Deliverable D2.9

Battery Passport Platform (Version II)

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Feasible Recovery of critical raw materials through a new circular Ecosystem for a Li-Ion Battery cross-value chain in Europe

WP2 - End-of-life LIBs Collection and Characterisation, Digital Tools and Battery Passport deployment

D2.9 - Battery Passport Platform (Version II)

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Versions

DATE	VERSION	AUTHOR	COMMENT
07/02/2025	1	Aleix Vila (EUT)	First draft of the document
24/02/2025	2	Aleix Vila (EUT)	Incorporation of reviewers' comments
26/02/2025	3	CARTIF	Final document

1. Content

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List of Abbreviations

ACRONYMS	DESCRIPTION
API	Application Programming Interface
BOL	Beginning of Life
BP	Battery Passport
BPP	Battery Passport Platform
CSS	Cascading Style Sheets
EOL	End of Life
EVs	Electric Vehicles
FR	Functional Requirement
GSN	Gas Station Network
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
JSON	JavaScript Object Notation
JS	JavaScript
LIBs	Lithium-Ion Batteries
MongoDB	NoSQL Database for Off-Chain Storage
OBJ	Objective
QR	Quick Response (Code)
RBAC	Role-Based Access Control
SoH	State of Health
TRL	Technology Readiness Level
TS	TypeScript
UI	User Interface
URL	Uniform Resource Locator

Table 1: List of Abbreviations

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Executive Summary

The development of the second version of the Battery Passport Platform (BPP) marks a significant milestone within the FREE4LIB project, the Horizon Europe initiative aimed at fostering a circular economy for Lithium-Ion Batteries (LIBs) through innovative recycling technologies and lifecycle management systems. Building upon the foundation established in the first version (D2.8), this deliverable documents the advancements made in the second version of the platform, focusing on usability improvements, technical refinements, and increased accessibility for project partners.

This second iteration of the BPP integrates key upgrades to address both technical and user feedback gathered during the development and testing of the initial prototype. The primary objective of this version is to offer a more functional and accessible platform, laying the groundwork for scalable deployment across the battery value chain. Among the core enhancements, the platform introduces a restructured user interface featuring a role-based login system, tailored dashboards for different stakeholders, and seamless blockchain wallet management. These refinements ensure that the platform meets the diverse requirements of manufacturers, recyclers, and regulators involved in the LIB lifecycle.

A central advancement in this version is the incorporation of blockchain meta-transactions, a feature not contemplated in the first deliverable but identified as critical during research and platform validation. This innovation significantly improves usability by enabling transaction execution without requiring users to manage blockchain gas fees directly, thereby lowering the technical barrier for stakeholders. Furthermore, the platform has improved its API architecture to enable smoother integration with external systems and potential interoperability with other battery passport solutions, ensuring future scalability and adaptability.

In addition to these enhancements, the platform includes preliminary data analytics capabilities to monitor basic activity metrics. While these analytics remain limited in scope, they demonstrate the potential for extracting actionable insights as the platform evolves.

The deliverable highlights the progress made in refining the platform's architecture, including improvements to the smart contracts that underpin the system's traceability and lifecycle management capabilities. These contracts now incorporate advanced role-based permissions and meta-transaction capabilities, ensuring secure and efficient operations regardless of the blockchain network used.

This second version of the Battery Passport Platform reflects both the project's commitment to sustainability and the technical sophistication required to achieve comprehensive LIB lifecycle management. Despite the reduced

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development time compared to the first deliverable, the platform achieves its intended objectives, positioning the FREE4LIB project to advance towards the third prototype with a robust foundation. Future efforts will focus on expanding the platform's analytical capabilities, refining interoperability with other systems, and scaling the deployment to meet the complex demands of the circular economy.

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1. Introduction

1.1 Background

The FREE4LIB project (Feasible Recovery of critical raw materials through a new circular Ecosystem for a Li-Ion Battery cross-value chain in Europe) is a Horizon Europe-funded initiative aimed at addressing the environmental and technological challenges of managing the lifecycle of Lithium-Ion Batteries (LIBs). These batteries, which are essential for the widespread adoption of electric vehicles (EVs) and the transition away from fossil fuel-dependent transportation, present significant challenges related to their end-of-life (EOL) management and recycling processes.

The project focuses on developing innovative solutions to enhance material recovery efficiency, improve the availability of secondary resources, and establish a circular economy framework for LIBs. One of the project's key objectives is the development of the Battery Passport Platform (BPP), a digital system designed to provide traceability and ensure data integrity throughout the LIB lifecycle. By leveraging blockchain technology, the BPP offers a secure and transparent solution for managing data from the beginning of life (BOL) to the EOL of LIBs.

The Battery Passport is envisioned as a comprehensive digital tool, capable of storing and sharing information on the production chain, sustainability metrics, and recycling status of LIBs. Beyond traditional static product data, the BPP integrates dynamic updates on key metrics such as state of health, usage history, and compliance with environmental regulations. This capability enhances stakeholder collaboration, streamlines regulatory compliance, and fosters sustainability by improving the reuse and recycling of critical raw materials.

The first version of the platform, documented in Deliverable D2.8, established the foundational elements of the BPP, including an initial data model, basic blockchain integration, and a simple user interface. These developments provided a proof of concept and served as the basis for further refinements. The second version, as described in this deliverable, builds on that foundation by incorporating advanced functionalities, such as meta-transactions, role-based access control, and enhanced usability features, positioning the platform closer to its goal of supporting a scalable, industry-wide adoption.

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1.2 Motivation

The motivation behind the development of the Battery Passport Platform (BPP) is driven by the urgent need to address the environmental, economic, and regulatory challenges associated with the lifecycle of Lithium-Ion Batteries (LIBs). LIBs play a critical role in the transition to electric vehicles (EVs) and sustainable mobility solutions, reducing dependency on fossil fuels and contributing to the European Union's Green Deal objectives of achieving climate neutrality by 2050. However, the current linear economic model of "take, make, dispose" presents significant hurdles in ensuring the sustainability of these technologies.

The end-of-life (EOL) stage of LIBs is particularly problematic due to the limited efficiency of traditional recycling technologies, which often result in high energy consumption and significant environmental impact. Current practices, such as pyrometallurgical recycling, are resource-intensive and fail to recover many critical raw materials essential for producing new batteries. This underscores the need for innovative solutions to improve material recovery, reduce waste, and support a circular economy for LIBs.

In addition to environmental concerns, regulatory pressures in Europe are increasingly mandating stricter standards for traceability, reuse, and recycling of batteries. The EU Battery Regulation, for instance, highlights the importance of digital systems like battery passports to ensure compliance with sustainability targets. These regulations aim to promote transparency in the battery value chain, enabling stakeholders to verify the origin of materials, assess environmental impact, and ensure proper recycling and disposal practices.

The FREE4LIB project, through the development of the BPP, seeks to address these challenges by leveraging blockchain technology to provide an immutable, transparent, and secure digital record of each battery's lifecycle. The platform's ability to track data from the beginning of life (BOL) to EOL ensures that all stakeholders—manufacturers, recyclers, regulators, and consumers—can access reliable and verifiable information, facilitating better decision-making and fostering collaboration across the value chain.

The BPP's dynamic capabilities, such as real-time updates on battery health, usage, and recycling status, further enhance its value as a tool for optimizing lifecycle management. By enabling stakeholders to make informed decisions about reuse, recycling, or disposal, the platform contributes to reducing environmental impact, extending battery lifespans, and improving resource efficiency.

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1.3 Objectives of Deliverable D2.9

This deliverable, D2.9 - Battery Passport Platform (Version II), captures the progress made in the development of the Battery Passport Platform (BPP), a system that combines blockchain technology with traditional database infrastructure to ensure data integrity, operational efficiency, and transparency across the lifecycle of Lithium-Ion Batteries (LIBs). While the blockchain serves as the backbone for ensuring traceability, immutability, and decentralization, a traditional database is used for managing operational data, such as login credentials, off-chain information, and other records that do not require the same level of decentralized integrity. This hybrid approach ensures the platform remains both scalable and usable, while fully leveraging the strengths of blockchain technology.

The primary objective of this deliverable is to document the development of the third prototype, which corresponds to the second operational version of the platform. This version integrates substantial enhancements to address both usability challenges and the complexities inherent in blockchain-based systems, while maintaining the decentralization and transparency that are central to the project's goals. Key objectives of D2.9 include:

1. **Hybrid Data Management Architecture**: The platform leverages blockchain technology for critical lifecycle data, ensuring that key information—such as traceability records and state transitions—is secure and immutable. At the same time, a traditional database is utilized to manage non-critical operational data, such as user logins, role assignments, and auxiliary records, optimizing performance without compromising the decentralized trust model.

2. **Enhanced Role-Based Access and User Experience**: This version introduces a role-based login system, ensuring tailored functionalities for stakeholders like manufacturers, recyclers, and regulators. Roles and permissions are managed through smart contracts, ensuring that access control remains auditable and decentralized, while the user experience is enhanced through a refined interface.

3. **Integration of Blockchain Meta-Transactions**: A standout feature in this version is the implementation of meta-transactions, which reduce friction by allowing blockchain operations to be executed without users needing to manage gas fees. This innovation eliminates the reliance on centralized intermediaries for transaction management, reinforcing the platform's decentralized nature and ensuring accessibility for non-technical users.

4. **Refined API for Interoperability**: The API has been enhanced to support seamless integration with external systems and to ensure compatibility with other blockchain-based platforms. This makes the BPP adaptable

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for future interoperability in an ecosystem of decentralized solutions, furthering its long-term scalability.

5. **Preliminary Analytics with Blockchain and Off-Chain Data**: Basic analytics capabilities are included in this version, combining blockchain-stored data with off-chain operational data to provide initial insights into platform usage. While still limited in scope, these analytics demonstrate the potential for data-driven decision-making in future iterations.
6. **Refinements in Smart Contracts and Blockchain Features**: The smart contracts have been optimized to include advanced role-based permissions, state transitions, and meta-transaction capabilities. These refinements ensure that the blockchain component of the platform provides tamper-proof traceability, while maintaining efficiency and usability.

This deliverable emphasizes the critical role of blockchain technology as the foundation for traceability and transparency, while acknowledging the complementary role of traditional database infrastructure in ensuring operational efficiency. The hybrid approach strikes a balance between the technical benefits of decentralization and the practical requirements of usability, ensuring that the platform meets the needs of diverse stakeholders without compromising its core principles.

Through this version, the FREE4LIB project demonstrates its commitment to leveraging blockchain as a transformative technology while addressing the challenges of complexity and scalability. The advancements documented here position the BPP as a scalable, hybrid platform capable of driving sustainable and transparent lifecycle management for Lithium-Ion Batteries, aligning with the European Union's sustainability objectives and the principles of a circular economy.

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2. Research on Blockchain Technology and Meta-Transactions

The Battery Passport Platform (BPP) is built on blockchain technology to ensure traceability, transparency, and decentralization across the lifecycle of Lithium-Ion Batteries (LIBs). However, blockchain's inherent complexity poses challenges for usability, particularly for non-technical stakeholders. To address these barriers, the FREE4LIB project has conducted research into meta-transactions, a solution designed to simplify blockchain interactions while preserving its decentralized principles.

The integration of meta-transactions reflects a strategic effort to ensure that the platform remains both scalable and accessible, avoiding centralized approaches that compromise trust and transparency. This deliverable details the research and decisions behind adopting this technology, ensuring the BPP aligns with the goals of efficiency, usability, and sustainability while maintaining blockchain's integrity as its core differentiator.

2.1 Brief Recap of Blockchain in D2.8

In Deliverable D2.8, the BPP introduced blockchain technology as the foundational element for ensuring data integrity, transparency, and decentralization across the lifecycle of LIBs. Blockchain was chosen for its ability to provide an immutable ledger where all lifecycle events, from the beginning of life (BOL) to the end of life (EOL), are securely recorded. This approach supports the goals of the FREE4LIB project to enable traceability, regulatory compliance, and stakeholder collaboration in a circular economy framework.

Blockchain's inherent characteristics—immutability, decentralized trust, and security—were identified as essential for creating a robust digital passport system for LIBs. These features ensure that all data recorded on the platform is tamper-proof, promoting transparency across the battery value chain and enabling stakeholders such as manufacturers, recyclers, and regulators to access verifiable information. The use of smart contracts[1] was a key component in this approach, enabling role-based access control and automating lifecycle processes like state transitions and compliance checks.

D2.8 also highlighted the decision to use a public blockchain, such as Polygon, for its compatibility with the Ethereum Virtual Machine (EVM)[2], low transaction costs, and energy efficiency compared to traditional proof-of-work systems.

[1] https://ethereum.org/ca/developers/docs/smart-contracts/
[2] https://ethereum.org/ca/developers/docs/evm/

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This choice reinforced the platform's alignment with sustainability goals, ensuring the scalability and cost-effectiveness needed for widespread adoption.

While the initial prototype focused on validating blockchain's technical feasibility, it also revealed challenges, such as usability barriers and the complexity of managing blockchain transactions. These insights set the stage for further research and development, including the exploration of meta-transactions, to address these limitations. The progress made in the second version of the platform builds on these foundations, refining the blockchain integration to ensure it remains central to the BPP's unique value proposition.

2.2 Meta-Transactions

To understand meta-transactions[3], it is essential to first grasp key technical concepts in blockchain systems. In a blockchain, every action or operation—such as transferring assets, updating smart contract data, or interacting with a decentralized application (dApp[4])—is executed as a transaction (see Figure 1). Each transaction is digitally signed by the user, ensuring authentication and non-repudiation. Once signed and broadcasted, these transactions are processed by the blockchain's nodes and added to the distributed ledger.

A **transaction** typically contains the following components:

- **Sender Address**: The wallet address initiating the transaction.
- **Receiver Address**: The wallet or smart contract that will execute or receive the operation.
- **Payload/Data**: Information or instructions for the operation, such as the function call and parameters in a smart contract.
- **Signature**: Cryptographic proof that the sender authorized the transaction.
- **Gas**: A measure of computational effort required to process the transaction, paid in the blockchain's native cryptocurrency.

The **gas fee mechanism**[5] ensures that the network remains operational by incentivizing nodes (miners or validators) to process transactions. Higher computational complexity demands more gas, making it a critical consideration for transaction execution.

[3] https://docs.web3j.io/4.11.0/use_cases/meta_transaction/
[4] https://ethereum.org/en/dapps/#what-are-dapps
[5] https://www.techtarget.com/searchcio/feature/What-are-the-4-different-types-of-blockchain-technology

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In a standard blockchain workflow:

1. A user signs a transaction with their private key, which guarantees authenticity.
2. The transaction is broadcast to the network and queued for processing.
3. The transaction is executed and included in a block, provided the user pays the required gas fee.

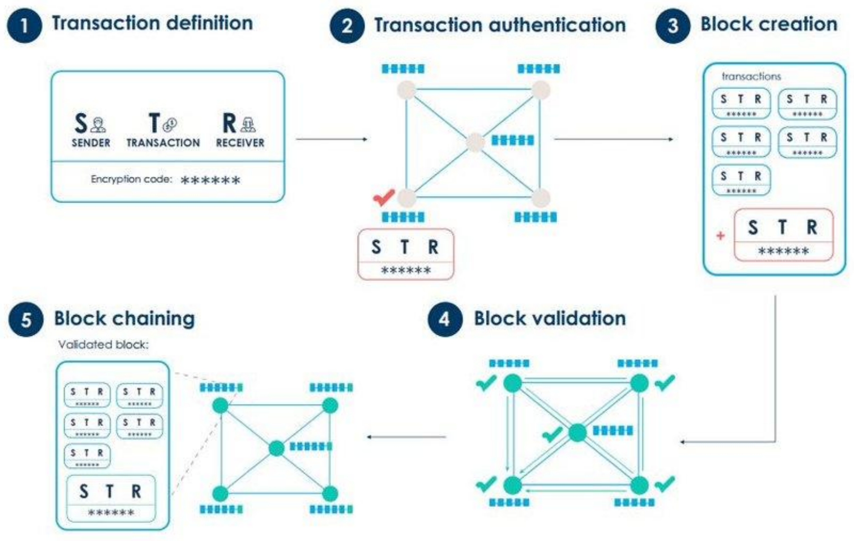

Figure 1: Blockchain transaction flow.[6]

However, this workflow assumes that every user has direct access to cryptocurrency to pay gas fees and the technical expertise to manage private keys and transaction payloads. These assumptions introduce significant barriers for non-technical users or organizations unaccustomed to blockchain environments, especially in general-purpose platforms like the BPP.

[6] Souce: https://www.researchgate.net/publication/324223735_BLOCKCHAIN_WITHIN_AN_ENTERPRISE_CONTEXT_technological_fit_and_adoption_process

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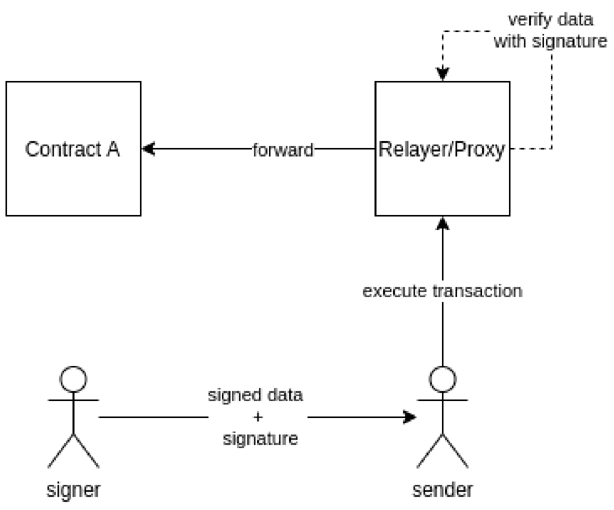

Figure 2: Interaction diagram involving meta transactions

Meta-transactions were introduced as a solution to simplify this interaction by decoupling the user's role in signing and initiating the transaction from the need to directly manage the gas fee payment. In this model, a relayer acts as an intermediary that:

1. Receives the user's signed transaction.
2. Pays the gas fee on behalf of the user.
3. Submits the transaction to the blockchain network for execution.

The relayer ensures that the user experience is simplified while maintaining decentralization, as the original transaction remains signed by the user. Importantly, the meta-transaction model does not compromise security or authenticity; the user retains full control over their private key and transaction authorization.

This technical foundation underpins the use of meta-transactions in the FREE4LIB project, where the BPP must support a diverse range of stakeholders, many of whom may lack familiarity with blockchain. By decoupling gas fee management from the end-user, meta-transactions present a pathway to achieving usability without compromising decentralization, a critical balance for platforms aiming to serve both blockchain-native and general-purpose audiences.

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2.3 Research on Meta-Transactions

The adoption of meta-transactions within the BPP required an extensive evaluation of existing standards, tools, and frameworks to identify the most effective and scalable approach. Meta-transactions, while conceptually simple, introduce technical and architectural challenges that must be addressed to maintain the security, decentralization, and usability of blockchain systems. The FREE4LIB project undertook a detailed investigation into the state-of-the-art solutions for implementing meta-transactions, focusing on tools such as OpenZeppelin's libraries[7], the Gas Station Network (GSN)[8], and other community-driven standards.

2.3.1 Existing Standards and Approaches for Meta-Transactions

Meta-transactions are a growing area of research and implementation in blockchain, with several frameworks and standards developed to address their complexity. At their core, all implementations aim to allow users to initiate transactions without directly handling gas fees, using **relayers** to execute transactions on their behalf. Key approaches include:

1. **EIP-712**:

   The **Ethereum Improvement Proposal (EIP) 712**[9] defines a standard for typed data signing. It enables structured and human-readable signatures that improve the security and usability of meta-transactions. By specifying the exact structure of the data to be signed, EIP-712 ensures that users can see a clear representation of the action they are authorizing, reducing the risk of phishing attacks or malicious payloads.

2. **Relayer Networks**:

   Decentralized relayer networks form the backbone of meta-transaction systems. Relayers are third-party services that:

   - Accept user-signed transaction payloads.
   - Pay the required gas fees.
   - Submit the transaction to the blockchain. Standards such as **EIP-2771[10] (Trusted Forwarders)** define how relayers verify and forward transactions without compromising

[7] https://www.openzeppelin.com/solidity-contracts
[8] https://docs.openzeppelin.com/contracts/2.x/api/gsn
[9] https://eips.ethereum.org/EIPS/eip-712
[10] https://eips.ethereum.org/EIPS/eip-2771

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security. These standards ensure that users' signatures remain authentic and that relayers cannot alter or misuse transaction payloads.

3. **Custom Smart Contract Logic**:

Platforms can implement meta-transaction logic directly into their smart contracts. This approach requires adding verification layers to check the validity of relayed transactions, including signature verification and replay attack prevention. While flexible, this method can introduce **complexity** and **higher gas costs** for smart contract deployment.

2.3.2 Gas Station Network (GSN)

The **Gas Station Network (GSN)** is a decentralized protocol designed specifically to simplify the integration of meta-transactions into blockchain applications. GSN provides a plug-and-play solution for developers, enabling users to interact with dApps without owning cryptocurrency for gas fees. Key components of the GSN include:

1. **Relayers**:
   These are nodes in the GSN network that execute transactions on behalf of users. Relayers are incentivized by a fee, which can be paid by the application or a third party.

2. **Paymasters**:
   The **Paymaster** (see Figure 3) is a smart contract that defines the rules for paying gas fees. For example, the Paymaster in the BPP could be configured to:

   - Cover gas fees for specific roles or actions, such as signing a battery lifecycle event.

   - Reject transactions that do not meet predefined criteria, ensuring that only authorized actions are subsidized.

3. **Forwarders**:
   GSN uses **trusted forwarder contracts** to manage transaction payloads and ensure that the relayed transaction preserves the user's signature and intent.

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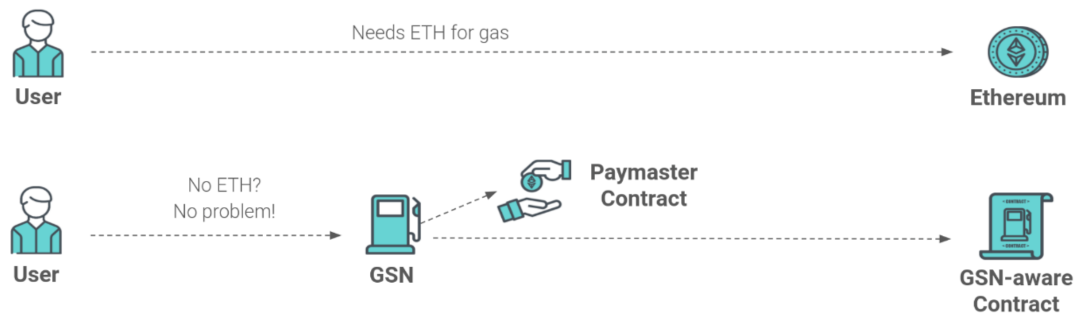

Figure 3: Example use case for GSN.[11]

The GSN protocol is particularly appealing for platforms like the BPP because it abstracts the complexity of gas fee management while maintaining the decentralized principles of blockchain.

2.3.3 Other Relevant Concepts and Frameworks

1. **Replay Protection**:

Meta-transaction systems must implement mechanisms to prevent **replay attacks**[12], where an attacker resubmits a valid signed transaction to execute it multiple times. Common solutions include:

- Nonce tracking: Ensuring that each transaction includes a unique identifier.
- Expiration timestamps: Limiting the time window in which a transaction can be executed.

2. **Account Abstraction**:

A long-term vision for Ethereum, account abstraction aims to unify externally owned accounts (EOAs[13]) and smart contract accounts, allowing users to define custom logic for transaction signing and execution. While still in development, this concept could simplify the implementation of meta-transactions by removing the reliance on EOAs for gas fee payment.

3. **Privacy and Security**:

The use of relayers introduces potential risks, such as transaction censorship or misuse of user data. To mitigate these risks, the platform implements strict verification protocols and ensures that relayers operate within transparent and auditable frameworks.

[11] Source: https://docs.opengsn.org/
[12] https://www.cyfrin.io/blog/replay-attack-in-ethereum
[13] https://ethereum.org/en/roadmap/account-abstraction/

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2.3.4 Decision Taken: Custom Meta-Transaction Smart Contract

After thorough research and evaluation of existing standards and tools for implementing meta-transactions, the decision was made to develop a custom smart contract specifically tailored for the BPP. This decision was influenced by several factors, including the challenges faced during development, the limitations of existing frameworks, and the need for a streamlined and robust solution that aligns with the FREE4LIB project's objectives.

KEY REASONS BEHIND THE DECISION

1. **Complexity in Debugging and Integration**:

During development, it became evident that integrating pre-existing frameworks such as the GSN or highly abstracted solutions added significant complexity to how transactions were executed. Debugging issues in blockchain environments is inherently challenging, as error sources are often opaque and difficult to trace. Many problems stemmed from how signatures were handled or how the relayers interacted with smart contracts, which introduced unnecessary friction in achieving a functional implementation.

2. **State of the Gas Station Network (GSN)**:

The GSN was initially considered a promising option due to its ability to abstract gas fee management. However, after deeper investigation, it was found that the GitHub repository for GSN[14] has not been updated in over three years, indicating that it is likely an abandoned project. Relying on an outdated framework would introduce unnecessary risk and dependency into the platform, making it an unviable solution for the long-term scalability of the BPP.

3. **Learning Opportunities and Customization Needs**:

Developing a custom implementation allowed the development team to gain a deeper understanding of the meta-transaction mechanism, including the challenges and best practices in designing such systems. Using an abstraction layer without fully understanding its internal workings was deemed counterproductive, especially given the technical nature of the FREE4LIB project and the need to ensure security and transparency in the implementation.

4. **Security and Control**:

By creating a custom solution, the platform ensures **tight control** over how transactions are verified and executed. Custom methodologies were

[14] https://github.com/opengsn/gsn

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incorporated to mitigate risks such as **replay attacks** and ensure that signature validation is robust. While this version represents an **initial implementation**, it sets the groundwork for future refinements and iterations as the platform evolves.

CUSTOM META-TRANSACTION CONTRACT OVERVIEW

The developed **MetaTransaction** smart contract integrates key methodologies to ensure security and usability. The architecture includes:

- **Relayer Management**: A system to authorize specific relayers to execute transactions on behalf of users, preventing unauthorized relayers from abusing the system.
- **Signature Validation**: Transactions are validated by recovering the **user's signature** and comparing it against the signed data (user address, transaction payload, and nonce). This ensures the transaction was legitimately authorized by the user.
- **Nonce Management**: Each user has an associated nonce that increments with every transaction, preventing replay attacks by ensuring that each transaction is unique.
- **Event Logging**: Events such as successful transaction execution and message hashes are emitted for debugging and tracking purposes, improving visibility into how the contract operates.

INTEGRATION IN THE BATTERY PASSPORT SMART CONTRACTS

The custom **MetaTransaction** contract is used as the base for all smart contracts in the BPP. For example, in the **CellBatteryPassport** smart contract:

- The *MetaTransaction* constructor is initialized with a list of authorized relayers.
- The *_msgSender()* method is used to dynamically identify the true caller of a transaction, whether it was executed directly by the user or relayed through a relayer. This replaces *msg.sender* throughout the contracts to ensure compatibility with meta-transactions.
- Role validation and access control rely on *_msgSender()* to ensure that **decentralized role-based permissions** function seamlessly with the relayer architecture.

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2.3.5 Flexibility in Interaction and Network Adaptability

The BPP has been designed with a flexible architecture that allows users to interact with the platform in two distinct ways: directly using the functions of the smart contracts or through the meta-transaction system. This dual approach ensures that the platform can cater to a wide range of stakeholders, from blockchain-savvy users who prefer to interact directly with the contracts to those who require the usability and abstraction offered by meta-transactions. This design choice reflects the platform's commitment to balancing accessibility and decentralization, ensuring inclusivity for all stakeholders involved in the battery value chain.

One of the critical advantages of implementing meta-transactions is the increased adaptability to different blockchain networks. Unlike solutions that rely on deploying the platform on semi-public or permissioned networks[15] with low or no transaction fees, the meta-transaction architecture ensures that the usability and scalability of the platform are preserved even in public blockchain environments where transaction fees are required. By decoupling the gas fee management from end users and allowing the platform or authorized relayers to cover these costs, the BPP remains functional and user-friendly regardless of the underlying blockchain network.

This adaptability is particularly significant given the uncertainty surrounding the deployment of semi-permissioned networks, such as a blockchain network managed by the European Union[16], which would be an ideal scenario for this project. Such a network could offer enhanced regulatory oversight, low fees, and dedicated governance, aligning perfectly with the sustainability and compliance goals of the FREE4LIB project. However, recognizing that such networks are not yet widely available, the platform has been designed to remain fully operational on existing public blockchains, such as Polygon[17], Ethereum[18], or other EVM-compatible networks.

By preparing the platform to operate seamlessly in fee-based public networks, the project ensures that the viability and scalability of the Battery Passport Platform are not contingent on specific network conditions. This flexibility future-proofs the platform, making it network-agnostic and capable of adapting to evolving technological and regulatory landscapes. Additionally, this approach aligns with the principles of decentralization and transparency, as it avoids reliance on overly centralized or restricted blockchain solutions.

In summary, the platform's ability to support both direct contract interaction and meta-transactions not only enhances user choice but also ensures that the BPP can thrive in diverse blockchain environments, from ideal EU-managed

15 https://www.techtarget.com/searchcio/feature/What-are-the-4-different-types-of-blockchain-technology
16 https://ec.europa.eu/digital-building-blocks/sites/display/EBSI/Home
17 https://polygon.technology/
18 https://ethereum.org/en/

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semi-permissioned networks to widely used public blockchains. This design provides the scalability and adaptability necessary for achieving the FREE4LIB project's goals of establishing a sustainable, transparent, and traceable circular economy for Lithium-Ion Batteries.

2.3.6 Conclusion on Meta-transactions

The integration of meta-transactions into the BPP represents a pivotal step towards enhancing the platform's usability and adaptability while preserving its core principles of decentralization and transparency. Through the development of a custom meta-transaction smart contract, the platform addresses the inherent complexities of blockchain interactions, providing stakeholders with a seamless way to interact with the system without being burdened by transaction fees or technical barriers.

This solution ensures that the platform remains network-agnostic, capable of functioning efficiently on public blockchains with gas fees while also being adaptable to semi-permissioned networks, should such an ecosystem—such as one managed by the European Union—become available. The flexibility to interact with the BPP either directly via smart contracts or through the meta-transaction system empowers a wide range of users, from technical experts to those less familiar with blockchain technology, ensuring inclusivity across the battery value chain.

By implementing state-of-the-art methodologies, such as nonce management, signature validation, and relayer authorization, the custom solution also lays the groundwork for future iterations that can refine and expand its capabilities. These advancements position the BPP as a scalable, secure, and user-friendly platform, ready to meet the evolving needs of stakeholders while advancing the objectives of the FREE4LIB project.

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3. Development of the Third Prototype (Version II of the Platform)

The third prototype of the Battery Passport Platform (BPP) represents a significant step forward in the evolution of the platform, introducing key technical improvements and new functionalities while consolidating the developments from previous iterations. This version maintains the core blockchain architecture established in the second prototype while integrating meta-transactions, enhancing backend capabilities, and completely restructuring the frontend to provide a more user-friendly experience.

The platform is structured into three main components: the backend, built using NestJS[19]; the frontend, developed in React[20]; and the blockchain layer, which has been tested on Alastria[21], a semi-public blockchain used to simulate a potential future European Union-managed network.

The backend has been expanded with new endpoints for user and wallet management, a MongoDB[22] database to store both user-related data and off-chain traceability information, and the addition of a blockchain oracle[23]. The oracle plays a crucial role by listening to events emitted by the smart contracts and processing the data within the backend, ensuring that the system maintains a synchronized, structured, and efficient representation of on-chain activities. Furthermore, the backend validates and processes signed meta-transactions, allowing the platform to abstract the complexity of blockchain interactions from end-users.

The frontend has been redesigned from scratch, except for the Battery Passport visualizer, which was inherited from Prototype 2. It now includes a role-based dashboard, allowing different stakeholders—manufacturer, assembler, recycler, admin, and standard users—to interact with the system in a customized environment. Users can register and log in, with the system generating and encrypting a wallet[24], which is stored securely on the backend. Importantly, wallet decryption and transaction signing are handled locally on the user’s device before sending transactions, ensuring security and user control over cryptographic keys.

On the blockchain side, the platform continues to use the five smart contracts developed in Prototype 2: CellBatteryPassport, ModuleBatteryPassport, PackBatteryPassport, RoleManager, and the newly introduced MetaTransaction contract. The MetaTransaction contract is the primary focus

[19] https://nestjs.com/
[20] https://react.dev/
[21] https://alastria.io/
[22] https://www.mongodb.com/en/company/what-is-mongodb
[23] https://chain.link/education/blockchain-oracles
[24] https://www.coinbase.com/learn/crypto-basics/what-is-a-crypto-wallet

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of this prototype, as it enables the execution of gas-free transactions through a relayer system, ensuring that users can interact with the blockchain without holding cryptocurrency.

This prototype builds on the lessons learned from previous iterations, introducing a more complete and usable version of the platform while maintaining its core principles of decentralization, transparency, and interoperability. The following sections detail the specific advancements in backend, frontend, and blockchain development, as well as the validation of the meta-transaction mechanism within the Battery Passport Platform.

3.1 Functional Requirements

This prototype introduces several new functionalities across its three main components: backend, frontend, and blockchain. The following functional requirements outline the key features implemented in this version, ensuring alignment with the platform's objectives and providing a basis for validation in later sections.

3.1.1 Backend Functional requirements

The backend, developed in NestJS, has been enhanced with new user management endpoints, a MongoDB database for storing off-chain data, and a blockchain oracle to synchronize on-chain and off-chain information. Additionally, it now processes signed meta-transactions, preparing them for execution via the relayer system.

Table 2: Backend Functional Requirements

ID	Requirement Name	Description
FR-BE-01	**User Registration & Wallet Generation**	The backend must allow users to register, generate a new wallet using **ethers.js**, encrypt it, and store it securely in MongoDB.
FR-BE-02	**Encrypted Wallet Storage & Retrieval**	The backend must store the **encrypted wallets**, ensuring that only the user can decrypt their wallet locally. The backend never has access to the private key in plaintext.
FR-BE-03	**User Authentication & Role Assignment**	The backend must provide authentication using **JWT tokens**, allowing admins to assign roles to users. Role assignments must be persisted in the database.
FR-BE-04	**Meta-Transaction Processing**	The backend must accept **signed meta-transactions** from the frontend, verify their integrity, and construct the final transaction

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		using the **relayer's wallet** before sending it to the blockchain.
FR-BE-05	**Blockchain Oracle for Event Listening**	The backend must listen to **on-chain events** from the **CellBatteryPassport, ModuleBatteryPassport,** and **PackBatteryPassport** smart contracts, extract relevant transaction data, and store it in **MongoDB**.
FR-BE-06	**On-Chain Data Synchronization**	The blockchain oracle must **decode transaction data** and, depending on the event type, store **structured traceability data** in the database, creating new objects when necessary.
FR-BE-07	**API Endpoints for Querying Blockchain Data**	The backend must expose API endpoints that allow users to retrieve **traceability data** from the database, reducing the need for direct blockchain queries.

3.1.2 Frontend Functional Requirements

The frontend, developed in React, has been redesigned to provide an improved role-based experience, including login, registration, and wallet management. Users must decrypt their wallets locally before signing transactions, ensuring security and user control.

Table 3: Frontend Functional Requirements

ID	**Requirement Name**	**Description**
FR-FE-01	**User Registration & Login**	The frontend must allow users to **register** and **log in**, retrieving their **encrypted wallet** from the backend and storing authentication tokens securely.
FR-FE-02	**Local Wallet Decryption**	Before signing transactions, users must **decrypt** their wallet locally using their password. The decrypted wallet must never be stored in memory persistently.
FR-FE-03	**Meta-Transaction Signing**	The frontend must allow users to sign **meta-transactions** using their **decrypted wallet** and send the signed payload to the backend for processing.

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FR-FE-04	**Role-Based Dashboards**	Each user role (manufacturer, assembler, recycler, admin) must have a **custom dashboard** with specific functionalities relevant to their role.
FR-FE-05	**Battery Passport Visualizer**	The **battery passport visualization module**, inherited from the second prototype, must be integrated into the user interface, allowing users to query traceability data.
FR-FE-06	**Transaction History View**	Users must be able to **view their transaction history**, with details on whether the transaction was executed on-chain or pending.
FR-FE-07	**Admin Role Management Interface**	The admin panel must allow **assigning roles** to new users through the frontend, ensuring correct role distribution.

3.1.3 Blockchain Functional Requirements

The blockchain layer, tested on Alastria, now incorporates meta-transactions, allowing transactions to be relayed on behalf of users without requiring them to pay gas fees. The key modifications focus on the new MetaTransaction contract, which interacts with the existing smart contracts.

Table 4: Blockchain Functional Requirements

ID	**Requirement Name**	**Description**
FR-BC-01	**Meta-Transaction Execution**	The **MetaTransaction contract** must accept **signed meta-transactions**, verify their signature, and execute them on behalf of users using an **authorized relayer**.
FR-BC-02	**Role-Based Access via Meta-Transactions**	The smart contracts must replace msg.sender with _msgSender() to ensure that role-based permissions work correctly when transactions are relayed.
FR-BC-03	**Relayer Authorization Management**	The **MetaTransaction contract** must allow the admin to **add or remove relayers**, ensuring only trusted entities can execute transactions.
FR-BC-04	**Nonce Tracking for Replay Protection**	The **MetaTransaction contract** must enforce **nonces per user**, ensuring each transaction is unique and preventing replay attacks.

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FR-BC-05	**On-Chain Event Emission for Oracle Integration**	The **CellBatteryPassport, ModuleBatteryPassport, and PackBatteryPassport** contracts must emit structured events to allow the backend oracle to **decode transaction data** and synchronize it with MongoDB.
FR-BC-06	**Compatibility with Public & Semi-Permissioned Networks**	The blockchain contracts must function correctly on both **public blockchains** and **semi-permissioned networks**, ensuring flexibility in deployment.

These requirements will serve as the basis for the validation phase, ensuring that each component functions as expected and aligns with the platform's decentralized, scalable, and user-friendly design.

3.2 Prototype Architecture

The third prototype of the Battery Passport Platform introduces a structured architecture that integrates client interactions, backend API, blockchain transactions, and off-chain data management. The architecture is built around a meta-transaction framework, enabling users to interact with the blockchain without directly handling gas fees. This section describes the key components and transaction flow, using the numbered sequence from the provided diagram.

3.2.1 Architecture Overview

The architecture consists of the following core components:

- **Client (User Wallet & Web Platform)**: Users sign messages and interact with the system through the web interface.
- **API (Backend Service)**: Handles authentication, transaction processing, and communication between users, the blockchain, and off-chain storage.
- **Blockchain (Alastria Network)**: Stores battery passport records and executes smart contracts.
- **Relayer Wallet**: Signs transactions on behalf of users to facilitate **gasless transactions**.
- **MongoDB (Off-Chain Storage)**: Stores metadata, transaction history, and additional data not required on-chain.

- **Blockchain Oracle**: Listens to blockchain events and updates off-chain databases accordingly.

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3.2.2 Transaction Flow

The process flow (see Figure 4) for **executing and storing battery passport transactions** is detailed below:

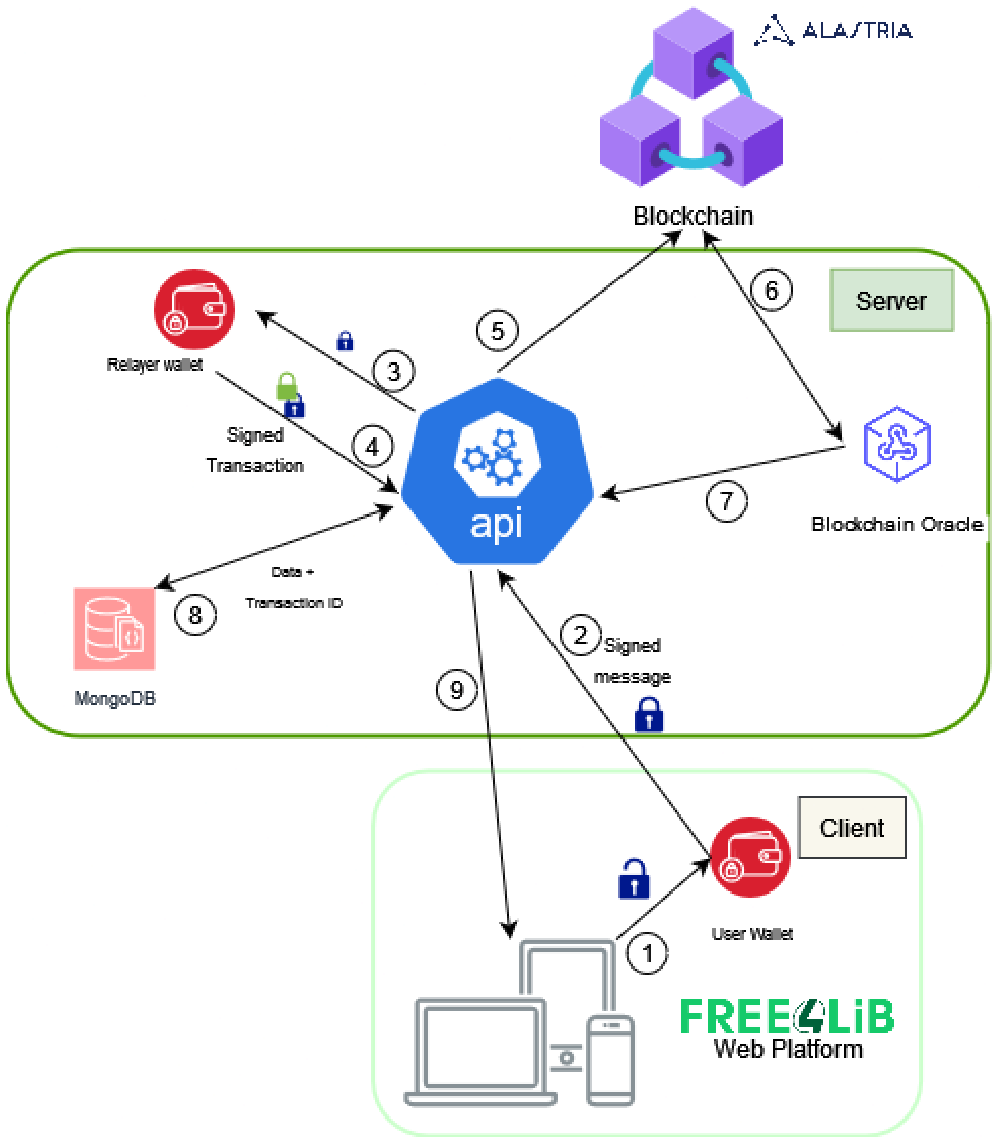

Figure 4: BPP Transaction Flow Diagram

1. **User Signs a Message (Client -> User Wallet)**
   - The user authenticates and interacts with the **FREE4LIB web platform** using their wallet.
   - Instead of signing a blockchain transaction, the user signs a **message** containing the transaction parameters.

2. **Signed Message Sent to API (Client → API)**
   - The **signed message** is securely transmitted to the backend API.
   - The API verifies the user's **signature** to ensure authenticity.

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3. **API Forwards the Request to the Signing Module (API → Signing Module)**
   - The API passes the **signed message** to the **signing module**, which securely holds the **relayer wallet's private key**.
   - This module is responsible for transforming the user-signed message into a valid blockchain transaction.

4. **Signing Module Creates a Signed Transaction (Signing Module → API)**
   - The signing module **transforms the received message into a fully signed blockchain transaction**.
   - This transaction is now **ready to be broadcasted** to the blockchain.

5. **API Submits the Signed Transaction to the Blockchain (API → Blockchain)**
   - The API takes the **signed transaction** and submits it to the **Alastria blockchain**.
   - The blockchain processes the transaction, executing the associated **smart contract operations** and storing the event on-chain.

6. **Blockchain Oracle Detects the Event (Blockchain → Oracle)**
   - The **blockchain oracle** listens for **events** triggered by the transaction.

7. **Blockchain Oracle forwards to the API (Oracle → API)**
   - The oracle retrieves the event data and forwards it to the **API**.
   - This ensures efficient data retrieval without overloading the blockchain.

8. **Transaction Data Stored in MongoDB (API → MongoDB)**
   - The API updates **MongoDB** with relevant **metadata, timestamps, and transaction IDs**.
   - The **transaction hash and metadata** are persistently stored for further queries.

9. **Client Retrieves Updated Data (API → Client)**
   - The updated transaction status is returned to the **user interface**.
   - The user can now visualize their battery passport details and transaction history.

3.2.3 Key Architectural Enhancements

Compared to the **previous prototype**, this architecture introduces several improvements:

- **Gasless Transactions via Meta-Transactions**

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- Users do not need to hold cryptocurrency to interact with the blockchain.
- The **relayer wallet** covers transaction fees, enhancing usability.

- **Blockchain Oracle for Off-Chain Synchronization**
  - Ensures real-time updates between blockchain events and off-chain storage.
  - Improves data integrity and retrieval efficiency.
- **Decoupled Frontend & Backend Transactions**
  - The frontend only signs messages, while the backend manages transaction execution.
  - Enhances security by preventing direct user exposure to blockchain complexities.

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3.3 Key Platform Enhancements

The third prototype of the BPP introduces critical improvements in backend, frontend, and blockchain integration, focusing on usability, security, and interoperability while maintaining blockchain as the core of the system. Key advancements include the integration of meta-transactions for gasless transaction execution, a blockchain oracle for synchronizing on-chain events with off-chain storage, and a fully redesigned frontend with secure wallet handling and role-based dashboards.

This version has been tested on Alastria, simulating a potential EU-managed blockchain, while ensuring compatibility with public networks for greater flexibility. The following sections detail these enhancements, demonstrating how they improve scalability, decentralization, and user experience.

3.3.1 Role-Based Dashboard and Navigation

This prototype introduces a structured and role-based dashboard, where users access dedicated screens and functionalities depending on their assigned role. This new interface ensures that users interact only with the data and actions relevant to their responsibilities, improving usability and efficiency while reinforcing security and compliance.

Upon logging into the platform, authenticated users are directed to a dashboard that dynamically adapts to their role. The navigation menu is structured to provide quick access to the essential actions each role must perform. The public user, who does not require authentication, is directed to the Battery Passport Visualizer via a QR code-based URL, allowing for transparent access to battery traceability data without requiring a blockchain wallet or login.

The platform consists of five main roles, each with its specific dashboard and interaction flow:

- **Admin**: Manages users, assigning or changing roles via a role management table.
- **Manufacturer**: Creates **battery cells**, assigns an initial **State of Health (SoH)**, and tracks created cells.
- **Assembler**: Builds **modules and packs**, assembling them from previously created cells, ultimately generating a **complete Battery Passport**.

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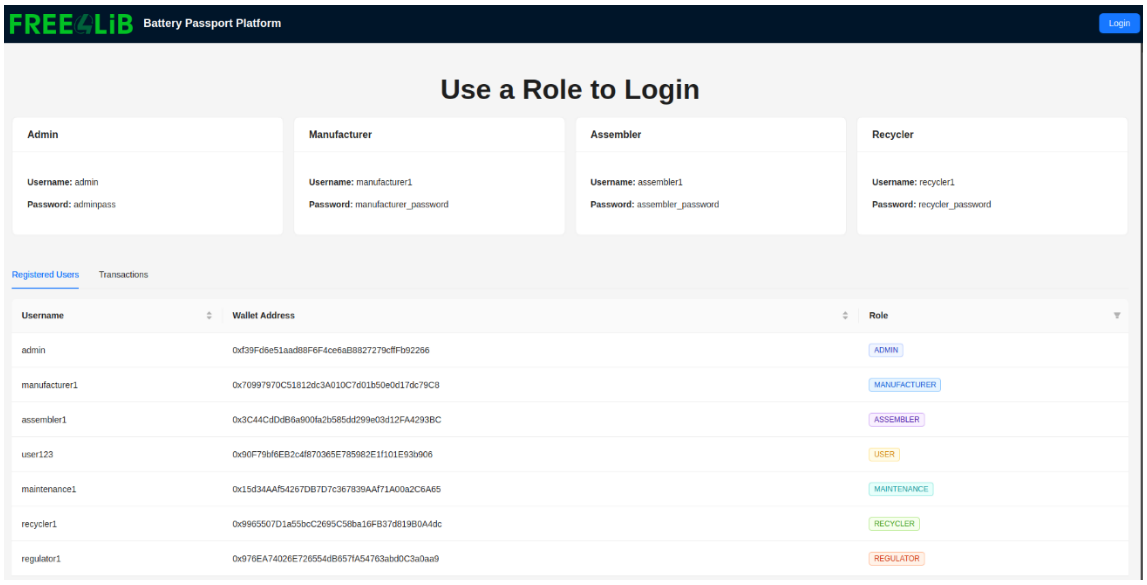
- **Recycler**: Updates the **State of Health** of cells, manages battery **recycling**, and determines if a cell is discarded or repurposed for **second-life use**.
- **Public User (Unauthenticated)**: Accesses **Battery Passport data** by scanning a **QR code**, which opens the passport visualization page.

Each role has a custom dashboard layout, where navigation elements, forms, and data views are tailored to the specific tasks and workflows required by that user. The next sections describe the homepage of the platform (visible to all logged-in users) and detail the specific dashboards for each role, explaining the actions they can perform within the system.

3.3.2 Home Dashboard and Navigation Structure

The home dashboard serves as the central entry point for users interacting with the Battery Passport Platform (BPP). It provides an overview of available roles, a login interface, and a list of registered users and their assigned roles. The structure is designed to ensure that users can quickly access the functionalities relevant to them, while administrators can manage role assignments efficiently.

3.3.2.1 Dashboard Layout and Features



Use a Role to Login

Admin
Username: admin
Password: adminpass

Manufacturer
Username: manufacturer1
Password: manufacturer_password

Assembler
Username: assembler1
Password: assembler_password

Recycler
Username: recycler1
Password: recycler_password

Registered Users | Transactions

Username	Wallet Address	Role
admin	0xf39Fd6e51aad88F6F4ce6aB8827279cffFb92266	ADMIN
manufacturer1	0x70997970C51812dc3A010C7d01b50e0d17dc79C8	MANUFACTURER
assembler1	0x3C44CdDdB6a900fa2b585dd299e03d12FA4293BC	ASSEMBLER
user123	0x90F79bf6EB2c4f870365E785982E1f101E93b906	USER
maintenance1	0x15d34AAf54267DB7D7c367839AAf71A00a2C6A65	MAINTENANCE
recycler1	0x9965507D1a55bcC2695C58ba16FB37d819B0A4dc	RECYCLER
regulator1	0x976EA74026E726554dB657fA54763abd0C3a0aa9	REGULATOR

Figure 5: Home Dashboard Overview

The home screen (see Figure 5) is divided into the following key sections:

1. **Role Selection for Login**
   - At the top of the dashboard, predefined **role cards** allow users to log in using one of the available **test accounts**.

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  - Currently, the prototype supports **Admin, Manufacturer, Assembler, and Recycler**, while additional roles (e.g., Maintenance, Regulator) are visible but not yet enabled.
  - Each role card displays a **predefined username and password** to facilitate testing and access control.

2. **Registered Users Table**
  - Below the login options, a **table displays registered users**, their **wallet addresses**, and their **assigned roles**.
  - Users without a role are visible in this table but cannot access platform features until an **Admin** assigns them a role.
  - Roles are color-coded for quick identification.

3. **Transactions Tab**
  - A **tab-based navigation** system at the bottom of the dashboard includes a **Transactions** section, which provide insights into blockchain activity.

3.3.2.2 User Authentication - Login Modal

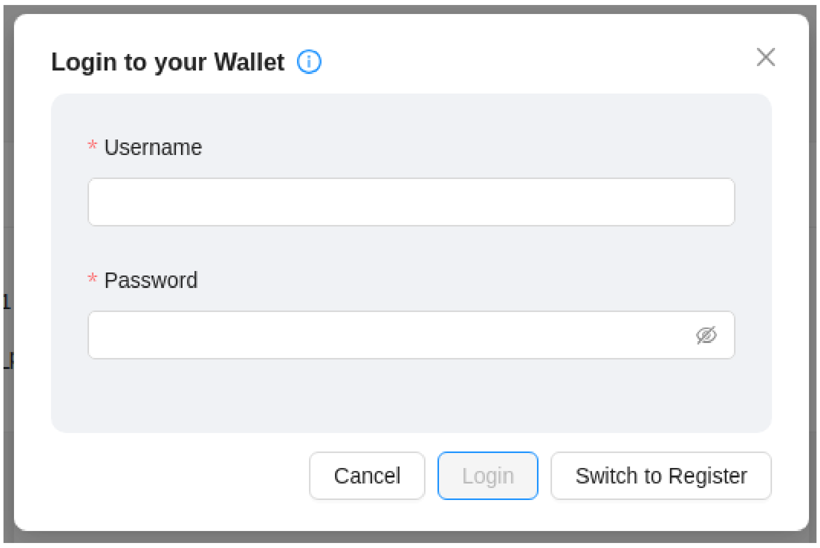


Figure 6: Login Modal UI

When a user selects the **Login** button in the top right corner, a **modal window** (see Figure 6) opens for authentication. The modal includes:

- **Username and Password Fields**: Required credentials for authentication.

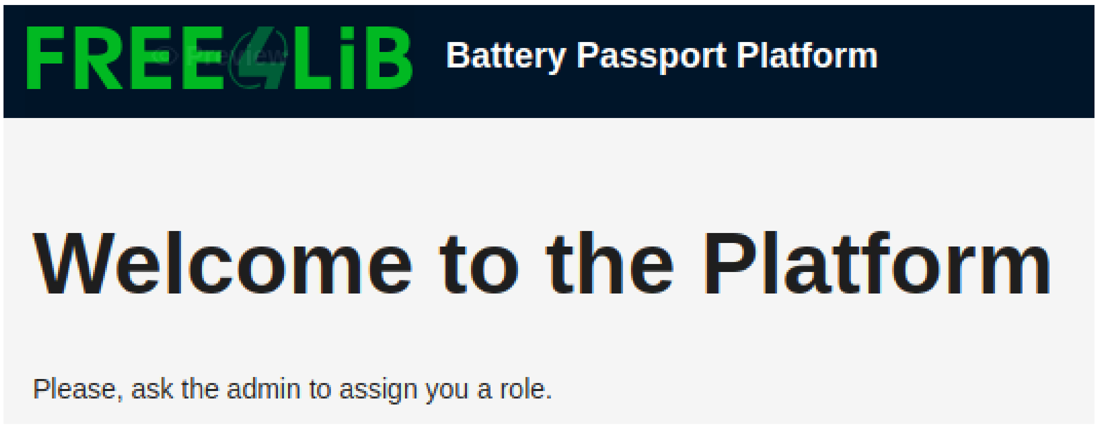
- **Switch to Register Option**: Allows new users to create an account if they do not already have one.
- **Cancel/Login Buttons**: The login button becomes active once both fields are filled.

Once authenticated, users are redirected to their **role-specific dashboard**, where they can access the features assigned to their role.

3.3.3 Admin Dashboard: User Management and Role Assignment

The **Admin Dashboard** provides the tools necessary to manage platform users by assigning or modifying their roles. The admin role simulates the function of a platform operator, sector regulator, or public administration entity, ensuring that users are correctly classified before they can interact with the system.

3.3.3.1 No-Role User Screen


Battery Passport Platform

Welcome to the Platform

Please, ask the admin to assign you a role.

Figure 7: No-Role User Screen

When a new user registers, they are directed to a holding page (see Figure 7) that informs them that they must wait for an admin to assign them a role before they can proceed. This mechanism enforces access control and ensures that only authorized users gain access to role-specific functionalities.

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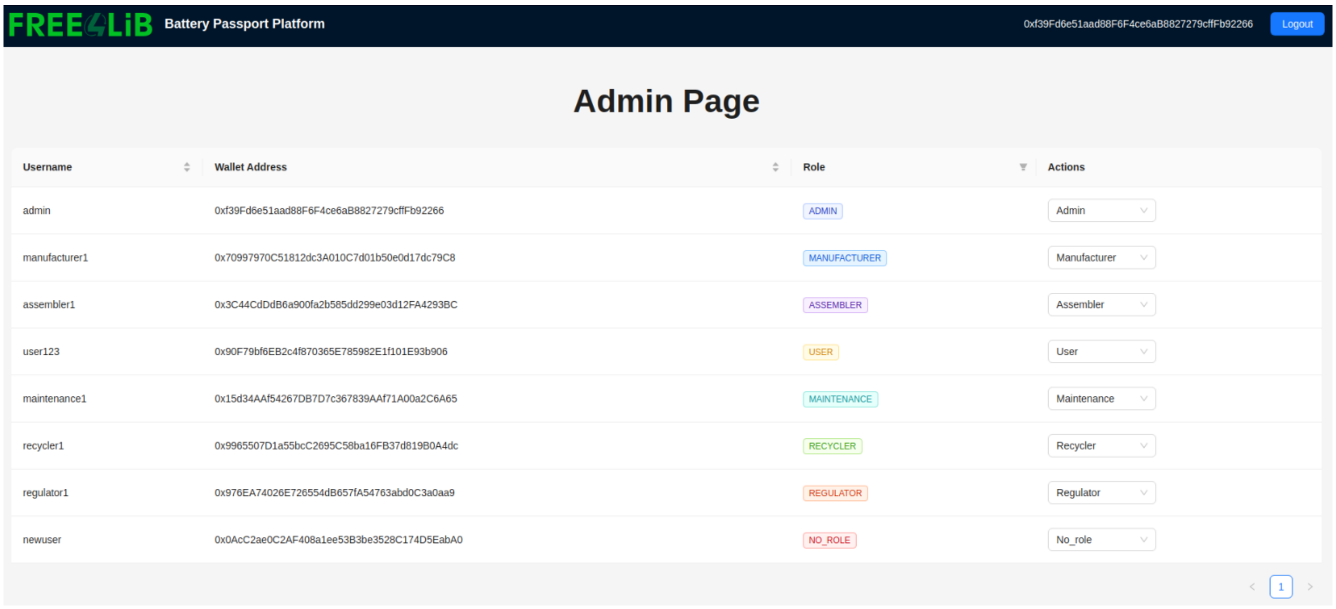
3.3.3.2 Admin User Management Interface


FREE4LiB Battery Passport Platform
0xf39Fd6e51aad88F6F4ce6aB8827279cffFb92266
Logout

Admin Page

Username	Wallet Address	Role	Actions
admin	0xf39Fd6e51aad88F6F4ce6aB8827279cffFb92266	ADMIN	Admin
manufacturer1	0x70997970C51812dc3A010C7d01b50e0d17dc79C8	MANUFACTURER	Manufacturer
assembler1	0x3C44CdDdB6a900fa2b585dd299e03d12FA4293BC	ASSEMBLER	Assembler
user123	0x90F79bf6EB2c4f870365E785982E1f101E93b906	USER	User
maintenance1	0x15d34AAf54267DB7D7c367839AAf71A00a2C6A65	MAINTENANCE	Maintenance
recycler1	0x9965507D1a55bcC2695C58ba16FB37d819B0A4dc	RECYCLER	Recycler
regulator1	0x976EA74026E726554dB657fA54763abd0C3a0aa9	REGULATOR	Regulator
newuser	0x0AcC2ae0C2AF408a1ee53B3be3528C174D5EabA0	NO_ROLE	No_role

Figure 8: Admin Page - Role Management Panel

Once logged in, the Admin Dashboard (see Figure 8) presents a list of all registered users, displaying:

- **Username**
- **Associated Wallet Address**
- **Current Role** (if assigned)

Each row includes a dropdown menu that allows the admin to assign or modify a user's role, with the following options:

- **Manufacturer**
- **Assembler**
- **Recycler**
- **User** (for general access)
- **Maintenance & Regulator** (currently disabled for future use)

Once a role is selected, the system updates the user's permissions, granting them access to their respective dashboard and functionalities.

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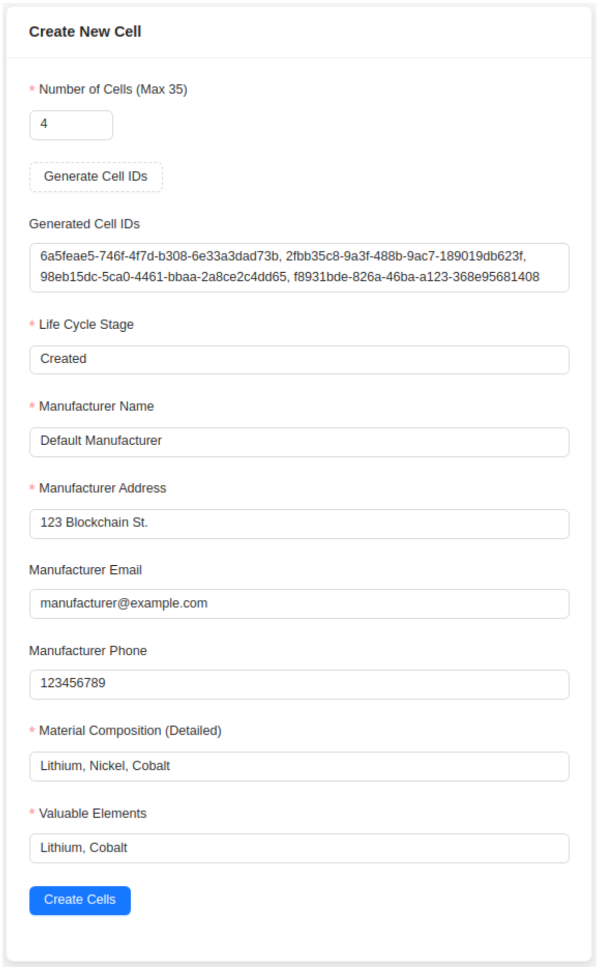
3.3.4 Manufacturer Dashboard: Creating and Managing Battery Cells

The Manufacturer Dashboard provides a dedicated interface for creating new battery cells, assigning their initial properties, and ensuring that each newly produced cell is registered on-chain from the moment it enters the supply chain. This approach builds upon the foundational manufacturing workflows presented in D2.8 Battery Passport (Version I), now enriched with the possibility of batch cell creation and more detailed metadata fields.

When accessing this dashboard, manufacturers can specify the number of cells they wish to create, generate unique cell IDs, and fill in essential attributes such as manufacturer name, address, email, and the material composition of each cell. The interface (see Figure 9. Create New Cell Form) allows for streamlined input, automatically populating multiple cell identifiers when needed. Once the user submits this form, a meta-transaction is signed locally and sent to the blockchain through the relayer, ensuring that each cell creation event is recorded immutably.


Create New Cell

* Number of Cells (Max 35)
4

Generate Cell IDs

Generated Cell IDs
6a5feae5-746f-4f7d-b308-6e33a3dad73b, 2fbb35c8-9a3f-488b-9ac7-189019db623f, 98eb15dc-5ca0-4461-bbaa-2a8ce2c4dd65, f8931bde-826a-46ba-a123-368e95681408

* Life Cycle Stage
Created

* Manufacturer Name
Default Manufacturer

* Manufacturer Address
123 Blockchain St.

Manufacturer Email
manufacturer@example.com

Manufacturer Phone
123456789

* Material Composition (Detailed)
Lithium, Nickel, Cobalt

* Valuable Elements
Lithium, Cobalt

Create Cells

Figure 9: Screenshot illustrating the form fields for creating battery cells, including the number of cells, manufacturer details, and material composition

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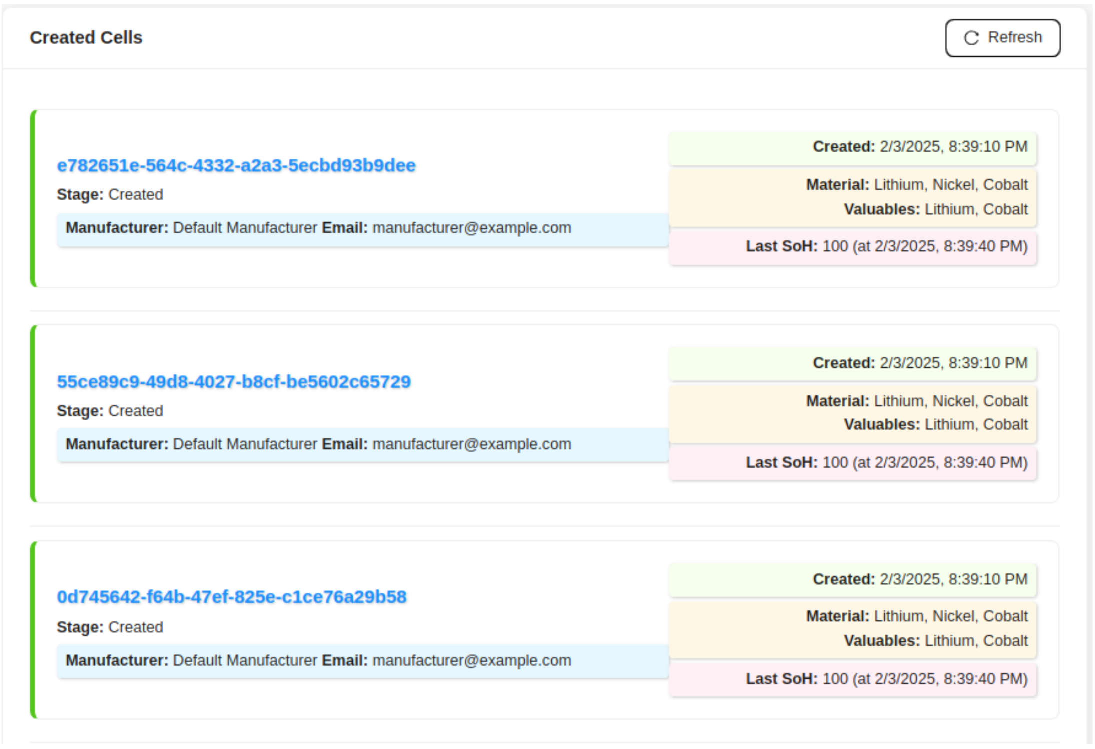
After the cells are created, the dashboard displays them in a concise list view (see Figure 10. Created Cells Overview), showing each cell's unique ID, date of creation, last recorded State of Health (SoH), and the corresponding metadata. This list is automatically updated after each transaction, giving manufacturers immediate feedback on the registration status and traceability data. The system also enables manual refreshes to fetch the latest on-chain state, ensuring consistent synchronization between the NestJS backend and the MongoDB database.



e782651e-564c-4332-a2a3-5ecbd93b9dee
Stage: Created
Manufacturer: Default Manufacturer **Email:** manufacturer@example.com
Created: 2/3/2025, 8:39:10 PM
Material: Lithium, Nickel, Cobalt
Valuables: Lithium, Cobalt
Last SoH: 100 (at 2/3/2025, 8:39:40 PM)

55ce89c9-49d8-4027-b8cf-be5602c65729
Stage: Created
Manufacturer: Default Manufacturer **Email:** manufacturer@example.com
Created: 2/3/2025, 8:39:10 PM
Material: Lithium, Nickel, Cobalt
Valuables: Lithium, Cobalt
Last SoH: 100 (at 2/3/2025, 8:39:40 PM)

0d745642-f64b-47ef-825e-c1ce76a29b58
Stage: Created
Manufacturer: Default Manufacturer **Email:** manufacturer@example.com
Created: 2/3/2025, 8:39:10 PM
Material: Lithium, Nickel, Cobalt
Valuables: Lithium, Cobalt
Last SoH: 100 (at 2/3/2025, 8:39:40 PM)

Figure 10: Screenshot showing the recently created battery cells, including their IDs, creation timestamps, SoH, and any relevant metadata

Whenever a blockchain transaction is initiated—such as creating a new cell batch or registering an updated SoH—the user is prompted with an Unlock Your Wallet modal (Figure 10 Wallet Unlock Modal). This modal requires the manufacturer to enter their wallet password, thereby decrypting the locally stored private key. Only once the user's wallet is unlocked can the meta-transaction be signed and transmitted to the blockchain via the relayer. By enforcing local decryption, the platform preserves the user-centric security model initially described in D2.8, ensuring that no private key ever leaves the user's device in plaintext.

When updating SoH records, the Manufacturer Dashboard also provides an additional form (see Figure 11. SoH Update Mechanism). Here, the user selects one or more cell IDs from a dropdown and inputs the State of Health value to be applied. Once submitted, the signed transaction is sent to the blockchain,

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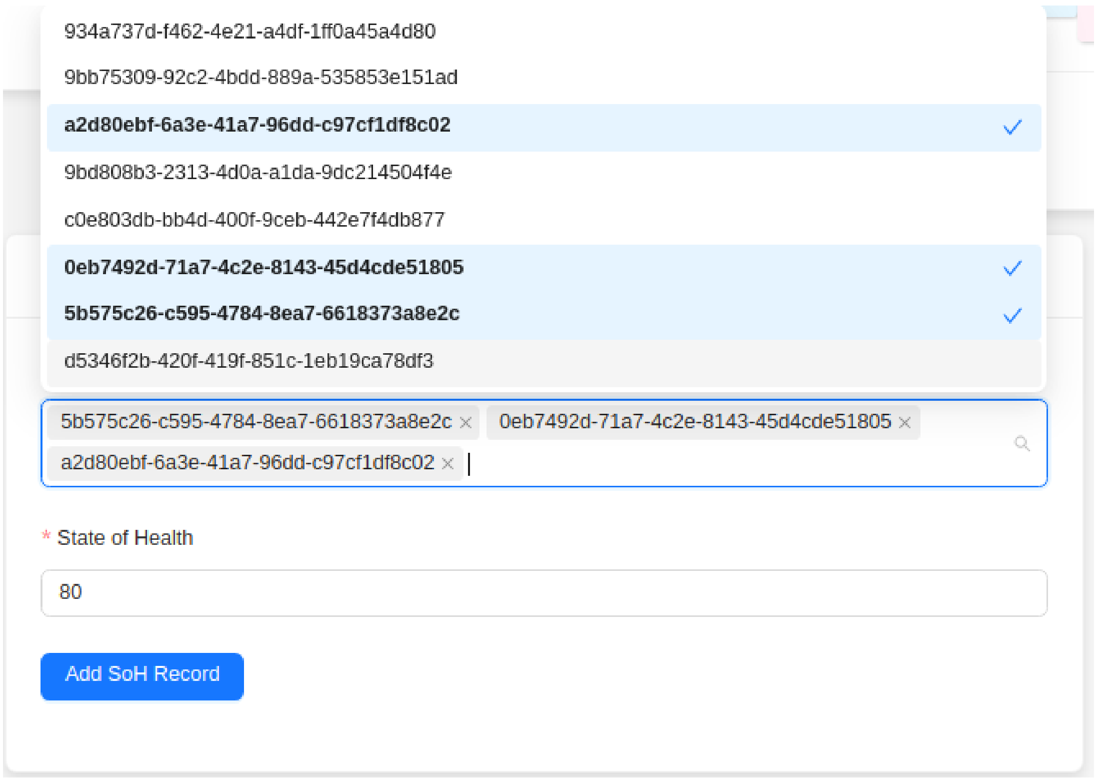
and an event is emitted so that the backend oracle can capture and store this updated information in the off-chain database.



934a737d-f462-4e21-a4df-1ff0a45a4d80
9bb75309-92c2-4bdd-889a-535853e151ad
a2d80ebf-6a3e-41a7-96dd-c97cf1df8c02 ✓
9bd808b3-2313-4d0a-a1da-9dc214504f4e
c0e803db-bb4d-400f-9ceb-442e7f4db877
0eb7492d-71a7-4c2e-8143-45d4cde51805 ✓
5b575c26-c595-4784-8ea7-6618373a8e2c ✓
d5346f2b-420f-419f-851c-1eb19ca78df3

5b575c26-c595-4784-8ea7-6618373a8e2c × 0eb7492d-71a7-4c2e-8143-45d4cde51805 × a2d80ebf-6a3e-41a7-96dd-c97cf1df8c02 ×

* State of Health: 80

Figure 11: Screenshot showing how a user can select multiple cell IDs in a dropdown and update their SoH before creating the respective blockchain transaction.

By separating **cell creation** and **SoH updates** into distinct operations, the manufacturer retains granular control over the lifecycle of each battery unit. This design adheres to the principle of **modularity** highlighted in D2.8, ensuring that each transaction—be it creation or health update—remains clear, auditable, and aligned with the **Battery Passport Platform**'s overall objective of transparent and verifiable traceability.

3.3.5 Assembler Dashboard: Building Modules and Packs

The Assembler Dashboard offers a streamlined interface for combining individual cells into functional modules and ultimately assembling complete battery packs. This role builds upon the logic introduced in D2.8 – Battery Passport (Version I), focusing on traceability, ease of assembly, and detailed metadata tracking at each stage of the battery's life cycle.

Upon logging in with the assembler role, users are greeted by a simplified tab-based navigation (see Figure 12. Assembler Page Navigation). The Modules tab centers on creating and managing battery modules, whereas the Pack Assembly tab covers the formation of fully assembled packs from existing modules.

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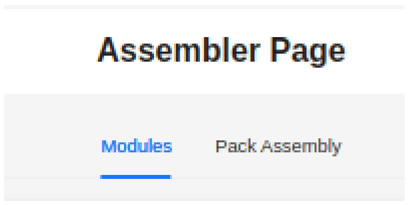
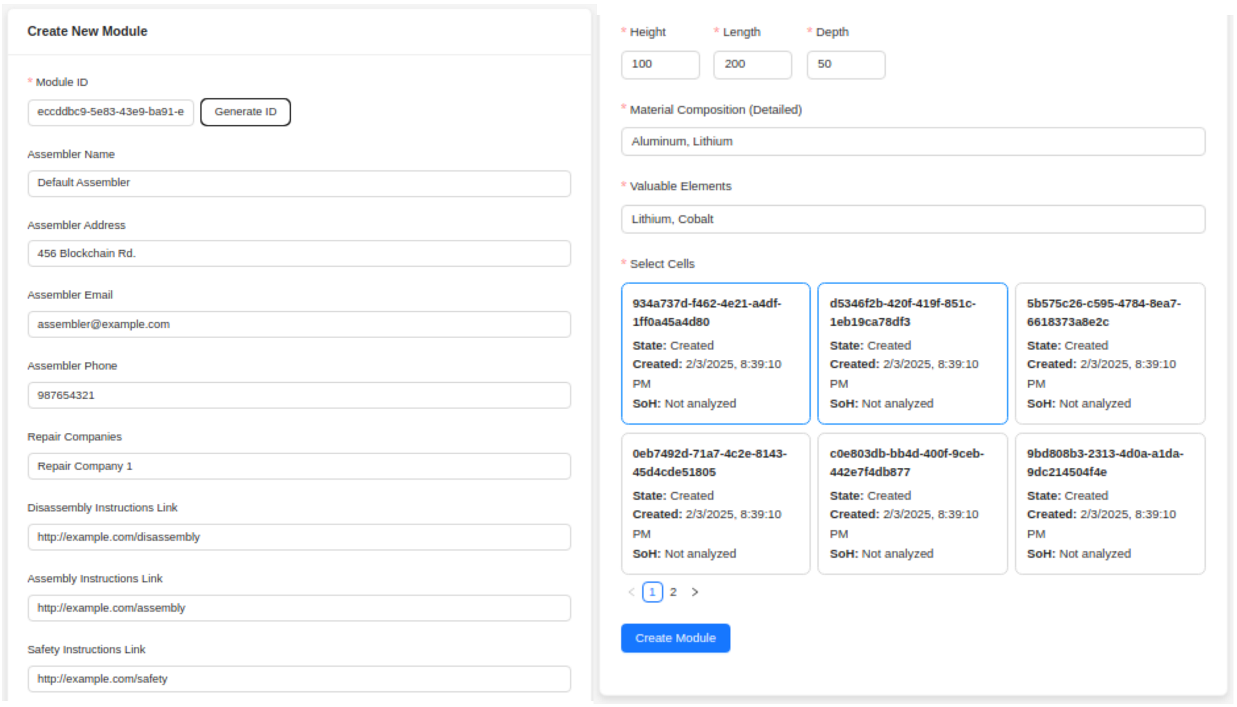


Figure 12: Screenshot showing the Assembler Page with the two main tabs: "Modules" and "Pack Assembly."

When creating a new module, the assembler must provide a unique Module ID, basic assembler information, and optional links for repair, disassembly, and assembly instructions (see Figure 2. Create New Module Form). The interface then prompts the assembler to select multiple cells—previously registered by a manufacturer—and combine them into a single on-chain module. Each meta-transaction is locally signed using the assembler's unlocked wallet, thereby recording the module creation event immutably on the blockchain. The new module's details—dimensions, materials, and valuable elements—are also captured, improving the traceability required for circular economy goals.


Create New Module

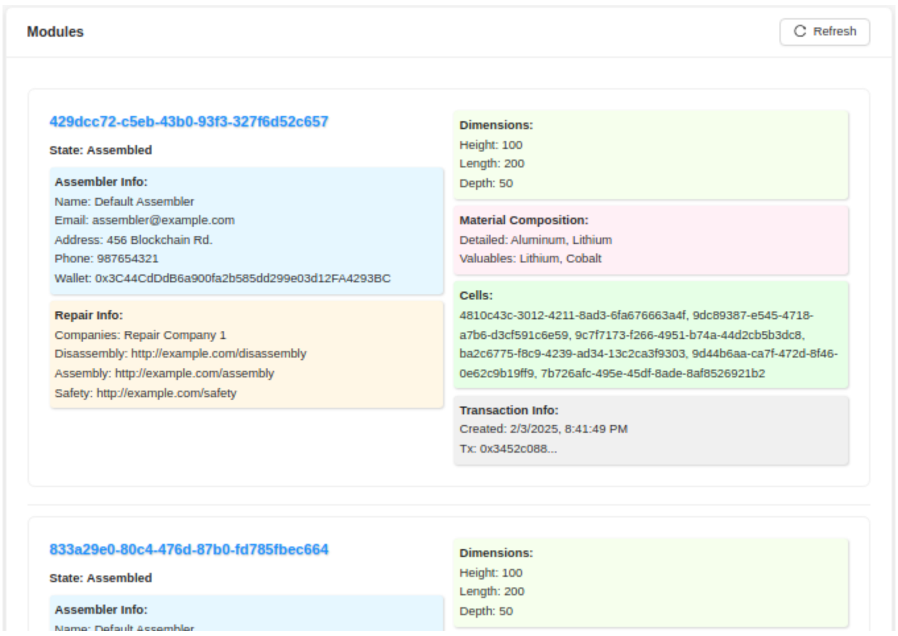
* Module ID	eccddbc9-5e83-43e9-ba91-e
Assembler Name	Default Assembler
Assembler Address	456 Blockchain Rd.
Assembler Email	assembler@example.com
Assembler Phone	987654321
Repair Companies	Repair Company 1
Disassembly Instructions Link	http://example.com/disassembly
Assembly Instructions Link	http://example.com/assembly
Safety Instructions Link	http://example.com/safety
* Height	100
* Length	200
* Depth	50
* Material Composition (Detailed)	Aluminum, Lithium
* Valuable Elements	Lithium, Cobalt

* Select Cells

934a737d-f462-4e21-a4df-1ff0a45a4d80 **State:** Created **Created:** 2/3/2025, 8:39:10 PM **SoH:** Not analyzed	**d5346f2b-420f-419f-851c-1eb19ca78df3** **State:** Created **Created:** 2/3/2025, 8:39:10 PM **SoH:** Not analyzed	**5b575c26-c595-4784-8ea7-6618373a8e2c** **State:** Created **Created:** 2/3/2025, 8:39:10 PM **SoH:** Not analyzed
0eb7492d-71a7-4c2e-8143-45d4cde51805 **State:** Created **Created:** 2/3/2025, 8:39:10 PM **SoH:** Not analyzed	**c0e803db-bb4d-400f-9ceb-442e7f4db877** **State:** Created **Created:** 2/3/2025, 8:39:10 PM **SoH:** Not analyzed	**9bd808b3-2313-4d0a-a1da-9dc214504f4e** **State:** Created **Created:** 2/3/2025, 8:39:10 PM **SoH:** Not analyzed

Figure 13: Screenshot illustrating the form used to create a new module, including module IDs, assembler details, instructions links, and selectable cells.

After each successful transaction, the newly created module is displayed in a module overview table or list (see Figure 13. Modules Overview). Each entry contains the module's on-chain state, assembler contact details, relevant URLs for repair or safety instructions, and information about the cells that compose it. This structure enables quick lookups and helps ensure each part of the battery system is uniquely identifiable and tamper-resistant.



Modules

Refresh

429dcc72-c5eb-43b0-93f3-327f6d52c657

State: Assembled

Assembler Info:
Name: Default Assembler
Email: assembler@example.com
Address: 456 Blockchain Rd.
Phone: 987654321
Wallet: 0x3C44CdDdB6a900fa2b585dd299e03d12FA4293BC

Repair Info:
Companies: Repair Company 1
Disassembly: http://example.com/disassembly
Assembly: http://example.com/assembly
Safety: http://example.com/safety

Dimensions:
Height: 100
Length: 200
Depth: 50

Material Composition:
Detailed: Aluminum, Lithium
Valuables: Lithium, Cobalt

Cells:
4810c43c-3012-4211-8ad3-6fa676663a4f, 9dc89387-e545-4718-a7b6-d3cf591c6e59, 9c7f7173-f266-4951-b74a-44d2cb5b3dc8, ba2c6775-f8c9-4239-ad34-13c2ca3f9303, 9d44b6aa-ca7f-472d-8f46-0e62c9b19ff9, 7b726afc-495e-45df-8ade-8af8526921b2

Transaction Info:
Created: 2/3/2025, 8:41:49 PM
Tx: 0x3452c088...

833a29e0-80c4-476d-87b0-fd785fbec664

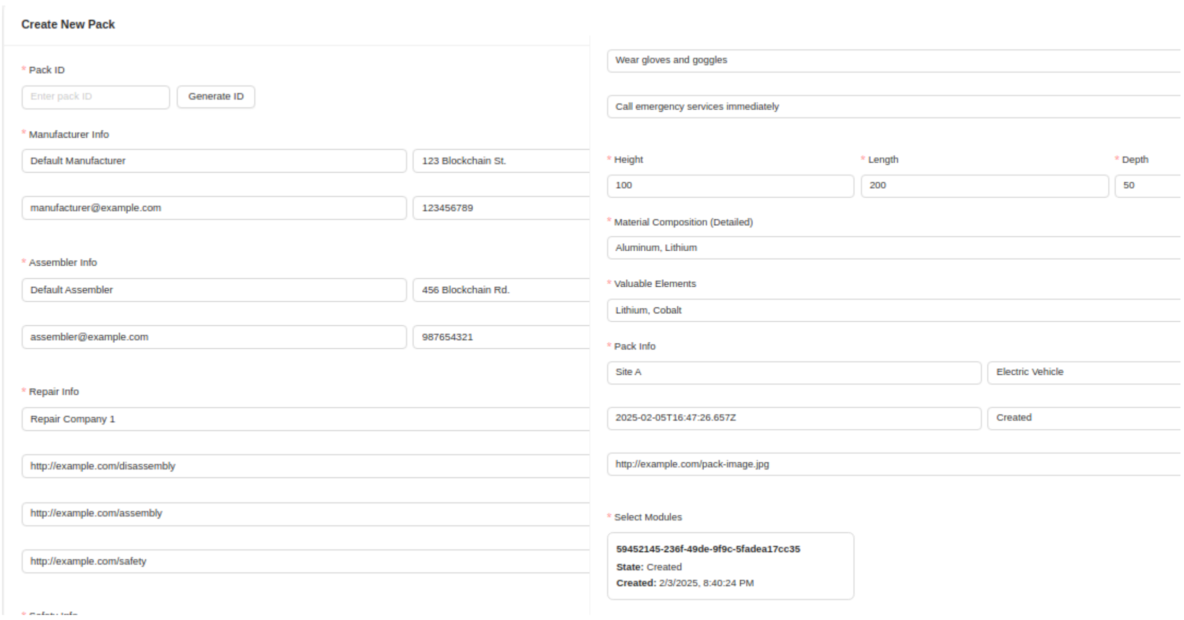
State: Assembled

Assembler Info:
Name: Default Assembler

Dimensions:
Height: 100
Length: 200
Depth: 50

Figure 14: Screenshot depicting the list of created modules, their recorded metadata, and associated cells

Moving from modules to full battery packs, the assembler navigates to the Pack Assembly tab and completes another form (see Figure 15. Create New Pack). In this step, the assembler specifies a Pack ID, references the manufacturer and assembler data, and optionally includes repair and safety instructions or other metadata. The user then selects one or more modules to incorporate into the new pack. Once submitted, this process triggers a meta-transaction that finalizes the pack on-chain, linking it unambiguously to the modules and cells that form its structure.



Create New Pack

* Pack ID
Enter pack ID | Generate ID

* Manufacturer Info
Default Manufacturer | 123 Blockchain St.
manufacturer@example.com | 123456789

* Assembler Info
Default Assembler | 456 Blockchain Rd.
assembler@example.com | 987654321

* Repair Info
Repair Company 1
http://example.com/disassembly
http://example.com/assembly
http://example.com/safety

Wear gloves and goggles
Call emergency services immediately

* Height	* Length	* Depth
100	200	50

* Material Composition (Detailed)
Aluminum, Lithium

* Valuable Elements
Lithium, Cobalt

* Pack Info
Site A | Electric Vehicle
2025-02-05T16:47:26.657Z | Created
http://example.com/pack-image.jpg

* Select Modules
59452145-236f-49de-9f9c-5fadea17cc35
State: Created
Created: 2/3/2025, 8:40:24 PM

Figure 15: Screenshot showing the form for assembling a new battery pack from existing modules, along with detailed pack metadata

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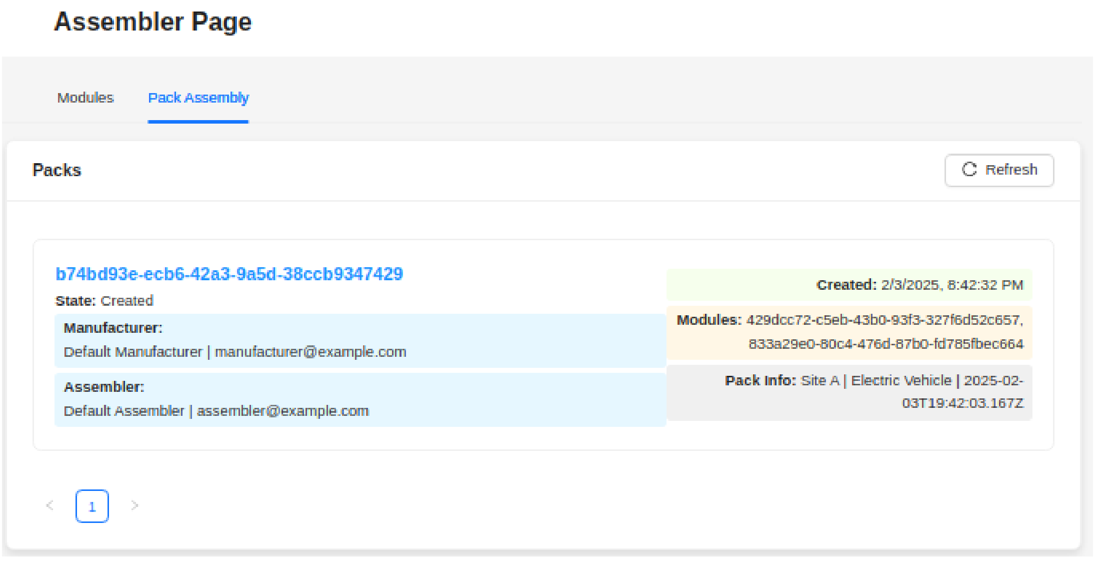
Finally, the newly generated packs appear in the Pack Assembly overview (see Figure 16. Pack Assembly Overview). Here, the assembler can verify the pack's unique ID, check each included module, and confirm that the blockchain transaction has been recorded. By aligning each stage of assembly with blockchain events, the platform ensures that every step—from cell creation to final pack assembly—contributes to an auditable traceability chain, fulfilling the decentralization and transparency requirements set forth in D2.8.



b74bd93e-ecb6-42a3-9a5d-38ccb9347429

State: Created

Manufacturer:
Default Manufacturer | manufacturer@example.com

Assembler:
Default Assembler | assembler@example.com

Created: 2/3/2025, 8:42:32 PM

Modules: 429dcc72-c5eb-43b0-93f3-327f6d52c657, 833a29e0-80c4-476d-87b0-fd785fbec664

Pack Info: Site A | Electric Vehicle | 2025-02-03T19:42:03.167Z

Figure 16: Screenshot illustrating the list of created packs, along with their metadata, modules, and recorded on-chain transaction details

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3.3.6 Recycler Dashboard: Managing Recycling and Second-Life Assignments

The Recycler Dashboard provides a specialized interface for overseeing the end-of-life phase of battery packs, modules, and cells. This dashboard enables recyclers to determine whether a cell is suitable for second-life usage or must be marked as recycled, thereby contributing to a more circular economy.

Upon accessing the dashboard, the user is greeted with a concise list of available packs (see Figure 17. Recycler Page – Available Packs), each displaying fundamental attributes such as status and usage. A Refresh Packs button allows the recycler to retrieve the most recent data from the blockchain, ensuring that all lifecycle information is up to date. Selecting a pack leads to its detailed view, where the system displays relevant pack metadata—including manufacturer, assembler, installation date, and current life cycle stage—along with an expanded breakdown of the modules and cells contained within (see Figure 18. Pack Dashboard).

Within this Pack Dashboard, each module’s state, dimensions, material composition, and the associated cells (along with their SoH) are listed. If a recycler determines that a particular cell has reached the end of its functional life, the user can prompt the system to recycle it. This triggers a confirmation modal (see Figure 19. Recycle Cell Confirmation), where the recycler finalizes the decision to mark the cell as recycled on the blockchain. As with all other transactions, a wallet decryption step is required before the signed meta-transaction is relayed to the chain. Once complete, the blockchain oracle captures the event, and the backend stores updated statuses and SoH values in MongoDB.

By enabling recyclers to validate and record end-of-life actions, the system ensures transparent handling of batteries and their components, in line with emerging regulations and sustainability goals. This role-based approach, in conjunction with secure meta-transactions, ensures that all recycling and second-life decisions are immutably recorded, further strengthening the trust and auditability of the Battery Passport Platform.

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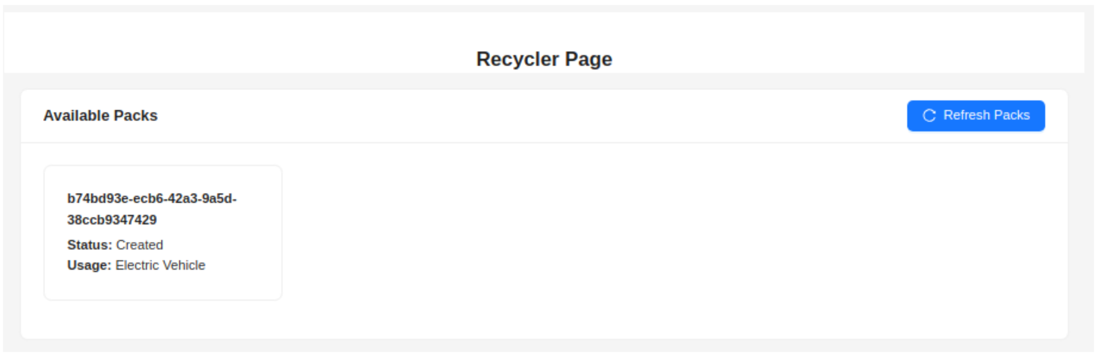


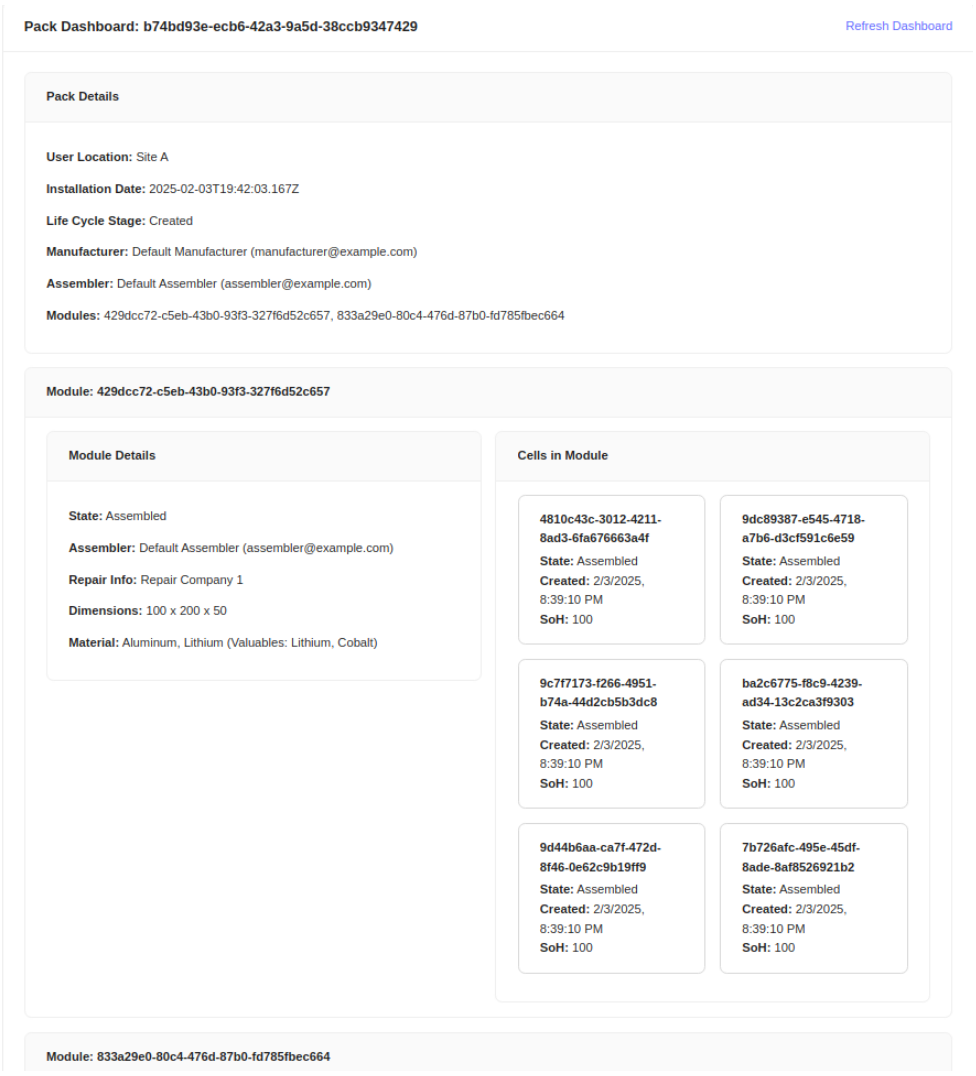
Recycler Page

Available Packs

Refresh Packs

b74bd93e-ecb6-42a3-9a5d-38ccb9347429
Status: Created
Usage: Electric Vehicle

Figure 17: Screenshot illustrating the Recycler Dashboard with a list of available packs, each showing its status and usage



Pack Dashboard: b74bd93e-ecb6-42a3-9a5d-38ccb9347429

Refresh Dashboard

Pack Details

User Location: Site A
Installation Date: 2025-02-03T19:42:03.167Z
Life Cycle Stage: Created
Manufacturer: Default Manufacturer (manufacturer@example.com)
Assembler: Default Assembler (assembler@example.com)
Modules: 429dcc72-c5eb-43b0-93f3-327f6d52c657, 833a29e0-80c4-476d-87b0-fd785fbec664

Module: 429dcc72-c5eb-43b0-93f3-327f6d52c657

Module Details

State: Assembled
Assembler: Default Assembler (assembler@example.com)
Repair Info: Repair Company 1
Dimensions: 100 x 200 x 50
Material: Aluminum, Lithium (Valuables: Lithium, Cobalt)

Cells in Module

4810c43c-3012-4211-8ad3-6fa676663a4f
State: Assembled
Created: 2/3/2025, 8:39:10 PM
SoH: 100

9dc89387-e545-4718-a7b6-d3cf591c6e59
State: Assembled
Created: 2/3/2025, 8:39:10 PM
SoH: 100

9c7f7173-f266-4951-b74a-44d2cb5b3dc8
State: Assembled
Created: 2/3/2025, 8:39:10 PM
SoH: 100

ba2c6775-f8c9-4239-ad34-13c2ca3f9303
State: Assembled
Created: 2/3/2025, 8:39:10 PM
SoH: 100

9d44b6aa-ca7f-472d-8f46-0e62c9b19ff9
State: Assembled
Created: 2/3/2025, 8:39:10 PM
SoH: 100

7b726afc-495e-45df-8ade-8af8526921b2
State: Assembled
Created: 2/3/2025, 8:39:10 PM
SoH: 100

Module: 833a29e0-80c4-476d-87b0-fd785fbec664

Figure 18: Screenshot displaying pack-level information, including modules, cells, SoH, and lifecycle data, as well as a "Refresh Dashboard" option

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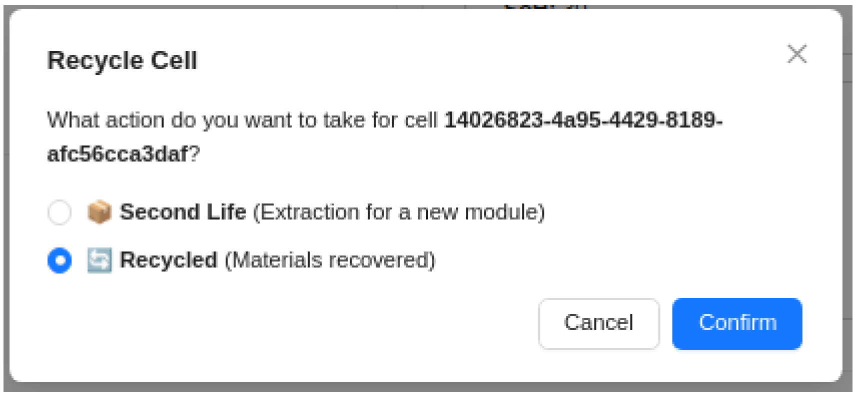

Recycle Cell

What action do you want to take for cell **14026823-4a95-4429-8189-afc56cca3daf**?

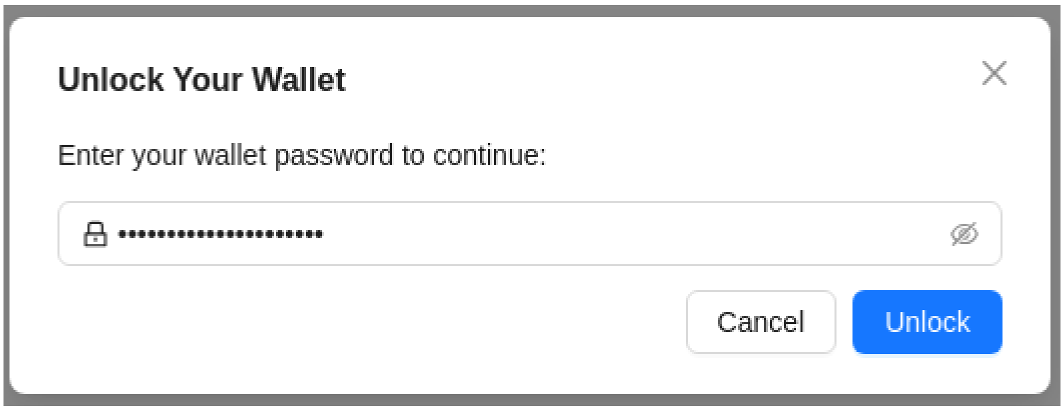
○ 📦 **Second Life** (Extraction for a new module)
● 🔄 **Recycled** (Materials recovered)

Figure 19: Screenshot of the modal confirming a recycler's decision to mark a specific cell as recycled

3.3.7 Wallet Decryption for Transaction Signing

One of the core security mechanisms implemented in the Battery Passport Platform (BPP) is the requirement for users to decrypt their wallet before executing any blockchain transaction. Since the platform encrypts user wallets for secure storage, every transaction that involves signing and submitting data to the blockchain requires the user to manually unlock their wallet.

1. **Wallet Decryption Process**


Unlock Your Wallet

Enter your wallet password to continue:

••••••••••••••••••••

Figure 20: Screenshot of the modal prompting for the user's wallet password, which is required before signing any blockchain transaction.

2. **Transaction Trigger**
   - Whenever a user performs an action that requires **signing a blockchain transaction** (e.g., creating a battery cell, assembling a module, or updating the state of health), the platform automatically prompts the **wallet unlock modal** (see Figure 20).
3. **Password Entry**
   - Users must enter their wallet password, which is used to decrypt the locally stored encrypted wallet.

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freeforlib.eu

  - The decrypted wallet remains only in memory during the signing process and is never sent to the backend or stored persistently.

4. **Transaction Signing**
   - Once the wallet is decrypted, the system **signs the transaction locally** using the user's **private key**.
   - The **signed transaction payload** is then sent to the **backend**, where the **relayer system** submits it to the blockchain.

5. **Security Considerations**
   - **No private keys are ever stored unencrypted**—only the **encrypted wallet** is saved in the backend.
   - The **password is never exposed or transmitted**, ensuring that users retain full control over their wallet security.

This approach ensures that only the rightful wallet owner can authorize transactions, reinforcing the security, decentralization, and user autonomy of the platform. By requiring manual decryption before every transaction, the system effectively prevents unauthorized transactions while maintaining a smooth and secure user experience.

3.4 Blockchain Enhancements and Smart Contract Implementation

The third prototype of the Battery Passport Platform (BPP) introduces refinements to the smart contract architecture, particularly with the integration of meta-transactions. This section details the enhancements made at the blockchain level, explaining how the MetaTransaction contract facilitates gasless interactions and how it is integrated within the Battery Passport smart contracts.

3.4.1 Meta-Transaction Smart Contract

The **MetaTransaction.sol** contract serves as the core component enabling **gasless transactions** by allowing users to sign transactions **off-chain**, which are then relayed and executed by an **authorized entity** (relayer).

3.4.1.1 Key Features of MetaTransaction.sol

- **Signature-Based Transaction Execution**
  Instead of requiring users to hold native tokens to pay for gas, transactions are signed **off-chain** and later executed by an authorized **relayer**, which pays the gas fee.

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- **Nonce Management for Replay Protectio**

A **nonce system** is implemented to ensure each transaction is unique, preventing **replay attacks** where a previously signed transaction could be re-executed maliciously.

- **Relayer Authorization Control**
  Only pre-approved relayers can submit meta-transactions, adding a layer of security and control to the execution process.

3.4.1.2 Contract Breakdown

Relayer Management

```
mapping(address => bool) public authorizedRelayers;

modifier onlyRelayer() {

    require(authorizedRelayers[msg.sender], 'Not an authorized relayer');

    _;

}
```

- **Relayers must be explicitly authorized** to execute transactions.
- The onlyRelayer modifier ensures that **unauthorized addresses** cannot execute transactions on behalf of users.

Transaction Signature Verification

```
bytes32 messageHash = keccak256(abi.encodePacked(user, data,
nonces[user]));

bytes32 ethSignedMessageHash = messageHash.toEthSignedMessageHash();

address signer = ethSignedMessageHash.recover(signature);

require(signer == user, 'Invalid signature');
```

- Transactions are **hashed** and signed by the user **off-chain**.
- The contract then **verifies the signature** to ensure authenticity.

- If the recovered signer **matches the expected user**, the transaction is executed.

Meta-Transaction Execution

```
(success, result) = address(this).call(abi.encodePacked(data, user));

require(success, 'Transaction failed without reason');
```

- The contract **delegates execution** of the signed transaction using call().
- This ensures that **users interact seamlessly** with the blockchain while relayers handle gas fees.

3.4.2 Integration with Battery Passport Smart Contracts

The Battery Passport smart contracts have been modified to support meta-transactions, allowing users to interact with the blockchain without needing to manage gas fees. Below, we present CellBatteryPassport as an example of these modifications, but it is important to note that similar changes have been applied to all Battery Passport contracts, including ModuleBatteryPassport and PackBatteryPassport.

Inheritance from MetaTransaction

All Battery Passport contracts now extend **MetaTransaction**, integrating the relayer-based transaction model:

```
contract CellBatteryPassport is MetaTransaction {
```

This ensures that all operations, whether related to cells, modules, or packs, can be executed through meta-transactions, reducing friction for end users.

Role-Based Access Using _msgSender()

Since transactions are now relayed, the standard msg.sender cannot be used, as it would always point to the relayer instead of the actual user. Instead, _msgSender() is used to extract the original sender:

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```
modifier onlyManufacturer() {
    require(
        roleManager.hasRoleInContract(
            _msgSender(),
            roleManager.MANUFACTURER_ROLE()
        ),
        'Caller is not a manufacturer'
    );
    _;
}
```

3.5 Backend Enhancements and API Development

This third prototype builds upon the foundation set in Prototype 2, expanding the API functionalities, enhancing off-chain data management, and introducing a blockchain oracle to synchronize on-chain and off-chain data.

A key focus of this version has been the streamlining of user interactions with the blockchain by refining wallet management, transaction signing, and meta-transaction processing. The API now handles the secure generation, encryption, and retrieval of user wallets, ensuring that private keys remain protected while allowing seamless meta-transaction signing and submission. Additionally, the relayer system has been integrated into the backend, enabling users to interact with the blockchain without requiring direct gas payments.

Another major enhancement is the introduction of MongoDB, which serves as an off-chain storage solution for user data, transaction records, and additional battery passport metadata. This integration ensures that querying and data retrieval remain efficient, reducing the need for expensive on-chain reads while preserving the necessary transparency and traceability.

To further improve data synchronization and event handling, the newly developed blockchain oracle listens for smart contract events, decodes transaction data, and updates relevant records in MongoDB. This ensures that the backend maintains an up-to-date representation of blockchain activity,

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eliminating the need for continuous blockchain polling while improving overall system efficiency.

The following sections detail the new API functionalities, blockchain oracle architecture, MongoDB integration, and security enhancements introduced in this prototype, highlighting their role in improving platform usability and performance.

3.5.1 Blockchain Oracle for On-Chain Event Processing

The integration of a blockchain oracle in the third prototype of the Battery Passport Platform (BPP) represents an advancement in data synchronization between on-chain and off-chain environments. The oracle acts as a real-time bridge between the blockchain and the backend database, ensuring that smart contract events are properly processed, decoded, and stored for efficient data retrieval and analysis.

This section details how the oracle operates, its role in processing blockchain transactions, and its specific implementation in this prototype.

What is a Blockchain Oracle?

A blockchain oracle is a service that listens for events emitted by smart contracts and processes them asynchronously to trigger off-chain actions. In the Battery Passport Platform, the oracle is responsible for:

- **Listening for emitted events** from the **CellBatteryPassport, ModuleBatteryPassport, and PackBatteryPassport** smart contracts.
- **Decoding on-chain transaction data**, extracting relevant metadata.
- **Storing structured data** in **MongoDB** for efficient querying.
- **Maintaining event logs** to ensure data **traceability and validation**.

Unlike traditional blockchain-based systems that require frequent on-chain queries, the oracle reacts to smart contract events, reducing latency, computational costs, and API requests to the blockchain.

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Architecture and Implementation

The oracle is implemented as a **NestJS service** using **ethers.js** to connect to the blockchain. It initializes when the backend starts, setting up **listeners** for relevant smart contract events.

```
async onModuleInit() {
    this.logger.log('Initializing OracleMetaTransactionService...');
    this.provider = this.blockchainService.provider;
    await this.setupListeners();
}
```

- The **onModuleInit()** method ensures that the oracle is automatically started when the backend module is initialized.
- It **retrieves the blockchain provider** and **sets up event listeners** for relevant smart contracts.

Once started, the service actively listens for events related to **battery passport operations**.

Event Listener and Meta-Transaction Handling

When a **meta-transaction** is executed on-chain, the oracle captures it, extracts the **method name**, and routes it to the appropriate handler.

```
this.cellMetaTransactionContract.on('Executed', async (...args) => {
    const [user, data] = args;
    const decodedData = contractInterface.parseTransaction({ data });
    this.logger.log(`Processing method: ${decodedData.name}`);
});
```

- **Identifies the executed smart contract function.**
- **Extracts relevant parameters for processing.**
- **Logs transaction metadata for tracking.**

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Handling Specific Transactions

1. **Adding a State of Health (SoH) Record**

When a SoH update is made on-chain, the oracle retrieves transaction data and saves it to MongoDB.

```
const cellIds = decodedData.args[0];

const stateOfHealth = Number(decodedData.args[2]);



await this.cellsMongoService.addSoHRecord({ cellIds, stateOfHealth });

this.logger.log(`SoH updated for cells: ${cellIds}`);
```

- **Extracts cell IDs and the new SoH value.**
- **Saves the data in MongoDB for traceability.**

2. **Recording New Battery Cells**

When a manufacturer registers a new battery cell, the oracle processes the event and stores its details.

```
const cellId = decodedData.args[0];

const manufacturerInfo = { name: decodedData.args[2][0] };



await this.cellsMongoService.createCell({ cellId, manufacturerInfo });

this.logger.log(`New cell added: ${cellId}`);
```

- **Captures cell ID and manufacturer details.**
- **Stores the structured data in the database.**

3.5.1.1 Oracle File Structure and Initialization

As shown in Figure 21. Oracle Services File Structure, the codebase contains dedicated services for cells, modules, and packs, each responsible for parsing and handling the corresponding smart contract events:

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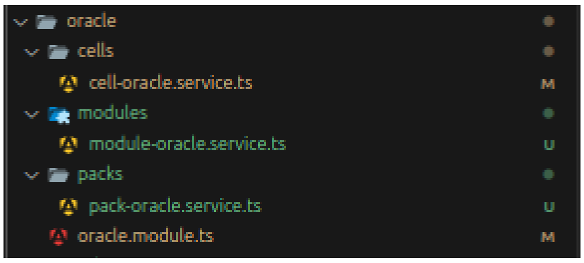
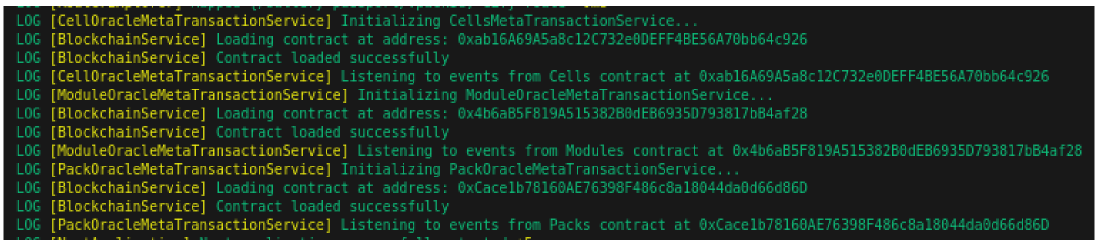


Figure 21: Screenshot showing separate NestJS services for Cells, Modules, and Packs, each in its own folder under oracle

Upon application start, each Oracle service (for example, **CellOracleMetaTransactionService**) is initialized, connects to the Ethereum provider through the **BlockchainService**, and loads the specific contract ABI. The logs displayed in Figure 22. Oracle Initialization Logs confirm that each service listens to the correct contract address, waiting for on-chain events to occur.



```
LOG [CellOracleMetaTransactionService] Initializing CellsMetaTransactionService...
LOG [BlockchainService] Loading contract at address: 0xab16A69A5a8c12C732e0DEFF4BE56A70bb64c926
LOG [BlockchainService] Contract loaded successfully
LOG [CellOracleMetaTransactionService] Listening to events from Cells contract at 0xab16A69A5a8c12C732e0DEFF4BE56A70bb64c926
LOG [ModuleOracleMetaTransactionService] Initializing ModuleOracleMetaTransactionService...
LOG [BlockchainService] Loading contract at address: 0x4b6aB5F819A515382B0dEB6935D793817bB4af28
LOG [BlockchainService] Contract loaded successfully
LOG [ModuleOracleMetaTransactionService] Listening to events from Modules contract at 0x4b6aB5F819A515382B0dEB6935D793817bB4af28
LOG [PackOracleMetaTransactionService] Initializing PackOracleMetaTransactionService...
LOG [BlockchainService] Loading contract at address: 0xCace1b78160AE76398F486c8a18044da0d66d86D
LOG [BlockchainService] Contract loaded successfully
LOG [PackOracleMetaTransactionService] Listening to events from Packs contract at 0xCace1b78160AE76398F486c8a18044da0d66d86D
```

Figure 22: Screenshot illustrating log output when NestJS initializes the Oracle services and connects to the relevant smart contracts

The Blockchain Oracle improves the Battery Passport Platform by ensuring real-time event processing and secure off-chain data storage. By integrating with MongoDB, it enables fast querying and historical tracking of battery passport interactions, making the system more practical and user-friendly.

3.5.2 MongoDB Integration and Off-Chain Data Management

The third prototype of the Battery Passport Platform (BPP) integrates MongoDB as the primary off-chain storage solution, ensuring efficient data management, retrieval, and scalability. This integration allows the platform to store and manage structured data that complements on-chain records, reducing the need for frequent blockchain queries while preserving data integrity and accessibility.

Purpose of MongoDB Integration

While blockchain is used for storing critical lifecycle events of the Battery Passport, not all data needs to be kept on-chain due to cost, performance, and privacy considerations. MongoDB is used to:

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- **Store Battery Passport metadata**: Data related to cells, modules, and packs, including **material composition, manufacturer details, and lifecycle history**.
- **Manage user authentication and roles**: Users, wallets, and role assignments are securely stored for **role-based access control (RBAC)**.
- **Record off-chain transaction logs**: Meta-transaction executions, event processing logs, and **State of Health (SoH) records** for batteries.

Data Storage and Query Optimization

MongoDB is structured to support efficient querying and scalability, ensuring that users and system components can quickly retrieve battery passport details and transaction histories.

- **Data is stored in a structured format**, optimizing retrieval.
- **Indexed queries** improve performance when searching for battery records.

MongoDB ensures that the Battery Passport Platform can efficiently store, manage, and retrieve data, balancing the immutability of blockchain with the performance of off-chain storage. This hybrid approach ensures that the system remains scalable, cost-effective, and responsive to real-world operational needs.

3.5.3 API Security and Transaction Signing Workflow

The third prototype an enhanced security model and transaction signing workflow, ensuring a secure, efficient, and user-friendly experience for interacting with the blockchain. The backend is responsible for handling user authentication, wallet management, and meta-transaction processing, enabling seamless blockchain interactions while maintaining data integrity and security.

3.5.3.1 Wallet Management and Secure User Authentication

The backend manages user registration and authentication, ensuring that users have a securely encrypted wallet stored in MongoDB.

User Registration and Wallet Storage

When a new user registers, their wallet is generated on the frontend, encrypted with a password, and sent to the backend for secure storage.

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```
async register(username: string, password: string, encryptedWallet:
string, address: string) {
   const hashedPassword = await bcrypt.hash(password, 10);
   const user = { username, hashedPassword, encryptedWallet,
walletAddress: address, role: 'no_role' };
   return await this.usersMongoService.createUser(user);
}
```

- **The password is hashed** before storage to prevent unauthorized access.
- **The encrypted wallet is stored**, ensuring that only the user can decrypt it locally.

Upon successful registration, the backend **generates a JWT token**, allowing users to authenticate and interact with the system securely.

3.5.3.2 Meta-Transaction Processing and Blockchain Integration

The API allows users to **sign transactions locally** and submit them to the backend, which **verifies and relays them** to the blockchain.

Meta-Transaction Submission Endpoint

The API exposes an endpoint to handle **signed meta-transactions**:

```
@Post('meta-transaction')
async submitMetaTransaction(@Body() metaTransactionDto) {
   return await this.blockchainBPService.submitMetaTransactionByType(
      metaTransactionDto.contractType,
      metaTransactionDto.userAddress,
      metaTransactionDto.data,
      metaTransactionDto.signature,
   );
}
```

- The backend **does not sign transactions**, ensuring the **user maintains full control** over their private key.
- The **relayer system** executes transactions on behalf of users, eliminating the need for gas payments.

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3.5.3.3 Backend Verification and Execution of Meta-Transactions

Once a **meta-transaction is submitted**, the backend verifies its **integrity** before relaying it.

Nonce and Signature Verification

```
const nonce = await
contractWithSigner.getFunction('getNonce').staticCall(userAddress);

const backendHash = ethers.solidityPackedKeccak256(

   ['address', 'bytes', 'uint256'], [userAddress, data, nonce]

);

if (contractHash !== backendHash) throw new Error('Hash mismatch!');
```

- **Nonces prevent replay attacks**, ensuring that transactions cannot be re-executed.
- **Hashes are compared** between the backend and smart contract, verifying that the signed data matches the expected execution.

Executing the Meta-Transaction via Relayer

```
const txResponse = await
contractWithSigner.getFunction('executeMetaTransaction')

   .send(userAddress, data, signature);

const receipt = await txResponse.wait();

return receipt;
```

- The relayer **submits the transaction** and covers the gas fees.
- Once mined, the **receipt is returned** to confirm successful execution.

3.5.3.4 Secure Wallet Unlocking for Local Signing

Before submitting a transaction, users must **decrypt their locally stored wallet** using a password.

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```
@Post('unlock-wallet')

async unlockWallet(@Body() unlockWalletDto) {

   const user = await
this.usersMongoService.findByUsername(unlockWalletDto.username);

   const decryptedWallet = decryptWallet(user.encryptedWallet,
unlockWalletDto.password);

   return { wallet: decryptedWallet };

}
```

- **The backend never accesses private keys**, maintaining decentralization.
- Users **decrypt wallets locally** before signing transactions.

The backend's security and transaction workflow ensure that users maintain control over their cryptographic assets, while still benefiting from a seamless interaction model enabled by meta-transactions and relayer execution. These enhancements contribute to platform usability, scalability, and security, ensuring that the Battery Passport Platform remains an efficient and decentralized solution.

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4. Validation of the prototype

The validation phase of the third prototype of the Battery Passport Platform (BPP) is designed to systematically verify that all functional requirements defined in this document have been implemented correctly. This process ensures that the platform functions as expected across user authentication, role-based interactions, meta-transaction execution, blockchain integration, and battery passport traceability.

To validate the platform, a structured test scenario is followed, simulating the full lifecycle of a battery passport. Each step is directly linked to a specific functional requirement (FR-ID), ensuring that the expected system behavior aligns with the actual platform performance.

The validation starts with user registration and wallet creation, progresses through battery cell registration and assembly, and concludes with battery recycling, second-life assignment, and data visualization. Each operation is tested against the backend API, the frontend interface, and blockchain components to assess security, efficiency, and usability.

The results of this validation will be summarized, highlighting which requirements have been successfully implemented, identifying any limitations, and outlining areas for future improvements to enhance platform scalability and functionality.

4.1 Validation Methodology

The validation process follows a structured approach to ensure that the functionalities introduced in the third prototype of the Battery Passport Platform (BPP) align with the defined requirements. The goal is to systematically test each component by simulating real-world interactions, verifying that all implemented features function correctly within the expected workflow.

Objective of the Validation Process

This validation aims to:

- Confirm that each functional requirement (FR-ID) is correctly implemented and operational.
- Evaluate the integration between the backend, frontend, and blockchain components.

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- Ensure that the platform supports role-based interactions and secure transaction processing.
- Verify the effectiveness of the meta-transaction system and gasless transaction execution.
- Assess the accuracy of data synchronization between the blockchain and MongoDB.

Validation Steps and Approach

The validation follows the logical sequence of a complete battery passport lifecycle, starting with user registration and role assignment, followed by battery cell creation, module and pack assembly, recycling, and data retrieval. Each action is tested in a controlled environment, with the results compared against expected behaviors.

For each validation step:

1. The user performs the action through the frontend or API.
2. The backend processes the request and interacts with the blockchain or database.
3. The blockchain executes the transaction (if applicable).
4. The oracle listens for events and updates MongoDB.
5. The frontend displays the results, confirming the operation’s success.

Each step is cross-referenced with the associated functional requirement to ensure traceability.

Reference to Functional Requirements

Throughout the validation process, each tested feature is mapped to its corresponding functional requirement. The validation report will explicitly indicate whether a requirement has been fully met, partially met, or requires further improvements. This structured approach ensures transparency in assessing the prototype’s readiness for deployment.

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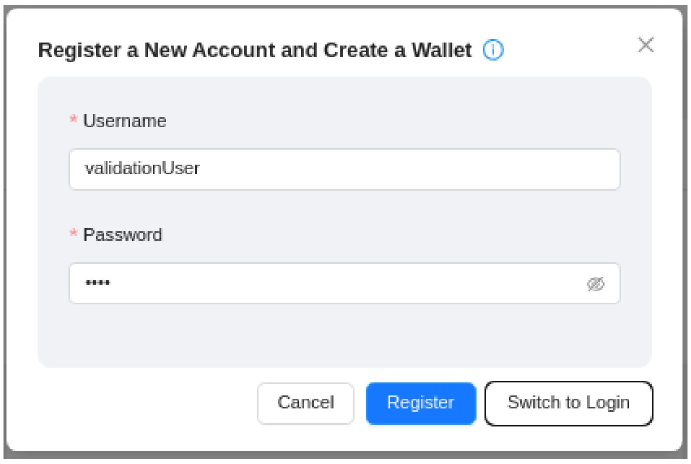
4.2 Step-by-Step Validation of the Battery Passport Creation Process

4.2.1 User Registration and Role Assignment

This validation step ensures that users can successfully register an account, generate a wallet, and receive a role assignment from the admin, allowing them to interact with the platform according to their designated permissions. Since the role management system was validated in previous prototypes, this section focuses primarily on confirming that the frontend components correctly guide the user through the process.

User Registration and Wallet Creation

The first step in the validation is the **registration of a new user**. The frontend provides a **registration form** where users enter a **username and password**, generating an encrypted wallet that is sent to the backend for secure storage.


Register a New Account and Create a Wallet

* Username

validationUser

* Password

••••

Figure 23:User Registration Modal

As shown in Figure 23, the user **validationUser** enters a username and password to create an account. Upon submission, the system generates an encrypted wallet and securely stores it in MongoDB, ensuring compliance with **FR-BE-01** and **FR-BE-02**.

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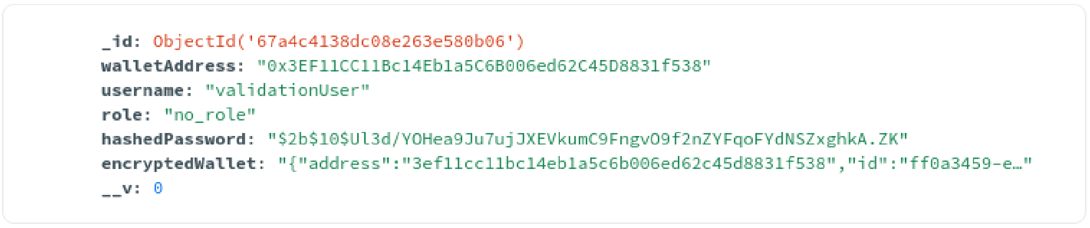


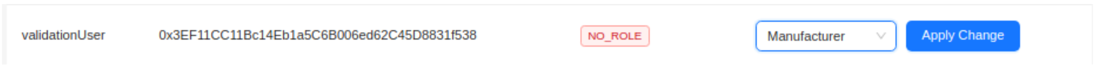
```
_id: ObjectId('67a4c4138dc08e263e580b06')
walletAddress: "0x3EF11CC11Bc14Eb1a5C6B006ed62C45D8831f538"
username: "validationUser"
role: "no_role"
hashedPassword: "$2b$10$Ul3d/YOHea9Ju7ujJXEVkumC9FngvO9f2nZYFqoFYdNSZxghkA.ZK"
encryptedWallet: "{"address":"3ef11cc11bc14eb1a5c6b006ed62c45d8831f538","id":"ff0a3459-e…"
__v: 0
```

Figure 24: User Data Stored in MongoDB

In Figure 24, we can see the stored user data in the database. The wallet address, hashed password, and encrypted wallet are securely recorded, ensuring that the system follows best practices for secure authentication and wallet management.

Role Assignment by the Admin

Once registered, the user is initially assigned the "no_role" status and requires an admin to grant them access to platform functionalities, as defined in **FR-BE-03**. The admin dashboard allows selecting a role from a dropdown menu and applying changes, ensuring compliance with **FR-FE-07**.



validationUser 0x3EF11CC11Bc14Eb1a5C6B006ed62C45D8831f538 NO_ROLE

Figure 25: Admin Assigning a Role

As shown in Figure 25, the admin selects the **Manufacturer** role from the dropdown list and applies the changes. The system updates the user's role in the database and records the assignment for future reference, ensuring proper role management according to **FR-BE-03** and **FR-FE-07**.

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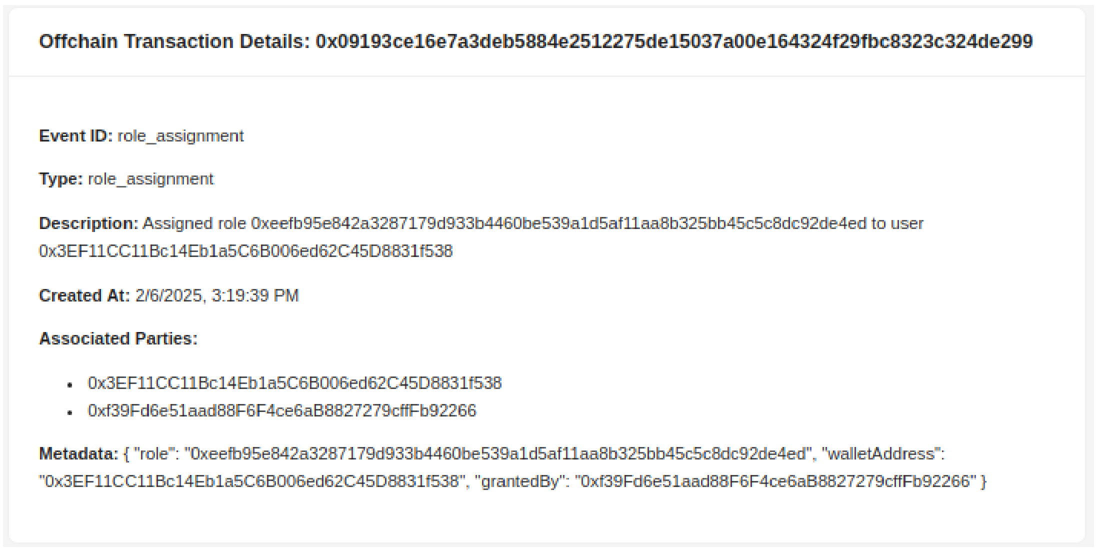

Offchain Transaction Details: 0x09193ce16e7a3deb5884e2512275de15037a00e164324f29fbc8323c324de299

Event ID: role_assignment

Type: role_assignment

Description: Assigned role 0xeefb95e842a3287179d933b4460be539a1d5af11aa8b325bb45c5c8dc92de4ed to user 0x3EF11CC11Bc14Eb1a5C6B006ed62C45D8831f538

Created At: 2/6/2025, 3:19:39 PM

Associated Parties:

- 0x3EF11CC11Bc14Eb1a5C6B006ed62C45D8831f538
- 0xf39Fd6e51aad88F6F4ce6aB8827279cffFb92266

Metadata: { "role": "0xeefb95e842a3287179d933b4460be539a1d5af11aa8b325bb45c5c8dc92de4ed", "walletAddress": "0x3EF11CC11Bc14Eb1a5C6B006ed62C45D8831f538", "grantedBy": "0xf39Fd6e51aad88F6F4ce6aB8827279cffFb92266" }

Figure 26: Off-Chain Role Assignment Record

Additionally, as shown in Figure 26, this role assignment is also recorded as an off-chain transaction, linking the assigned role to both the admin and the user. This ensures that role assignments are traceable and can be audited if necessary.

This step validates **FR-FE-07**, confirming that users receive the appropriate permissions.

Accessing the Manufacturer Dashboard

After role assignment, the user can log in and access their designated dashboard, in this case, the Manufacturer Page.

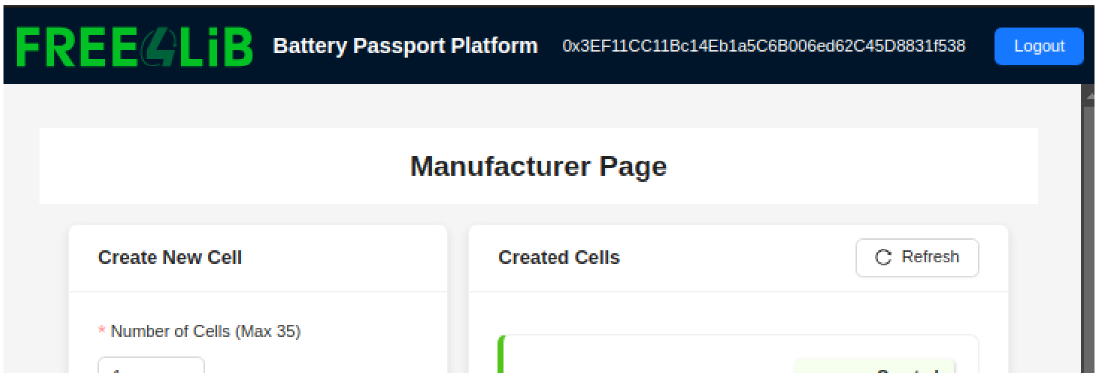
FREE4LiB
Battery Passport Platform
0x3EF11CC11Bc14Eb1a5C6B006ed62C45D8831f538
Logout
Manufacturer Page
Create New Cell
Created Cells
Refresh
* Number of Cells (Max 35)

Figure 27: Manufacturer Dashboard

As shown in Figure 27, after logging in, the user is now recognized as a **Manufacturer** and gains access to cell creation functionalities, confirming compliance with **FR-FE-01**.

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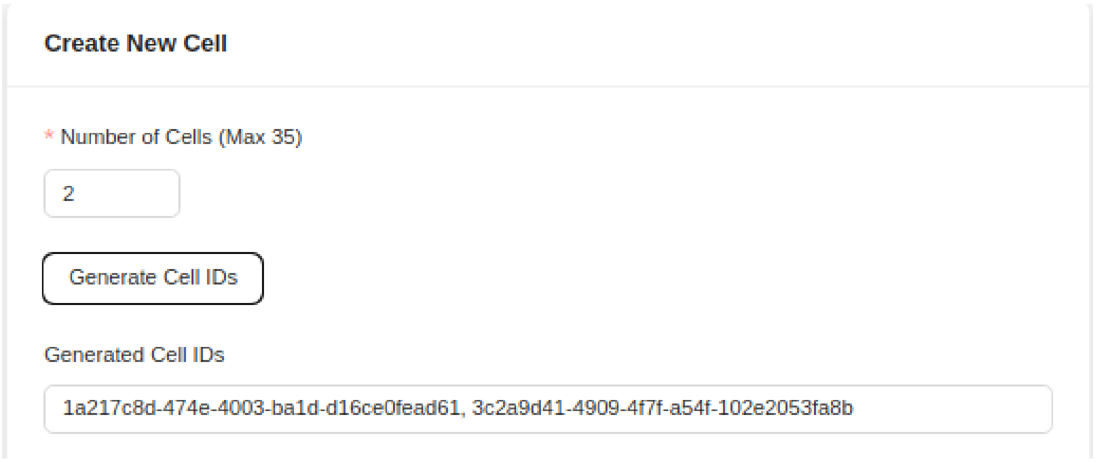
4.2.2 Cell Creation and State of Health (SoH) Management

This validation step ensures that manufacturers can successfully create battery cells, assign unique identifiers, and manage the State of Health (SoH) records. It validates the correct interaction between the frontend, backend, and blockchain components, ensuring that data is recorded and retrieved accurately.

Battery Cell Creation

The manufacturer initiates the process by specifying the number of cells to create. The system generates **unique identifiers** for each new cell.


Create New Cell

* Number of Cells (Max 35)

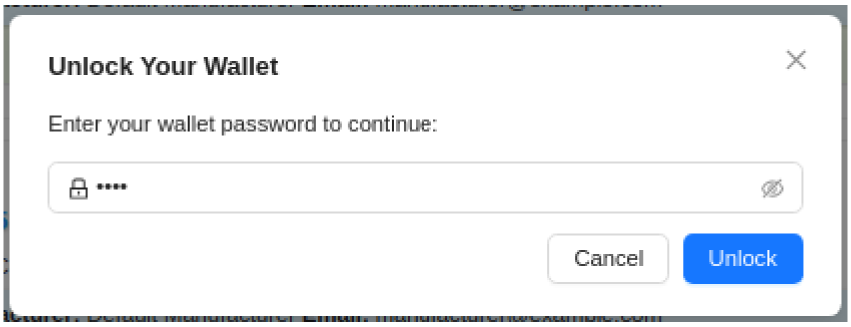
2

Generated Cell IDs

1a217c8d-474e-4003-ba1d-d16ce0fead61, 3c2a9d41-4909-4f7f-a54f-102e2053fa8b

Figure 28: Cell Creation Form

As shown in Figure 28, the user specifies the number of cells (in this case, two) and clicks the "Generate Cell IDs" button. The system assigns unique identifiers to each cell, ensuring compliance with **FR-FE-04** and **FR-BC-01**.


Unlock Your Wallet

Enter your wallet password to continue:

••••

Figure 29: Wallet Unlock for Transaction Signing

Before the transaction is submitted to the blockchain, the user must unlock their wallet to sign the meta-transaction, as seen in Figure 29. This step

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ensures secure transaction execution, aligning with **FR-FE-03**, **FR-BE-04**, and **FR-BC-02**.

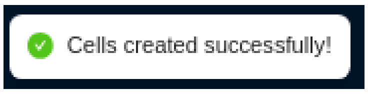
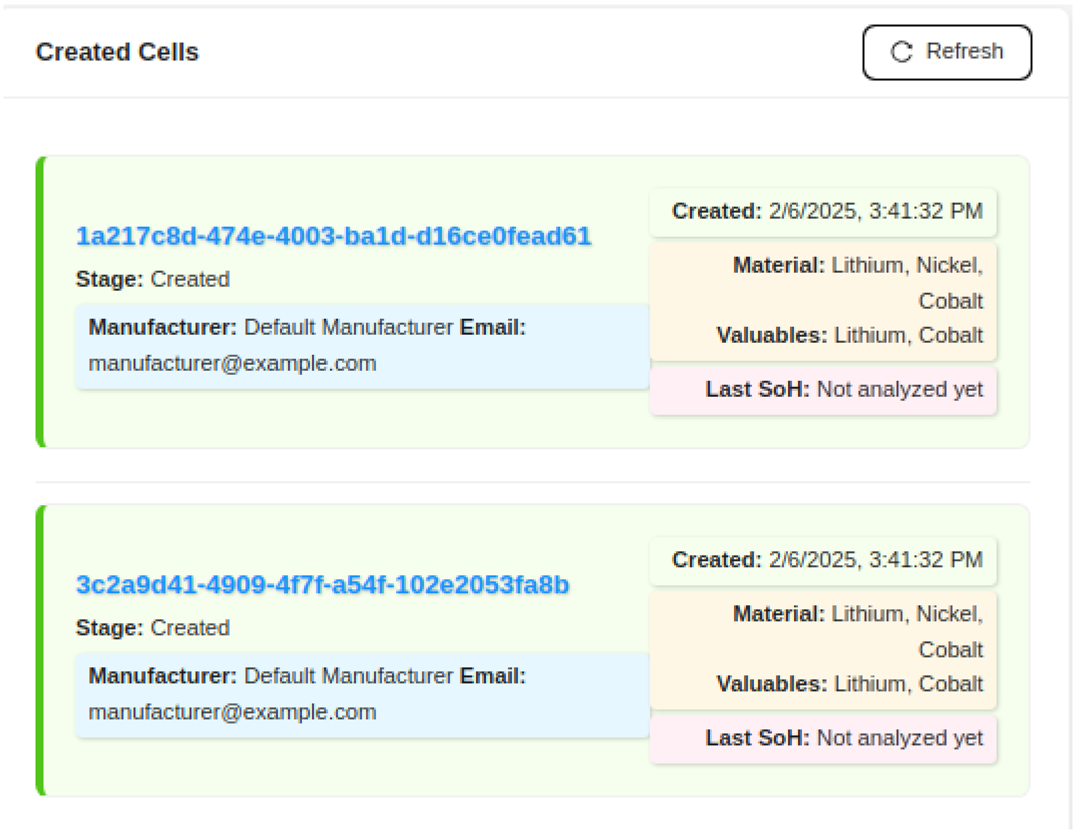

Cells created successfully!

Figure 30: Cell Creation Confirmation

Upon successful submission, the system displays a confirmation message, as illustrated in Figure 30. This confirms that the transaction has been successfully broadcasted to the blockchain, validating compliance with **FR-BC-01**.


Created Cells

1a217c8d-474e-4003-ba1d-d16ce0fead61

Stage: Created

Manufacturer: Default Manufacturer **Email:** manufacturer@example.com

Created: 2/6/2025, 3:41:32 PM

Material: Lithium, Nickel, Cobalt

Valuables: Lithium, Cobalt

Last SoH: Not analyzed yet

3c2a9d41-4909-4f7f-a54f-102e2053fa8b

Stage: Created

Manufacturer: Default Manufacturer **Email:** manufacturer@example.com

Created: 2/6/2025, 3:41:32 PM

Material: Lithium, Nickel, Cobalt

Valuables: Lithium, Cobalt

Last SoH: Not analyzed yet

Figure 31: Created Cells Overview

Once the transaction is confirmed, the newly created cells are displayed in the manufacturer's dashboard, as seen in Figure 31. Each cell contains metadata, including the creation timestamp, manufacturer details, material composition, and SoH status, ensuring compliance with **FR-FE-04** and **FR-BC-01**.

Adding a State of Health (SoH) Record

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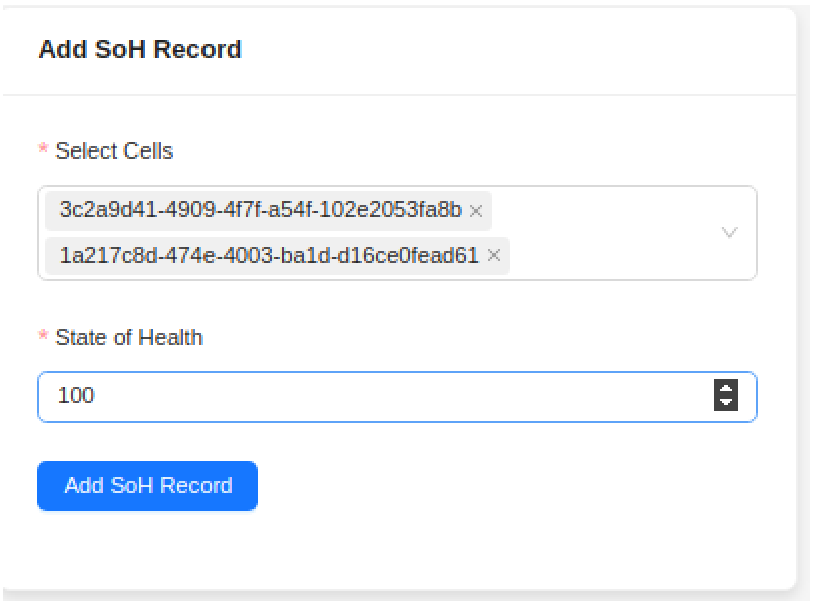
After cell creation, the manufacturer or an authorized user can **record an SoH value** for each battery cell.



Add SoH Record

* Select Cells

3c2a9d41-4909-4f7f-a54f-102e2053fa8b

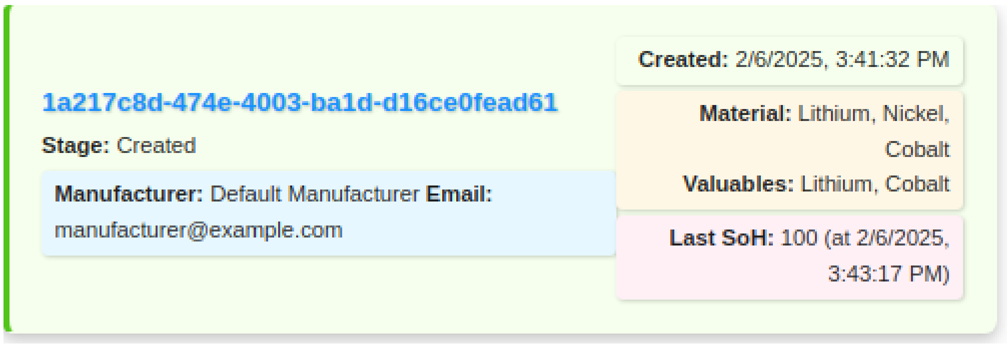
1a217c8d-474e-4003-ba1d-d16ce0fead61

* State of Health

100

Figure 32: Adding SoH Record

In Figure 32, the user selects the previously created cells and assigns an initial SoH value of 100. Once submitted, the transaction is processed via the blockchain, confirming compliance with **FR-BC-05**.



1a217c8d-474e-4003-ba1d-d16ce0fead61

Stage: Created

Manufacturer: Default Manufacturer **Email:** manufacturer@example.com

Created: 2/6/2025, 3:41:32 PM

Material: Lithium, Nickel, Cobalt

Valuables: Lithium, Cobalt

Last SoH: 100 (at 2/6/2025, 3:43:17 PM)

Figure 33: Updated SoH in Dashboard

As seen in Figure 33, the SoH value is updated in the frontend, displaying the last assessment timestamp and the assigned SoH value, validating **FR-FE-06** and **FR-BC-05**.

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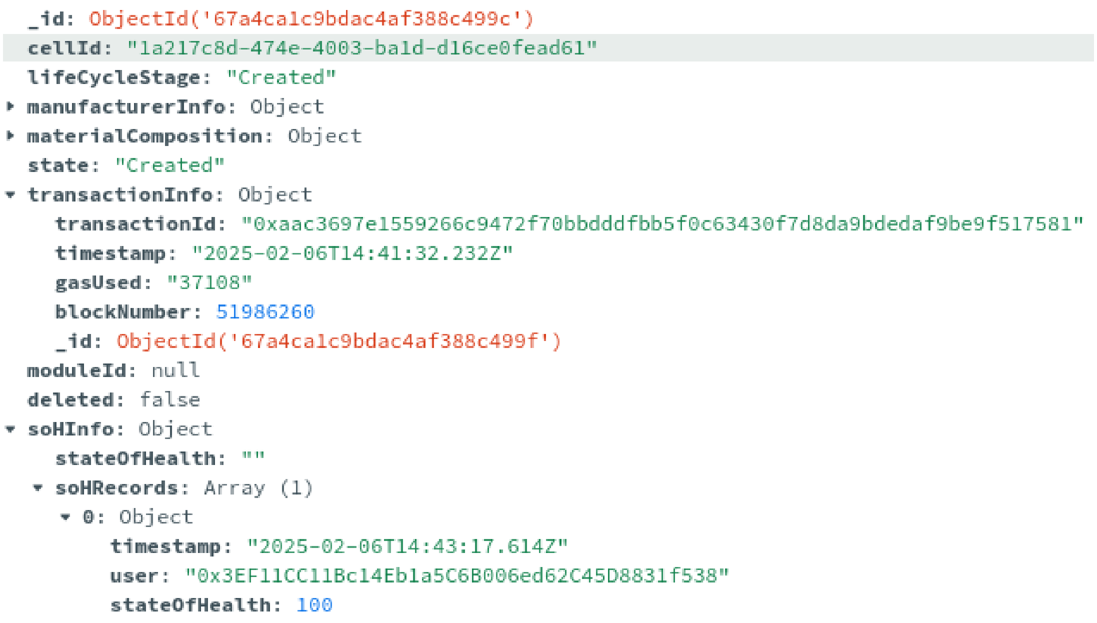

```
  _id: ObjectId('67a4ca1c9bdac4af388c499c')
  cellId: "1a217c8d-474e-4003-ba1d-d16ce0fead61"
  lifeCycleStage: "Created"
▸ manufacturerInfo: Object
▸ materialComposition: Object
  state: "Created"
▾ transactionInfo: Object
    transactionId: "0xaac3697e1559266c9472f70bbdddfbb5f0c63430f7d8da9bdedaf9be9f517581"
    timestamp: "2025-02-06T14:41:32.232Z"
    gasUsed: "37108"
    blockNumber: 51986260
    _id: ObjectId('67a4ca1c9bdac4af388c499f')
  moduleId: null
  deleted: false
▾ soHInfo: Object
    stateOfHealth: ""
  ▾ soHRecords: Array (1)
    ▾ 0: Object
        timestamp: "2025-02-06T14:43:17.614Z"
        user: "0x3EF11CC11Bc14Eb1a5C6B006ed62C45D8831f538"
        stateOfHealth: 100
```

Figure 34: MongoDB Storage of SoH Record

Finally, Figure 34 shows how the SoH record is stored in MongoDB, ensuring that the backend properly processes and retrieves SoH updates, in compliance with **FR-BE-06** and **FR-BE-07**.

4.2.3 Module and Pack Assembly

This validation step ensures that assemblers can successfully select battery cells to form modules and later combine multiple modules to create a pack. The objective is to confirm that the frontend correctly guides the user through these steps, while the backend and blockchain ensure that the data is processed and stored correctly.

Module Creation

The assembler selects a set of battery cells from those previously created and assigns them to a new module.

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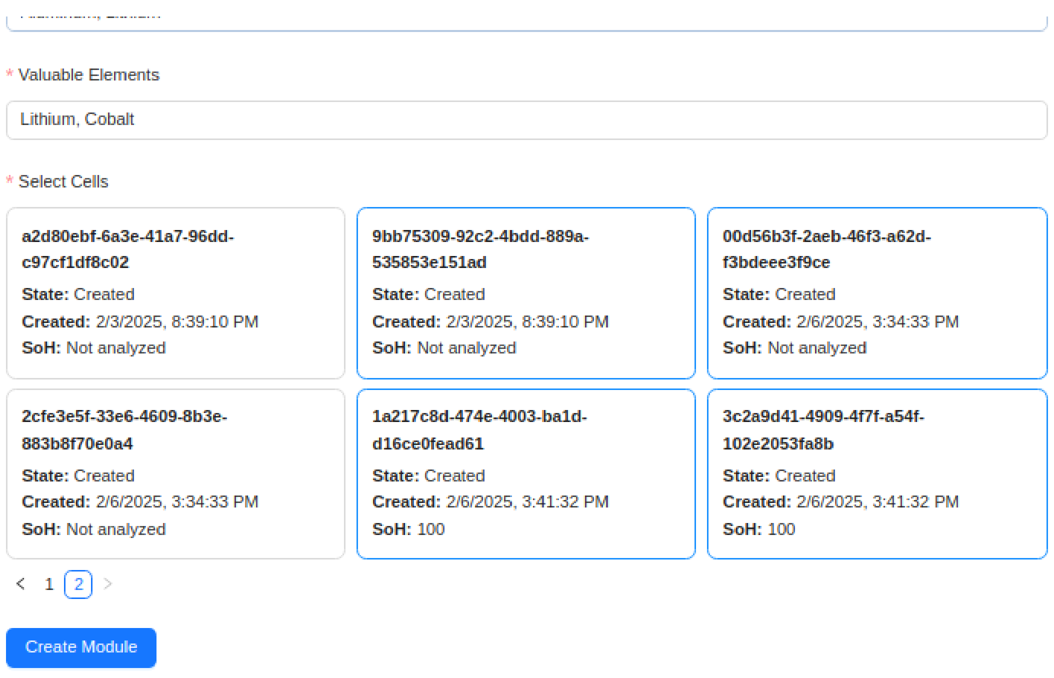

* Valuable Elements

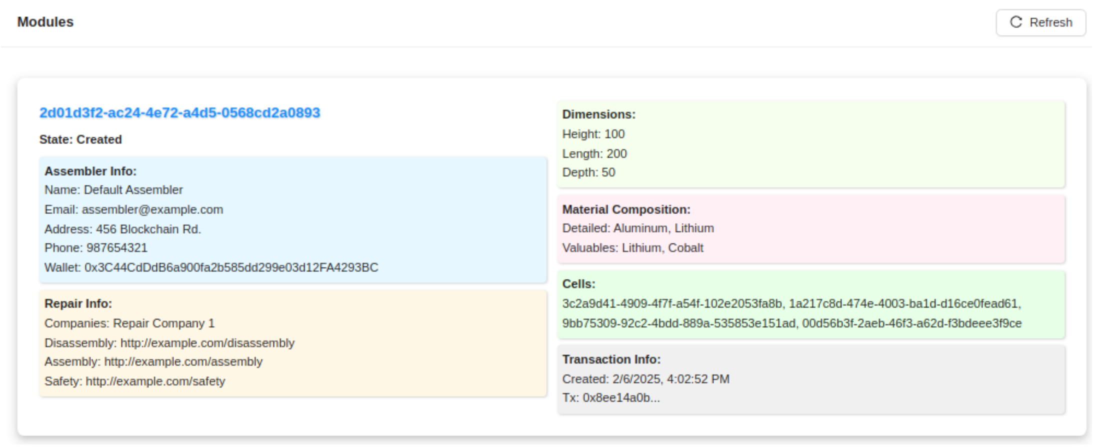
Lithium, Cobalt

* Select Cells

a2d80ebf-6a3e-41a7-96dd-c97cf1df8c02 **State:** Created **Created:** 2/3/2025, 8:39:10 PM **SoH:** Not analyzed	**9bb75309-92c2-4bdd-889a-535853e151ad** **State:** Created **Created:** 2/3/2025, 8:39:10 PM **SoH:** Not analyzed	**00d56b3f-2aeb-46f3-a62d-f3bdeee3f9ce** **State:** Created **Created:** 2/6/2025, 3:34:33 PM **SoH:** Not analyzed
2cfe3e5f-33e6-4609-8b3e-883b8f70e0a4 **State:** Created **Created:** 2/6/2025, 3:34:33 PM **SoH:** Not analyzed	**1a217c8d-474e-4003-ba1d-d16ce0fead61** **State:** Created **Created:** 2/6/2025, 3:41:32 PM **SoH:** 100	**3c2a9d41-4909-4f7f-a54f-102e2053fa8b** **State:** Created **Created:** 2/6/2025, 3:41:32 PM **SoH:** 100

Figure 35: Selecting Cells for Module Assembly

As shown in Figure 35, the assembler chooses cells that will be used to assemble a new module. The interface displays each cell's state and SoH information, ensuring that only valid cells are selected, in compliance with **FR-FE-04** and **FR-BC-01**.



2d01d3f2-ac24-4e72-a4d5-0568cd2a0893

State: Created

Assembler Info:
Name: Default Assembler
Email: assembler@example.com
Address: 456 Blockchain Rd.
Phone: 987654321
Wallet: 0x3C44CdDdB6a900fa2b585dd299e03d12FA4293BC

Repair Info:
Companies: Repair Company 1
Disassembly: http://example.com/disassembly
Assembly: http://example.com/assembly
Safety: http://example.com/safety

Dimensions:
Height: 100
Length: 200
Depth: 50

Material Composition:
Detailed: Aluminum, Lithium
Valuables: Lithium, Cobalt

Cells:
3c2a9d41-4909-4f7f-a54f-102e2053fa8b, 1a217c8d-474e-4003-ba1d-d16ce0fead61, 9bb75309-92c2-4bdd-889a-535853e151ad, 00d56b3f-2aeb-46f3-a62d-f3bdeee3f9ce

Transaction Info:
Created: 2/6/2025, 4:02:52 PM
Tx: 0x8ee14a0b...

Figure 36: Created Module Overview

After confirming the module creation, the system processes the transaction, and the assembled module appears in the assembler's dashboard, as illustrated in Figure 36. This module now contains key metadata, including assembler details, material composition, associated repair information, and transaction details, ensuring compliance with **FR-FE-04** and **FR-BC-01**.

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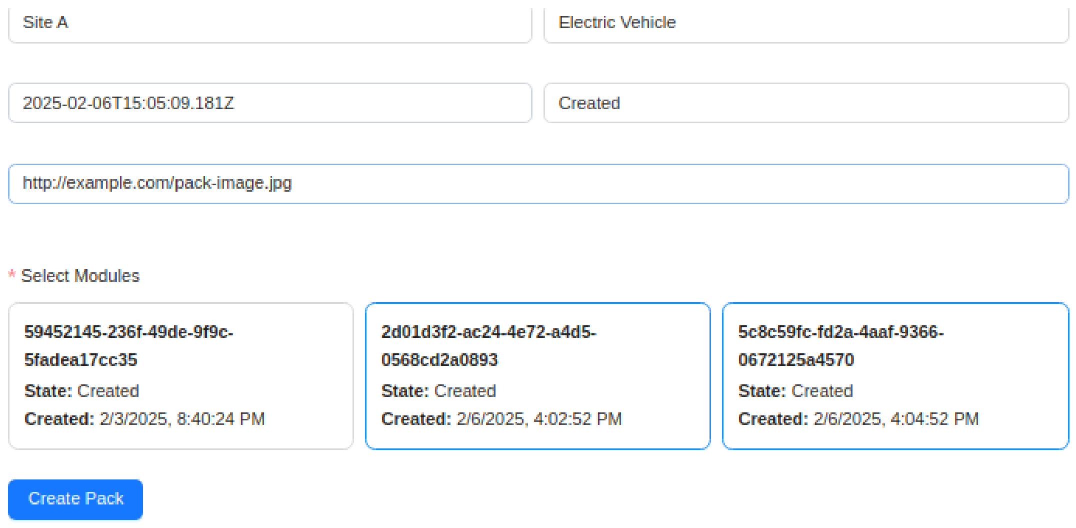
Pack Assembly

Once modules are created, the assembler can proceed to **pack assembly**, which involves selecting multiple modules to form a complete battery system.



Site A	Electric Vehicle
2025-02-06T15:05:09.181Z	Created

http://example.com/pack-image.jpg

* Select Modules

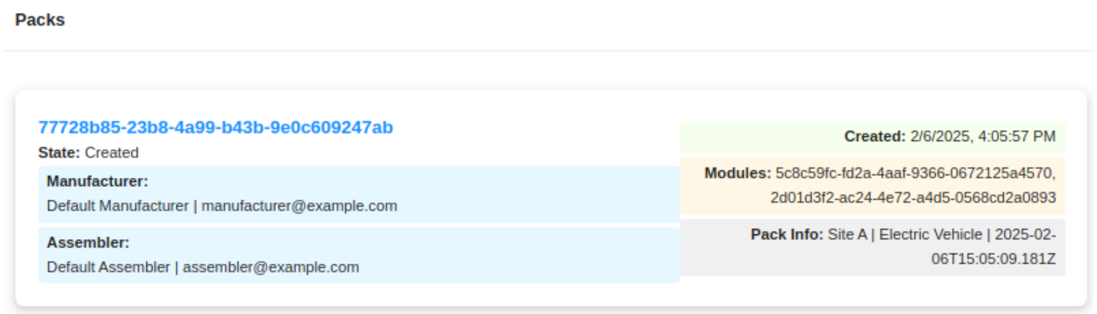
59452145-236f-49de-9f9c-5fadea17cc35
State: Created
Created: 2/3/2025, 8:40:24 PM

2d01d3f2-ac24-4e72-a4d5-0568cd2a0893
State: Created
Created: 2/6/2025, 4:02:52 PM

5c8c59fc-fd2a-4aaf-9366-0672125a4570
State: Created
Created: 2/6/2025, 4:04:52 PM

Figure 37: Selecting Modules for Pack Assembly

As seen in Figure 37, the user selects previously created modules to form a new battery pack. Additional pack-specific metadata, such as manufacturing location, application type, and safety data, is also provided.



Packs

77728b85-23b8-4a99-b43b-9e0c609247ab
State: Created
Manufacturer:
Default Manufacturer | manufacturer@example.com
Assembler:
Default Assembler | assembler@example.com

Created: 2/6/2025, 4:05:57 PM
Modules: 5c8c59fc-fd2a-4aaf-9366-0672125a4570, 2d01d3f2-ac24-4e72-a4d5-0568cd2a0893
Pack Info: Site A | Electric Vehicle | 2025-02-06T15:05:09.181Z

Figure 38: Created Pack Overview

After submission, the assembled pack appears in the dashboard, as displayed in Figure 38. The pack is now linked to both the manufacturer and assembler, and its associated modules are listed, ensuring compliance with **FR-FE-04** and **FR-BC-01**.

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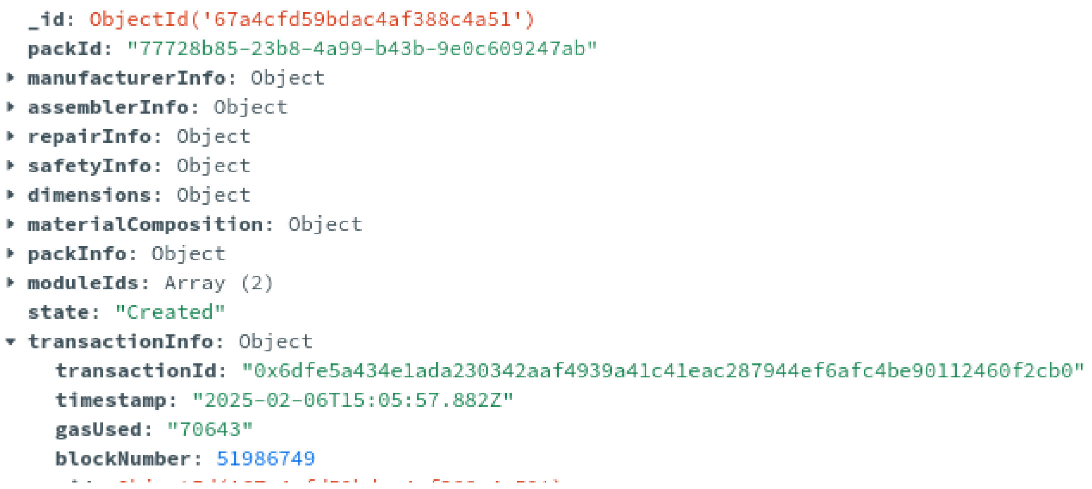

```
  _id: ObjectId('67a4cfd59bdac4af388c4a51')
  packId: "77728b85-23b8-4a99-b43b-9e0c609247ab"
▸ manufacturerInfo: Object
▸ assemblerInfo: Object
▸ repairInfo: Object
▸ safetyInfo: Object
▸ dimensions: Object
▸ materialComposition: Object
▸ packInfo: Object
▸ moduleIds: Array (2)
  state: "Created"
▾ transactionInfo: Object
    transactionId: "0x6dfe5a434e1ada230342aaf4939a41c41eac287944ef6afc4be90112460f2cb0"
    timestamp: "2025-02-06T15:05:57.882Z"
    gasUsed: "70643"
    blockNumber: 51986749
```

Figure 39: Pack Data Stored in MongoDB

Finally, Figure 39 showcases how the pack data is stored in MongoDB, with complete transaction metadata, ensuring consistency between on-chain and off-chain data, in compliance with **FR-BE-06** and **FR-BE-07**.

4.2.4 Recycling and Second-Life Assignment

This section validates the Recycler role, ensuring that users in this role can properly manage battery end-of-life processes, including marking cells as recycled or assigning them a second life. The objective is to confirm that the frontend correctly guides recyclers through these actions while ensuring consistency with backend and blockchain records.

Accessing the Pack Dashboard

The recycler begins by accessing the Pack Dashboard, which provides an overview of pack details, including its location, manufacturing, and associated modules.

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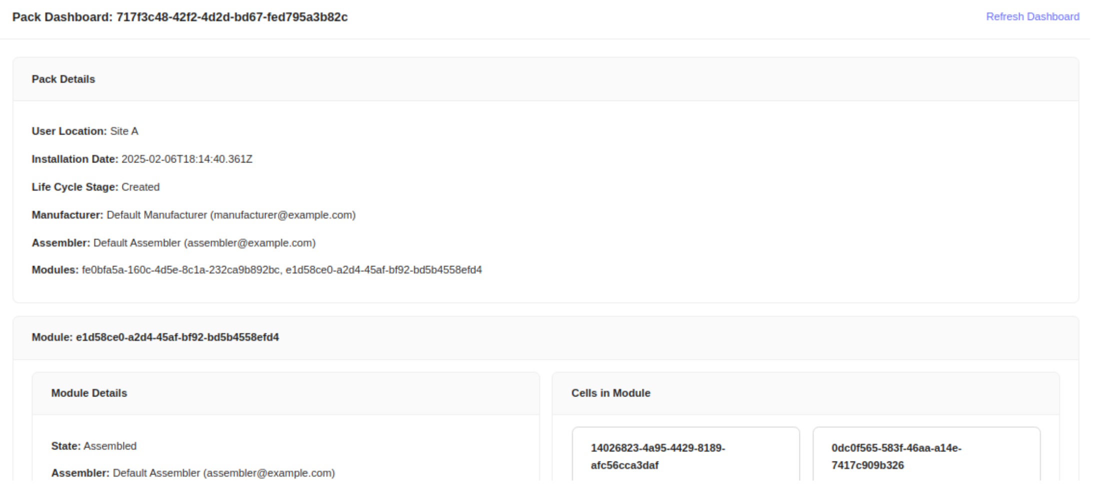

Pack Dashboard: 717f3c48-42f2-4d2d-bd67-fed795a3b82c

Refresh Dashboard

Pack Details

User Location: Site A

Installation Date: 2025-02-06T18:14:40.361Z

Life Cycle Stage: Created

Manufacturer: Default Manufacturer (manufacturer@example.com)

Assembler: Default Assembler (assembler@example.com)

Modules: fe0bfa5a-160c-4d5e-8c1a-232ca9b892bc, e1d58ce0-a2d4-45af-bf92-bd5b4558efd4

Module: e1d58ce0-a2d4-45af-bf92-bd5b4558efd4

Module Details

State: Assembled

Assembler: Default Assembler (assembler@example.com)

Cells in Module

14026823-4a95-4429-8189-afc56cca3daf

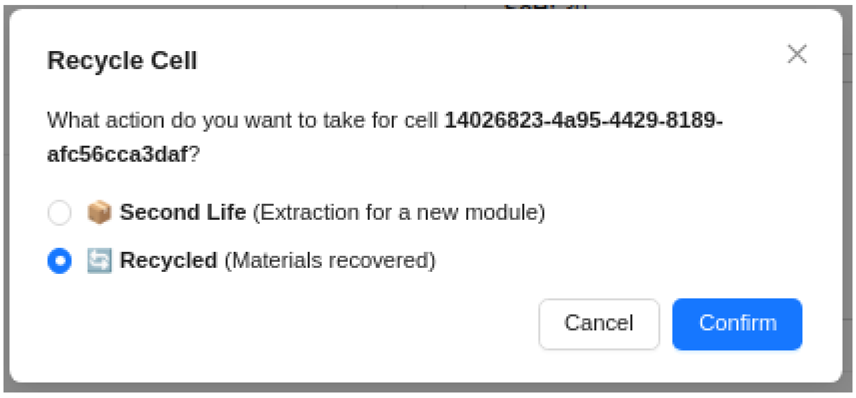
0dc0f565-583f-46aa-a14e-7417c909b326

Figure 40: Pack Dashboard View

As shown in Figure 40, the recycler can inspect a pack's modules and cells, ensuring they have complete visibility into the battery's lifecycle before taking any action, ensuring compliance with **FR-FE-09**.

Initiating the Recycling Process

The recycler selects a specific cell from a module and initiates the recycling process, where they must choose between marking the cell as fully recycled (materials recovered) or assigning it to a second life (reuse in a new module).


Recycle Cell

What action do you want to take for cell **14026823-4a95-4429-8189-afc56cca3daf**?

📦 **Second Life** (Extraction for a new module) [✓ 🔄 **Recycled** (Materials recovered)]

Figure 41 : Recycling Action Modal

As seen in Figure 41, the system prompts the recycler to select an action, ensuring clear decision-making, confirming compliance with **FR-FE-10**.

Confirming the Recycling Status

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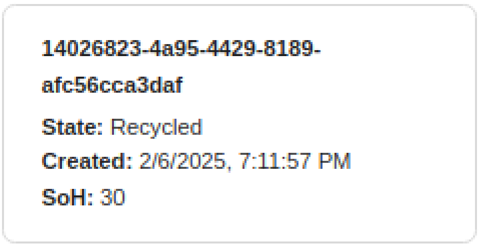
Once confirmed, the system updates the cell's **status**, indicating whether it has been recycled or assigned a second life.


14026823-4a95-4429-8189-afc56cca3daf

State: Recycled
Created: 2/6/2025, 7:11:57 PM
SoH: 30

Figure 42: Cell Status Updated to Recycled

Figure 42 shows that the cell's state has changed to "Recycled", with a recorded timestamp and an updated State of Health (SoH) value, ensuring compliance with **FR-BC-05**.

4.2.5 Querying and Visualizing Battery Passport Data

The **Battery Passport Platform** allows users to easily access and visualize battery passport data through a structured, interactive interface. This functionality was already introduced in the **previous prototype**, and in this version, it remains accessible with some optimizations.

Accessing the Battery Passport

Users can query any battery passport directly via URL, using: /battery-passport/{pack-id}, ensuring compliance with **FR-BE-07** and **FR-FE-05**.

Where {pack-id} corresponds to the unique identifier of the battery pack stored in the system. This makes it easy for external stakeholders to access the passport without requiring authentication, validating compliance with **FR-FE-06**.

Additionally, QR codes embedded in the platform allow for a quick lookup of battery details using mobile devices, ensuring alignment with **FR-FE-05**.

Data Visualization

As shown in **Figure X - Battery Passport Visualization**, the system provides a **hierarchical view** of the battery structure, displaying:

- **Battery Pack (Top Level)**: Contains high-level details such as **installation date, manufacturer, and usage type**.
- **Modules (Middle Level)**: Groups cells into larger units with their corresponding **material composition** and **repair history**.

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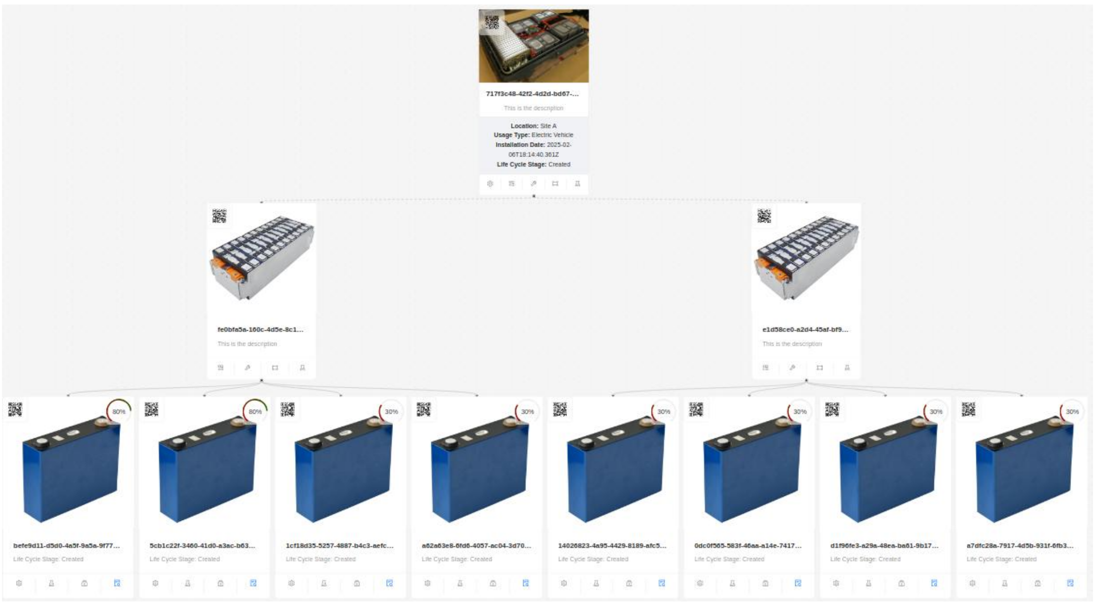
- **Cells (Bottom Level)**: Each individual cell is displayed with key attributes such as **State of Health (SoH)** and **recycling status**.



717f3c48-42f2-4d2d-bd67-...
This is the description
Location: Site A
Usage Type: Electric Vehicle
Installation Date: 2025-02-06T18:14:40.361Z
Life Cycle Stage: Created

fe0bfa5a-160c-4d5e-8c1...
This is the description

e1d58ce0-a2d4-45af-bf9...
This is the description

80% befe9d11-d5d0-4a5f-9a5a-9f77...
Life Cycle Stage: Created

80% 5cb1c22f-3460-41d0-a3ac-b63...
Life Cycle Stage: Created

30% 1cf18d35-5257-4887-b4c3-aefc...
Life Cycle Stage: Created

30% a62a63e8-6fd6-4057-ac04-3d70...
Life Cycle Stage: Created

30% 14026823-4a95-4429-8189-afc5...
Life Cycle Stage: Created

30% 0dc0f565-583f-46aa-a14e-7417...
Life Cycle Stage: Created

30% d1f96fe3-a29a-48ea-ba61-9b17...
Life Cycle Stage: Created

30% a7dfc28a-7917-4d5b-931f-6fb3...
Life Cycle Stage: Created

Figure 43: Battery Passport Visualization

As shown in Figure 43, the system provides a hierarchical view of the battery structure, displaying information in compliance with **FR-FE-06**.

4.3 Summary of Validation Results

The validation process successfully confirmed that the functional requirements (FRs) established in Section 3.1 were implemented and correctly tested. This section summarizes the validation results, identifying which FRs were fully validated, which were partially addressed, and where improvements may be necessary.

4.3.1 Requirements Successfully Validated

The following table summarizes the fully validated functional requirements, indicating the relevant test cases and validation steps that confirm their implementation:

Table 5: Validated Functional Requirements

Functional Requirement (FR)	Validation Reference	Validation Evidence
FR-BE-01	4.2.1	User registration and wallet creation tested
FR-BE-02	4.2.1	Wallet encryption and secure storage in MongoDB validated
FR-BE-03	4.2.1	Role assignment correctly registered and persisted
FR-BE-04	4.2.2	Meta-transaction signing and processing validated
FR-BE-06	4.2.3	Blockchain event synchronization with MongoDB
FR-BE-07	4.2.5	Data retrieval endpoints for querying battery passports validated
FR-FE-01	4.2.1	Login and retrieval of encrypted wallet validated
FR-FE-03	4.2.2	Meta-transaction signing validated in UI
FR-FE-04	4.2.2, 4.2.3	Cell, module, and pack creation validated
FR-FE-05	4.2.5	QR code generation and scanning tested for data retrieval
FR-FE-06	4.2.5	Frontend visualization of battery passport data tested
FR-FE-07	4.2.1	Role assignment interface confirmed in Admin Dashboard
FR-FE-09	4.2.4	Recycler access to pack information validated
FR-FE-10	4.2.4	Recycler decision-making interface validated
FR-BC-01	4.2.2, 4.2.3	Blockchain smart contract execution for cell, module, and pack creation validated

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FR-BC-02	4.2.2	Role-based transaction execution confirmed in smart contracts
FR-BC-05	4.2.2, 4.2.4	SoH updates and recycling validation recorded in smart contracts

All the fully validated requirements were successfully tested in real conditions, confirming the correct integration of backend, frontend, and blockchain components.

4.3.2 Partially Validated Requirements

Some functional requirements were partially validated, meaning they were implemented but lack explicit test evidence in the validation section or require additional verification.

Table 6: Partially Validated Functional Requirements

Functional Requirement (FR)	Validation Reference	Missing Validation / Improvement Needed
FR-BE-05	Not explicitly tested	Blockchain Oracle should have a dedicated test to verify event listening and data storage updates.
FR-BC-04	Not explicitly tested	Replay protection (nonce tracking) is implemented, but a test should confirm that repeated transactions are rejected.
FR-BC-06	Not explicitly tested	Validation of compatibility with both public and semi-permissioned networks should be explicitly tested.

For these partially validated requirements, additional tests should be conducted in the next iteration to ensure full compliance with the defined specifications.

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4.3.3 Identified Limitations and Areas for Improvement

While the functional validation was largely successful, the following areas require further testing, refinement, or optimization:

Blockchain Oracle Synchronization (FR-BE-05)

The backend listens to on-chain events but does not have a dedicated validation step confirming that all emitted blockchain events are correctly processed and stored.

Replay Protection (FR-BC-04)

Nonce tracking is implemented, but a negative test case (attempting to replay a transaction) should confirm that the system correctly rejects duplicate transactions.

Multi-Network Deployment (FR-BC-06)

The system is designed to work on both public and semi-permissioned networks, but a deployment test should explicitly confirm correct functionality on both.

These aspects should be addressed in the next development iteration to further enhance platform robustness and security.

4.3.4 Final Considerations on Prototype Readiness

This validation confirms that the Battery Passport Platform (Version II) successfully meets the majority of its functional requirements. The following conclusions can be drawn:

- The core functionalities of the platform work as expected, including user authentication, role-based access, blockchain smart contracts, and frontend interfaces.
- Meta-transactions are correctly implemented, allowing users to execute blockchain operations without managing gas fees.
- Battery passport data is accurately stored and retrieved, with seamless integration between MongoDB and the blockchain ledger.
- Certain advanced security and scalability features require additional validation, including nonce tracking, blockchain oracle event processing, and network compatibility tests.
- Future improvements should focus on full automation of validation tests, enhanced analytics for battery passport insights, and improved network adaptability.

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This prototype provides a strong foundation for the next development phase, where the identified improvements will be incorporated to further enhance the platform's usability, security, and scalability.

5. Conclusions and Next Steps

5.1 Conclusions

The development of the third prototype of the Battery Passport Platform has been a key step in exploring how blockchain technology can enhance battery lifecycle management. This deliverable has focused on consolidating previous research and technological advancements into a fully functional prototype, integrating meta-transactions, blockchain oracles, and an improved API architecture. The objective has been to test and validate whether blockchain-based solutions can provide added value in terms of data integrity, transparency, and interoperability for battery passports.

A significant improvement in this version has been the implementation of meta-transactions, allowing users to interact with the blockchain without needing to manage gas fees. By introducing a relayer wallet, transaction costs are handled by the system rather than the end user, making blockchain interactions more seamless. This feature directly addresses one of the biggest challenges in blockchain adoption—user accessibility—by removing the need for end users to manage cryptocurrency wallets for transaction fees.

Additionally, this prototype enhances the role-based access model, ensuring that each actor in the battery value chain—manufacturers, assemblers, recyclers, and regulatory entities—can interact with the system under controlled permissions. The authentication and role management system has been validated, confirming that users can securely register, manage their wallets, and gain appropriate access to the platform's functionalities based on their roles.

The backend architecture has been significantly improved, introducing a blockchain oracle that allows the system to listen to on-chain events and synchronize off-chain data in MongoDB. This ensures that relevant battery passport information remains accessible and query-efficient, without requiring constant blockchain interactions. By combining on-chain and off-chain data storage, this approach balances decentralization with performance optimization.

The frontend now provides a structured interface for battery passport management, covering key lifecycle stages such as cell creation, module and

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pack assembly, SoH tracking, and recycling processes. Users can visualize battery passport data in a hierarchical manner, ensuring better traceability. Additionally, the integration of QR codes allows for quick access to passport data, further enhancing usability.

While most of the functional requirements defined in this deliverable have been successfully validated, there are still areas that require further refinement. Certain aspects, such as nonce tracking for replay protection, advanced analytics, and platform interoperability, have been partially implemented but need additional testing and optimization. The next steps will focus on refining these elements to further evaluate the platform's potential in the battery passport ecosystem.

5.2 Next Steps

Moving forward, the focus remains on refining the prototype, expanding interoperability, and evaluating the practical advantages of using blockchain in this context. While significant progress has been made in establishing a solid foundation, several areas have been identified for further development and validation:

- **Enhanced Analytics and Data Insights**: Although basic analytics are already in place, future efforts will emphasize deeper State of Health (SoH) analyses, battery efficiency metrics, and compliance reporting. These extended insights will help determine whether blockchain-driven data transparency genuinely optimizes decision-making processes across the battery lifecycle.
- **User Testing and Platform Refinements**: Further usability evaluations will be conducted with representative stakeholders to gauge how effectively different user roles interact with the system and whether the blockchain integration demonstrably enhances workflow efficiency. Feedback from these sessions will guide targeted improvements in UI/UX, transaction performance, and data accessibility.
- **Public Blockchain Experimentation for Meta-Transactions**: While testing to date has validated the viability of gasless transactions, the next phase involves a public blockchain pilot to confirm scalability and performance under typical network loads. This will help ascertain whether meta-transactions remain a feasible strategy across diverse real-world conditions.
- **API Redefinition for Cross-Platform Integration**: To explore interoperability with other battery passport systems, the API will be

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refined to ensure standardization of endpoints and data interchange formats. This step aims to foster seamless integration with external platforms and strengthen the platform's capacity to accommodate multi-system collaborations.

- **Integration with an External Battery Passport System**: Efforts will be directed toward testing cross-platform data consolidation, allowing external passport systems to synchronize essential battery information with this platform. Such interoperability trials will illuminate whether blockchain-based traceability demonstrably improves transparency and efficiency at an ecosystem level.
- **Monitoring Regulatory Frameworks and Data Model Adaptation**: Given the dynamic nature of EU regulations surrounding battery lifecycle management, maintaining an adaptable data model remains essential. Ongoing surveillance of policy developments will ensure the platform's architecture is readily aligned with future requirements.
- **Exploring Real-World Data Simulations**: Instead of pursuing immediate large-scale production deployment, carefully designed data simulations will be conducted to replicate operational scenarios. These simulations will help assess whether blockchain integration delivers tangible benefits in transparency, compliance, and cross-stakeholder communication.

In addition, roles for maintenance personnel and regulatory authorities, already defined at the smart contract level, have yet to be fully realized in the graphical interface. Time constraints have limited their implementation, but upcoming iterations will incorporate these roles into the UI to reinforce the platform's comprehensive role-based model. Aligning these additions with the enhanced analytics and interoperability features described above will ensure a robust, end-to-end solution for managing the battery lifecycle.

By prioritizing these objectives, the BPP will continue to evolve as a well-rounded, technical solution that not only aligns with the iterative insights from D2.8 – Battery Passport Platform (Version I) but also responds effectively to the sustainability and efficiency demands in modern battery management.

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