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Generative AI-Enabled Digital Battery Passports for Closed-Loop Resource Allocation in New EV Supply Chains: A Conceptual Framework

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Abstract: Digital battery passports (DBPs) make lifecycle data easier to reach, but reachability by itself does not settle where a returned battery should go—whether it should stay in service, be redeployed for a second life, enter remanufacturing, or be dismantled for materials. This paper advances a decision architecture built around Generative AI. In this design, the DBP acts as the verified evidence base, while Generative AI is assigned to interpret, compare, and explain closed-loop allocation choices. The architecture is informed by current battery-passport regulation, recent scholarship, and observations of industrial practice in new energy vehicle supply chains. Four connected functions are specified: trusted lifecycle evidence, controlled generative reasoning, support for allocation decisions, and feedback from outcomes. The aim is not to let language-model outputs displace engineering or compliance judgment. Instead, the framework harmonizes disparate lifecycle records, exposes absent or conflicting evidence, evaluates viable recovery routes, and records why a circular resource decision was made.

Keywords: Generative artificial intelligence; Digital battery passport; New energy vehicles; Closed-loop supply chain; Resource allocation; Circular economy

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1. Introduction

Electric mobility's worldwide rise has shifted the meaning of battery sustainability. What was once framed mainly as in-vehicle performance is now a governance problem spanning the entire lifecycle. Traction batteries hold critical minerals, embodied energy, carbon burdens, safety hazards, and considerable residual worth. After a battery is removed from its original vehicle, actors must decide among continued service, repair, refurbishment, second-life use, remanufacturing, component harvesting, or material recovery. Such choices are more accurately viewed as allocation decisions in a closed-loop supply chain than as routine end-of-life recycling, since the quality of information shapes how much technical and economic value can be

preserved [1].

DBPs are meant to counteract fragmented information. European Commission guidance describes the battery passport as a lifecycle information tool with access rights that vary by user [2]. Under the EU Batteries Regulation, certain battery classes—EV batteries among them—will need an electronic battery passport starting 18 February 2027 [3]. Scholarship indicates that DBPs can structure information on identity, sustainability, diagnostics, maintenance, performance, and value-chain participants [4]. Work centered on end-of-life choices also stresses that material composition, state of health, and use-phase records matter when batteries are assessed for reuse or recovery [5].

A basic limitation remains, however. A passport documents evidence; it does not convert that evidence into a disposal or allocation choice on its own. Even with comprehensive lifecycle information, automakers, recyclers, remanufacturers, and second-life operators must integrate technical, economic, environmental, and regulatory considerations when determining the most appropriate pathway. Accordingly, existing DBP research has focused primarily on information provision and its contribution to circularity. Related stakeholder research has also examined information availability and accessibility [6]. At the same time, supply-chain studies on Generative AI suggest that the technology can support coordination, scenario building, and decision assistance when it is embedded in governed organizational routines [7]. The opportunity explored here sits where these two lines of work meet.

This paper puts forward a Generative AI–DBP architecture for closed-loop allocation. The DBP stays the authoritative evidence source; Generative AI functions as a bounded reasoning and explanation layer that sits above verified data. The central contribution is a decision design that helps translate traceability into practical recovery choices. Industrial practice is used only to describe operational readiness.

2. Digital battery passports and closed-loop battery resource allocation: background

2.1. Regulatory and information basis of the DBP

The Digital Battery Passport (DBP) functions as a battery-specific digital information carrier that preserves relevant data throughout the product lifecycle and makes such information available to authorized stakeholders when operational or strategic decisions are required. In the European Union, the DBP forms part of the emerging regulatory infrastructure for battery traceability and sustainability, with access to information differentiated according to stakeholder roles. Its application to designated battery categories is intended to strengthen transparency, accountability, and information continuity across production, use, reuse, remanufacturing, and end-of-life management.

The relevance of such passports is not limited to Europe: manufacturers serving global markets increasingly require interoperable records covering product identity, recycled content, carbon data, due diligence, and lifecycle events.

Recent studies have provided a clearer picture of the information architecture required for Digital Battery Passports. Existing research generally covers several core categories, including basic battery characteristics, sustainability and circularity indicators, diagnostic and performance data, and information on actors across the value chain. At the same time, stakeholder-based studies reveal that information regarded as highly important for sustainability purposes is not always readily available in practice. This problem is particularly evident at the end-of-life stage, where recyclers and other downstream actors often depend on

material composition data, battery condition indicators, and updated state-of-health information. In many cases, however, records generated during the use phase remain incomplete or fragmented. These findings indicate that progress toward battery circularity depends not only on advances in recovery technologies, but also on the continuity, quality, and accessibility of lifecycle data.

2.2. Resource allocation in the closed loop

No single recovery route suits every battery that comes back. What is feasible depends on condition, safety incidents, chemistry, remaining capacity, disassembly properties, market demand, transport cost, carbon effects, regulatory obligations, and the capacity available for second-life or remanufacturing operations. Studies of circular supply chains indicate that battery second-life pathways involve a sequence of interconnected activities, including collection, condition assessment, sorting, repurposing, refurbishment, maintenance, and final recycling. These activities are typically distributed across multiple organizations and require coordination among different participants throughout the battery's extended lifecycle. Recent work on EV battery business models similarly treats remanufacturing, repurposing, recycling, leasing, and service-based models as parallel ways of retaining value [8].

The decision problem is therefore multi-criteria by nature. Technical reuse potential may not match local demand; valuable materials do not automatically make immediate recycling the best lifecycle option; and the cheapest route may not be the one with the lowest carbon footprint. Age or residual-capacity cut-offs alone overlook these trade-offs. A defensible allocation process needs to bring together engineering limits, logistics, economics, environmental data, and compliance duties, while keeping an auditable record of why a pathway was selected.

2.3. Generative AI as bounded reasoning, not truth source

Generative AI matters here because allocating batteries usually demands interpretation across structured and unstructured evidence, not merely the solution of one numerical problem. Passport data may include technical fields together with maintenance histories, supplier declarations, carbon records, repair notes, and regulatory documents. A controlled Generative AI layer can align terminology, condense long records, detect inconsistencies, compare possible pathways, and produce short decision briefs for human reviewers. Its practical contribution arises from being embedded within organizational decision processes rather than from the standalone generation of textual outputs.

The architecture consequently sets a firm line between evidence and generation. A language model must not fabricate state-of-health figures, material composition, safety events, or regulatory status; those facts have to originate from validated passport fields or linked enterprise systems. Generative AI is used to reason over the evidence at hand, expose uncertainty, and explain alternatives. Any recommendation should be traceable to the data retrieved, the rules applied, and the person or role accountable for final approval. This separation is critical because disposition decisions can affect safety, warranty duties, environmental compliance, and ownership of recovered materials.

3. Empirical context and analytical framework informed by survey evidence

3.1. Readiness signals observed in industrial practice

The framework draws on observational insights from manufacturing and supply-chain practice in the new

energy vehicle sector. Four existing dimensions act as descriptive readiness signals for deploying a GenAI-enabled DBP architecture: networked equipment, AI-assisted production scheduling, closed-loop material recycling, and cross-border carbon accounting. These dimensions are treated solely as contextual indicators of digital and circular maturity; they are not measures of DBP adoption or causal effects.

Networked equipment supplies connected operational data and visibility for collecting lifecycle evidence. AI-supported production scheduling reflects prior organizational experience with AI-assisted recommendations and decision workflows. Closed-loop material recycling points to established circular-material practices relevant to managing recovered battery materials. Cross-border carbon accounting indicates an ability to integrate product and supply-chain carbon information for compliance and allocation choices. Together, these practices form an operational base on which a GenAI-DBP architecture can be constructed.

3.2. A four-layer GenAI–DBP framework for resource allocation

The proposed framework has four linked layers. Layer one is trusted evidence. Here, the DBP and connected enterprise systems provide battery identity, chemistry, material composition, manufacturing provenance, maintenance and safety history, state of health, carbon information, recycled-content data, and lifecycle events. At this stage, the priority is not advanced analytics but evidence that is reliable and traceable.

Layer two offers controlled generative reasoning. A retrieval-constrained system reaches only authorized passport and enterprise records, aligns incompatible formats, marks missing or contradictory fields, and prepares scenario-based explanations. It can show what evidence supports second-life use, which safety or warranty conditions rule out a pathway, how recycling alters the availability of recovered materials, or what further inspection is required. The result is a documented decision aid, not an autonomous final disposition.

Layer three provides allocation decision support. Human decision-makers, assisted by engineering thresholds and conventional optimization tools, choose among continued first-life service, repair or refurbishment, second-life deployment, remanufacturing or component harvesting, and material recycling. The allocation logic also reaches into forward sourcing: recovered materials and reusable components can be matched to procurement needs, while second-life batteries can be directed to compatible applications.

Layer four closes the loop through outcome feedback. Inspection findings, actual recovery yields, second-life performance, carbon results, and economic returns are fed back into the lifecycle record or related enterprise databases. By comparing recommendations with realized outcomes, decision rules can be refined over time. The DBP thus remains the authoritative evidence source while also becoming part of a learning process for circular resource allocation.

4. Designing pathways for generative AI-enabled closed-loop resource allocation

4.1. Creating a passport ready for evidence-based decisions

Implementation should start with evidence that supports real disposition choices, not merely disclosure fields. Compliance data are necessary, but downstream actors also require battery identification, chemistry, module configuration, state of health, repair and incident records, disassembly instructions, carbon data, and custody-change information at the moment of decision. If dynamic information is absent, the system should show the gap openly instead of inserting unverified estimates. This approach responds to a persistent weakness in end-of-life battery management: the lack of complete and usable information for downstream decision-making.

Previous stakeholder-oriented studies have similarly shown that sustainability and circularity data often remain fragmented, difficult to obtain, or unevenly accessible across the value chain.

An operational passport also needs to connect with manufacturing execution systems, battery management systems, quality databases, supplier master data, carbon accounting platforms, and recycling records. Equipment connectivity and digital carbon management are becoming more common, but a DBP architecture requires records to be linked at battery or batch level instead of staying isolated in separate departmental systems.

4.2. Producing scenario options for second life, remanufacturing, and recycling

The next step is to convert verified evidence into recovery options that can be compared directly. A GenAI system can draft a structured brief for each returned battery, summarizing condition, identifying mandatory exclusions, comparing feasible destinations, and explaining the main trade-offs. High residual capacity and a stable safety record may support second-life use; uneven module degradation may point toward remanufacturing or component harvesting; severe damage with little remaining utility may favor material recovery. These are not fixed rules. Engineering thresholds, market conditions, environmental factors, and inspection requirements still determine which options are feasible.

Generative AI is most valuable when numerical and textual evidence must be read together. Maintenance notes, repair histories, supplier certificates, safety events, and regulatory documents can be examined alongside state-of-health and carbon indicators. Condensing this varied evidence lowers the workload for reviewers and makes large return volumes more manageable. After pathways are narrowed, established optimization and scheduling systems take over routing, capacity assignment, and logistics planning. Generative AI therefore complements rather than replaces mathematical optimization.

4.3. Linking reverse flows to forward material purchasing

Closed-loop value is fully realized only when recovered resources re-enter future demand. Recycling generates material streams whose timing, volume, quality, and certification status matter to procurement teams. A DBP-supported reasoning layer can aggregate expected recovery volumes from incoming batteries, compare them with material requirements, and build sourcing scenarios that mix primary and secondary materials. End-of-life decisions then become directly integrated with forward procurement planning.

Carbon concerns add a further dimension to trade-off analysis. Second-life use delays material recovery but may extend service value; immediate recycling returns critical materials sooner yet produces different transport and processing emissions. Combining passport carbon information with logistics and procurement data makes these assumptions visible to reviewers. The aim is not to declare one pathway universally best, but to make the basis of each decision explicit and comparable across alternatives.

4.4. Human validation, accountability, and controls against hallucination

Governance controls are necessary because fluent generated explanations can seem more certain than the evidence warrants. Each recommendation should state which source fields were consulted, which data gaps remain unresolved, and what confidence limitations apply. Mandatory engineering and safety thresholds should, wherever possible, be encoded outside the language model, and the model must not be allowed to override them. Human authorization must remain mandatory for safety-sensitive, warranty-related, legally significant, or high-value material decisions. Audit logs should retain the model version, retrieved evidence,

generated recommendation, and final disposition for accountability.

Evaluation of the architecture should center on factual grounding, reproducibility, traceability, and reviewer usefulness, not on how persuasive the generated text sounds. In this architecture, a high-quality model is one that helps decision-makers reach better-documented allocation decisions from verified information, not one that produces the most elaborate narrative.

5. Implementation and policy coordination recommendations

Deployment should begin with a bounded pilot, not enterprise-wide automation. An initial scope could be one battery platform or one return channel, connected only to the minimum data needed for identity verification, condition assessment, carbon accounting, and recovery planning. Organizations can then test whether decision briefs reduce information-search time, improve reviewer consistency, and reveal missing data gaps before extending the system to more suppliers and recovery partners.

A shared data dictionary and governance structure should be created across automakers, battery manufacturers, service organizations, recyclers, and second-life operators. Passport data create value only when terminology keeps a consistent meaning from one organization to another. Access controls should separate public data, commercially sensitive records, regulator access, and technical information needed by repair or recovery actors. Responsibility for data provenance and updates should be assigned to specific parties.

Performance measurement should go beyond simple recycling rates. Allocation rules need to consider circularity, safety, economics, and carbon performance together. Useful indicators include the share of batteries directed to higher-value feasible uses, the proportion of recovered material returned to procurement, decision cycle time, how often human reviewers override recommendations, and compliance with safety and carbon objectives. Such measures make the architecture testable without assuming that any one pathway is always preferable.

Cross-border interoperability is especially relevant for export-oriented manufacturing regions. Product identity, carbon disclosure, recycled-content evidence, and supply-chain compliance information increasingly need to travel between domestic and international systems. Policy support can target common identifiers, interoperable data standards, pilot verification services, and training for smaller suppliers that might otherwise become weak links in the information chain.

Finally, Generative AI should be governed as an interface to verified information, not treated as a substitute source of compliance facts. Technical standards, validation procedures, and audit rules should specify when generated recommendations may be used, what evidence must accompany them, and which decisions require human authorization. This arrangement lets Generative AI reduce interpretation effort without weakening accountability.

6. Conclusions

DBPs improve the visibility of lifecycle information, but visibility alone does not guarantee better circular decisions. The managerial challenge is to turn that information into timely choices among continued use, second life, remanufacturing, and material recovery. This study addresses that challenge through an architecture informed by practice, in which the DBP remains the trusted evidence base, and Generative AI provides a controlled interpretation and explanation function.

The framework makes three core contributions. First, it frames the DBP as an operational input to

closed-loop allocation, not only as a compliance record. Second, it clearly separates the roles of verified data, Generative AI, engineering rules, optimization tools, and human approval in the decision process. Third, it links reverse battery flows with forward procurement and carbon management through feedback from realized outcomes, creating a continuous improvement cycle.

Future research should assess the architecture using battery-level passport records, observed state-of-health data, actual recovery yields, carbon measurements, and realized allocation outcomes. Comparative testing could examine whether GenAI-assisted decision briefs improve speed, consistency, traceability, or circular value retention relative to manual or rule-based processes. Such evidence would move the research question from what information a passport should contain to how verified lifecycle data can be converted into higher-quality resource allocation decisions.

Disclosure statement

The author declares no conflict of interest.

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