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Deliverable D2.8

Battery Passport Platform (Version I)

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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

D3.3 - Battery Passport Platform (Version I)

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Versions

DATE	VERSION	AUTHOR	COMMENT
2024-07-09	1	Aleix Vila	first draft of the document
2024-08-13	2	Aleix Vila	corrections added to the document
	3		final document

Content

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List of Abbreviations

ACRONYMS	DESCRIPTION
LIBs	Lithium-Ion Batteries
EVs	Electric Vehicles
BP	Battery Passport
BPP	Battery Passport Platform
EOL	End of Life
BOL	Beginning of Life
TRL	Technology Readiness Level
API	Application Programming Interface
UI	User Interface
QR	Quick Response
FR	Functional Requirement
OBJ	Objective
HTML	Hypertext Markup Language
CSS	Cascading Style Sheets
JS	JavaScript
HTTP	Hypertext Transfer Protocol
URL	Uniform Resource Locator
JSON	JavaScript Object Notation
TS	Typescript

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Executive summary

The burgeoning environmental impact from traditional 'take, make, dispose' economic models, particularly in the mobility sector, is undergoing a critical transformation driven by the advent of electric vehicles (EVs). Despite this progress, Lithium-Ion Batteries (LIBs), essential for EVs, continue to present significant environmental challenges. Current recycling technologies such as pyro-metallurgy, while prevalent, are highly energy-intensive and contribute to environmental degradation. On the other hand, emerging hydrometallurgical processes offer a less energy-intensive solution but are hindered by their complexity and the lengthy series of operations they require.

In response, the FREE4LIB project seeks to develop new, sustainable technologies aimed at enhancing the efficiency of recycling processes at a technology readiness level (TRL) of 5-6. These technologies are designed to improve the recovery rates of critical raw materials from end-of-life (EOL) LIBs and introduce innovative recycling solutions that enhance the availability of secondary resources within the EU. A pivotal element of this initiative is the development of the Battery Passport Platform (BPP), leveraging blockchain technology to ensure robust data integrity and lifecycle traceability of LIBs.

This document presents the initial deployment of the Battery Passport Platform, detailing the development and validation of two distinct prototypes. The first prototype was a foundational version designed to validate the core technologies involved, including blockchain, smart contracts, and a basic API. It featured a simple data model and demonstrated the basic functionalities necessary to manage battery lifecycle data. The second prototype built upon this foundation, incorporating feedback from stakeholders to enhance the data model, develop advanced smart contracts, and introduce a more interactive user interface.

The development of these two prototypes, spearheaded by EURECAT and supported by a consortium including AVL, UNIGRAZ, CARTIF, ERION, and IREC-CERCA, has been crucial in iterating and refining the platform. The Battery Passport Platform integrates sophisticated data management and blockchain technologies to provide a digital identity for each battery, thereby linking critical battery components from the beginning of life (BOL) to EOL. These prototypes lay the groundwork for a scalable, secure framework that can support complex, data-driven decision-making processes and automate tasks through smart contracts.

The Battery Passport Platform represents a foundational step towards achieving the ambitious goals of the FREE4LIB project. It embodies a strategic approach to battery lifecycle management, aiming to enhance material recovery processes and facilitate a shift towards a sustainable,

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circular economy. This executive summary outlines the design, development, and validation phases of the platform, setting the stage for further enhancements in future versions. This document is intended to inform project stakeholders and partners about the progress and strategic direction of the BP initiative.

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1. Introduction

1.1 Background

The FREE4LIB project, formally known as "Feasible Recovery of critical raw materials through a new circular Ecosystem FOR a Li-Ion Battery cross-value chain in Europe," is an ambitious Horizon Europe-funded initiative aimed at enhancing the recycling processes of Lithium-Ion Batteries (LIBs). These batteries are pivotal to the advancement of electric vehicles (EVs), which are critical in transitioning away from traditional combustion engines in the mobility sector. Despite their environmental benefits, the lifecycle management of LIBs presents significant challenges, primarily due to the environmental burdens associated with their current recycling processes.

A critical innovation within FREE4LIB is the development of the BPP, utilizing blockchain technology to ensure robust data integrity and lifecycle traceability of LIBs. This platform is part of a broader strategy to integrate environmental and social sustainability perspectives into battery passports, as explored in Work Package 5 (WP5). BPs, conceptualized in Task 5.4, represent a novel approach to product information management. They are envisioned to transition from static to dynamic systems, potentially acting as digital twins that provide real-time updates on a battery's charge levels, health status, and usage history.

The concept of a Digital Battery Passport (DBP) is specifically tailored for LIBs within the project. It is envisaged as a digital platform where not just conventional product data but extensive production chain details, sustainability information, and end-of-life data are accessible to various stakeholders including consumers, producers, and recyclers. The DBP is seen as a crucial initiative for establishing a systematic framework for information sharing and enhancing transparency throughout the battery value chain.

1.2 Motivation

The transition towards a sustainable, circular economy in the mobility sector is imperative to mitigate the environmental impacts of traditional transportation methods. This shift is critically underscored by the European Union's ambitious targets set forth in the Green Deal, which aims to render Europe climate-neutral by 2050. Central to achieving these targets is the

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optimization of the lifecycle management of Lithium-Ion Batteries (LIBs), which are integral to the proliferation of electric vehicles (EVs).

LIBs, while instrumental in reducing vehicular emissions, pose significant environmental challenges at their end-of-life stage due to the traditional linear 'take, make, dispose' model of consumption. Current recycling technologies, though functional, fall short in terms of energy efficiency and environmental sustainability. The need for a transformational approach in recycling practices is thus evident, aiming to maximize material recovery, minimize energy consumption, and reduce the overall carbon footprint of these processes.

The FREE4LIB project is motivated by the necessity to develop and deploy innovative recycling technologies that not only enhance the recovery of critical raw materials from EOL LIBs but also integrate seamlessly into a new BP system. This system is envisioned to change the way information about LIBs is managed across their lifecycle, facilitating a transparent, traceable, and efficient circular economy model.

The development of the BPP within this framework serves several key purposes:

1. **Enhancing Traceability**: By leveraging blockchain technology, the platform provides an immutable, secure record of each battery's history, from production through to recycling. This traceability is crucial for verifying the authenticity of raw materials and ensuring compliance with environmental standards.

2. **Supporting Decision Making**: The dynamic capabilities of the platform, akin to a digital twin, offer real-time data on battery health, usage, and potential for reuse or recycling. This information is pivotal for stakeholders to make informed decisions about battery life extension, reuse, and optimal recycling strategies.

3. **Facilitating Regulatory Compliance**: As regulatory frameworks around battery recycling evolve, the platform will enable stakeholders to stay compliant with new regulations and standards by providing necessary documentation and data effortlessly and transparently.

4. **Promoting Stakeholder Collaboration**: By providing a shared platform that encompasses all phases of the battery's lifecycle, the BP facilitates collaboration among manufacturers, consumers, recyclers, and regulatory bodies, ensuring that all parties have access to critical information that enhances sustainability practices.

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The motivation for the BPP thus lies in its potential to act as a catalyst for change, driving forward the principles of a circular economy in the battery sector and supporting the EU's broader environmental and economic goals.

1.3 Task Description

Task 2.4 of the FREE4LIB project, titled "Battery Passport Deployment," is a critical element of Work Package 2, focused on enhancing the traceability and sustainability of Lithium-Ion Batteries (LIBs) through their lifecycle. This task involves the design, development, and deployment of the BPP, utilizing advanced data management and blockchain technology to ensure comprehensive and secure tracking of LIBs from their beginning of life (BOL) to end of life (EOL).

The initial phase, led by EURECAT along with partners AVL, UNIGRAZ, CARTIF, ERION, and IREC-CERCA, centres on the architectural design of the platform. This phase encompasses establishing a robust data model to handle diverse information needs, developing an API[1] for seamless integration with existing systems, and implementing blockchain technology to guarantee data integrity, security, and transparency.

Following design and development, the platform undergoes integration testing with existing processes and systems integral to battery lifecycle management, ensuring operational harmony within the distributed environment of the FREE4LIB project. Concurrently, an analytical assessment led by AVL evaluates the platform’s data handling capabilities, focusing on optimizing battery reuse or recycling timing and maximizing energy efficiency across the battery's lifecycle.

The final phase involves validating the BPP through pilot testing with real-world data and scenarios, ensuring its effectiveness in enhancing the traceability and sustainability of LIBs. Feedback from this phase is critical for refining the platform in preparation for subsequent versions and broader deployment.

The deliverables for this task include:

- **D2.8 Battery Passport Platform (version I)**: This deliverable is the initial deployment of the platform, documenting the design, integration, and preliminary testing results.

[1] https://en.wikipedia.org/wiki/API

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- **D2.9 Battery Passport Platform (version II and III)**: Subsequent versions will incorporate enhancements based on feedback and additional functionalities to improve platform performance and user experience.

Through Task 2.4, the FREE4LIB project aims to establish a BPP that supports the circular economy by improving recycling rates and material recovery, while facilitating a shift in how battery lifecycle data is managed across the European Union.

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2. Rationale for Using Blockchain Technology

In the evolving landscape of digital transformation, blockchain technology has emerged as a cornerstone for enhancing transparency, security, and efficiency in various industries. Blockchain is a decentralized digital ledger technology that records transactions across a network of computers in a secure, transparent, and immutable manner, meaning that once data is recorded, it cannot be altered or deleted, making it ideal for ensuring data integrity and trust in various applications. Its application within the scope of the FREE4LIB project is particularly pertinent given the complex requirements for data integrity and traceability in the lifecycle management of Lithium-Ion Batteries (LIBs). As the demand for sustainable and circular economy practices intensifies, particularly in the battery sector, blockchain stands out as a transformative technology capable of addressing several key challenges. As illustrated in Figure 1, the key features of blockchain—decentralization, transparency, immutability, and security—are crucial for the effective management of battery lifecycle data.

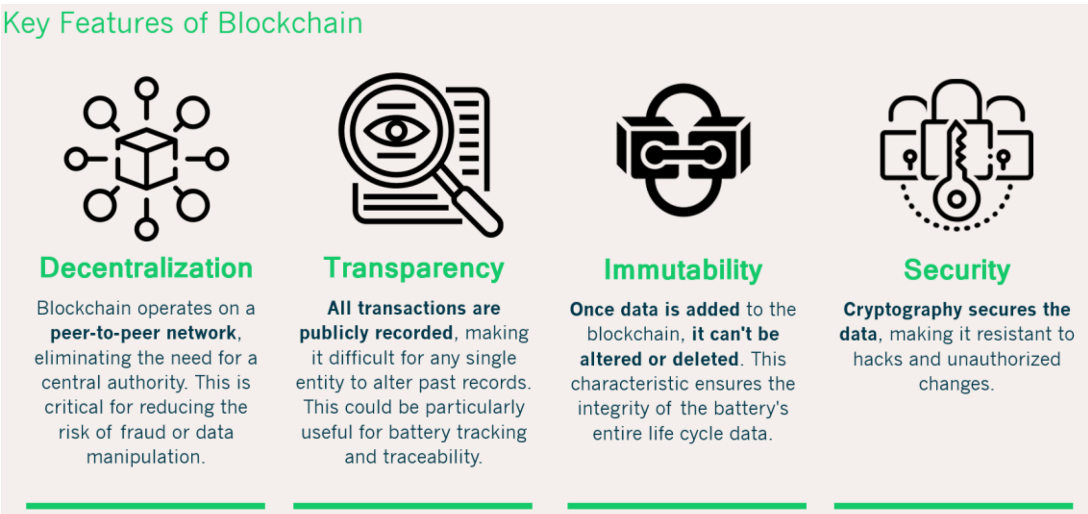

Figure 1: Key features of Blockchain Technology[2]

Blockchain technology is not just a tool for financial transactions but a robust framework for decentralized data management. It offers an immutable ledger

[2] Source: Author

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of transactions, which is crucial for the traceability of materials and compliance with stringent environmental regulations. In the context of the FREE4LIB project, using blockchain technology helps to ensure that every piece of data related to the battery's lifecycle—from manufacturing through to recycling—is securely recorded and easily verifiable. This capability is essential for creating a transparent supply chain that stakeholders can trust and depend upon.

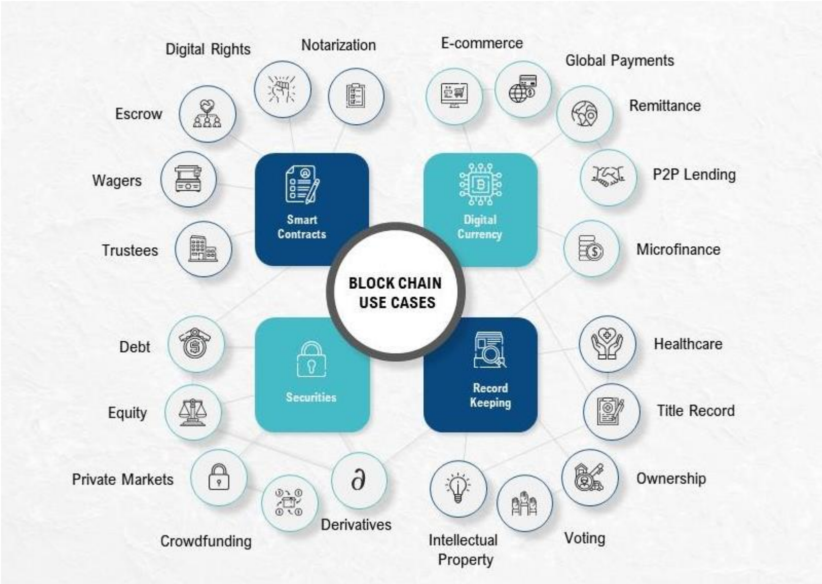

Figure 2: Blockchain different use cases.[3]

As illustrated in Figure 2, blockchain technology has a wide range of use cases beyond financial transactions, including smart contracts, digital currency, and record keeping. The application of blockchain in the BPP is designed to address specific needs in battery lifecycle management by providing a comprehensive, tamper-proof record of battery data. This includes detailed information on material origins, manufacturing processes, usage history, and recycling data. Such a detailed and secure record is instrumental in promoting accountability and sustainability in the battery industry, ensuring that all stakeholders—manufacturers, consumers, recyclers, and regulatory bodies—have access to reliable and unalterable data.

This section will delve deeper into the specific benefits of blockchain technology for the BPP, highlighting how it facilitates the implementation of circular economy principles in the battery value chain, and supports the broader goals of environmental sustainability and economic efficiency within the European Union.

[3] Source: https://mavink.com/explore/Blockchain-Use-Case-Diagrams

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2.1 Benefits of blockchain for battery passports

Blockchain technology offers several distinct advantages that make it particularly suited for the implementation of BPs in the context of the FREE4LIB project. These benefits are critical in addressing the challenges associated with the lifecycle management of Lithium-Ion Batteries (LIBs), especially in enhancing transparency, security, and the facilitation of a circular economy.

Common Infrastructure for Information Sharing: One of the foundational benefits of employing blockchain technology in BPs is its ability to serve as a common infrastructure that standardizes data across different entities. This unified platform facilitates seamless integration between diverse systems and databases used by various stakeholders in the battery value chain. By using a single, shared ledger, companies involved in the manufacture, use, and recycling of batteries can easily and securely access and exchange information, significantly reducing the complexities and inefficiencies associated with using disparate systems.

Enhanced Traceability and Transparency: One of the primary benefits of using blockchain in BPs is the ability to maintain a comprehensive and immutable ledger of all transactions and interactions associated with each battery. This traceability extends from the extraction of raw materials to manufacturing, usage, and recycling stages. Blockchain's inherent transparency ensures that all stakeholders in the value chain, including manufacturers, consumers, recyclers, and regulators, have access to the same verified data, reducing disputes and increasing trust.

Improved Security and Data Integrity: Blockchain's decentralized nature makes it highly resistant to tampering and fraud. Each transaction recorded on the blockchain is encrypted and linked to the previous transaction, creating a secure and unalterable chain of data. For BPs, this means that every piece of data related to the battery's provenance, performance, and end-of-life handling is protected from unauthorized alterations, ensuring that the data remains accurate and reliable over the battery's lifecycle.

Facilitation of Regulatory Compliance: As regulatory requirements for battery production and disposal become more stringent, compliance becomes increasingly complex and critical. Blockchain technology simplifies compliance by providing a transparent and auditable trail of all necessary documentation and data. Regulators can easily verify compliance through the blockchain without the need for extensive audits, saving time and resources while ensuring that all standards are met.

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Automation of Processes through Smart Contracts: Blockchain facilitates the use of smart contracts, which are self-executing contracts with the terms of the agreement directly written into code. In the case of BPs, smart contracts can automatically enforce agreements related to warranty, recycling responsibilities, and other lifecycle events based on the data recorded on the blockchain. This automation not only reduces administrative overhead but also speeds up processing times, enhancing efficiency across the battery's lifecycle.

Support for Circular Economy Initiatives: By providing a reliable and secure method for tracing battery components and materials, blockchain technology supports the principles of the circular economy. It enables more effective recycling and reuse strategies by ensuring that accurate information about the battery's materials and condition is readily available. This facilitates the recovery of valuable materials and supports the sustainable reuse of battery components, contributing to reduced environmental impact and enhanced resource efficiency.

Challenges in Implementing Blockchain for BPs

Technical Complexity and Integration Challenges: Integrating blockchain technology with existing IT systems can be technically complex. Establishing interoperability between legacy systems and new blockchain solutions requires significant technical expertise and can lead to substantial initial setup costs.

Scalability Concerns: While blockchain provides numerous benefits, its scalability remains a challenge, especially in environments requiring high transaction throughput. The technology must be capable of handling the volume of data generated by entire networks of batteries without compromising performance.

Energy Consumption: The energy consumption associated with certain types of blockchain, particularly those that use proof-of-work (PoW) consensus mechanisms, can be substantial. This could counteract some of the environmental benefits that battery recycling seeks to achieve, making the choice of blockchain architecture crucial.

Regulatory Uncertainty: As blockchain is a relatively new technology, regulatory frameworks around its use are still evolving. This can lead to uncertainties, particularly regarding data privacy, cross-border data flows, and compliance with global standards.

Cost Implications: The cost of implementing and maintaining a blockchain infrastructure can be significant. These costs include not only initial

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deployment, but also ongoing expenses related to network maintenance, updates, and security measures.

Stakeholder Collaboration and Adoption Hurdles: For a blockchain-based BP to be effective, it requires widespread adoption by all stakeholders in the battery lifecycle. Achieving this consensus and collaboration, especially in a competitive industry with diverse interests, can be challenging.

Change Management and Training Needs: Implementing a blockchain system requires change management to ensure that all users are trained and comfortable with the new technology. There may be resistance to adopting new processes, and significant effort must go into managing the transition.

While blockchain technology significantly enhances the traceability, security, and efficiency of battery lifecycle management through the BPP, it is not without its challenges. The implementation of this technology faces several hurdles, including technical complexities, scalability concerns, significant energy demands, regulatory uncertainties, and potentially high costs. Furthermore, achieving broad adoption across diverse stakeholders and managing the transition effectively necessitates extensive collaboration and commitment.

Successfully addressing these challenges requires careful planning, robust stakeholder engagement, and ongoing management to ensure that the benefits of blockchain technology can be fully realized without compromising the overarching goals of environmental sustainability and economic efficiency in the battery industry. By navigating these obstacles thoughtfully, the FREE4LIB project can harness blockchain's potential to foster a more sustainable and circular economy for Lithium-Ion Batteries.

2.2 Selection of the blockchain network for the prototypes

The selection of an appropriate blockchain network for the BPP prototypes is a critical decision that hinges on a variety of factors, including compatibility with existing technologies, scalability, energy efficiency, and ease of integration. Given that the platform's smart contracts are developed using Solidity[4], the network chosen must be compatible with the Ethereum Virtual Machine (EVM) to ensure seamless operation and deployment of these contracts.

[4] https://soliditylang.org/

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EVM Compatibility: Solidity is a programming language specifically designed for developing smart contracts on the Ethereum blockchain, which operates on the EVM. Therefore, the blockchain network selected for the BPP must support EVM to allow for the direct deployment and execution of these Solidity-based contracts. This requirement significantly narrows the choice of suitable blockchain networks.

Scalability and Performance: Considering the scalability concerns mentioned earlier, the network must handle a substantial number of transactions and data entries efficiently. Many EVM-compatible blockchains have implemented various scaling solutions that could potentially address these needs. The network must demonstrate the capability to scale as the number of BPs and associated transactions grows.

Energy Efficiency: The environmental impact of blockchain technology, particularly the energy consumption associated with networks that use proof-of-work (PoW) consensus mechanisms, is a crucial consideration. To align with the sustainability goals of the FREE4LIB project, the selected network should ideally employ a more energy-efficient consensus mechanism like proof-of-stake (PoS) or an equivalent that reduces the overall energy footprint.

Cost Effectiveness: The operational costs associated with transactions on the blockchain — commonly referred to as "gas fees" — are an important factor, especially during the testing and development phases. Networks with lower transaction fees are preferable to keep the project costs manageable.

Test Network Availability: For the initial development and testing phases, the availability of a robust test network is essential. This allows developers to test new features, smart contracts, and integrations without incurring high costs or risking significant disruptions on a live network.

Network Security and Maturity: The maturity and security of the blockchain are paramount to prevent vulnerabilities in the smart contracts and to ensure the integrity and security of the data recorded on the blockchain. A well-established network with a strong track record of security and community support is desirable.

Considering these factors, Ethereum and its test networks (like Ropsten, Rinkeby, and Goerli) emerge as the leading candidates due to their widespread adoption, extensive developer support, and continuous improvements in scalability and efficiency. However, for a project focusing on sustainability and cost efficiency, networks like **Polygon**[5] or **Binance Smart**

[5] https://polygon.technology/

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Chain, which are EVM-compatible and offer lower energy consumption and transaction costs, also present viable alternatives.

2.2.1 Understanding Blockchain Types: Public, Private, and Hybrid

Public Blockchains are decentralized and non-restrictive, allowing anyone to participate and view all transactions. Examples include Bitcoin and Ethereum. They offer high transparency and security but can suffer from scalability issues and higher transaction costs due to the energy-intensive nature of their consensus mechanisms.

Private Blockchains are centralized within one organization or a consortium, restricting participation to only those who are permitted. This setup allows for faster transactions and greater scalability at lower costs but at the expense of decentralization, potentially reducing security and transparency.

Hybrid Blockchains combine elements of both public and private systems. They enable controlled access and permissioned features alongside public transparency for certain parts of the blockchain. As shown in Figure 3, hybrid blockchains are particularly suitable for organizations that require both privacy for internal data and transparency for compliance or public verification.

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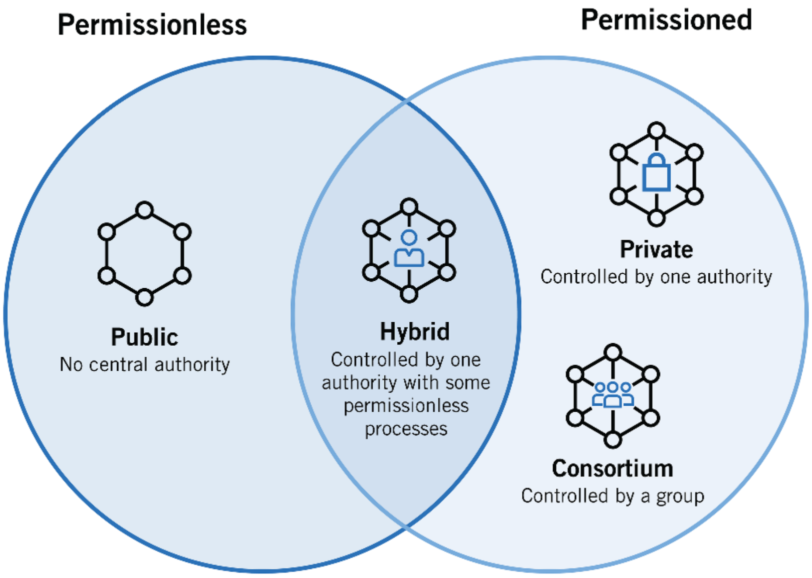

Figure 3: Types of Blockchain.[6]

2.2.2 Why Consider Polygon?

Polygon (formerly Matic Network) stands out among EVM-compatible blockchains due to several key advantages (Figure 4):

Figure 4: Polygon Blockchain logo.

- **Scalability**: Polygon provides enhanced scalability through a multi-chain system. It uses a Layer 2 scaling solution that operates on top of the Ethereum network, helping to manage large volumes of transactions efficiently, which is crucial for the BPP as it scales.
- **Lower Transaction Costs**: By processing transactions off the main Ethereum chain, Polygon significantly reduces gas fees, making it cost-effective for testing and frequent transactions, a critical consideration during the prototype phase.

[6] Source: https://www.simplilearn.com/ice9/free_resources_article_thumb/Types_of_Blockchain_4.png

- **High Throughput**: The network can handle more transactions per second than Ethereum's main chain, addressing potential bottlenecks as the number of BPs increases.
- **Energy Efficiency**: While still leveraging the security of Ethereum, Polygon's Layer 2 solutions consume less energy per transaction, aligning with the environmental sustainability goals of the FREE4LIB project.
- **Developer Community and Support**: Polygon has a robust developer community and a wealth of resources, making it easier to find solutions and support for developing and maintaining the BPP.

2.2.3 The Case for Hybrid Blockchain in BPs

A hybrid blockchain could be particularly advantageous for the BPP for several reasons:

- **Regulatory Compliance**: It can maintain sensitive data (like proprietary battery composition or detailed user data) on a private ledger while recording transactional data (like battery recycling or change of ownership) on a public ledger, helping to meet varying regulatory requirements across jurisdictions.
- **Controlled Accessibility**: Key stakeholders such as battery manufacturers, recyclers, and regulatory bodies can be given different levels of access and permissions, enhancing data security while still providing necessary transparency.
- **Customizability**: Hybrid blockchains offer flexibility to customize features according to specific needs of the battery lifecycle management, allowing for a tailored approach to data sharing and process automation.

2.2.4 Conclusion

This section is not intended as an exhaustive study of all available blockchain platforms but rather serves to justify the choice of Polygon as a well-suited option for the initial deployment of the BPP prototypes. Polygon is selected based on its ability to enhance scalability, reduce transaction costs, and improve energy efficiency, which aligns with the operational needs and sustainability goals of the FREE4LIB project at this developmental stage.

While Polygon offers a compelling combination of features for the project's current requirements, it is acknowledged that other blockchain solutions might also be suitable. **As the project evolves, particularly with increasing needs for enhanced privacy, role management, and differentiated data**

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accessibility, incorporating a hybrid blockchain model will be considered. This approach would ideally balance the need for privacy and control with the imperative for transparency and compliance, making it a strategic fit for future iterations of the BPP as regulatory and operational landscapes evolve.

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3. Development of First Prototype

The development of the first prototype for the FREE4LIB BPP marked a pivotal step in validating and demonstrating the practical application of blockchain technology within the lifecycle management of Lithium-Ion Batteries (LIBs). Initiated for the Brussels General Assembly in October, this prototype was specifically designed to test the integration of a robust API, smart contracts, and a simple user interface, all deployed on the Polygon blockchain network.

The primary objectives of this prototype were to validate the technological components involved in battery passporting, simulate the battery's lifecycle stages from production through recycling in a simplified manner, and test role-based access control functionalities. This prototype served not only as a technical demonstration but also as a foundational experiment to assess the interaction between various system components under real-world-like conditions.

Key elements of this prototype included a straightforward API to handle data transactions, smart contracts for enforcing role-based permissions and tracking battery states, and a basic HTML[7] interface for visualizing BPs. The design kept the data model intentionally simple, focusing on demonstrating core functionalities rather than complexity, thus ensuring clarity in the validation of each component's effectiveness.

The following sections will delve deeper into each key element of the platform, outlining the technical specifics of the API, the structure and roles defined in the smart contracts, and the features of the user interface. This detailed exploration will also cover the initial validation processes applied to test the system's functionality and the role management within the prototype environment.

3.1 Description of the prototype

The first prototype of the BPP was developed with several specific objectives aimed at testing the feasibility and functionality of a blockchain-based system for managing the lifecycle of Lithium-Ion Batteries (LIBs). The primary objectives were:

[7] https://en.wikipedia.org/wiki/HTML

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1. **Technology Validation (Objective ID: OBJ-01)**: To validate the integration of core technologies—blockchain, smart contracts, and APIs—ensuring that they function effectively together to create a secure and robust platform for battery passporting.

2. **Lifecycle Simulation (Objective ID: OBJ-02)**: To simulate the different lifecycle stages of a battery, including manufacturing, assembly, usage, and recycling, through a digital platform. This objective was crucial for demonstrating the platform's ability to track and manage battery data through each stage using blockchain technology.

3. **Role-Based Access Control Testing (Objective ID: OBJ-03)**: To test role-based access controls within the platform to ensure that different stakeholders—manufacturers, assemblers, recyclers, and government entities—can interact with the system in ways that are appropriate to their roles. This includes accessing, entering, and modifying data as permitted by their role definitions.

4. **Simplified Data Model Validation (Objective ID: OBJ-04)**: Although the data model was kept simple for this initial prototype, validating this model was essential to ensure it could effectively capture and handle essential battery information while supporting scalability and expansion in future iterations.

5. **Interface Usability (Objective ID: OBJ-05)**: To develop and test a simple HTML interface that allows users to easily access and visualize BP data. The interface was designed to demonstrate the practicality and effectiveness of accessing blockchain-stored data through a user-friendly web page.

6. **QR Code Integration (Objective ID: OBJ-06)**: To integrate and test QR code generation and scanning functionality that links directly to the battery's digital passport, providing a quick and easy method to access detailed battery information securely.

These objectives (Table 1) guided the development and implementation strategies for the prototype, ensuring that each component was not only tested individually but also as part of an integrated system that reflects real-world operational needs.

Table 1 Objectives of the first prototype

Objective ID	Title	Description
OBJ-01	Technology Validation	Validate the integration of blockchain, smart contracts, and APIs to ensure effective system

		functionality.
OBJ-02	Lifecycle Simulation	Simulate various stages of a battery's lifecycle, from manufacturing to recycling, using digital tracking.
OBJ-03	Role-Based Access Control Testing	Test the role-based access controls to ensure appropriate data access and modifications per user role.
OBJ-04	Simplified Data Model Validation	Validate a simplified data model to ensure it captures essential information effectively and can scale.
OBJ-05	Interface Usability	Develop and test a user-friendly HTML interface for easy access and visualization of BP data.
OBJ-06	QR Code Integration	Integrate and test QR code functionality that links directly to the battery's digital passport.

3.1.1 Functional requirements

The functional requirements of the BPP prototype are designed to ensure that the system meets its intended objectives effectively. Below is a detailed breakdown of these requirements:

1. **API Functionality (ID: FR-01)**
    - **Requirement**: The API must support operations to create, update, view, and manage BPs based on user roles.
    - **Objective Alignment**: Supports OBJ-01 (Technology Validation) and OBJ-03 (Role-Based Access Control Testing).
2. **Smart Contract Implementation (ID: FR-02)**
    - **Requirement**: Smart contracts must enforce role-based permissions and manage the state transitions of BPs from creation to recycling.
    - **Objective Alignment**: Supports OBJ-01 (Technology Validation) and OBJ-03 (Role-Based Access Control Testing).
3. **Lifecycle State Management (ID: FR-03)**
    - **Requirement**: The system must simulate the battery lifecycle, capturing state changes such as assembled, in use, and recycled.
    - **Objective Alignment**: Supports OBJ-02 (Lifecycle Simulation).

4. **Data Model Integrity (ID: FR-04)**
   - **Requirement**: The data model must capture essential battery information such as unique ID, chemical composition, dimensions, and manufacturer details.
   - **Objective Alignment**: Supports OBJ-04 (Simplified Data Model Validation).
5. **User Interface Accessibility (ID: FR-05)**
   - **Requirement**: The HTML interface must provide clear and accessible information on BPs, including QR code display.
   - **Objective Alignment**: Supports OBJ-05 (Interface Usability).
6. **QR Code Functionality (ID: FR-06)**
   - **Requirement**: QR codes must be generated for each BP and displayed on the HTML interface to link directly to detailed battery information.
   - **Objective Alignment**: Supports OBJ-06 (QR Code Integration).
7. **Role-Based Data Access (ID: FR-07)**
   - **Requirement**: The system must restrict data access and actions based on user roles such as manufacturer, assembler, and recycler.
   - **Objective Alignment**: Supports OBJ-03 (Role-Based Access Control Testing).
8. **Security and Data Privacy (ID: FR-08)**
   - **Requirement**: Ensure secure data transactions and privacy compliance, especially for sensitive battery data.
   - **Objective Alignment**: Aligns with overall system security and integrity needs.

These functional requirements are essential for the prototype to fulfill its purpose as a testbed for further development and refinement of the BPP. They ensure that the system is not only technically sound but also aligns with the practical needs and regulations of battery lifecycle management.

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Table 2: Functional requirements

ID	Functional Requirement	Description	Objective Alignment
FR-01	API Functionality	The API must support operations to create, update, view, and manage BPs based on user roles.	OBJ-01, OBJ-03
FR-02	Smart Contract Implementation	Smart contracts must enforce role-based permissions and manage the state transitions of BPs.	OBJ-01, OBJ-03
FR-03	Lifecycle State Management	The system must simulate the battery lifecycle, capturing state changes such as assembled, in use, and recycled.	OBJ-02
FR-04	Data Model Integrity	The data model must capture essential battery information efficiently and support scalability.	OBJ-04
FR-05	User Interface Accessibility	The HTML interface must provide clear and accessible information on BPs, including QR code display.	OBJ-05
FR-06	QR Code Functionality	QR codes must be generated for each BP and displayed on the HTML interface.	OBJ-06
FR-07	Role-Based Data Access	The system must restrict data access and actions based on user roles such as manufacturer, assembler, and recycler.	OBJ-03
FR-08	Security and Data Privacy	Ensure secure data transactions and privacy compliance, especially for sensitive battery data.	General system integrity

3.1.2 Data Model

The data model in the first prototype of the BPP (Table 3) is crafted to be straightforward yet effective, focusing on capturing essential elements crucial for validating the platform's functionality. This simplification is pivotal, allowing the prototype to demonstrate the core capabilities of the platform without the complexities of an advanced data structure, which is planned for future development.

Core Components of the Data Model:

The heart of the data model is the BatteryInfo struct, which records all pertinent details about each battery. It encompasses identifiers like a unique ID and timestamps, physical characteristics such as chemical composition and dimensions, and tracks the various stages of the battery's lifecycle through status updates such as Created, Assembled, In Use, and Recycled.

To enhance the depth and applicability of the data stored, the model includes descriptors that categorize data based on its sensitivity, granularity, certainty, and relevance. These descriptors are instrumental in managing how data is displayed or accessed depending on the user's role and permissions within the system.

Table 3: First prototype data model

	Data Model

Prototype 1	{
	"uniqueID": "AB123456",
	"timestampLocation": "2023.08.02-Graz-Austria",
	"composition": "25% copper, 75% Aluminum",
	"dimensions": "5x10x20 cm",
	"manufacturer": "0x432476E646F4E4058170f449d6F90455e1509304",
	"manufacturerDetails": "ID1234-Tokyo-Japan-Machining",
	"assemblerDetails": "FREE4LIB-Brussels",
	"userLocation": "Barcelona, Spain",
	"stateOfHealth": "Good",
	"userAnonymousID": "User1234",
	"state": "InUse",
	"descriptor": {
	"sensitivity": "Restricted",
	"granularity": "Detailed",
	"certainty": "Sure",
	"relevance": "VeryImportant"
	},
	"qrCode":
	"data:image/png;base64,iVBORw0KGgoAAAANSUhEUgAAAKQAAACkCAYAAl"
	}

Role management is embedded directly into the data model, with defined roles such as manufacturer, assembler, recycler, and government entity. Each role is equipped with specific permissions that regulate interactions with the data, ensuring operations within the platform adhere to strict security protocols and governance rules.

3.2 Key elements of the platform

The first prototype of the FREE4LIB BPP is underpinned by several core technologies that ensure its functionality and robustness. This section delves into the key components that constitute the backbone of the platform, including the API, smart contracts, and the user interface. Each of these components plays a crucial role in managing the lifecycle of Lithium-Ion

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Batteries (LIBs) and ensuring secure, transparent interactions among various stakeholders.

API: Developed using TypeScript[8] and ExpressJS[9], the API facilitates the platform's communication with the blockchain and serves as the interface through which users interact with the battery data. Integrated with Swagger[10], the API provides a well-documented, user-friendly interface that promotes ease of use and ensures consistency across different user interactions.

Smart Contracts: Written in Solidity and managed with the Truffle Suite[11], the smart contracts are essential for enforcing the business logic of the BPs. They handle role-based access control, manage state transitions of battery statuses, and ensure that all transactions are immutable and verifiable.

User Interface: A simple, yet functional HTML interface, enhanced with QR code functionality, allows end-users to visualize BP data seamlessly. This interface not only supports the easy retrieval of data but also aids in the practical demonstration of the battery's lifecycle and status updates in real time.

This combination of technologies ensures that the BPP is not only functional but also scalable and secure. The following subsections will provide a detailed examination of these key components, highlighting their development, functionality, and the role they play in achieving the objectives of the prototype.

3.2.1 API

The API for the BPP serves as the central interface through which all interactions between users and the blockchain are mediated. Developed using modern and efficient web technologies, the API ensures robustness, scalability, and security in handling data transactions.

Technology Stack:

- **TypeScript**: Chosen for its strong typing and object-oriented features, TypeScript enhances the development experience by providing better syntax and error checking, which leads to more reliable code.
- **ExpressJS**: This lightweight and flexible Node.js web application framework is used to build the API. It simplifies the routing and

[8] https://www.typescriptlang.org/
[9] https://expressjs.com/
[10] https://swagger.io/
[11] https://archive.trufflesuite.com/

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middleware setup, making it easier to manage the HTTP[12] requests and responses.

- **Swagger**: Used for documenting the API (Figure 5), Swagger allows for easy testing and interaction by users and developers. It defines clear, executable documentation of API methods, required parameters, and other information necessary to interact with the API effectively.

Features:

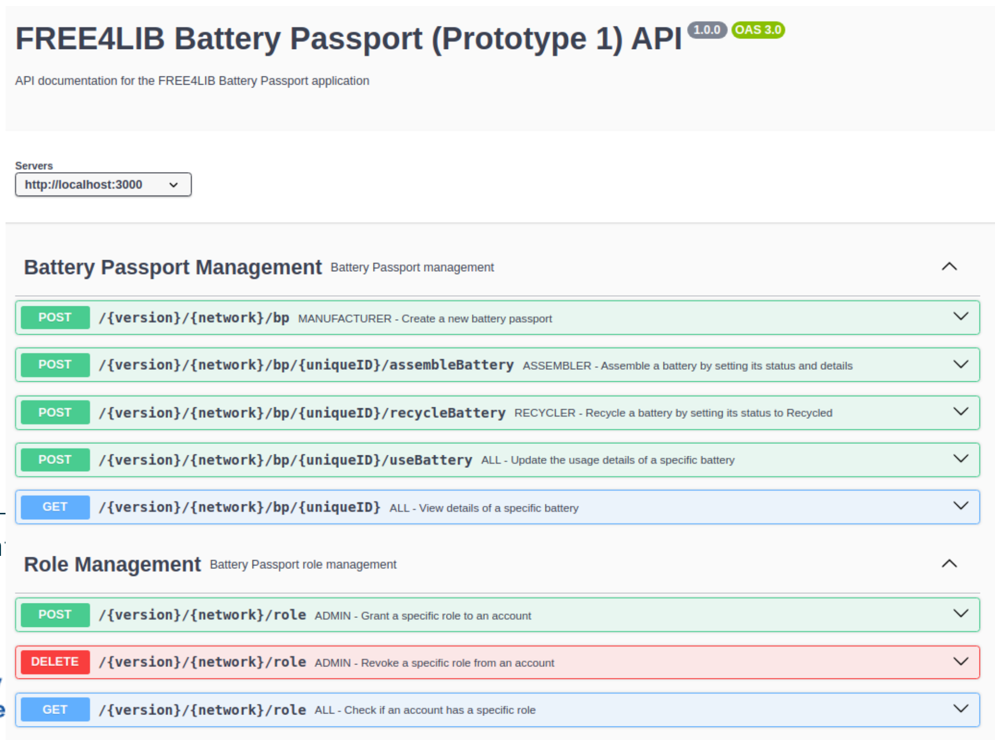
- **Role-Based Access Control**: The API integrates role-based access control within its endpoints, specifying which roles can perform certain actions. This is crucial for ensuring that only authorized users can execute sensitive operations, such as creating or modifying battery data.

- **Data Validation and Sanitization**: Leveraging express-validator, the API includes robust validation to ensure that incoming data meets the expected formats and types before processing. This helps prevent common web security issues such as SQL injection and cross-site scripting (XSS).

- **Error Handling**: The API is designed to provide clear error messages and appropriate HTTP status codes when requests fail, which aids in troubleshooting and improves the user experience.

Endpoints:

The API provides a series of endpoints designed to manage the entire lifecycle of a BP efficiently. Each endpoint is tailored to specific roles within the



[12] h

system, ensuring role-appropriate access and functionalities:

Figure 5: Swagger Interface with all the endpoints

- **Create Battery Passport (POST/{version}/{network}/bp)**: This endpoint allows manufacturers to initiate a new BP. It requires details such as the battery's unique ID, chemical composition, and manufacturer information. This operation is restricted to users with the manufacturer role.

- **Assemble Battery (POST/{version}/{network}/bp/{uniqueID}/assembleBattery)**: Accessed by assemblers, this endpoint is used to update the battery's status to "Assembled" and log assembler details. It emphasizes the transition of battery status and is critical for tracking the battery through its lifecycle phases.

- **Recycle Battery (POST /{version}/{network}/bp/{uniqueID}/recycleBattery)**: This endpoint allows recyclers to update the battery's status to "Recycled," marking the final stage of the battery's lifecycle. It's a key component in promoting sustainability and ensuring the battery materials are earmarked for reuse or proper disposal.

- **Use Battery (POST /{version}/{network}/bp/{uniqueID}/useBattery)**: Available to all roles, this endpoint updates the usage details of a battery, including user location and the battery’s state of health. It supports dynamic updates to a battery's status and is essential for monitoring its condition and usage in real-time. Example shown in Figure 6.

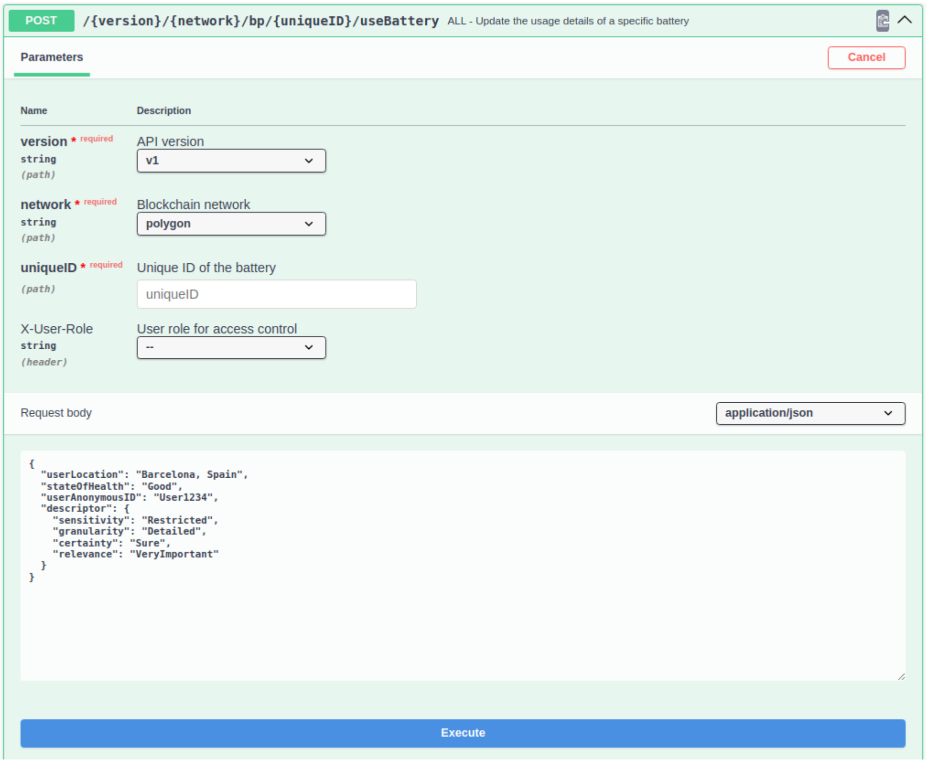


Figure 6: /use Battery endpoint example data in the Swagger Interface

- **View Battery Passport (GET /{version}/{network}/bp/{uniqueID})**: This endpoint provides detailed information about a specific BP. It is accessible to all roles and is crucial for transparency and traceability, offering a comprehensive view of the battery's history and current status.
- **Role Management Endpoints**:
    - **Grant Role (POST /{version}/{network}/role)**: Allows admin users to assign roles to various stakeholders within the system, which is fundamental for controlling access based on the user's responsibilities and needs. Example shown in Figure 7.

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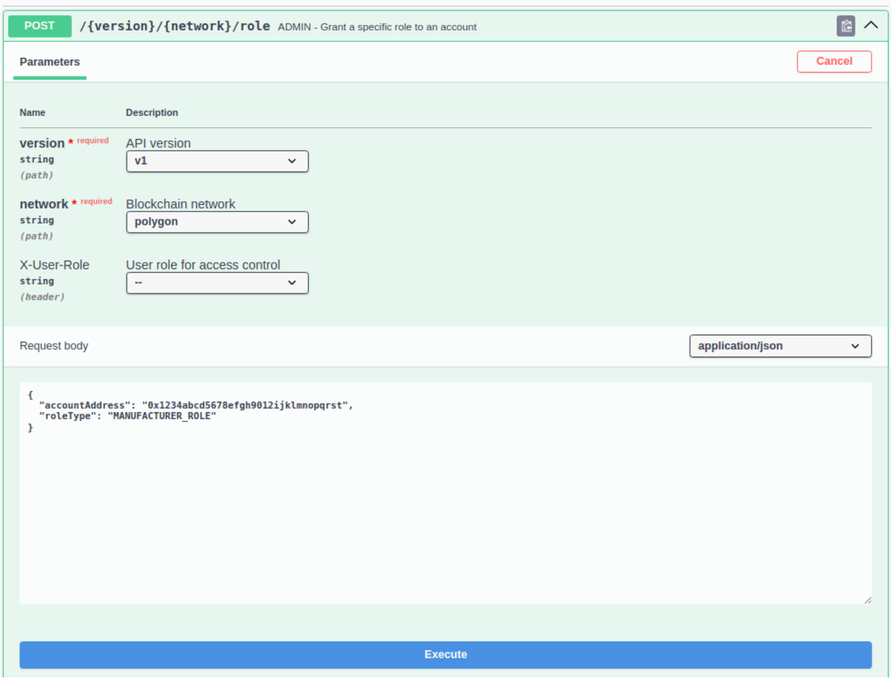

Figure 7: Grant manufacturer role example using an Ethereum address

- **Revoke Role (DELETE /{version}/{network}/role)**: Used by admins to remove roles from users, ensuring that access rights are dynamically manageable and reflect current operational requirements.
- **Check Role (GET /{version}/{network}/role)**: Enables checking whether a particular account holds a specific role, aiding in verification and role validation processes.

Security and Integration:

- **Web3 Integration**: The API uses the web3[13] library to interact directly with Ethereum-based blockchain networks like Polygon. This integration is critical for executing transactions and smart contract calls from the API.
- **QR Code Generation**: Utilizing the QR code package, the API facilitates the generation of QR codes for each BP, allowing easy access to battery information through the user interface.

Deployment:

- The API is configured to run locally during the prototype phase for ease of testing and development. This setup allows developers to

[13] https://web3js.readthedocs.io/

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rapidly test changes and ensure everything functions as expected before any live deployment.

This API architecture not only supports the fundamental operations of the BPP but also ensures that these operations are performed securely and efficiently. The use of modern web development tools and practices underpins the robustness of the API, preparing it for future scalability and more complex implementations.

3.2.2 Smart Contracts

The smart contracts for the BPP are crucial for enforcing the business logic associated with the lifecycle management of batteries. Developed using Solidity and deployed on the Polygon blockchain, these contracts handle role-based access controls, state management, and interaction records, ensuring that all transactions are secure, transparent, and immutable.

Development Framework and Tools:

- **Solidity**: The primary programming language used for writing the smart contracts, chosen for its maturity and robust support within the Ethereum developer community.
- **Truffle Suite**: Utilized for developing, testing, and deploying the smart contracts. Truffle provides a comprehensive development environment that simplifies many aspects of smart contract management.
- **OpenZeppelin Contracts**[14]: Leveraged for secure, standard implementations of common contract modules like access controls, which are critical for establishing reliable and secure smart contracts.

Key Features of the Smart Contracts:

- **Role-Based Access Control**: The contracts utilize the AccessControl module from OpenZeppelin to manage permissions across different roles such as manufacturers, assemblers, recyclers, and government entities. This setup ensures that only authorized parties can execute certain actions within the platform, aligning with the established business rules.
- **Lifecycle State Management**: The contracts define several states for a battery — Created, Assembled, InUse, and Recycled — each representing a stage in the battery's lifecycle. Transition between these

[14] https://www.openzeppelin.com/contracts

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states is strictly governed by role permissions, ensuring that the battery's status is updated correctly and transparently.

- **Data Handling and Storage**: Each battery is represented as a BatteryInfo struct, which contains detailed information including a unique identifier, chemical composition, dimensions, manufacturer details, and current status. This structured approach ensures that all relevant data is captured and maintained securely on the blockchain.
- **Event Logging**: For transparency and auditability, the contract emits events such as BatteryAdded, BatteryAssembled, BatteryInUse, and BatteryRecycled. These events help external observers or interfaces to track state changes and actions performed within the platform without direct access to the blockchain state.
- **Security Measures**: The smart contracts include checks to prevent common vulnerabilities such as reentrancy attacks and ensure that actions cannot be performed unless the caller has the appropriate role. Additionally, conditions are checked to prevent duplicate entries or unauthorized state changes.

Example Contract Functions:

- **addBattery**: Allows a manufacturer to create a new battery entry. It requires role validation and checks for the non-existence of the battery ID in the system.
- **assembleBattery**: Used by assemblers to update the battery's status to Assembled and log assembly details.
- **recycleBattery**: Enables recyclers to mark a battery as Recycled, effectively moving it to the end of its lifecycle.
- **useBattery**: Can be called by any role to update usage details such as location and health status, reflecting real-time use of the battery.

3.2.3 Interface

The user interface for the BPP in its first prototype (Figure 8) is fundamentally a simple and direct visualization tool, primarily intended to demonstrate the potential ease of accessing and presenting data stored on the blockchain. This interface showcases essential details of a battery's lifecycle, including its unique ID, composition, dimensions, and information about the stakeholders involved, such as manufacturers, assemblers, and users.

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The design of this prototype interface is minimalist, focusing on clarity and ease of use. It organizes battery data into clearly defined sections and includes a QR code for quick access, linking directly to the digital record of the battery. This functionality illustrates how seamlessly physical elements, like QR codes, can integrate with digital records, enhancing the interface's practical utility.

Figure 8: Example of the basic HTML that represents the BP.

It's important to note that this interface is developed without advanced security features or role-based access controls. At this stage, it serves as a basic representation, illustrating how data can be displayed from the blockchain without the complexities of a fully operational system. This approach ensures that the focus remains on understanding the data structure and flow rather than on the operational security measures which are critical in a production environment.

Alongside this basic HTML interface, the Swagger interface is utilized primarily for development purposes. While Swagger is a powerful tool that allows developers to test and interact with the API, it is not intended for use as a user interface within the BP system itself. Instead, it serves as a valuable

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development aid, providing clear documentation and a sandbox for testing API functionalities.

3.3 Validation

The validation process for the first prototype of the BPP was designed to ensure that all functional requirements and objectives were comprehensively tested and met. This section outlines the methodologies used and the outcomes of these validations.

Validation of Functional Requirements:

1. **API Functionality (FR-01)**:
   - **Test**: API endpoints were tested, as shown in Figure 9, for response accuracy, role-based access control, and error handling. Figure 11 provides an example of the error message encountered when attempting to create a BP without the appropriate manufacturer role.

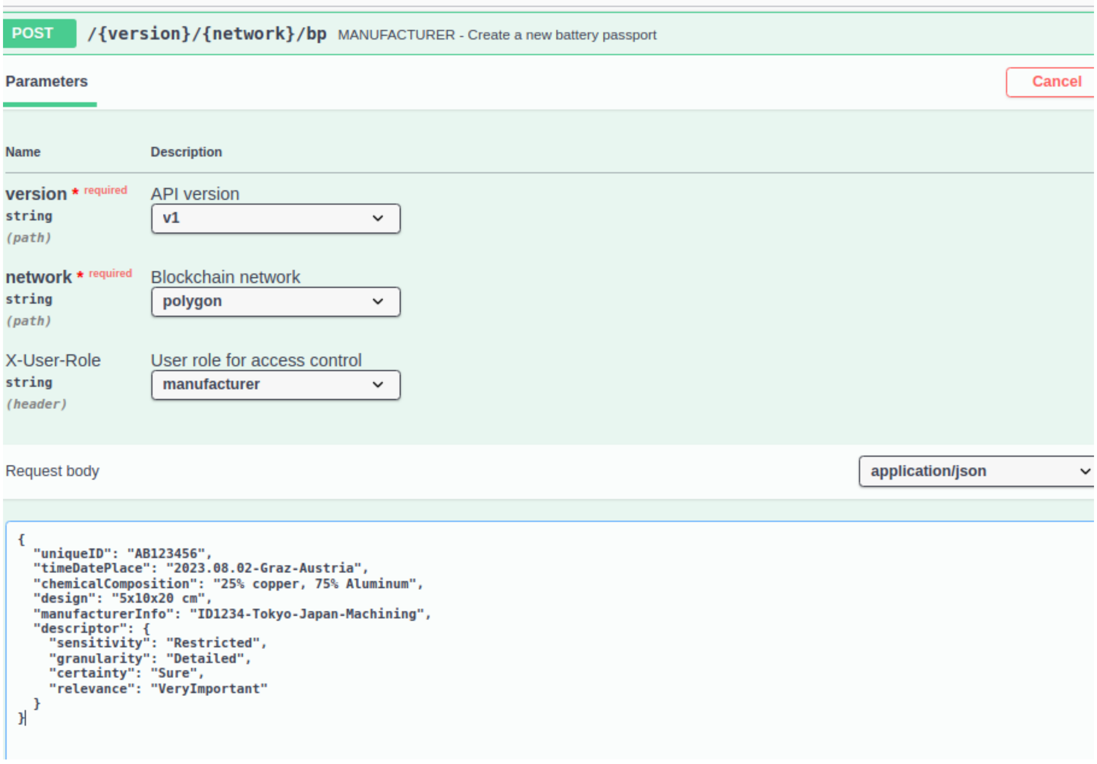

Figure 9: Example in Swagger showing how to create a BP with the manufacturer role.

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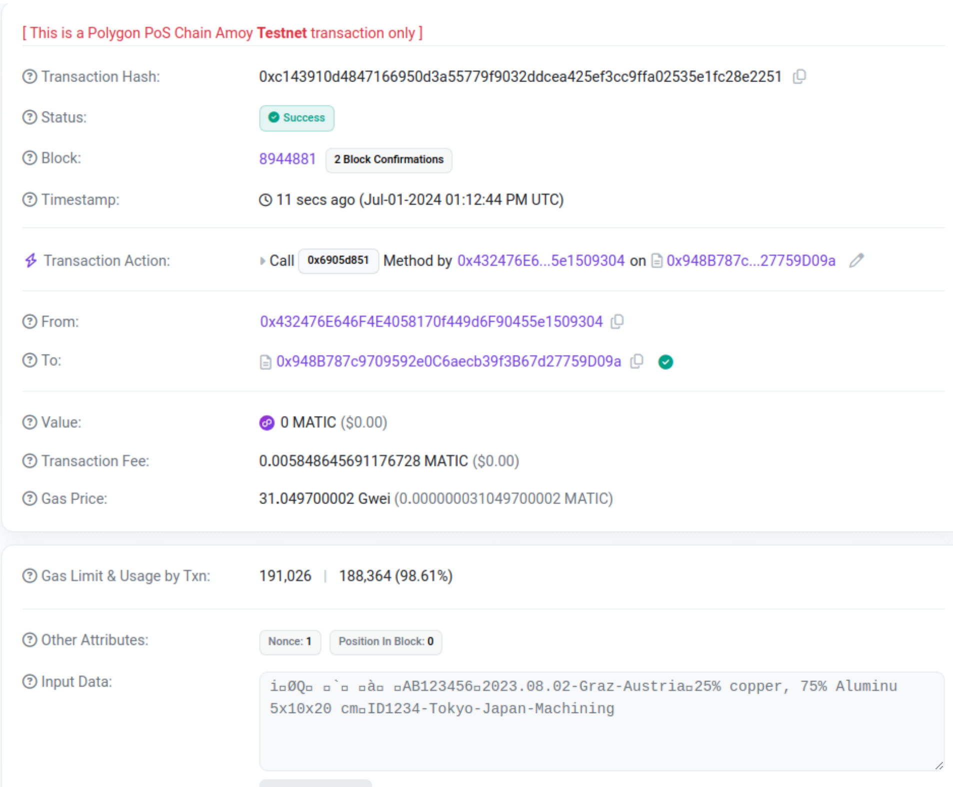

Figure 10: Screenshot of the block explorer showing the BP information on the Blockchain. URL: https://amoy.polygonscan.com/tx/0xc143910d4847166950d3a55779f9032ddcea425ef3cc9ffa02535e1fc28e2251

Figure 11: Example of the error message when you want to create a BP without the manufacturer role.

- **Outcome**: All endpoints responded correctly according to user roles, successfully managing data creation, updates, and retrieval. Figure 10 shows the successful recording of BP information on the blockchain, with a transaction viewable on the block explorer. These results confirm the achievement of **Objective OBJ-01 (Technology Validation)** and **Objective OBJ-03 (Role-Based Access Control Testing)**.

2. **Smart Contract Implementation (FR-02)**:

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- **Test**: Deployed smart contracts on the Polygon test network to validate their execution and role enforcement logic, as demonstrated in Figure 12. This figure provides a screenshot of the Blockchain's block explorer displaying the contract and its transactions.

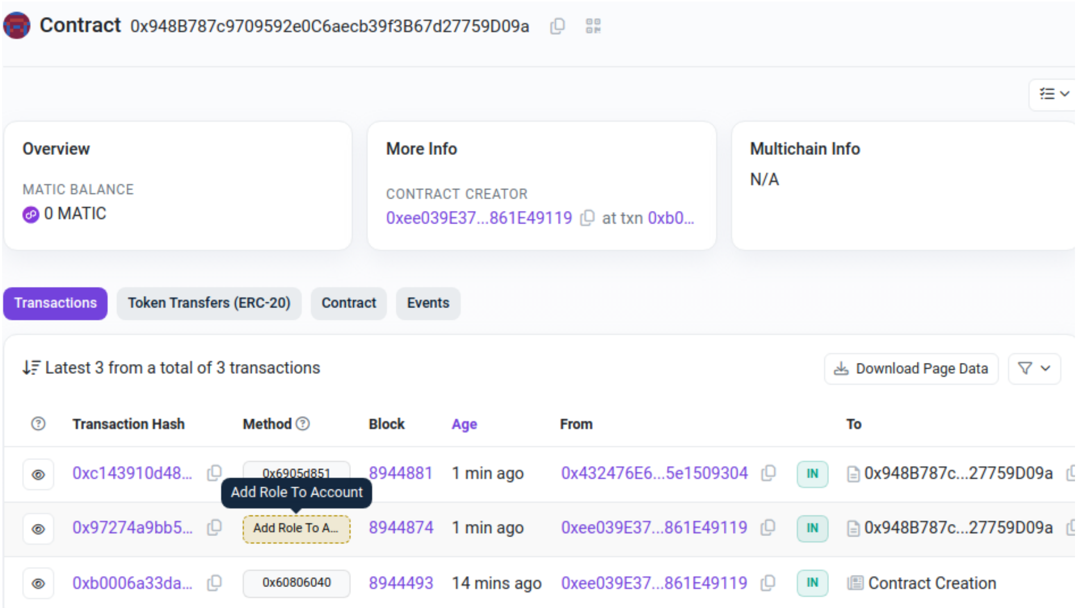

Figure 12: Screenshot of the Blockchain's block explorer showing the contract displayed and its transactions. URL: https://amoy.polygonscan.com/address/0x948b787c9709592e0c6aecb39f3b67d27759d09a

- **Outcome**: Smart contracts correctly enforced role-based permissions and managed battery states as per the lifecycle definitions, supporting **Objective OBJ-01** and **Objective OBJ-03**.

3. **Lifecycle State Management (FR-03)**:

- **Test**: Simulated the transition of a battery's state from creation to recycling to ensure accurate state management. This process was demonstrated through Figure 13, which shows an example of a GET request of the Battery Passport (BP) data using Swagger. Figure 14 illustrates the API call used to add the battery assembly data, and Figure 15 shows a subsequent GET request, reflecting how the assembler data is now included in the BP information.

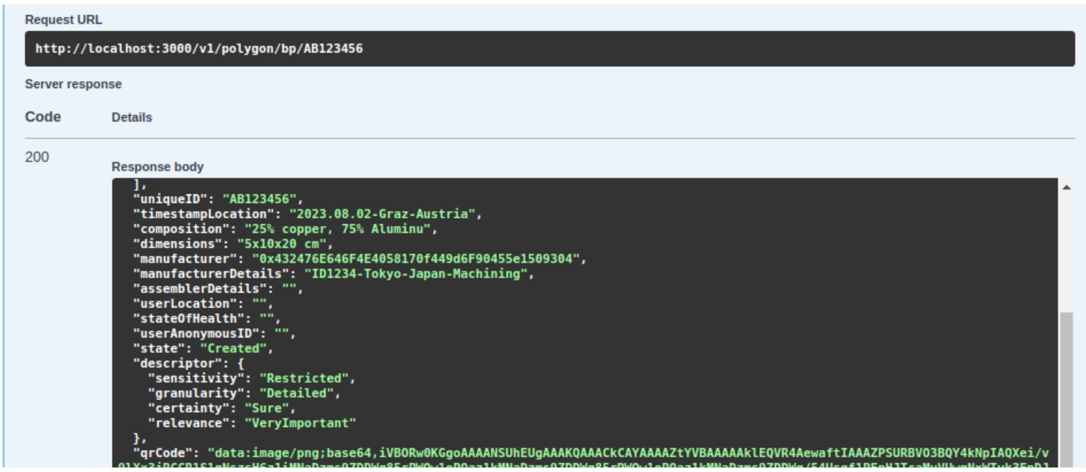

Figure 13: Example of a GET of the BP data with Swagger.

Figure 14: API call to add the battery assembly data.

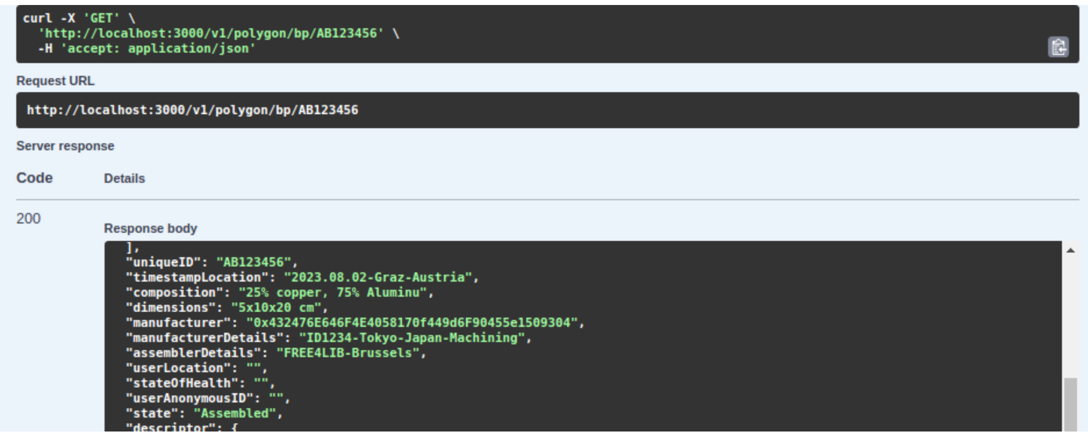

Figure 15: Second GET call from the BP to see how the assembler data is now reflected in the data.

- **Outcome**: State transitions were accurately logged and reflected in the system, verifying **Objective OBJ-02** (Lifecycle Simulation).

4. **Data Model Integrity (FR-04)**:
    - **Test**: Input and retrieval tests were conducted to ensure the integrity and accuracy of the stored data. The results of these tests are shown in the various screenshots above, including the block explorer and the data model returned by the API, such as in Figure 13, Figure 14, and Figure 15.
    - **Outcome**: The data model effectively captured and returned accurate battery information, upholding **Objective OBJ-04** (Simplified Data Model Validation).
5. **User Interface Accessibility (FR-05)**:
    - **Test**: User trials were conducted to assess the ease of navigating the interface and accessing information.
    - **Outcome**: As shown in Figure 8, users can successfully access and understand battery information through the interface, confirming **Objective OBJ-05** (Interface Usability).
6. **QR Code Functionality (FR-06)**:
    - **Test**: Generated QR codes were scanned to verify correct redirection to the associated BP details. This process is illustrated in Figure 16, which shows the QR code generated within the Battery Passport.

Figure 16: QR generated in the BP.

    - **Outcome**: QR codes functioned correctly, aligning with **Objective OBJ-06** (QR Code Integration).
7. **Role-Based Data Access (FR-07)**:
    - **Test**: Role-specific scenarios were tested to ensure data access was correctly restricted based on user roles. Figure 17 shows an example in the Swagger interface of how a new blockchain address is assigned the role of manufacturer, Figure 18 displays the Role Assignment API Response, and Figure 19 provides a screenshot of the block explorer, confirming that the transaction has been successfully recorded.

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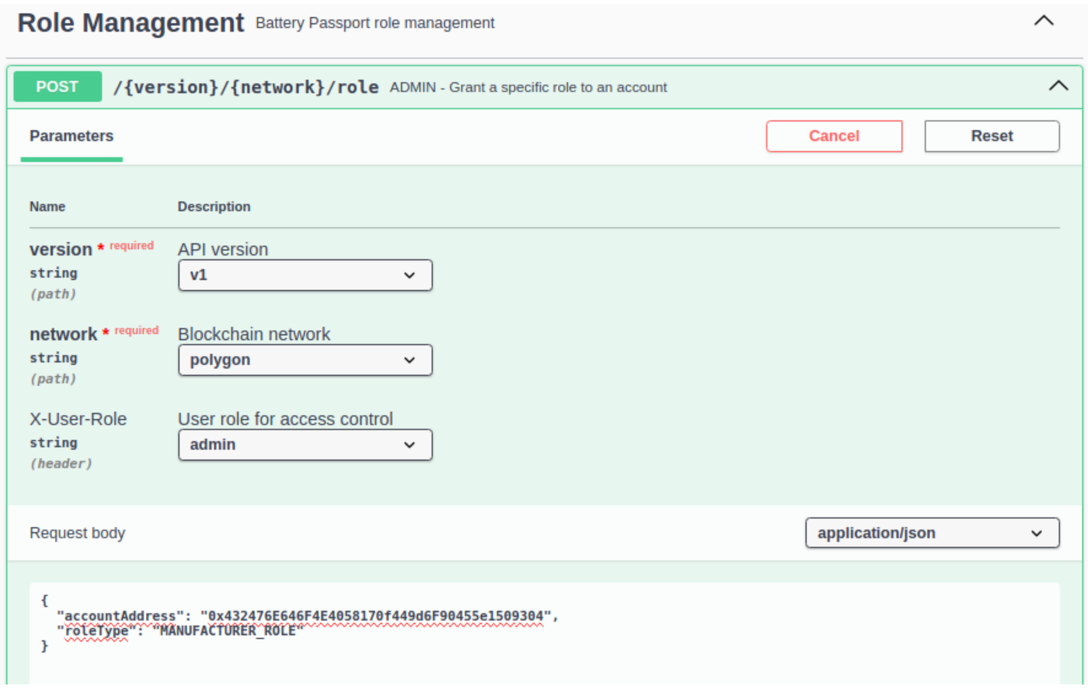

Figure 17: Example in the swagger of how a new blockchain address is assigned the role of manufacturer.

Figure 18: Role Assignment API Response

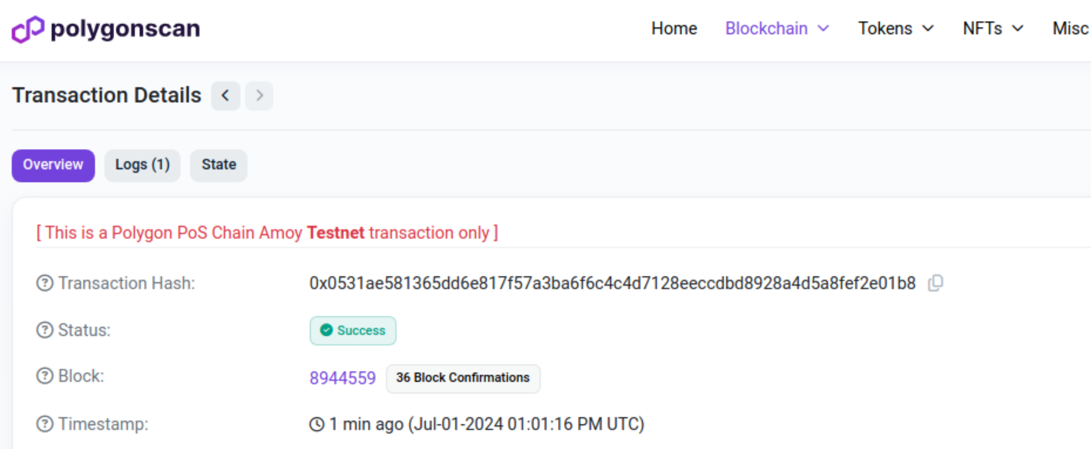

Figure 19: Screenshot of the block explorer showing that the transaction has been successfully recorded.

- **Outcome**: Access control measures functioned as intended, supporting **Objective OBJ-03**.

Overall Validation Conclusion: The first prototype effectively demonstrated the core functionalities envisioned for the BPP. Each functional requirement was met, confirming that the foundational technologies and strategies are sound and capable of supporting the intended operations of the platform. The validations have also highlighted areas for improvement, particularly in enhancing security features and expanding the data model to accommodate more complex scenarios as the platform evolves.

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4. Feedback and Iteration

Following the presentation of the first prototype of the BPP at the Brussels General Assembly, a structured series of feedback sessions and iterative development processes were initiated, spearheaded by the University of Graz as part of Work Package 5.4. These sessions were instrumental in refining the platform's approach to managing the lifecycle of batteries through the integration of blockchain technology.

UNIGRAZ conducted three workshops that gathered input from various stakeholders within the FREE4LIB consortium. These workshops served not only as a platform to assess the functionality of the initial prototype but also to identify essential enhancements and data requirements needed for a BP system. The discussions and exercises conducted, like the workshop done in a Miro board like shown in Figure 20, focused on the practical aspects of battery production, usage, and recycling, and explored the regulatory and compliance frameworks necessary to support these activities effectively.

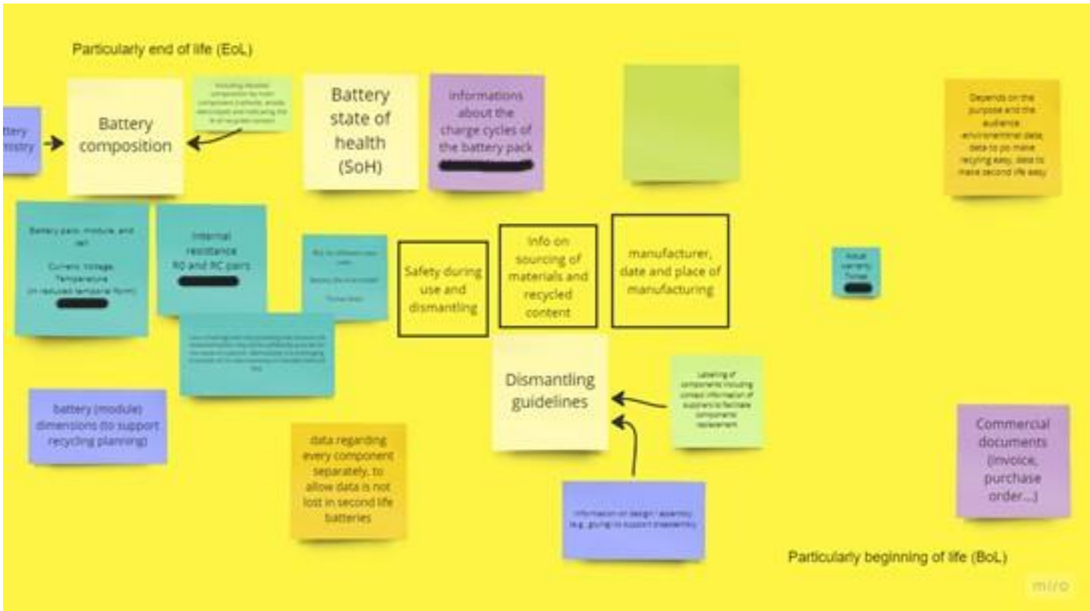

Figure 20: Miro board snapshot from a Workshop, extracted from D.5.4

Simultaneously, these workshops provided the foundation for Deliverable D.5.4, marking the culmination of a year-long research initiative under Task 5.4. The deliverable synthesized the outcomes of these workshops and integrated them into a refined theoretical framework that proposed a more detailed and realistic data model for the BP.

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The feedback from these workshops, combined with the theoretical analysis conducted by Uni Graz, was crucial in shaping the next iteration of the BPP. The insights gained were directly translated into enhancements in the data model, which now better accommodates the complexities of real-world battery lifecycle management. This revised model aims to improve traceability, increase data accuracy, and enhance the decision-making capabilities across various stages of the battery's lifecycle.

4.1 Initial feedback from partners

The initial unveiling of the BPP prototype and the subsequent workshops facilitated by UNIGRAZ provided a crucial opportunity to gather feedback from various partners involved in the FREE4LIB project. The insights obtained from these sessions were instrumental in identifying strengths and areas for improvement, as well as in aligning the platform's development with the real-world needs of stakeholders.

Key Themes from Feedback:

- **System Usability and Accessibility**: Partners appreciated the user-friendly design of the initial interface and the straightforward manner in which battery information was presented. However, they expressed a need for more detailed data visualizations and enhanced interface functionalities to better manage and track the battery lifecycle comprehensively.

- **Data Accuracy and Depth**: While the simplicity of the data model was suited for initial demonstrations, partners highlighted the need for a more complex and detailed data model that could handle a broader spectrum of battery-specific information. This includes more granular details about battery chemistry, usage history, and recycling data, which are critical for making informed decisions throughout the battery's lifecycle.

- **Regulatory Compliance and Adaptability**: Partners stressed the importance of ensuring that the platform remains adaptable to evolving regulatory requirements. They emphasized the need for the system to be flexible enough to accommodate changes in environmental regulations and battery management standards without requiring significant overhauls.

- **Integration with Existing Systems**: There was a consensus on the need for better integration capabilities with existing enterprise and supply chain management systems. Partners expressed the desire for the platform to seamlessly connect with other software tools and databases to streamline operations and data sharing across the battery value chain.

4.2 Adaptations made to meet partner needs

Following the initial feedback from partners, significant adaptations were made to the BPP to enhance its effectiveness and ensure it meets the evolving needs of stakeholders involved in the lifecycle management of Lithium-Ion Batteries (LIBs).

The data model was expanded to incorporate a wider range of detailed information, including precise chemical compositions and comprehensive recycling data. This enhancement allows for more accurate tracking and better compliance with regulatory changes, ensuring that stakeholders have access to the necessary information for informed decision-making.

Table 4: New data mode (with dummy examples) proposed for the second prototype, based on feedback in JSON [15] format.

<table>
<tr><th>Version</th><th>Data Model</th></tr>
<tr><td>1.0</td><td><pre>{
  "uniqueID": "AB123456",
  "timestampLocation": "2023.08.02-Graz-Austria",
  "composition": "25% copper, 75% Aluminum",
  "dimensions": "5x10x20 cm",
  "manufacturer": "0x432476E646F4E4058170f449d6F90455e1509304",
  "manufacturerDetails": "ID1234-Tokyo-Japan-Machining",
  "assemblerDetails": "FREE4LIB-Brussels",
  "userLocation": "Barcelona, Spain",
  "stateOfHealth": "Good",
  "userAnonymousID": "User1234",
  "state": "InUse",
  "descriptor": {
    "sensitivity": "Restricted",
    "granularity": "Detailed",
    "certainty": "Sure",
    "relevance": "VeryImportant"
  },
  "qrCode":
"data:image/png;base64,iVBORw0KGgoAAAANSUhEUgAAAKQAAACkCAYAAl"
}</pre></td></tr>
<tr><td>2.0</td><td><pre>{
  "uniqueID": "AB123456",
  "timestampLocation": "2023.08.02-Graz-Austria",
  "composition": {
    "detailed": "25% copper, 75% Aluminum",
    "valuableElements": "Copper, Aluminum",
    "deviationFromStandard": "5% more copper, 5% less aluminum",
    "byPart": {</pre></td></tr>
</table>

[15] https://en.wikipedia.org/wiki/JSON

```
      "case": "Aluminum",
      "connectors": "Copper",
      "insulation": "Plastic"
    }
  },
  "dimensions": "5x10x20 cm",
  "manufacturer": {
    "id": "0x432476E646F4E4058170f449d6F90455e1509304",
    "details": "ID1234-Tokyo-Japan-Machining",
    "contactInfo": "contact@example.com",
    "role": "Primary Battery Manufacturer",
    "traceability": "Verified",
    "preTreatmentRecommendations": "Specific disassembly process A",
    "modificationHistory": [
      {
        "date": "2023.08.01",
        "change": "Added 5% copper"
      }
    ]
  },
  "assemblerDetails": "FREE4LIB-Brussels",
  "certifiedRepairCompanies": ["RepairCo1", "RepairCo2"],
  "userLocation": "Barcelona, Spain",
  "stateOfHealth": "Good",
  "SoHAssessment": {
    "responsibleAgent": "AgentXYZ",
    "lastAssessmentDate": "2023.08.01",
    "methodology": "StandardMethod",
    "recommendation": "2ndLife"
  },
  "SoHRecords": [
    {
      "date": "2023.08.01",
      "user": "User1234",
      "SoH": "Good"
    }
  ],
  "state": "InUse",
  "lifeCycleStage": "1stLife",
  "recyclingStatus": "Recycled",
  "recyclingEfficiency": "90%",
  "certifiedAluminumSource": "CertifiedSource123",
  "userAnonymousID": "User1234",
  "archiveStatus": "Active",
  "batteryLifeModelLink": "http://example.com/batteryModel",
  "safetyInformation": "Wear protective gear when handling",
  "recyclerFeedback": {
    "suggestions": "Add more modular components for easy repair",
    "contactInfo": "recycler@example.com"
  },
  "usageType": "Automotive",
  "disassemblyProcedure": "Procedure XYZ",
  "descriptor": {
    "sensitivity": "Restricted",
    "granularity": "Detailed",
    "certainty": "Sure",
    "relevance": "VeryImportant"
  },
  "qrCode":
"data:image/png;base64,iVBORw0KGgoAAAANSUhEUgAAAKQAAACkCAYAAl"
}
```

In response to requests for improved data visualization and accessibility, the user interface was upgraded.

Additionally, to facilitate seamless integration with existing systems used by partners, new APIs and data exchange protocols were developed. These tools improve interoperability with various enterprise systems, making data imports and exports more efficient and reducing integration complexities.

Finally, the architecture of the platform was redesigned to be more modular, enhancing its scalability and flexibility. This change allows for quicker adaptations to technological advancements or shifts in business processes, ensuring the platform remains responsive to partner needs without requiring extensive modifications.

These focused adaptations have substantially increased the platform's capacity to support effective battery lifecycle management, aligning closely with partner expectations and industry standards. **All these modifications, the integration of new technologies, and the details of further enhancements will be discussed more comprehensively in the next section, which delves into the development of the second prototype.**

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5. Development of Second Prototype

Following the initial prototype and subsequent feedback, the development of the second prototype of the BPP marked a significant evolution in the project's approach to battery lifecycle management. This prototype was a direct response to the refined needs highlighted by partners and the detailed study conducted with the University of Graz, which underscored the necessity for a more complex and realistic data model.

The second prototype introduced a hierarchical structuring of battery data into packs, modules, and cells. This structure allows for detailed tracking and management of each component, enhancing the granularity and utility of the BP. By segmenting the data in this way, stakeholders can obtain specific insights about different parts of a battery pack, from individual cells to entire modules, facilitating better control and maintenance throughout the battery's lifecycle.

To support this refined data model, three distinct types of smart contracts were developed, each tailored to handle the unique aspects of cells, modules, and packs. This approach not only simplifies the management of state and health data for different battery components but also enhances the platform's scalability and flexibility in handling various scenarios encountered in battery usage and recycling.

In parallel, a complete overhaul of the API was undertaken using NestJS[16], a progressive Node.js framework that offers improved performance and developer productivity. This new API framework supports more robust and maintainable code, essential for the complex interactions expected in the revised platform.

An interactive application was also developed, utilizing the React Flow[17] library to provide a dynamic and user-friendly interface. This application visually represents the relationships and health status of packs, modules, and cells, enriched with QR codes for easy access to detailed information. This interface makes it significantly easier for users to interact with the platform, offering intuitive navigation and immediate access to critical data, such as state of health assessments and material composition details.

[16] https://nestjs.com/
[17] https://reactflow.dev/

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These advancements represent a thoughtful integration of technical improvements and user-centric design, aiming to provide a comprehensive and practical tool for managing BPs across the lifecycle of battery components. The next sections will delve deeper into each aspect of the prototype's development, illustrating how these innovations contribute to the overarching goals of the BPP.

Here are the defined objectives for the second prototype of the BPP, tailored to emphasize the significant enhancements and strategic goals of this iteration:

1. **Advanced Data Model Implementation (Objective ID: OBJ-01)**: To implement and validate a hierarchical data model that segregates battery information into packs, modules, and cells. This objective is crucial for managing detailed component-level information and supporting complex interactions within the battery lifecycle.

2. **New Smart Contract Integration (Objective ID: OBJ-02)**: To validate the integration of three types of smart contracts designed specifically for packs, modules, and cells. This setup aims to ensure that the platform can handle distinct functionalities accurately and efficiently, enhancing the blockchain framework's capability to manage state transitions and role-based access control.

3. **Interactive Interface Development (Objective ID: OBJ-03)**: To develop and test an interactive user interface using the React Flow library. This interface should effectively demonstrate the platform's ability to visually represent and manipulate the hierarchical structure of battery components, facilitating user-friendly access to detailed data and operations.

4. **Comprehensive System Testing (Objective ID: OBJ-04)**: To conduct thorough testing of the entire platform, including smart contracts, the API, and the user interface, to ensure that all components work seamlessly together to perform their intended functions. This includes verifying the integration of the new data model with the platform's backend and frontend systems.

5. **Role-Based Access Control Enhancement (Objective ID: OBJ-05)**: Although primarily managed at the smart contract level, testing and validating enhanced role-based access control mechanisms within the new smart contract framework is essential. This objective aims to confirm that different user roles can interact with the system appropriately, adhering to security and operational protocols.

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6. **User Experience and Accessibility Improvement (Objective ID: OBJ-06)**: To refine the user interface to improve accessibility and usability, ensuring that it is intuitive and capable of displaying complex data structures in a clear and engaging manner. This objective is vital for facilitating broader adoption and ease of use, particularly for non-technical stakeholders.

Objective ID	Name	Description
OBJ-01	Advanced Data Model Implementation	To implement and validate a hierarchical data model for packs, modules, and cells.
OBJ-02	New Smart Contract Integration	To validate the integration of distinct smart contracts for packs, modules, and cells.
OBJ-03	Interactive Interface Development	To develop and test an interactive user interface using the React Flow library.
OBJ-04	Comprehensive System Testing	To conduct thorough testing of the platform, ensuring seamless interaction among all components.
OBJ-05	Role-Based Access Control Enhancement	To enhance and validate role-based access control mechanisms within the smart contract framework.
OBJ-06	User Experience and Accessibility Improvement	To refine the user interface for improved accessibility and usability, displaying complex data clearly.

5.1 Functional Requirements

The functional requirements for the second prototype of the BPP are designed to ensure that the system effectively meets the complex needs identified during the feedback phase and study with the University of Graz. These requirements are crucial for advancing the platform's capabilities in handling detailed battery component data and lifecycle management.

1. **Hierarchical Data Management (Requirement ID: FR-01)**

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- **Requirement**: The platform must manage data hierarchically to differentiate between packs, modules, and cells, facilitating detailed control and monitoring at each level.
- **Objective Alignment**: Supports OBJ-01 (Advanced Data Model Implementation).

2. **Multi-Smart Contract System (Requirement ID: FR-02)**
    - **Requirement**: Implement distinct smart contracts for cells, modules, and packs to handle specific functionalities and state transitions appropriately.
    - **Objective Alignment**: Supports OBJ-02 (New Smart Contract Integration).
3. **Advanced API Capabilities (Requirement ID: FR-03)**
    - **Requirement**: The API must support complex data interactions, handle high volumes of requests efficiently, and provide endpoints specific to the operations of packs, modules, and cells.
    - **Objective Alignment**: Supports OBJ-04 (Comprehensive System Testing).
4. **Interactive User Interface (Requirement ID: FR-04)**
    - **Requirement**: Develop an interactive user interface that visually represents the hierarchical structure of battery components and allows easy navigation and real-time data updates.
    - **Objective Alignment**: Supports OBJ-03 (Interactive Interface Development) and OBJ-06 (User Experience and Accessibility Improvement).
5. **State of Health Tracking (Requirement ID: FR-05)**
    - **Requirement**: Incorporate comprehensive tracking of the state of health for each battery component, allowing for real-time updates and historical data analysis.
    - **Objective Alignment**: Supports OBJ-04 (Comprehensive System Testing).
6. **Material Composition Details (Requirement ID: FR-06)**
    - **Requirement**: Provide detailed material composition information for each battery component to support recycling processes and compliance with environmental regulations.
    - **Objective Alignment**: Supports OBJ-01 (Advanced Data Model Implementation).

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7. **Role-Based Access Control (Requirement ID: FR-07)**
   - **Requirement**: Maintain role-based access control within the smart contracts to manage permissions and secure access based on user roles.
   - **Objective Alignment**: Supports OBJ-05 (Role-Based Access Control Enhancement).

Requirement ID	Name	Description
FR-01	Hierarchical Data Management	Manage data hierarchically for packs, modules, and cells to facilitate detailed tracking and control.
FR-02	Multi-Smart Contract System	Implement specific smart contracts for different battery components to handle functionalities accurately.
FR-03	Advanced API Capabilities	Support complex data interactions and provide efficient endpoints for managing battery components.
FR-04	Interactive User Interface	Develop an interface that visually represents battery components and allows for easy navigation and real-time updates.
FR-05	State of Health Tracking	Enable comprehensive tracking of health for each battery component, allowing real-time and historical data analysis.
FR-06	Material Composition Details	Provide detailed material composition information to aid recycling processes and regulatory compliance.
FR-07	Role-Based Access Control	Maintain strict role-based access control within the smart contracts to ensure data security and integrity.

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5.2 Data Model Integration

The second prototype of the BPP incorporates a sophisticated data model that reflects the hierarchical structure of battery systems, dividing them into packs, modules, and cells. This model is essential for capturing and managing the detailed data necessary for comprehensive battery lifecycle management. Each level of the model—pack, module, and cell—is designed to capture specific data points relevant to its operational and management needs, which are then encoded into smart contracts to ensure integrity and accessibility of the data on the blockchain.

Pack Data Model:

- **Pack Information**: Includes user location, usage type, installation date, and lifecycle stage, alongside a unique identifier for each pack. This information helps track the pack's deployment environment and usage history, which is crucial for warranty management and regulatory compliance.
- **Material Composition and Dimensions**: Detailed descriptions of the pack's materials and dimensions are stored to aid in maintenance, recycling, or repurposing efforts.
- **State Management**: Tracks the current state of the pack (Created, Assembled, InUse, Recycled), allowing for dynamic updates that reflect real-time changes in status.
- **Safety Information**: Includes links to safety protocols, assembly/disassembly instructions, which are vital for ensuring safe handling and operation procedures.

Module Data Model:

- **Module Details**: Each module's data includes an assembler's information, dimensions, and specific material composition, providing a detailed profile that aids in quality control and assembly line management.
- **Cell Association**: Modules link to individual cells they contain, enabling traceability down to the cell level within the assembled module.

- **Repair and Safety Records**: Information about certified repair services and specific repair history, including safety audits and updates, which are critical for maintaining module integrity over its operational life.

Cell Data Model:

- **State of Health (SoH)**: A dynamic record of the cell's health status, including time-stamped SoH assessments and links to detailed records of assessments made over time. This provides a critical input for predictive maintenance and end-of-life decision-making.
- **Manufacturing Details**: Information about the cell's manufacturer, batch number, and date of manufacture, which are important for recall management and quality assurance.
- **Lifecycle Stage**: Detailed tracking of the cell's stage within its lifecycle (e.g., InUse, Recycled), which helps in regulatory reporting and efficiency analysis.

5.3 Advances over the first prototype

The development of the second prototype of the BPP brought significant technological and functional enhancements that addressed the limitations identified in the first prototype. These improvements were aimed at creating a more robust, scalable, and user-friendly system that could handle the complex realities of battery lifecycle management more effectively.

Hierarchical Data Structure: One of the most crucial advancements in the second prototype was the implementation of a hierarchical data structure, organizing battery information into packs, modules, and cells. This structure allows for detailed tracking and management at each level of a battery's lifecycle, providing precise control and better data integrity. The hierarchical model facilitates the isolation of issues to specific components, improving maintenance and replacement processes, and extending the overall life of battery systems.

Enhanced Smart Contracts: Replacing the singular smart contract approach of the first prototype, the second prototype features three distinct types of smart contracts corresponding to the new data structure. Each contract—dedicated to cells, modules, and packs—supports specific operations and states relevant to that component, enhancing the specificity and security of data transactions on the blockchain. This segmentation not only improves the management of state and health data but also enhances the overall security framework by isolating contract functions.

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Modernized API using NestJS: The complete redevelopment of the API using NestJS provided a more modern, efficient, and scalable framework. NestJS's modular architecture allows for better organization of code and easier maintenance, essential for handling the more complex interactions required by the new data model. The new API ensures faster response times, improved error handling, and greater flexibility in integrating new features or changes as the platform evolves.

Interactive User Interface: The introduction of an interactive user interface designed with React Flow significantly enhanced the user experience. This tool provides visual representations of the relationships between packs, modules, and cells, complete with real-time health status updates. It offers users an intuitive way to monitor and manage the components of battery systems effectively, with features like drag-and-drop editing and zoom functionality to navigate complex data structures easily.

State of Health Tracking and Updates: Enhanced state of health (SoH) tracking features in the smart contracts allow for continuous monitoring and updating of each battery component's health status. This ensures that all stakeholders have up-to-date information on the condition of the batteries, facilitating timely interventions and improving the reliability of the battery systems.

These advancements not only addressed the immediate feedback and requirements that emerged from the initial prototype testing but also laid a robust foundation for future enhancements. The second prototype represents a significant step forward in achieving a comprehensive and reliable platform for BP management, showcasing a commitment to continuous improvement and alignment with industry needs.

5.4 Description of new technologies and structural changes

The second prototype of the BPP embodies a leap forward in the integration of cutting-edge technologies and structural innovations tailored to enhance the functionality and scalability of the system. This prototype not only addresses the complexities involved in battery lifecycle management but also introduces new technologies and architectures that significantly improve system performance and user interaction.

In developing this prototype, a deliberate focus was placed on three core areas: refining the API technology, restructuring the smart contracts, and redesigning the user interface. Each of these areas received substantial upgrades to meet the evolving needs of the battery management ecosystem, driven by feedback from the initial prototype and ongoing research into best practices in technology application.

5.4.1 New API technology

The transition to NestJS for the API in the second prototype of the BPP represents a strategic overhaul aimed at enhancing both the scalability and maintainability of the platform. NestJS (Figure 21), a progressive Node.js framework, was chosen for its robust architecture and its **compatibility with Typescript**, which brings strong typing and object-oriented programming to the server-side, ensuring that the API is not only more reliable but also easier to develop and debug.

Figure 21: NestJS logo.

NestJS's modular approach allows for clear separation of concerns, where each module encapsulates all the related functionalities, making the system more organized and manageable. This architecture is particularly beneficial for the BPP as it scales to accommodate more complex data structures and interactions, driven by the new hierarchical data model of packs, modules, and cells. The modular system simplifies updates and changes, as modifications to one part of the system can be made with minimal impact on others.

Moreover, NestJS integrates well with modern front-end frameworks, which was crucial for ensuring seamless interaction between the backend and the new interactive user **interface developed with React Flow**. This integration capability supports real-time data updates and synchronization across the platform, enhancing the user experience by providing immediate feedback and updates.

Performance and efficiency were also key considerations in adopting NestJS. The framework's efficient handling of asynchronous operations and its support for advanced features like Dependency Injection make it highly performant, which is essential for processing the significant volumes of data involved in BP management. Furthermore, NestJS's built-in support for RESTful services ensures that the API can handle complex request-response cycles efficiently, which is vital for the operations of the BPP.

In addition to technical benefits, NestJS also offers extensive support for testing frameworks, which is critical for ensuring the reliability of the API. Automated testing frameworks integrated within NestJS allow for rigorous testing of all aspects of the API, ensuring that it functions correctly under various scenarios and can handle unexpected errors gracefully.

The adoption of NestJS for the API technology in the second prototype thus provides a strong foundation for the BPP, supporting its current functionality and preparing it for future expansion and integration with other systems. This move underscores the project’s commitment to using advanced technology to improve the platform's performance and user satisfaction.

5.4.2 New structure for smart contracts

In the development of the second prototype for the BPP, a significant restructuring of the smart contracts was implemented to accommodate the **needs of battery management**. This restructuring involved creating separate smart contracts for cells, modules, and packs, each tailored to manage the specific attributes and lifecycle stages of these components. This approach not only enhances the granularity of data management but also increases the security and efficiency of blockchain transactions within the platform.

The introduction of distinct smart contracts for different components allows for specialized functions that address the unique needs of each battery component. For example, the **cell smart contract focuses on detailed attributes** like state of health assessments, material compositions, and lifecycle data specific to individual cells. Similarly, module and pack contracts manage broader aspects such as assembly details, repair information, and overall state transitions. This separation ensures that operations are handled at the appropriate level of the hierarchy, which improves the accuracy and reliability of data on the blockchain.

Each of these smart contracts incorporates advanced features to handle **complex data structures and relationships** inherent in the battery management system. For instance, the module contract must manage links between multiple cells, while the pack contract aggregates several modules. These relationships are critical for tracking the entire battery system's performance and health, enabling more effective maintenance and lifecycle management.

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Security is another area greatly enhanced by this new structure. By decentralizing the functions across multiple contracts, the system minimizes risk and exposure to vulnerabilities. Each contract can be updated or fixed independently, **without the need to deploy a new version of a monolithic contract**, which enhances the system's adaptability and responsiveness to security threats.

Moreover, these contracts are integrated with a **role management system**, ensuring that only authorized users can perform certain actions based on their assigned roles.

5.4.3 New interface

The second prototype of the BPP introduced a completely redesigned user interface, leveraging the React Flow library to create a dynamic, interactive experience that significantly enhances user engagement and data visualization. This new interface is tailored to meet the intricate requirements of managing hierarchical battery data, as shown in Figure 22, providing users with a comprehensive view of battery packs, modules, and cells in a visually intuitive format.

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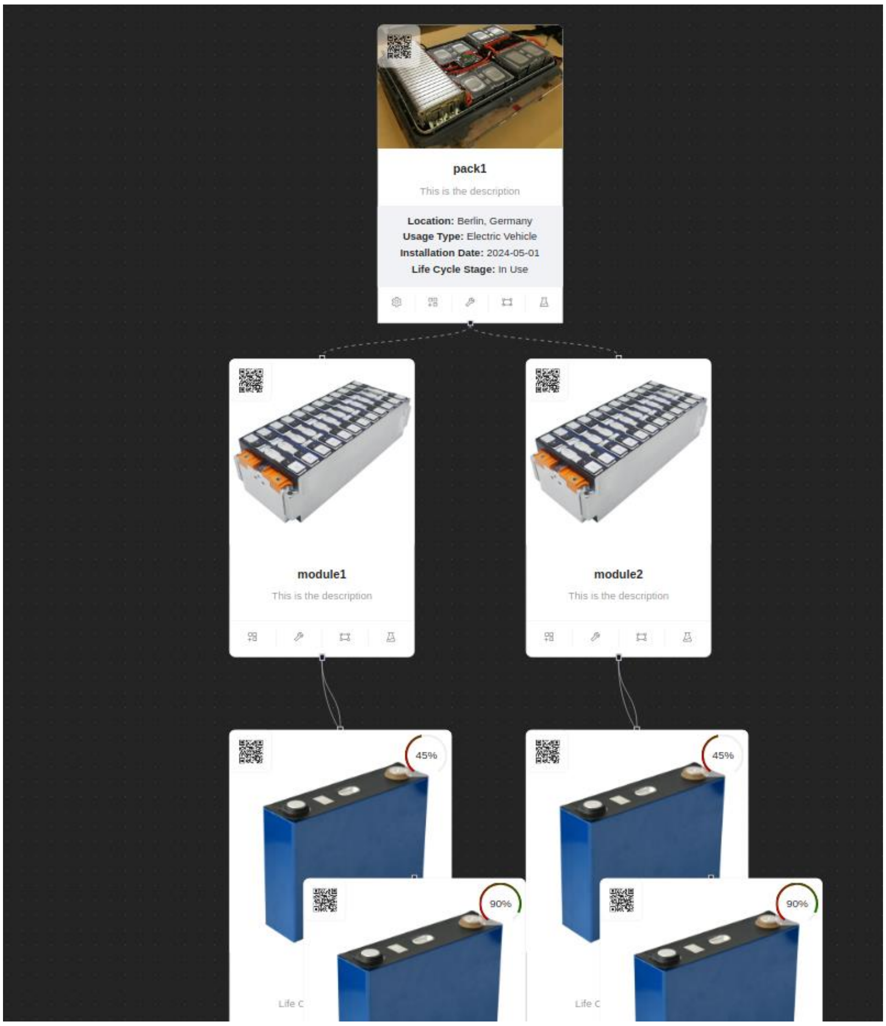

Figure 22: Screenshot of an example of the new interface with the hierarchical battery data

The core advancement of the interface lies in its ability to **visualize complex relationships** between battery components in real-time. Users can see how packs are assembled from modules and how modules incorporate various cells, complete with state-of-health indicators and other critical metrics. This visual mapping is not just static; it allows for interaction, where users can click on individual components to get detailed data or update information as needed.

Enhanced Usability Features include drag-and-drop capabilities, allowing users to reconfigure views according to their specific needs or preferences. Zoom functionality makes it easy to navigate between detailed views of cells and more aggregated views of entire packs, ensuring that users can easily access the level of detail they need. These features make the interface not only more useful for technical users such as engineers and technicians but

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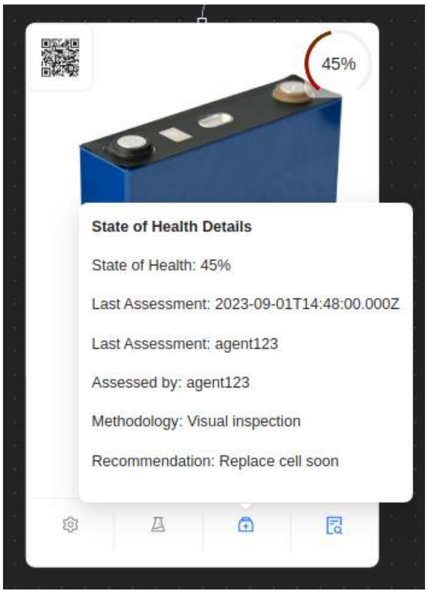
also accessible for managerial staff who require an overview of the battery system's status.

A particularly innovative feature is the integration of **QR codes**. Each battery component within the interface is associated with a QR code, like in Figure 23, which simplifies the process of retrieving data. While currently implemented with placeholder QR codes as examples, the plan is for each component to be uniquely identified by a QR code that, when scanned, brings up detailed information about that component's history, current status, and projected lifecycle.



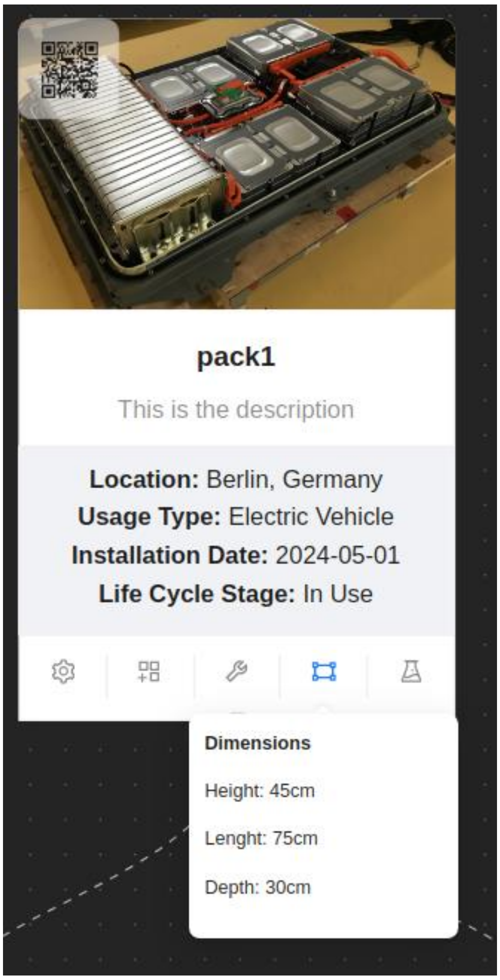


Figure 23: Example of information in pack and cell level.

Real-time Data Updates are a critical feature of the new interface, facilitated by the backend improvements in the API. Changes in the data or state of any battery component are immediately reflected in the interface, which helps in maintaining a current and accurate view of the system's status. This real-time update capability is essential for operations requiring immediate attention and action, such as fault detection and response in battery management systems.

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5.5 Validation

The validation of the second prototype focuses on ensuring that the implemented features and functionalities meet the specified objectives and functional requirements. Each validation step is designed to test different aspects of the platform, from data management and smart contract operations to user interface usability and role-based access control.

Validation of Hierarchical Data Management (FR-01 / OBJ-01) To validate the hierarchical data model implementation:

- **Test Case**: Create a series of battery packs, modules, and cells, ensuring that each level of the hierarchy correctly references and integrates with the others.

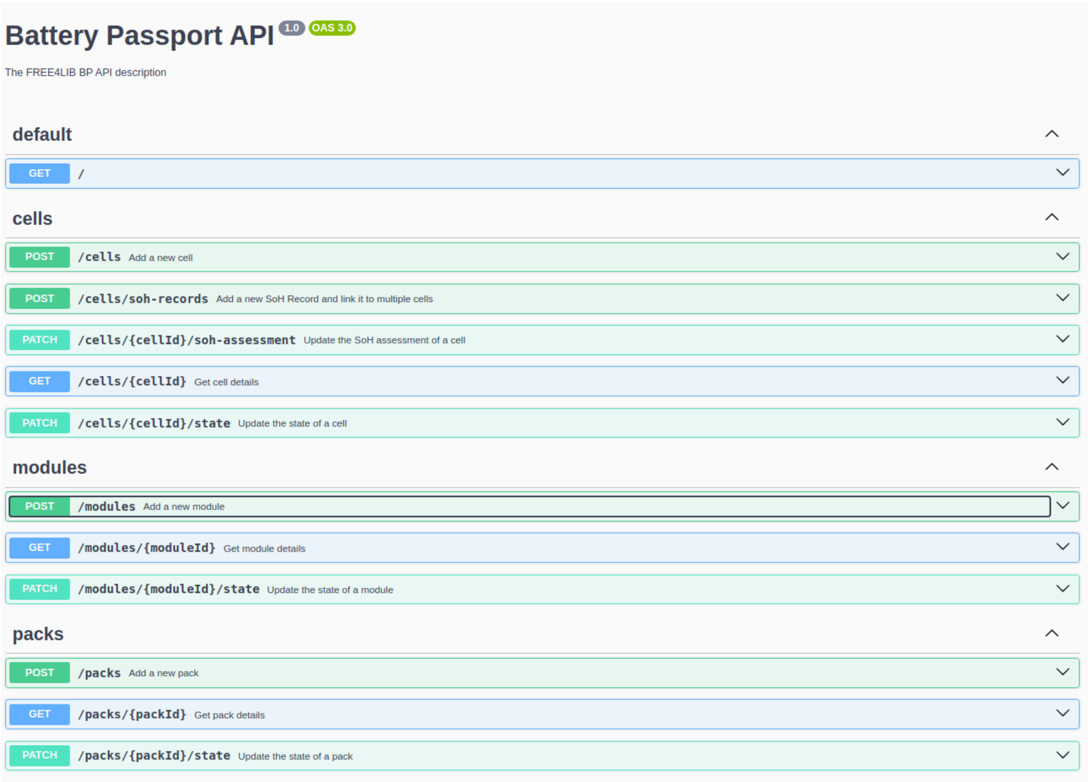

Figure 24: Example in the swagger showing the different endpoints to manage each BP component.

- **Outcome**: **As shown also in** Figure 22: Screenshot of an example of the new interface with the hierarchical battery data, the system manages and displays the hierarchical relationships correctly, allowing for detailed tracking and control of each component.

Validation of Multi-Smart Contract System (FR-02 / OBJ-02) To validate the distinct smart contracts for cells, modules, and packs:

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- **Test Case**: Deploy the smart contracts for packs, modules, and cells and execute state transition functions, such as creation, assembly, usage, and recycling.

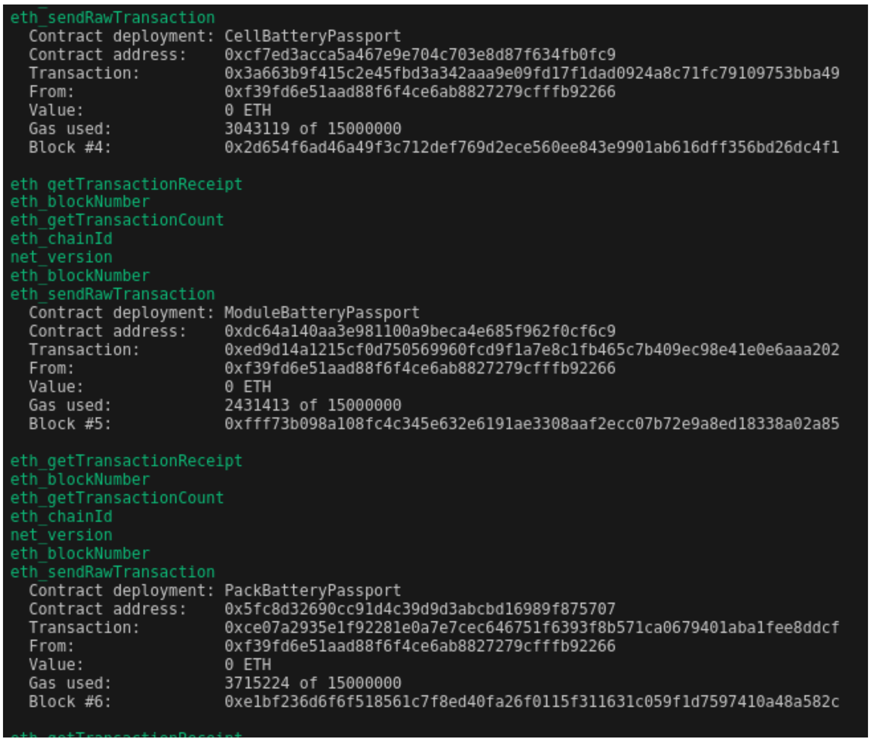

Figure 25: Logs screenshot of the deployment of the three smart contracts.

- **Outcome**: Each smart contract functions correctly.

Validation of Advanced API Capabilities (FR-03 / OBJ-04) To validate the new API:

- **Test Case**: Perform a series of operations through the API.

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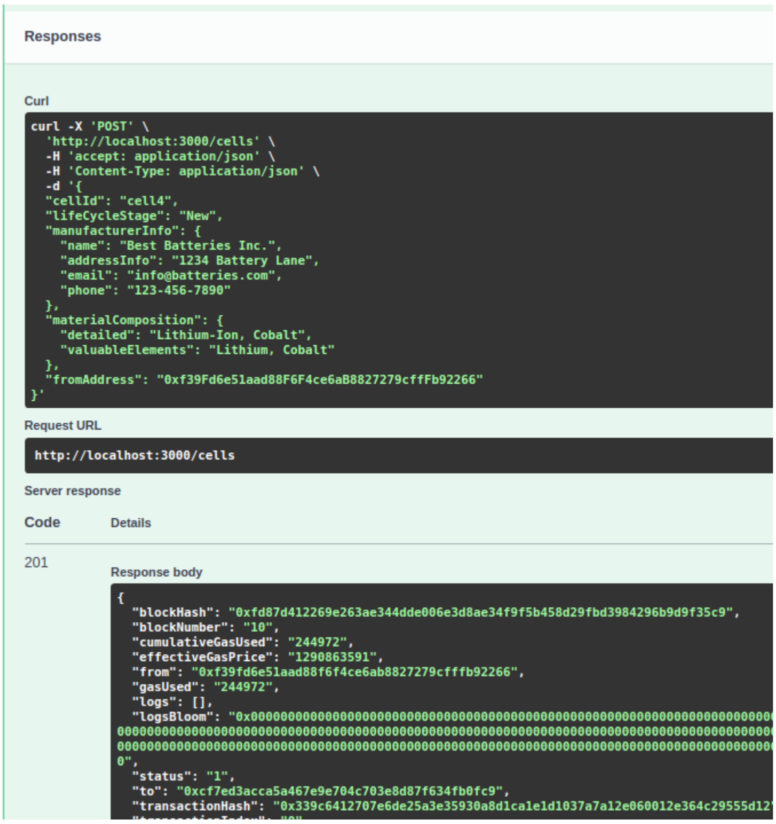

Figure 26: Example in the swagger where a new cell is registered.

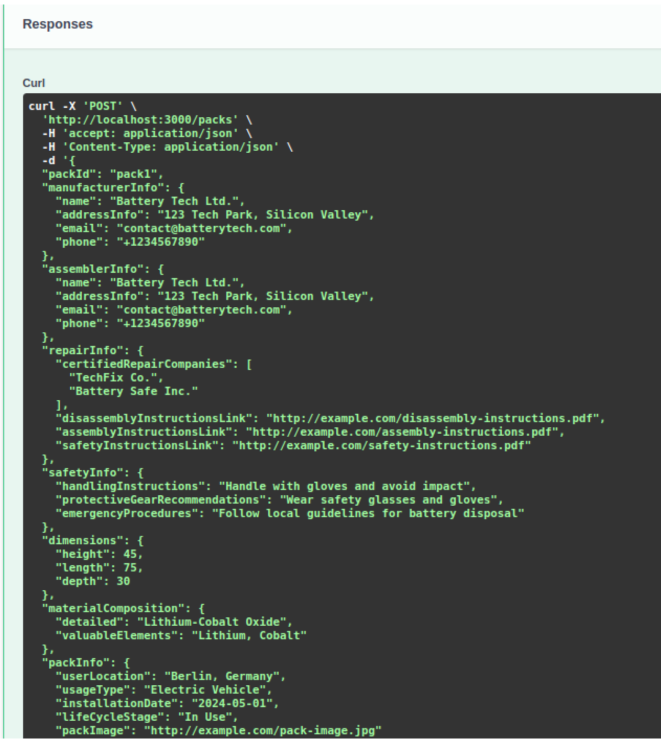

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Figure 27: Example in the swagger where a new pack is registered, with all associated data.

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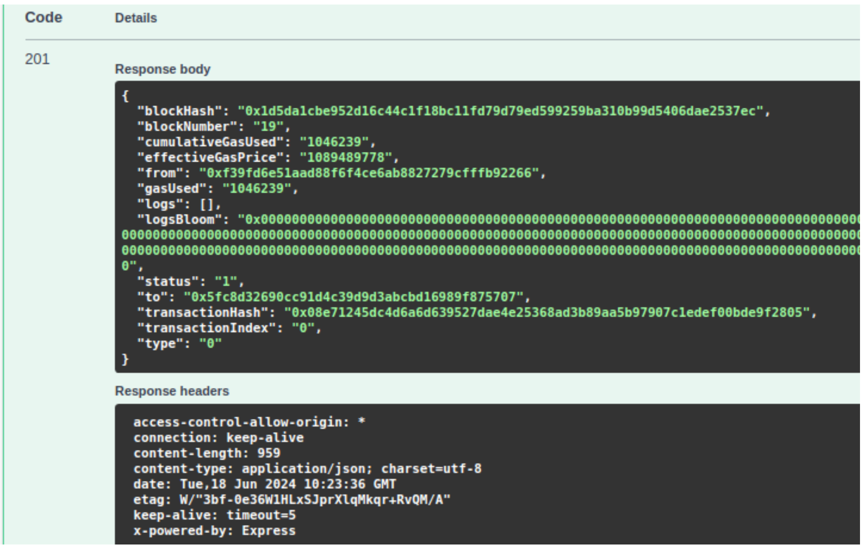

Figure 28: Example of the swagger response showing the generated transaction id.

- **Outcome**: The API requests efficiently and returns the correct responses for each operation, maintaining performance and reliability.

Validation of Interactive User Interface (FR-04 / OBJ-03 and OBJ-06) To validate the usability and functionality of the interactive user interface:

- **Test Case**: Use the React Flow-based interface to navigate the hierarchical structure of battery components, access detailed data, and perform operations.

- **Outcome**: As shown in Figure 22 and 23, the interface is intuitive and responsive, allowing users to easily visualize relationships between battery components and access detailed information. Real-time updates and QR code functionality work seamlessly.

Validation of State of Health Tracking (FR-05 / OBJ-04) To validate the comprehensive state of health tracking for battery components:

- **Test Case**: Record state of health (SoH) data for cells and ensure that this data is accurately reflected in the platform, including historical records and real-time updates.

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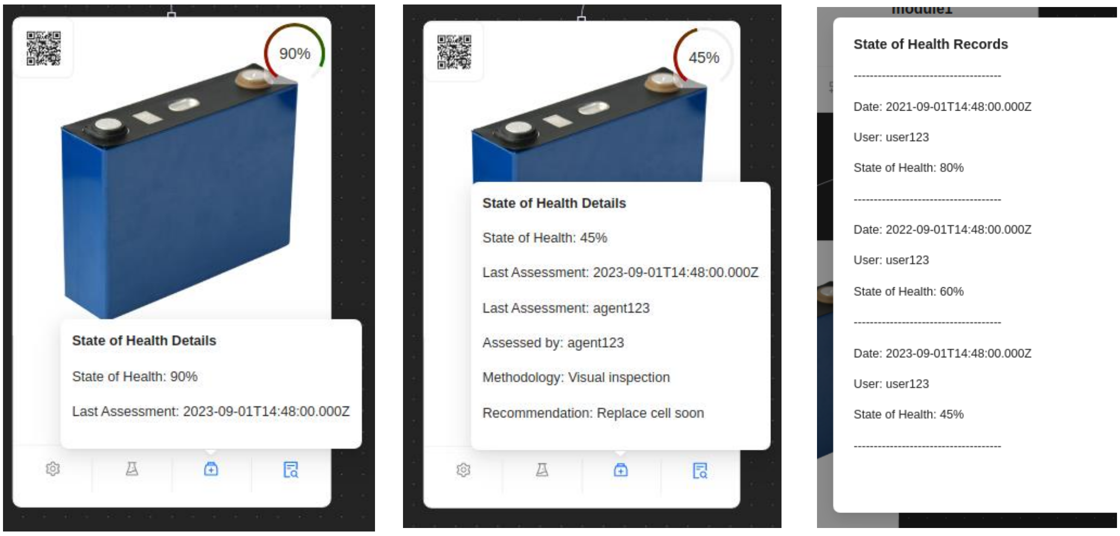

Figure 29: Screenshots of the interface showing the improved health status and the records that have been made in the cell concerned.

- **Outcome**: The platform correctly tracks and displays SoH data, allowing for detailed health assessments and historical analysis.

Validation of Material Composition Details (FR-06 / OBJ-01) To validate the detailed material composition information:

- **Test Case**: Input and retrieve material composition data for various battery components, ensuring that all required information is captured and displayed correctly.

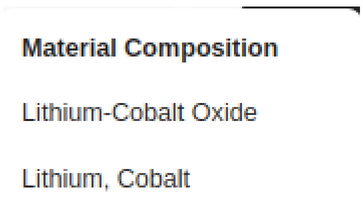

Figure 30:Screenshot of the interface showing the component material.

- **Outcome**: The platform stores and displays material composition details, supporting recycling processes and regulatory compliance.

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6. Conclusions and Future Directions

The development of the second prototype for the BPP marks a significant milestone in the project. This phase has brought about substantial improvements in the data model, smart contract architecture, and user interface, addressing the key feedback received from stakeholders and aligning with the theoretical groundwork laid by our partners. As we conclude this phase, it is essential to reflect on the achievements, challenges, and the roadmap ahead for future iterations of the platform.

In this section, we will summarize the key outcomes and insights gained from the second prototype development, highlighting how the platform has evolved to better meet the needs of battery lifecycle management. Furthermore, we will outline the planned future directions, focusing on the enhancements and innovations that will continue to drive the project forward. These future directions will include addressing remaining challenges, exploring new technologies, and expanding the platform’s capabilities to ensure it remains at the forefront of battery passporting solutions.

6.1 Milestones

The development of the second prototype for the BPP involved several key milestones, each representing significant progress towards an effective battery lifecycle management solution.

The first milestone was enhancing the data model by implementing a hierarchical structure that differentiates between packs, modules, and cells. This development enabled comprehensive tracking and management of battery components, addressing critical feedback needs.

Next, specialized smart contracts for cells, modules, and packs were developed and deployed. These contracts manage state transitions and enforce role-based permissions, ensuring precise and secure operations.

An advanced API using NestJS was implemented to support complex data interactions and high performance, seamlessly integrating with the new data model and smart contracts.

An interactive user interface using React Flow was created, providing intuitive navigation and real-time data visualization. This user-friendly interface significantly improved the platform's accessibility and practicality.

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Detailed state of health (SoH) tracking was incorporated, allowing for real-time updates and historical data analysis. This feature enhances the platform's capability to monitor and assess battery health accurately.

Role-based access control mechanisms within the smart contracts were tested and validated, confirming that permissions are correctly enforced, ensuring security and proper operations management.

Achieving a modular and scalable system architecture was another crucial milestone. This architecture allows the platform to integrate new features and components easily, demonstrating its flexibility and future-proof design.

Finally, incorporating feedback from stakeholders through workshops led to significant improvements in the data model, smart contracts, and user interface. This iterative process ensured the platform evolved in alignment with user needs and industry standards.

Table 5: Summary table of the key milestones of the development of the second prototype

Milestone	Description
Enhanced Data Model	Implemented a hierarchical structure to differentiate between packs, modules, and cells.
Smart Contracts Development and Deployment	Developed and deployed specialized smart contracts for cells, modules, and packs.
Advanced API Implementation	Implemented a high-performance API using NestJS to support complex data interactions.
Interactive User Interface	Created an intuitive and real-time data visualization UI using React Flow.
Detailed State of Health (SoH) Tracking	Incorporated real-time updates and historical data analysis for battery health monitoring.
Role-Based Access Control Testing	Tested and validated role-based access control mechanisms within smart contracts.
Modular and Scalable System Architecture	Achieved a system architecture that allows easy integration of new features and components.
Stakeholder Feedback Incorporation	Integrated feedback from stakeholders through workshops to improve the data model, smart contracts, and UI.

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6.2 Future developments for the platform

Looking ahead, the future development of the BPP will focus on several strategic initiatives aimed at enhancing its capabilities and addressing the complex challenges of battery lifecycle management.

A primary focus will be the continued refinement and expansion of the data model. While the second prototype introduced a hierarchical structure, future iterations will incorporate even more detailed and nuanced data points. This includes enhanced tracking of the environmental impact of each component and deeper insights into the recycling processes. One significant challenge in this phase will be sourcing and integrating this data. Identifying reliable data sources and ensuring consistent data acquisition will require substantial effort and coordination with various stakeholders across the battery value chain.

Table 6: Summary table of future developments for the BPP.

Strategic Initiative	Description
Data Model Expansion	Continue refining the data model, adding detailed data points on environmental impact and recycling processes.
Privacy and Security Enhancements	Explore hybrid blockchain architectures and other privacy-preserving technologies to secure sensitive data.
User Interface Enhancements	Develop more sophisticated visualization tools for web access, enhancing user experience and accessibility.
Enhancing Interoperability	Establish standardized APIs and data exchange protocols to integrate with other systems and platforms.
Advanced Analytics Capabilities	Integrate advanced analytics into the platform to provide actionable intelligence and optimize battery usage.
Expanding User Base and Collaboration	Engage with a broader range of stakeholders across the battery value chain to drive adoption and meet diverse needs.
Continuous Improvement and Feedback Loops	Implement regular workshops, user testing, and consultations to ensure responsiveness to the evolving technology landscape.

Privacy and security will remain critical priorities as we advance the platform. Future versions will explore hybrid blockchain architectures, combining the transparency and security of public blockchains with the privacy and control of private blockchains. Additionally, we will investigate other advanced privacy-preserving technologies to protect sensitive data while maintaining the integrity and traceability of the information. Ensuring confidential data is

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handled securely will be essential, particularly as we aim to meet stringent regulatory requirements and build trust with all stakeholders.

The user interface will continue to evolve with a focus on enhancing user experience and accessibility. While the platform will be developed exclusively for web access, we plan to implement more sophisticated visualization tools, enabling users to interact with the platform seamlessly and intuitively. These improvements will help users better understand and manage the complex data associated with battery lifecycles.

Another significant direction for future development is enhancing interoperability with other systems and platforms. We aim to establish standardized APIs and data exchange protocols to facilitate seamless integration with existing enterprise systems and other BP solutions. Our goal is to collaborate rather than compete, developing a solution that is usable in various environments and adaptable to different contexts. This collaborative approach will involve working with other projects exploring similar concepts, ensuring our platform can integrate effectively and provide maximum value to a broader audience.

Moreover, we plan to integrate advanced analytics capabilities into the platform. These enhancements will transform the platform into a valuable source of actionable intelligence, providing insights that can optimize battery usage and improve decision-making processes for stakeholders.

In addition to technological advancements, we will focus on expanding the platform's user base and fostering greater industry collaboration. Engaging with more stakeholders across the battery value chain—manufacturers, recyclers, regulators, and consumers—will be crucial to ensure the platform meets diverse needs and drives widespread adoption.

Finally, continuous feedback loops and iterative improvements will remain integral to our development process. Regular workshops, user testing sessions, and stakeholder consultations will help us identify areas for enhancement and ensure the platform remains responsive to the evolving landscape of battery technology and sustainability requirements.

These future plans outline a clear roadmap for the continued growth and enhancement of the BPP, ensuring it remains a leading solution for comprehensive battery lifecycle management.

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