.3.7.1 Enabling Circular Design and Second Life

Short battery lifespan (about seven years), premature disposal, and limited design consideration for reuse have created massive inefficiencies in the battery value chain. Most batteries are treated as disposable once their first-use application ends, even though many retain substantial residual capacity. This not only accelerates resource depletion but also contributes to growing volumes of battery waste that is often difficult or costly to recover due to poor design.

The Battery Passport directly addresses this issue by embedding real-time lifecycle data into each battery's digital identity. This allows stakeholders to monitor usage patterns, performance degradation, and state of health, enabling predictive maintenance and extending the functional life of each unit. Batteries that no longer meet mobility-grade requirements can be repurposed for second-life applications, such as stationary energy storage, where performance demands are lower but longevity and reliability remain critical.

By providing real-time lifecycle data, the Battery Passport enables predictive maintenance, preventing premature disposal and maximizing battery longevity.

The Battery Passport documents the entire lifecycle of each unit, allowing spent batteries to be evaluated for potential reuse or repurposing in second-life applications.

Facilitates repurposing of spent batteries for alternative applications such as stationary storage systems, which extend utility and reduce pressure on raw material supply chains.

However, in many cases, it will likely be more economical and resource-efficient to directly recycle spent batteries rather than repurposing them, particularly as recycling processes become increasingly sophisticated and cost-effective. Recycling can recover valuable materials at higher purity levels, reintegrating them efficiently into new battery production, thus further reducing the environmental footprint and dependency on raw material extraction.

Furthermore, by mandating transparency in battery design and component labeling, the Battery Passport makes disassembly easier, improving recyclability and lowering the cost of recovery.

The Battery Passport encourages manufacturers to adopt design-for-recyclability practices, ensuring that batteries are easier to process at end-of-life and minimizing material loss.

This approach aligns directly with the core principles of the circular economy. As the Ellen MacArthur Foundation notes:

At the heart of the circular economy is the principle that waste and pollution are not inevitable byproducts but preventable outcomes. This model advocates for designing products and materials with the explicit goal of eliminating waste and pollution from the outset [17].

This requires prioritizing durability, reparability, and recyclability in product design, enabling materials to flow through a closed-loop system that mirrors the efficiency of natural cycles. By adopting this proactive approach, the circular economy minimizes environmental impact while maximizing resource efficiency [18].

The circular economy emphasizes the need to keep products, components, and materials in continuous use at their highest utility and value, extending the lifespan of materials, reducing the demand for virgin resources, and minimizing waste [17].

Additionally, the United Nations Development Programme (UNDP) identifies innovative business models, such as product-as-a-service, as key drivers of this transformation [18], which will be explained in more detail in a following chapter (Figure 1.16).

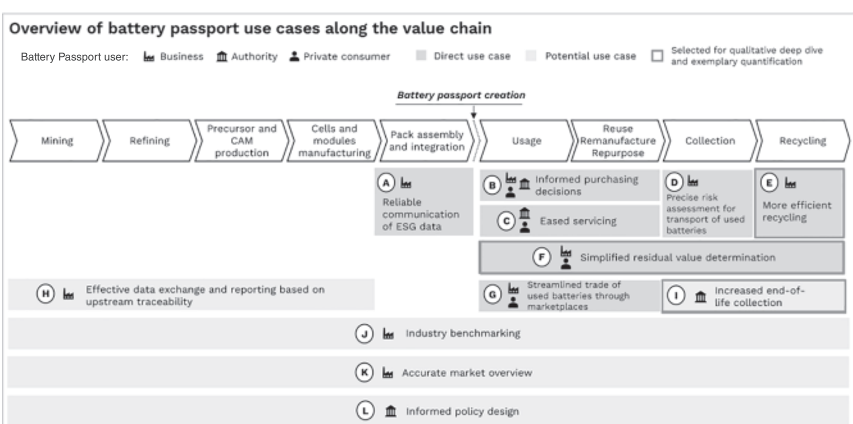

Figure 1.16 Overview of Battery Passport use cases along the value Chain. *Source:* Battery Pass Consortium / Unlocking the Value of the EU Battery Passport. https://thebatterypass.eu/assets/images/value-assessment/pdf/2024_BatteryPassport_Value_Assessment_Synthesis.pdf (accessed 12 November 2025) / CC BY-NC 4.0.

1.3.7.2 Facilitating Recycling and Material Recovery

By acting as a comprehensive digital record that tracks a battery from manufacture to final disposal, it provides the technical detail and historical transparency recyclers need to recover materials efficiently and safely. The passport includes information on design, chemistry, usage history, and performance degradation, giving recyclers a full picture of what is inside before disassembly begins [9].

During a battery's operational life, the passport serves as a repository of real-time performance data, including capacity, energy output, state of charge, and internal resistance. This information allows users to optimize battery performance, extending its usable life and delaying the need for replacements. By maximizing usage, Battery Passports reduce the environmental impact of frequent manufacturing and disposal cycles, aligning with circular economy principles [9].

At end-of-life, this same infrastructure plays a different role: streamlining recovery. With granular, machine-readable data on cathode and electrolyte composition, battery architecture, and hazardous substances, the passport allows treatment facilities to sort and prioritize batteries with precision. This not only improves our ability to increase material recovery yields but also reduces the labor, risk, and uncertainty involved in recycling operations.

When a battery reaches the end of its lifecycle, the detailed information contained in its passport will be a valuable resource for recyclers. The passport provides a comprehensive overview of the battery's composition and history, enabling the efficient recovery of valuable materials such as lithium, cobalt, and nickel. This process minimizes waste sent to landfills and ensures these materials are reintroduced into the production cycle, closing the loop in the circular economy [9].

This closed-loop functionality is increasingly essential as regulatory frameworks evolve. The EU Battery Regulation sets ambitious recovery targets for critical raw materials – targets that will be difficult or impossible to meet without accurate, component-level information. By providing that data up front, the Battery Passport enables recyclers to meet compliance requirements more easily, while helping producers document their contribution to circularity goals.

Ultimately, the Battery Passport serves as a bridge between today's fragmented recovery systems and the high-efficiency, low-waste recycling models demanded by a sustainable energy economy. It turns information into action, powering better decisions, higher yields, and reduced environmental impact at every stage of the battery's end-of-life journey.

1.3.7.3 Advancing ESG and Ethical Supply Chains

Battery manufacturing relies on a complex web of global suppliers, many of which operate in regions with heightened risks of environmental harm, labor violations, and conflict mineral extraction. Without end-to-end visibility, it becomes nearly impossible for manufacturers or regulators to ensure responsible sourcing. This opacity presents growing liability in an era where ESG compliance is no longer optional but expected.

The Battery Passport offers a solution grounded in traceability. By recording supply chain data at each stage of the battery's lifecycle from raw material extraction to *component assembly, it enables manufacturers to verify where materials come from, how they are sourced, and whether suppliers meet environmental and social standards.*

The Battery Passport drives sustainable material sourcing and ethical practices within the battery manufacturing sector. By enabling traceability of materials from their origin, it ensures transparency across the supply chain, discouraging the use of conflict minerals and promoting environmentally and socially responsible procurement. Manufacturers are held accountable for sourcing practices, advancing industry alignment with global environmental and social sustainability goals [19–21].

This traceability is powered by secure technologies. These tools support due diligence reporting, streamline regulatory compliance, and reduce the risk of greenwashing by corroborating sustainability claims with verifiable data.

Battery Passports also help companies meet mandatory disclosure requirements. For example, supply chain due diligence is increasingly required under EU regulations, including documentation of carbon intensity, hazardous content, and ethical sourcing [9]. With the passport, this data is collected systematically and stored in a format accessible to auditors, investors, and consumers alike.

As ESG reporting becomes a decisive factor in investor confidence and corporate valuation, the Battery Passport gives firms a competitive edge. It identifies ethical gaps and helps close them, enabling a proactive shift toward sustainable, resilient, and socially responsible supply chains.

1.3.7.4 Driving Regulatory and Market Transformation

The Battery Passport has the potential to become a catalyst for structural change in how the battery industry is regulated, funded, and globally aligned. By turning lifecycle data into a standardized and verifiable format, the passport gives policymakers and investors the clarity they need to act decisively.

The passport's granular, traceable data enables the development of new policy instruments. Governments can move beyond static reporting requirements toward dynamic, real-time compliance frameworks. Delegated acts and regulatory amendments like those under the EU Battery Regulation are increasingly being shaped around the capabilities the passport introduces: carbon footprint thresholds, recycled content quotas, and due diligence standards that are trackable, enforceable, and future-proof.

The comprehensive data provided by Battery Passports has a considerable influence on policymaking and investment decisions. The verifiable data from Battery Passports also attract investments in renewable energy infrastructure and innovative battery storage solutions, accelerating the global shift to a low-carbon economy [13].

This policy-aligned data structure also builds investor confidence. With ESG performance now central to financial decision-making, Battery Passports offer a layer of credibility that reduces risk and increases transparency. Lenders, asset managers, and insurers can assess sustainability performance not just from self-reported disclosures but from a tamper-proof digital trail.

The Battery Passport is also accelerating cross-border harmonization. Initiatives like the GBA and the EU-funded Battery Pass project are setting precompetitive

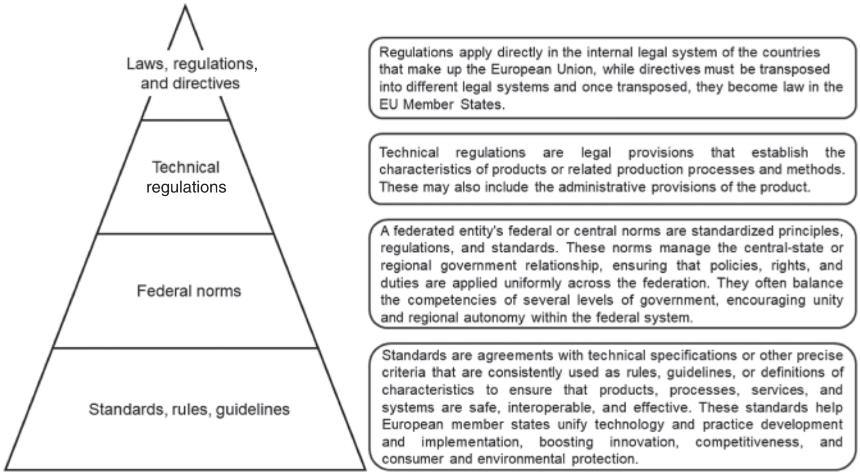

Figure 1.17 Definition of laws, technical regulations, federal norms, and standards. *Sources:* Federal Register [24] and Rufino Júnior et al. [25].

standards that enable interoperability between markets. This is essential for an industry built on global supply chains but increasingly governed by regional policy frameworks. By aligning technical standards with policy requirements, the passport system supports smoother trade, regulatory convergence, and operational consistency across jurisdictions.

The widespread adoption of Battery Passports is likely to influence policy and regulation on both national and international levels. Governments may establish new standards to ensure effective implementation and maintenance of the passport system. These developments could lead to a harmonized global approach to battery management, facilitating international trade while upholding strict environmental and ethical standards. This alignment will ensure that companies remain compliant with evolving regulations while driving policy advancements that prioritize sustainability [21].

Finally, the passport's architecture based on blockchain and interoperable data layers acts as a template for future digital infrastructure. It enables real-time monitoring, automated compliance verification, and AI-driven insights, setting the foundation not just for better batteries but for smarter regulation across the clean tech economy (Figure 1.17).

1.4 How? Setting the Global Standard

1.4.1 EU, US, China, and Global Alignment Challenges

1.4.1.1 The EU: Regulatory Leader and First-Mover

The European Union has emerged as the global frontrunner in regulating battery sustainability, traceability, and circularity. Through a tightly coordinated policy ecosystem, it has positioned the Battery Passport not just as a compliance mechanism but as a driver of industrial transformation.

The Battery Passport aligns closely with the EU Battery Regulation Amendment, a comprehensive framework designed to mitigate the environmental and social impacts of battery production. By focusing on reducing hazardous substances and enhancing recycling rates, the amendment reinforces the principles of a circular economy.

This regulatory push is embedded in the broader CEAP and ESPR, which mandate DPPs across multiple sectors. For the battery industry, this means enforceable obligations backed by a structured, long-term timeline.

The EU Battery Regulation establishes a comprehensive timeline spanning from 2023 to 2040, setting ambitious milestones to advance sustainability and safety across the battery industry. Key phases include (Table 1.5)*:*

The regulation applies tailored requirements to specific battery types:

- *EV batteries*
- *Industrial batteries exceeding 2 kWh (excluding external ESS)*
- *Light mobility (LMT) batteries*

These provisions align with key regulatory articles, such as Article 8(1) for documentation and Articles 8(2) and 8(3) for establishing minimum recycled content requirements [22].

Through this timeline and sector-specific mandates, the EU is setting standards for internal markets, but by doing so, it is influencing global best practices. By embedding digital traceability and lifecycle accountability into law, the EU is establishing the blueprint for how sustainable battery ecosystems should operate worldwide (Figure 1.18).

1.4.1.2 China: Strategic Follower and System Integrator

While the European Union has led the charge in Battery Passport regulation, China has emerged as a fast-moving strategic follower, leveraging its manufacturing

Table 1.5 Battery recycling key phases.

Date	Milestone/event
August 2023	*Regulation enters into force*
February 2027	*Mandatory adoption of Battery Passports for relevant battery types*
August 2027	*Delegated Act adopted for methodologies to calculate recycled content (Co, Li, Ni, Pb)*
December 2027	*European Commission assesses recycled content targets*
August 2030	*Minimum recycled content targets for Co, Pb, Li, and Ni come into effect*
August 2033	*Revised targets + new Delegated Act with documentation rules for recycled content*
August 2036	*Further amended recycled content targets implemented*

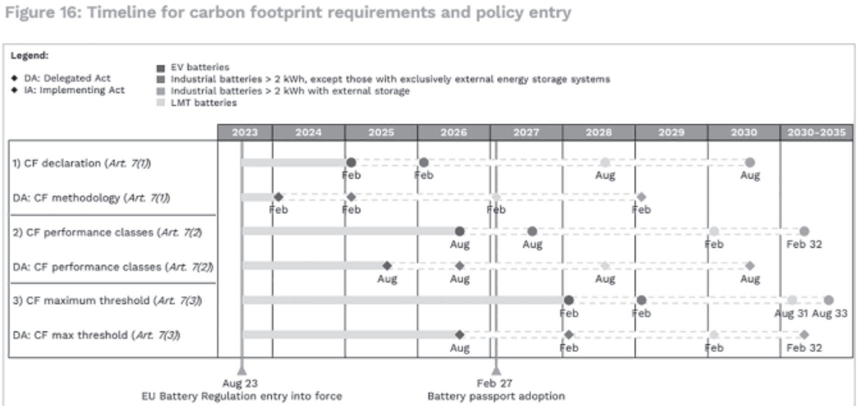

Figure 1.18 Timeline for carbon footprint requirements and policy entry. *Source:* Battery Passport Content Guidance / Battery Pass consortium.

dominance to shape its own framework aligned with global norms. The 2023 update to the EU's Battery Legislation catalyzed similar efforts in China, where policymakers initiated the development of a digital Battery Passport program inspired by the EU's transparency framework. China's initiative prioritizes key aspects such as carbon footprint, circularity, and ESG metrics. By mirroring EU standards, China aims to facilitate smoother trade relations with European partners while ensuring alignment with global sustainability objectives. This growing international momentum highlights the opportunity for policymakers worldwide to standardize reporting parameters, integrate technical frameworks with existing systems, and foster greater engagement from the battery industry [23].

China's regulatory approach is built on a well-established infrastructure. The Interim Provisions on Traceability Management of Power Battery Recycling in New Energy Vehicles, introduced in 2018, mandated end-to-end tracking from cell manufacturers to recyclers. This early legislation laid the foundation for a national digital battery traceability system focused on lifecycle oversight [23, 24].

More recent policies build on that traceability backbone, extending accountability deeper into the supply chain and aligning with international benchmarks. China's evolving Battery Passport framework includes carbon footprint tracking, mandatory lifecycle disclosures, and strict documentation of reuse and recycling activities, all aimed at harmonizing with EU models and enabling cross-border interoperability.

Unlike the more fragmented policy environment in the United States, China has adopted a centralized regulatory stance. National-level rules impose clear obligations on EV battery manufacturers for safe collection, second-life deployment, and end-of-life recycling. These policies go beyond traceability; they also address battery safety, material integrity, and environmental impact throughout reuse cycles [25].

China's strategy includes technical mandates as well. Manufacturers must incorporate reuse- and recycling-friendly design features, including labeling standards and detailed component documentation. This improves transparency and enables more effective disassembly and recovery. In parallel, import/export restrictions have been implemented to prevent the displacement of electronic waste, including used batteries, into lower-regulation regions, reinforcing China's commitment to environmental protection and domestic processing standards [25].

Together, these developments signal China's intent to maintain global competitiveness while enhancing control over its internal battery supply chain. By integrating traceability, sustainability, and trade facilitation into a unified system, China is positioning itself as a systems integrator capable of shaping the next phase of international battery governance.

It is also important to recognize that the overwhelming majority of the world's batteries are either made in China or by Chinese manufacturers. This gives China a unique structural advantage in adopting Battery Passport frameworks: the companies expected to comply with the EU Battery Passport (BP) are, for the most part, already operating under Chinese jurisdiction or influence. As these firms integrate EU-aligned systems into their operations to meet export requirements, the groundwork for broader adoption within China is already being laid regardless of whether domestic policy mandates it. This embedded infrastructure makes it easier for Chinese regulators to scale similar initiatives nationally and aligns market behavior with global norms even in the absence of binding legislation.

1.4.1.3 United States: Fragmented but Evolving

In contrast to the EU's centralized regulatory push and China's integrated strategy, the United States presents a fragmented landscape for battery governance. While the country plays a major role in global EV and battery markets, it lacks a comprehensive federal framework for digital Battery Passports.

In the United States, there is currently no comprehensive federal legislation specifically dedicated to digital Battery Passports comparable to the EU's framework. However, several state-level initiatives and existing federal regulations indirectly contribute to managing end-of-life EV batteries. Federal-level regulation is largely focused on environmental protection, recycling processes, and disposal guidelines. The Resource Conservation and Recovery Act (RCRA) is central in regulating hazardous wastes, including lithium-ion batteries (LIBs). Yet, it lacks explicit guidance or standards tailored specifically to second-life applications or Battery Passports [25].

Instead, regulatory momentum in the United States is driven primarily by a patchwork of state-level EPR initiatives. These frameworks vary significantly by state. California, for example, has adopted stricter rules promoting battery reuse, recycling, and transparency. Still, this decentralized approach creates operational uncertainty for manufacturers and recyclers operating across multiple jurisdictions. Without federal harmonization, Battery Passport implementation remains inconsistent.

Federal efforts have shown potential to shift the narrative. In the United States, recent legislation such as the Inflation Reduction Act emphasizes localizing supply chains and enhancing material traceability. Specifically, the Clean Vehicle Tax Credit, outlined in Section 30D of the Act, mandates detailed provenance data for battery materials to qualify for tax incentives. These efforts demonstrate a growing recognition of the importance of robust traceability and transparency frameworks in ensuring the sustainable production and management of batteries [23, 24]. Though not a full Battery Passport mandate, it represents a policy-level signal that traceability is becoming a prerequisite for economic incentives.

Much of the momentum in the United States has come from the private sector, where major automakers and tech companies are experimenting with their own digital transparency tools, often influenced by EU standards or in preparation for global compliance.

However, the policy outlook remains volatile. The future of federal climate and energy policy is uncertain in the context of the second Trump administration. Key provisions of the Inflation Reduction Act such as traceability-linked tax credits could be delayed, weakened, or repealed. The potential policy reversal raises questions about whether battery passport initiatives will gain traction at the federal level or continue to rely on state action and corporate leadership.

In short, the U.S. Battery Passport landscape is constantly evolving. However, without clear national coordination, its trajectory will likely remain shaped by state policy diversity, market forces, and shifting federal priorities.

Interestingly, even in the absence of a federal mandate, the widespread presence of Chinese batteries in the U.S. market may indirectly accelerate adoption of Battery Passport practices. These companies, already adapting to EU requirements and implementing traceability systems across their global operations, may carry over those practices as standard operating procedure. This habitual compliance could lead to informal alignment with international norms, regardless of domestic policy clarity, embedding passport-like systems into U.S. supply chains through the global habits of the manufacturers involved. This potential ripple effect may have been a factor in the EU's adoption of the Battery Passport.

1.4.1.4 Global Alignment: Challenges and Cooperation

As the Battery Passport moves toward international adoption, global alignment remains one of its most urgent and complex challenges. While the European Union has taken the lead with a binding regulatory framework, other regions, including the United States, China, and various global stakeholders, are still in the early phases of development or alignment. The success of the Battery Passport depends on a unified global effort among industry players, regulators, and other stakeholders. The highly globalized nature of battery value chains necessitates a collaborative approach to designing a scalable, interoperable system. Regional disparities in policies and practices risk undermining the passport's potential unless addressed through coordinated international efforts [26].

1.4.1.5 Challenges: Fragmentation, Interoperability, and Trust

Significant challenges include regional variation in standards, regulatory fragmentation, data silos, and confidentiality concerns. Creating a standardized framework for Battery Passports that is globally accepted poses significant challenges. Regional variations in regulatory standards complicate the development of a universal passport format. Navigating these differences and achieving harmonization is essential to unlock the full potential of Battery Passports [26].

The EU Battery Regulation establishes stringent requirements for the content and functionality of Battery Passports, including detailed manufacturer data, certifications, carbon footprint tracking, and supply chain due diligence. While no significant technological barriers have been identified, subtler issues persist. Ensuring interoperability across various digital systems, safeguarding data privacy and security, and maintaining data accuracy throughout the battery's lifecycle are key challenges. A report in the *Journal of Cleaner Production* highlights the importance of overcoming these barriers through infrastructure investments and the adoption of standardized practices across the battery value chain [27]. Additionally, the need for seamless integration between existing and emerging technologies will require industry-wide collaboration to achieve interoperability and scalability.

Ensuring the accuracy and integrity of data throughout a battery's lifecycle is a core requirement for the Battery Passport's success. Challenges include collecting, storing, and managing data in a tamper-proof manner while maintaining accessibility for stakeholders.

The development and implementation of Battery Passports entail considerable costs, including initial investments in technology for data tracking and storage, ongoing maintenance, and necessary upgrades. Smaller manufacturers may face disproportionate financial burdens, potentially impacting market competition and innovation. Other expenses include training personnel and adapting production lines to meet the new requirements [28].

Widespread stakeholder buy-in is crucial for the successful deployment of Battery Passports. However, manufacturers may resist due to concerns about disclosing proprietary information and the added complexity of compliance. Consumers may worry about data privacy and potential price increases, while recyclers require accurate and actionable data to optimize their operations [29].

Achieving stakeholder acceptance will require clear communication of the benefits, such as improved supply chain transparency, enhanced environmental accountability, and reduced lifecycle costs. Early engagement with all stakeholders and targeted financial and technical support for SMEs will be critical to addressing these concerns and fostering collaboration [29].

1.4.2 Global Standards and Regulations

Battery Passport policies exhibit significant regional and global diversity, shaped by distinct regulatory, market, and technological landscapes. These variations influence how Battery Passports are adopted, impacting trade, market access, and stakeholder collaboration. To address these challenges, international standards bodies like the International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO), and others provide unified frameworks that ensure consistency, interoperability, and sustainability across borders.

1.4.2.1 Global Standards and Regulations

Global standards form the backbone of Battery Passport systems, harmonizing technical, environmental, and trade-related requirements. They enable seamless collaboration between regions while supporting sustainability objectives.

1.4.2.2 IEC Standards: Technical Specifications for Safety and Data

The IEC, among other standardization bodies, establishes technical guidelines for battery systems, focusing on safety, performance, and reliability. These standards, including IEC 62133, contribute to ensuring consistency in safety requirements for secondary cells and batteries, particularly in portable applications. By setting uniform testing and performance criteria, IEC guidelines help reduce safety risks, enhance compliance, and support global interoperability in battery systems.

1.4.2.3 ISO Standards: Environmental Management and Sustainability

ISO standards emphasize environmental responsibility, providing structured frameworks for material traceability, lifecycle emissions monitoring, and circular economy practices. These guidelines align Battery Passport systems with global sustainability goals, such as the UN's Sustainable Development Goals (SDGs), by ensuring responsible resource management.

1.4.2.4 Uniformity and Trade Facilitation

International standards, including those from the IEC and ISO, facilitate global trade by reducing regulatory barriers and standardizing compliance requirements. Harmonized regulations lower administrative costs, streamline cross-border trade, and create a level playing field for companies operating in multiple jurisdictions.

1.4.2.5 Impact on Data Management and Privacy

Global standards also address critical issues of data governance and privacy. For instance, regulations like the General Data Protection Regulation (GDPR) in the EU shape how Battery Passport systems handle personal and business data. These standards provide clear protocols for secure data storage, access, and sharing, ensuring compliance with ethical and legal obligations [30].

1.4.2.6 Supporting Technological Integration

Emerging technologies such as blockchain, the Internet of Things (IoT), and AI highlight the need for global standards. These technologies rely on interoperable systems and secure data formats to function effectively. For example, blockchain can track battery materials securely across borders, while IoT devices monitor performance and lifespan data in real time. IEC and ISO guidelines provide the technical foundation for integrating such advanced technologies, ensuring they operate seamlessly within Battery Passport systems.

1.5 Nonexhaustive List of Standards

To ensure interoperability, traceability, and compliance across the battery value chain, the EU Battery Regulation mandates the development and application of standards governing unique identifiers for Battery Passports. These identifiers must enable consistent identification at various levels of granularity (model, batch, and item) and align with existing Union legislation and global identification frameworks. The standards must support both centralized and decentralized approaches, accommodate diverse existing practices, and ensure semantic and syntactic integrity. Table 1.6 summarizes the most relevant standards and their specific functions.

Table 1.6 Standards for unique identifiers in the Battery Passport system.

Standard	Title/scope	Function in Battery Passport system
ISO/IEC 15459	Automatic identification and data capture – Unique identification	Defines structure for globally unique identifiers across products and supply chains
ISO/IEC 61406	Identification Link	Supports digital links between physical products and online information
ISO/IEC 29161	Unique identification for the Internet of Things	Enables consistent identification of IoT-enabled battery components
ISO/IEC 15418	GS1 and ASC MH10 Data Identifiers	Ensures standardized formatting of identifiers for product categories and packaging
ISO/IEC 9834-8/ RFC 4122	Universally Unique Identifiers (UUIDs)	Defines the generation of globally unique digital identifiers
ISO 17442	Legal Entity Identifier (LEI)	Identifies economic operators legally involved in battery manufacturing and handling
ISO/TR 23249	Blockchain – Identity management overview	Supports identity systems in distributed ledger environments, relevant for decentralized identifiers
ISO/TR 6039	Blockchain – Identifiers of subjects and objects	Structures identifiers for subjects/ objects in blockchain-based tracking
ISO 22383	Authentication solutions for material goods	Provides methods for verifying authenticity of battery data and identifiers
ISO 22385	Trust and Interoperability Framework	Establishes rules for trust mechanisms in cross-system interoperability
ISO 22387	Confirmation procedures for artifact metrics	Offers verification protocols for product metrics and digital seals
ISO 22376	Visible Digital Seal (VDS) data specifications	Defines formats for embedding digital authentication into physical battery labels
ISO 22372	Trustworthy supply chain framework	Guides secure data exchange and identification along the battery supply chain

Table 1.6 (Continued)

Standard	Title/scope	Function in Battery Passport system
ISO/IEC 19762	AIDC – Harmonized vocabulary	Provides a unified terminology for identification and data capture systems
ITU-T X.1403	DLT Security – Secure applications and services	Establishes security requirements for distributed identifier systems
W3C – DID	Decentralized Identifiers (DIDs)	Enables self-sovereign, decentralized identity models for battery items and stakeholders
W3C – Verifiable Credentials	Digital verifiability of credentials	Enables tamper-evident, digitally signed identity claims within the passport system
EN IEC 63365	Digital Nameplate	Standardizes digital product marking, key for linking physical items to digital passports
ISO/IEC 20248	Digital signature schema for AIDC	Ensures secure, machine-verifiable digital signatures embedded in identification codes
ISO/IEC 19845:2015	Universal Business Language (UBL) v2.1	Supports structured business data exchange across supply chain actors
EN 16931 (Parts 1, 3–2, 3–3)	Electronic Invoicing – Core semantics and profiles	Ensures semantic interoperability in invoice data that may be linked to product or passport transactions
ISO 22378	Interoperability of product authentication systems	Facilitates communication across different product ID/authentication systems
ISO 22381	Interoperability of object identification and authentication	Builds frameworks for systems that must operate across independent data environments
CEFACT Cross Industry Invoice	UNECE standard for cross-industry invoice exchange	Supports trusted transactional data related to batteries

To enable traceable, interoperable, and verifiable DPPs, the Battery Passport system must rely on standardized data carriers such as QR codes, Radio Frequency Identification (RFID) chips, or barcodes that link each physical battery to its corresponding digital identity. These data carriers must follow common rules regarding their construction, encoding, durability, and visual identity. They must also contain or reference key types of data: the DPP itself, control data for authentication, and offline-accessible cross-sectoral information. Table 1.7 presents the most relevant existing and proposed standards that serve these functions.

Battery Passports will contain both public and restricted data ranging from technical specifications to sensitive commercial or repair history. To ensure that this information is securely accessed, transferred, and maintained, robust standards are needed for identity management, cybersecurity, and access control. These standards must define how different users (e.g., manufacturers, repairers, recyclers) access specific data elements based on attributes such as role or ownership, while safeguarding

Table 1.7 Standards for data carriers linking physical batteries to digital passports.

Standard	Title/description	Function in Battery Passport system
EN IEC 61406-1	Identification Link	Establishes structure for linking a product to its digital representation
EN IEC 63365	Digital Nameplate – Digital Product Marking	Provides rules for embedding digital identifiers on physical product surfaces
CLC/TR 50489	Feasibility of RFID in EEE for WEEE management	Explores the use of RFID tags for tracking and recycling electronics, applicable to batteries
ISO/IEC 24458	Bar code printer and reader performance testing	Ensures reliable encoding and decoding of barcode data carriers
ISO/IEC 22603-1	Digital representation of product information – General requirements	Lays foundational rules for digital product data formatting
ISO/IEC 21471	Extended rectangular Data Matrix symbology	Specifies a compact, robust barcode format used on small or curved surfaces
ISO/IEC 18004	QR code symbology specification	Defines structure, error correction, and use of QR codes for product data links
ISO/IEC 16022	Data Matrix symbology specification	Standard for 2D matrix codes often used in durable goods like batteries
ISO/IEC 15426-2	Barcode verifier conformance for 2D symbols	Provides conformance criteria for barcode quality
ISO/IEC 15424	Data Carrier Identifiers	Assigns symbology identifiers to distinguish among types of barcodes
ISO/IEC 15415	Print quality test specification for 2D symbols	Establishes metrics for evaluating print clarity and durability
ISO/IEC 15418	GS1 Application Identifiers and ASC MH10 Data Identifiers	Facilitates structured data encoding for supply chain tracking
ISO 23354	Business requirements for visibility of logistics flow	Supports end-to-end tracking, enabling persistent links across logistics phases
ISO 15000-2:2021	AS4 Profile of ebXML Messaging v3	Enables secure business messaging, useful in DPP-linked invoice and logistics data
PEPPOL eDelivery	Secure document transport system for digital procurement	Used for integrating transaction and DPP data
GS1 DataMatrix Guideline	Best practices for implementing GS1-encoded DataMatrix barcodes	Provides encoding structure and implementation guidance
ISO/IEC NP 18975	Encoding and resolving identifiers over HTTP	Defines how digital identifiers can be persistently resolved online
GS1 Digital Link	Embeds GS1 identifiers into URLs	Links physical items directly to online DPPs using globally unique links
W3C DIDs	Decentralized Identifiers	Enables decentralized linking between objects and their digital identities

Table 1.7 (Continued)

Standard	Title/description	Function in Battery Passport system
W3C DID Resolution	DID Resolution Protocol	Specifies how systems can interpret and resolve DIDs into usable digital records
W3C DID Registration	DID registration processes	Defines how new decentralized identifiers can be registered and maintained
Digital Object Identifier (DOI)	Persistent identifier system for digital content	Supports long-term, immutable linking to Battery Passport records
Uniform Resource Names (URN)	Standard for unique and persistent resource naming	Ensures battery DPPs are consistently and uniquely addressable
PEPPOL Service Metadata Locator	Metadata discovery for PEPPOL networks	Helps locate and validate DPP-related data exchange endpoints

integrity, confidentiality, and regulatory compliance. Table 1.8 provides a consolidated view of the existing and proposed standards relevant to these objectives.

Effective implementation of the Battery Passport system depends on seamless interoperability across platforms, actors, and regions. Interoperability must be ensured at three levels: technical (data exchange and system integration), semantic (shared understanding of data meanings), and organizational (harmonized processes and governance models). This requires standardized vocabularies, metadata, data formats, and common information models that allow different stakeholders (manufacturers, recyclers, and regulators) to exchange and interpret data consistently. Table 1.9 presents the core standards guiding this effort.

A robust Battery Passport system relies on seamless, secure, and structured data exchange between various stakeholders (manufacturers, recyclers, regulators, etc.). To enable this, standardization of data exchange protocols, data formats, and data processing rules is essential. These standards define how product passport data is introduced, updated, and transmitted, ensuring system-wide interoperability, auditability, and alignment with the principles of the circular economy. Table 1.10 presents key standards that define these technical foundations.

To maintain long-term access to product passport data, especially for market surveillance and regulatory enforcement, standards must ensure that data remains securely stored, persistent, and accessible, even if the originating economic operator becomes inactive. These standards must support decentralized storage, ensure archival integrity, and allow for trusted retrieval of historical passport versions (Table 1.11).

Table 1.8 Standards for access rights, cybersecurity, and confidentiality in the Battery Passport system.

Standard	Title/description	Function in Battery Passport system
EN IEC 63278-3	Security provisions for Asset Administration Shells	Provides a secure framework for managing asset-specific data, relevant for battery-level passport access
ISO/IEC 29146	A framework for access management	Defines policies and mechanisms to control access to restricted product passport data
ISO/IEC 24760	Identity management framework	Outlines how organizations, devices, and services are uniquely identified and authenticated
ISO/IEC 24761	Authentication context for biometrics	Supports advanced, identity-specific access mechanisms (if biometrics are used in operator environments)
ISO/IEC TS 29003	Identity proofing	Guides on how to securely verify identities before granting passport access
ISO/IEC 20248	Digital signature data structure schema	Ensures data authenticity and tamper-proofing of digital passport entries
ISO/IEC 30147	Trustworthiness methodology for IoT systems	Ensures secure management of IoT-connected battery data and access logs
ISO/IEC AWI 30149	IoT Trustworthiness Framework	Provides standards for evaluating trust levels in systems sharing DPP data
ISO 22385	Framework for Trust and Interoperability	Supports policy-level trust design for system-to-system access coordination
ISO/IEC 27040	Storage security	Ensures secure storage of DPP data in enterprise or cloud environments
ISO 15000-2:2021	AS4 profile of ebXML Messaging v3	Secures DPP-related data exchanges between stakeholders
ISO/TR 6039	Blockchain ID systems	Enables secure object/operator identification on decentralized platforms
ISO 23257	Blockchain reference architecture	Serves as a structural framework for secure DLT-based access control
ISO/TS 23635	Blockchain governance guidelines	Ensures data rights and roles are clearly managed in blockchain environments
ISO/WD TR 23642	Smart contract security best practices	Helps mitigate vulnerabilities when using smart contracts in DPP systems
IEC 62443 series	Industrial cybersecurity	Secures industrial infrastructure handling DPP data
IEC 63069	Security of industrial communication networks	Protects DPP information as it flows through secure communication layers
IEC TR 63283-3 and series	Digital twin/AAS cybersecurity	Addresses security for digital twins linked to product passports

Table 1.8 (Continued)

Standard	Title/description	Function in Battery Passport system
ITU-T Rec X.1144 (XACML v3)	XML Access Control Markup Language	Defines access policies in digital environments, supporting fine-grained passport access control
Verifiable Credentials (W3C)	Digital credentialing for access control	Enables decentralized verification of access rights
ODRL Model & Vocabulary (W3C)	Open Digital Rights Language	Defines machine-readable access policies for data exchange
OAuth2	Secure authorization protocol	Widely used framework for managing user and system access permissions
IETF RFC7515	JSON Web Signature	Defines integrity-protected digital data, used in access tokens and signed DPP payloads
Certificate Transparency (RFCs 6962, 9162)	Public logging of certificate issuance	Ensures visibility and traceability of digital certificate usage in DPP systems
OCSP Stapling (RFC 6066)	Online certificate status validation	Secures and accelerates real-time validation of certificates for authentication

Table 1.9 Standards supporting interoperability in the Battery Passport system.

Standard	Title/description	Function in Battery Passport system
EN IEC 63278	Asset Administration Shell for Industrial Applications	Provides a digital twin model enabling structured data exchange between assets and systems
EN IEC 61360-1	Standard data element types with classification scheme – Definitions and methods	Defines a vocabulary and metadata schema to ensure consistent meaning and data structure
ISO/IEC 21823	Internet of Things (IoT) – Interoperability for IoT systems	Guides integration of IoT devices with Battery Passports through layered interoperability architecture
Baseline Protocol	Protocol for secure and interoperable workflows across companies using blockchain and messaging layers	Ensures business process interoperability using zero-knowledge proofs and private computation
ISO 11354-1:2011	Enterprise Interoperability Framework – Part 1	Provides a framework for aligning business processes, organizational structures, and IT systems

Table 1.10 Standards for data processing, exchange protocols, and data formats in Battery Passports.

Standard	Title/description	Function in Battery Passport system
ISO 9735	EDIFACT syntax rules	Standard for structured electronic data interchange (EDI) across parties
ISO 14533	Long-term digital signature profiles for documents	Enables verifiable and legally compliant data records across time
ISO/IEC 19845	Universal Business Language (UBL)	Standard for electronic business documents (invoices, logistics, etc.)
ISO/IEC 20248	Digital signature data structure for AIDC	Provides machine-verifiable data integrity for barcodes and RFID
EN 16931	Semantic model for electronic invoicing	Ensures standardized and interoperable invoice data linked to DPP records
ISO 23247	Digital twin framework for manufacturing	Aligns passport data with real-time production information
ISO 10303 series	STEP: Product data representation and exchange	Provides comprehensive data formats for technical product information
ISO 15000-2:2021	AS4 Profile of ebXML Messaging	Protocol for secure and standardized B2B message exchange
ISO 23354	Visibility in logistics flow	Ensures supply chain transparency with product-specific data
EN ISO 23386	BIM: Property modeling methodology	Describes and maintains digital properties in standardized data dictionaries
EN ISO 12006-3	BIM: Framework for object-oriented construction data	Organizes construction data for integration with DPPs (especially for battery housing/components)
EN 17549-2	BIM: Configurable construction objects	Defines modular data templates for parts used in battery manufacturing
ISO 59040 (draft)	Circular Economy – Product Circularity Data Sheet	Captures lifecycle attributes supporting repair, reuse, and recycling
ISO/CD TR 6277	DLT – Data flow model	Supports distributed ledger applications for decentralized DPP access and transfer
ISO/AWI TS 23516	DLT – Interoperability framework	Standardizes how distributed ledger systems interconnect for data sharing
PEPPOL eDelivery	Secure e-document transport	Framework for safely exchanging DPP and transactional data between systems

Table 1.10 (Continued)

Standard	Title/description	Function in Battery Passport system
ISO/IEC 19987	EPCIS – Event capture and sharing	Enables standardized event data capture for product traceability
ISO/IEC 19988	Core Business Vocabulary	Defines reusable terms for business events and transactions
IEC 62720	Units of Measurement	Ensures consistency in reporting physical battery characteristics
IEC 61360-4 DB	Common Data Dictionary	Reference database for standardized product descriptors
ECLASS	International standard for classifying and describing products	Supports interoperable product categorization across industries
W3C Web of Things (WoT)	IoT integration framework	Connects physical battery components with DPP systems via semantic web tech
W3C WoT Thing Description (TD)	Device-level metadata specification	Makes battery subcomponents machine-readable and network-interoperable
SAREF (ETSI TS 103 264)	Smart Applications Reference ontology	Provides an ontological model for integrating smart battery and IoT systems
UNECE Cross Industry Invoice	Multisector invoice interoperability	Aligns economic and transaction data with DPP use cases
UNECE SCRDM	Supply Chain Reference Data Model	Cross-industry framework for structuring supply chain data
UNCCL/UNCL/UNLOCODE	UN/CEFACT code lists	Identifiers for logistics, product categories, and geographies
OpenIDConnect/OID4VC/OID4VP	Identity/authentication protocols	Manages secure digital credentialing for DPP actors
W3C Verifiable Credentials	Data model for verifiable digital claims	Enables secure proof of authenticity and ownership for DPP data
JSON-LD/VC-JSON Schema	Semantic web vocabulary formats	Standardizes DPP data representation in linked data contexts
GS1 Digital Link/Data Matrix/GDM	Supply chain linking and traceability standards	Converts product identifiers into web links that resolve to digital passport data
GS1 General Specifications	Barcode and RFID data structures	Governs encoding of key product attributes used in DPPs
Global Traceability Standard	Cross-industry event-level traceability	

Table 1.11 Standards for data storage, archiving, and persistence.

Standard	Title/description	Function in Battery Passport system
EN IEC 63278	Asset Administration Shell for Industrial Applications	Includes data structuring and persistence mechanisms for digital twins and passports
Decentralized Web Node (DWN)	Spec for decentralized, permissioned data storage	Enables distributed, resilient passport storage systems
Encrypted Data Vaults (EDV)	Encrypted cloud storage containers for personal/enterprise data	Provides secure long-term storage of sensitive DPP information
Certificate Transparency (RFC 6962/9162)	Logs for digital certificate issuance and revocation	Verifies authenticity and traceability of archived passport data and credentials

Table 1.12 Standards for data authentication, reliability, and integrity.

Standard	Title/description	Function in Battery Passport system
ISO/IEC 20248	Digital signature schema for AIDC	Provides trusted, machine-verifiable data signatures for QR codes and identifiers
ISO 22378	Interoperability of product identification systems	Supports authentication across multiple product ID frameworks
ISO 22383	Evaluation of authentication solutions for material goods	Defines testing criteria for anti-counterfeiting technologies
ISO 22385	Framework for trust and interoperability	Supports consistent handling of digitally signed passport data across systems
ISO 22387	Artifact metrics confirmation procedures	Provides verification techniques for embedded physical or digital authentication markers
ISO 8000	Data quality principles	Ensures completeness, accuracy, and consistency of passport datasets
Certificate Transparency (RFCs 6962/9162)	Secure verification of public keys and certificates	Supports nonrepudiation and trust in authentication processes

Battery Passports must be authentic, reliable, and tamper-proof throughout their lifecycle. This requires secure mechanisms to verify data origin, ensure content has not been altered, and authenticate the actors accessing or updating information. Standards here cover digital signatures, verifiable credentials, anti-counterfeiting mechanisms, and logging (Table 1.12).

Standardized Application Programming Interfaces (APIs) are essential for enabling automated passport creation, access, updates, and queries, especially

Table 1.13 Standards for APIs in Battery Passport lifecycle and searchability.

Standard	Title/description	Function in Battery Passport system
REST/HTTP/ SOAP/WS-	Standard protocols for web-based APIs	Defines communication and data exchange patterns (e.g., CRUD operations)
OpenAPI Specification	API documentation and schema standard	Facilitates uniform API development and integration
ISO/IEC 21778	JSON data syntax standard	Defines the structure of JSON payloads for DPP API communications
IETF RFC7515/ RFC7519	JSON Web Signature/Token	Ensures secure authentication and authorization of API users
JSON-LD	Linked data format	Supports semantic richness in API responses
eDelivery/ PEPPOL eDelivery	Secure communication frameworks	Enables trusted API connections between government and economic actors
ISO/IEC 19845	Universal Business Language	Aligns API-based DPP data with transaction and logistics standards
ISO/IEC NP 18975	Encoding/resolving identifiers over HTTP	Ensures links in APIs are persistent and interoperable
OpenID Connect/ OpenID for VC	Authentication and authorization protocols	Provides secure access and identity verification for API users
ISO EN 301549	Accessibility for ICT systems	Ensures APIs meet accessibility standards for public services
JRC APIs4DGov	EU guidance on public sector API design	Provides methodology and best practices for building APIs in digital government systems

from regulators or other third parties. These APIs must be secure, interoperable, and scalable, supporting a range of operations including lifecycle tracking, system integration, and search functionalities across national platforms and registries (Table 1.13).

1.5.1 DIN DKE SPEC 99100: A Key Framework

Incorporating the DIN DKE SPEC 99100 into the global standards discussion adds a critical dimension to the regulatory framework for Battery Passports. This specification, closely aligned with the EU Battery Regulation (EU) 2023/1542, defines the essential data attributes required for digital Battery Passports. These attributes include general battery information, material composition, performance metrics, working conditions in raw material extraction, and carbon footprint. By clearly outlining these elements, DIN DKE SPEC 99100 ensures transparency and sustainability in the battery value chain, helping stakeholders adhere to consistent data reporting and management practices [9].

The integration of DIN DKE SPEC 99100 with existing international standards, such as those from the IEC and ISO, enhances interoperability and data consistency across borders. This harmonized approach facilitates the global adoption of Battery Passports, enabling efficient compliance with diverse regulatory requirements and supporting sustainable practices worldwide. By establishing clear data attribute guidelines, the specification aids companies in implementing the Battery Passport and lays the groundwork for future international standardization efforts. This proactive approach positions the battery industry to adapt to evolving regulatory landscapes and technological advancements, fostering a more sustainable and transparent global battery market [9].

1.5.1.1 Progress: Cooperation, Pilots, and Technical Enablers

Despite these challenges, the global policy and technical landscape are beginning to converge. The GBA advocates for a multistakeholder approach, bringing together businesses, regulators, IT solution providers, and public entities to design a global Battery Passport infrastructure. By enabling secure and efficient data exchange across the battery lifecycle, the GBA aims to foster transparency and standardization, paving the way for a globally recognized system [26].

Projects like Battery Pass, supported by the German Federal Ministry for Economic Affairs and Climate Action, are laying the groundwork for harmonized implementation. The Battery Pass Project is actively working to set standardized requirements and implement them in a demonstrator to align with the EU Battery Regulation [29]. It emphasizes the importance of creating a digital record that documents production conditions, usage history, and essential end-of-life data. This transparency is critical for enabling informed decision-making by end users and recyclers, ensuring that Battery Passport effectively supports sustainable practices [31].

Parallel initiatives like CIRPASS, Catena-X, and programs coordinated through UNEP, UNICEF, and Horizon Europe are also contributing frameworks for DPPs, machine-readable data formats, and blockchain integration. Blockchain technology is especially critical, providing tamper-proof storage and decentralized verification to protect sensitive commercial data while ensuring traceability and compliance across complex, multijurisdictional supply chains.

Additionally, bilateral policy convergence, especially between the EU and China, points to a growing recognition that common standards are not just desirable but necessary. China's recent efforts to build a Battery Passport model inspired by the EU framework underscore the global relevance of harmonized digital systems for carbon reporting, ethical sourcing, and lifecycle oversight.

The global battery economy cannot operate with fractured systems. There is a need for a foundation of interoperability, built on secure digital infrastructure, policy alignment, and industry-wide collaboration. Pilot programs show that alignment is possible. Now, the challenge is scaling it together.

Despite growing momentum and visible pilot efforts, delays in global Battery Passport implementation are highly likely. Aligning diverse regulatory systems, overcoming technical integration hurdles, and securing buy-in across fragmented markets will take time, possibly years longer than current roadmaps suggest. Progress will be uneven, especially where political shifts, infrastructure gaps, or economic pressures slow adoption. Even where rollout proceeds on schedule, not all features of the Battery Passport are expected to be functional from day one. Initial versions may focus on basic traceability and carbon reporting, while more complex capabilities like full lifecycle tracking, interoperability with recycling systems, or integration of ESG metrics could be phased in over time. Stakeholders should plan accordingly, balancing ambition with pragmatism.

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