BUILDING A SUSTAINABLE BATTERY SUPPLY CHAIN WITH DIGITAL BATTERY PASSPORTS

Veronika Siska, Astrid Al-Akrawi

AIT Austrian Institute of Technology GmbH
veronika.siska@ait.ac.at, astrid.al-akrawi@ait.ac.at

Mats Zackrisson

RISE Research Institutes of Sweden
mats.zackrisson@ri.se

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Abstract

The digital battery passport is an essential driver of sustainable production and circular economy as it enables storing and tracking data for batteries throughout the whole value chain. The BatWoMan project is paving the way towards carbon-neutral Li-ion battery cell production via new sustainable and cost-efficient methods, and by building a prototype for a digital battery passport. In this article, we outline the concept of the battery passport, including the status of relevant regulations, standards and initiatives. We then present the BatWoMan project and its design for a battery dataspace and passport. We describe relevant stakeholders and their interactions within the data space and introduce the system architecture, which is based on the International Data Spaces and Gaia-X frameworks. Finally, limitations of the research outcome are presented.

1. Introduction

Batteries are crucial for affordable and clean energy, one of the 17 Sustainable Development Goals (SDGs) defined in the United Nation's Agenda 2030 for Sustainable Development (United Nations, 2015). Efficient energy storage enables the use of renewable, dynamic energy sources like solar or wind power and supports the transition towards electromobility. However, source materials of batteries often include hazardous or rare materials, whose mining and production processes cause a substantial environmental footprint (Peters et al., 2017). At their end-of-life, disposed batteries are an additional burden, while reuse or recycling is often hampered due to suboptimal design for sustainability, a lack of information on the battery's materials, structure and status and the complexity and variety of recycling processes (Harper et al., 2019).

1.1. Digital product passports

An important driver of a sustainable battery lifecycle is a standardised digital battery passport, a Digital Product Passport (DPP) for each battery. A DPP is a digital representation of an individual product that describes its properties and current state and accompanies it throughout and after its operation time. The passport's goal is to support sustainability and circularity, with participation from all actors along the supply chain (Adisorn et al., 2021; Walden et al., 2021). Data stored in the passport provides means for regulatory compliance, supports informed decision-making, and enables a circular economy by providing crucial information for collectors, second-life operators, and recyclers.

The DPP concept spans various sectors, but is still relatively new as a research domain, despite ongoing standardization efforts fueled by regulations (van Capelleveen et al., 2023). Battery passports are one of the focal areas of DPP research. Bai et al., 2020 conceptualise a Battery Identity Global Passport, focusing on its role in recycling strategies. Berger et al., 2022 present the concept and information requirements of a digital battery passport. Plociennik et al., 2022 describe a passport with a direct interface to production machines using the Asset Administration Shell (AAS).

Upcoming regulations are a strong driver for DPPs, particularly in Europe. The *EU Ecodesign for Sustainable Products Regulation* lays the foundation for cross-sectoral digital product passports; to be accompanied by separate sector-specific regulations. The new *EU Battery Regulation* on sustainable and circular batteries will establish a Battery Passport, describing content and technical requirements. From 42 months into its entry into force (expected August 2023), all electric vehicle and LMT (light means of transport, such as e-scooters or e-bikes) batteries, as well as industrial batteries with a capacity above 2 kWh, shall be equipped with a digital battery passport.

There are several DPP initiatives; some enforced by regulations and some optional. *Material Passports* (Luscuere, 2017) describe a general early passport concept, which found voluntary applications particularly in the construction sector, to facilitate the reuse and recycling of building materials. Although there is no operative battery passport as of now, multiple projects and initiatives are working towards that goal, with participation from major industrial players. The German-driven *BatteryPass* project develops content and technical guidelines as well as a demonstrator, while the European *CIRPASS* project prepares the ground for DPP across industries. On a global scale, the *Global Battery Alliance* conceptualised a framework for a Battery Passport, as well as rulebooks for key sustainability indicators: the Greenhouse Gas rulebook and the Child Labour and Human Rights indices. The battery passport demonstrator in BatWoMan builds on these initiatives to enable interoperability, validate their guidelines and contribute to best practices.

1.2. Data spaces

Data spaces have been proposed as the data management system supporting digital product passports (Walden et al., 2021). The concept of data spaces originated from computer science as a new kind of data management platform, where participants manage their own data (Franklin et al., 2005). According to modern definitions, a data space is a decentralised data ecosystem based on data sovereignty, i.e. the "capability of a legal entity or natural person to determine and execute usage rights when it comes to their data" (Otto, 2022). All participants agree to a shared set of rules that serve as a basis for trust. In a DPP system, actors of the supply chain and beyond (see section 3.4) can share data under mutually agreed terms, without losing control over who uses them and how.

Data spaces were formalised at Fraunhofer ISST, leading to the establishment of the International Data Spaces Association (IDSA) in 2015 and the creation of the initial concept and framework for data spaces, described in the International Data Spaces Reference Architecture Model (IDS RAM). Gaia-X, a European initiative for the establishment of a federated and secure framework for sovereign data exchange, takes the dataspace concept one step further. Gaia-X considers generic data-related services (e.g. storage, web servers) to enable interoperability between different cloud providers and IT infrastructures and also builds a common trust layer shared between dataspaces. The BatWoMan architecture builds on both the IDS and Gaia-X frameworks and principles.

Multiple data space initiatives focus on sharing data across the supply chain. Catena-X, established in the automotive sector, is one of the most mature of such projects. Members of Catena-X span the whole value chain: the project enables sovereign data exchange between suppliers, manufacturers, handlers, repairers, second life operators and so on. Due to the strong ties between batteries and the automotive industry, Catena-X is also involved in European and global battery passport initiatives.

2. Methodology

From a practical point of view, a battery passport follows the process below. Relevant data from the entire supply chain is shared with authorized parties, from raw materials and manufacturing to usage and end-of-life. Before the battery enters the market, the manufacturer creates a unique identifier, physically accessible on the product, e.g. as a QR (Quick Response) code, a URI (Uniform Resource Identifier) or an RFID (Radio Frequency Identification) tag. They then publish a passport with the required content and links to related data (e.g. battery model information). During its operation, the battery passport can be constantly updated by authorized entities, e.g. with data on its current status or about repairs. When reaching its end-of-life, second-hand users or recyclers can retrieve these data to guide their decisions about recycling, repair or reuse. Publishing, accessing, using or updating data is regulated by policies defined by data owners and compliant with regulations; also respecting privacy requirements.

The technical architecture for battery passports consists of a decentralised system (referred to as "electronic exchange system" in the upcoming new EU Battery Regulation), potentially combined with information stored in centralised storage. The decentralised system will be implemented as a dataspace containing the passports and related data, with sovereign data exchange under access and usage restrictions; and an additional publicly available area containing unrestricted data. Using dataspace standards (e.g. from the already mentioned European Gaia-X and IDSA initiatives), such data can also be integrated with other existing data ecosystems, such as Catena-X for electric vehicle batteries. The centralised part may contain information about battery models or simply a searchable catalogue of data available in the decentralised dataspace. According to the new battery regulation, the Commission should set up and maintain a product passport registry with records of all data carriers and unique identifiers linked to products placed on the market or put in service. In the BatWoMan battery passport demonstrator, this registry is realised via the dataspace's data catalogue.

3. BatWoMan battery passport demonstrator

3.1. The BatWoMan project

The project BatWoMan aims to develop new sustainable and cost-efficient Li-ion battery cell production concepts, paving the way towards carbon-neutral cell production within the European Union. It started in September 2022 and is funded by the European Union's Horizon Europe research and innovation programme. Regarding production processes, it focuses on electrode processing with water-based slurries of high dry mass content, without volatile organic compounds, improved electrolyte filling and low-cost, energy-efficient cell conditioning (wetting, formation and aging). These improvements will be supported by an Artificial Intelligence (AI)-driven platform for smart retooling (adapting machine parameters to optimise production). As part of the project, a battery dataspace and passport demonstrator will be built, using data generated and collected in the project, building on the previously mentioned frameworks and standards, and in alignment with other European product passport initiatives, particularly with BatteryPass and CIRPASS.

3.2. Data sources

The battery passport in BatWoMan uses data collected on raw battery materials, as well as from each step of the improved, data-driven manufacturing process developed in the project, following the content guidance (Battery Pass Consortium, 2023) from the Battery Pass project, based on the new EU Battery Regulation. This is complemented by the results of a full life-cycle assessment, in which the battery's carbon footprint throughout its lifetime and other sustainability-related indicators are estimated.

Raw materials to be used for battery cell production in BatWoMan are investigated, based on the bill-of-material for NMC622/graphite batteries. This investigation considers main players in the global battery materials supply chain for the main electrode materials lithium, cobalt, manganese, nickel and graphite; with further studies on other battery materials such as collectors, paper-based separators, pouch foil and electrolyte components. The focus lies on sustainable sources, with special attention to European suppliers, to facilitate sustainable production within the project.

During the manufacturing process in pilot factories of consortium members, data is collected from each produced battery cell. Aside from general metadata (battery type, ID, manufacturing date and location, manufacturer information, etc.), details of the battery cell's weight, chemistry and composition is recorded, with special attention to hazardous materials and critical or expensive elements to facilitate recycling. Performance and durability metrics are also calculated and recorded.

A life-cycle assessment (LCA) is also part of BatWoMan, to be used for design work within the project as well as assessing the overall environmental performance of the final design for BatWoMan battery cells. Results of the LCA, including sustainability indicators such as the carbon footprint, also provide data for the battery passport.

3.3. Users and their interactions

The BatWoMan demonstrator considers a minimal set of user categories to support basic use cases. We distinguish between suppliers, battery producers, actors within the usage or second life phases, authorities and the general public. Except for the latter, participants interact with the dataspace through their dedicated connector services, which enable interactions according to dataset-specific policies. Participants and their interactions via the battery dataspace are shown in Figure.

Suppliers are registered participants of the underlying dataspace who may publish and consume data, but do not create a passport. They correspond to industry players involved with the supply chain, who do not produce a finished product which is placed on the market (in our case, a battery), and are not legally responsible for creating passports. Within BatWoMan, consortium partners take this role.

The *battery producer* represents the organization placing the battery on the market, who is responsible for creating its passport according to the new EU battery regulation. Like suppliers, they are dataspace members who may publish and consume data, but they also publish passports for each battery. Within BatWoMan, this will be emulated, as no commercial products are produced.

Participants related to the *usage (e.g. user, repairer)* or *second life (e.g. collector, recycler)* phases also play an important part. They provide and consume dynamic data related to individual batteries, for example information regarding its status, repairs being done or whether the battery is reused in a different context. Such dynamic, personal data is out of scope for BatWoMan. However, a simplified "recycler" role, handling only static data (disregarding the usage phase), will be considered.

Authorities may also participate in the dataspace. They have access to all public and restricted data that they require for regulatory purposes, but cannot obtain other datasets which may be sensitive and shared only between particular participants (e.g. manufacturer and their suppliers). In a real scenario, regulatory bodies would fall under this category, within BatWoMan this role will be emulated.

The last category of users of the dataspace is the *general public*. They only have access to publicly available data of a battery, either directly via its unique identifier (e.g. after scanning a QR code physically present on the product) or by searching in the dataspace catalogue.

It is also worth noting that a dataspace participant does not necessarily belong to a single category. A recycling company for instance may appear at the end of a battery's life and also as a supplier. It may consume data related to the battery to be recycled (e.g. to choose the optimal recycling procedures) and also publish data as a supplier (on recycled raw materials for use in new batteries).

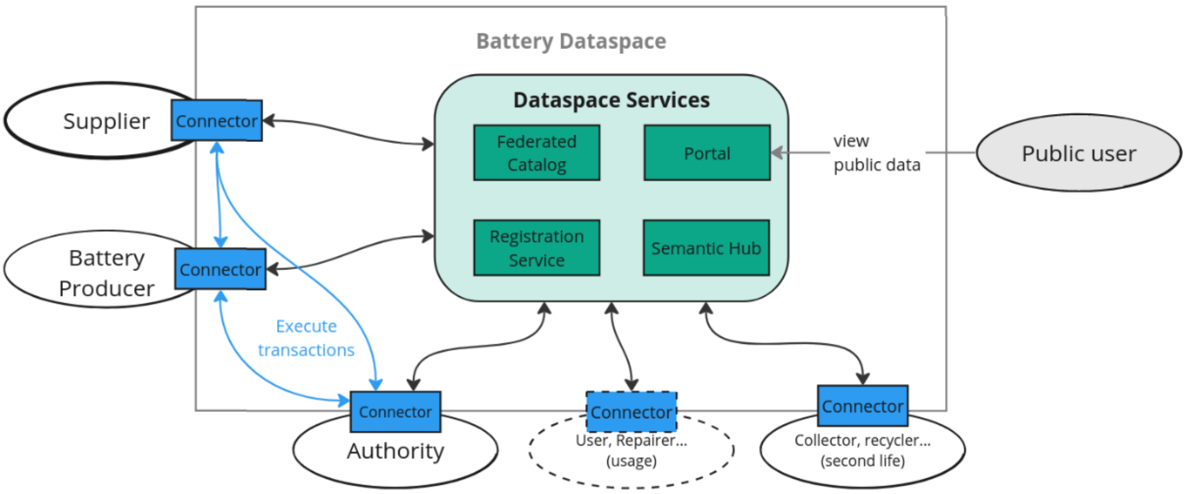

Figure 1. Users and their interactions within the battery dataspace. In BatWoMan, supplier data will be provided by consortium partners (bold line) and the usage phase is out of scope (dashed line)

Source: Own visualization

3.4. System architecture

The BatWoMan demonstrator, as mentioned above, builds on the IDS-RAM and Gaia-X architecture models to realise a decentralised ecosystem for sharing data, including individual battery passports. Participants and datasets are identified via verifiable credentials (VCs), that is, cryptographically signed certificates stored at their owner. The concrete architecture and implementation will be based on Eclipse Dataspace Components (EDC), an open-source software suite used also by Catena-X and other dataspace initiatives, with an expressed goal to comply with both IDS and Gaia-X architectures. The BatWoMan architecture consists of dataspace services and connectors, both of which we will describe using terminology from the IDS-RAM and Gaia-X.

Dataspace services are operated for a dataspace to facilitate interaction between its participants (see Figure 2). The BatWoMan dataspace architecture includes four such services: a *portal*, a *registration service*, a *semantic hub* and a *federated catalogue* (the latter will be explained later). The *portal* provides user-friendly access to the dataspace, both to public and restricted functionalities. Using the *portal*, participants can browse content or provide and consume data, respecting access and usage restrictions. The *registration service* accepts requests to join the dataspace (optionally associated with a particular role) and if the conditions are satisfied, issues VCs that participants can use as a proof of their membership. It also connects to external services for the verification, particularly the Gaia-X Trust Services. The *semantic hub* stores and provides machine-readable definitions of standardised data descriptions for battery passports and other kinds of datasets, to enable services to automatically interpret data available via the dataspace.

Following the IDS architecture, so-called *connectors* are deployed for each registered participant. A connector is a dedicated component for sending and receiving data, which acts as a secure gateway and enables authorized access to the dataspace. Participants can interact both with dataspace services and directly with each other via their corresponding connectors. In EDC, processes related to data exchange are separated into a control and a data plane to provide better scalability and a separation of concerns. The control plane handles all processes that prepare and follow a transaction, including publishing data and associated policies (e.g. for access and usage control), validating participants and datasets, contracting and logging. The data plane's responsibility lies in the execution of a transaction after successful contract negotiation. Additionally, an identity hub is part of each connector, which is a module to store, manage and present VCs as a proof of identity.

A *catalogue* complements the system to allow participants to search and select datasets. It builds on a federated architecture, consisting of nodes in each connector and a crawler - potentially with multiple instances - for the dataspace (see Figure). The crawler polls the nodes of each registered participant's connector, which respond with currently registered policies and assets. The portal relies on the crawler to enable interaction with the contents of the dataspace. In addition to the catalogue, battery passports are also directly accessible via their unique identifier, e.g. by scanning a QR code on the battery which directly leads to the page of that particular product's passport in the portal.

A participant can *register* themself to the dataspace as follows (see Figure 2, "Registration"):

1. Participant initiates registration with the registration service, sending required metadata (e.g. company registration number, self-signed VC and other credentials).
2. Registration service sends signed VC of dataspace membership to the participant.
3. Participant stores membership credential in its connector's Identity Hub.

Data exchange in the system would consist of the following steps (see Figure 2 "Data Exchange"):

1. Producer publishes a dataset offer with an associated policy via its connector.
2. Consumer initiates contract negotiation via its connector.
3. The connectors negotiate the contract. In this step, they verify VCs of each other and of services and datasets, and ensure that the conditions of policies are met.
4. The connectors execute the data transfer. This may happen using different protocols, such as HTTPS file transfer or cloud-based solutions.

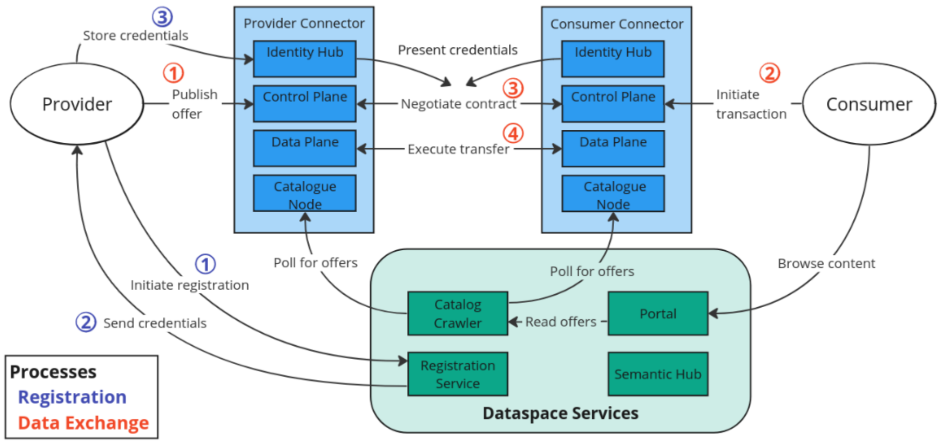

Figure 2. Components of the BatWoMan Passport (dataspace) architecture and their interactions. Steps for two processes are depicted: participant registration (blue) and data exchange (red) Source: Own visualization

3.5. Limitations

The battery passport demonstrator of BatWoMan has some limitations when compared with an operational system. Our system is demonstrated as part of battery production, but not in an operational environment pipeline, corresponding to Technology Readiness Level 6. The BatWoMan battery cells will not be placed on the market, which has implications on the dataspace and passport. First, documents legally required for commercially sold batteries will not all be available. Second, we work with a reduced supply chain and thus emulate certain business roles (battery manufacturer, authority) and omit or limit others (user, repairer, second life operator, recycler...). Related to the reduced supply chain, we also have reduced data availability. Only data from the battery cell production process will be generated as part of BatWoMan, complemented by external data from materials sourcing and estimated data on sustainability from the life cycle assessment. Data related to the usage phase, to the batteries' second life or even from assembled batteries past battery cells (e.g. modules or packs) are not directly included. However, data relevant to the recycling phase, complemented by recommendations on the recycling route, will be included via the LCA.

4. Conclusion

The BatWoMan battery passport and data sharing ecosystem might serve as a validation testbed for battery research and production, to help prepare a suitable set of guidelines, develop best practices and promote an innovative, green battery life cycle. The goal should be to lay a good foundation with sensible standards and guidelines and an architecture that focuses on sustainability, but without a heavy bureaucratic burden on industry that would impede European innovation. Validating the emerging standards and guidelines for battery passports based on real production data is essential to prove their applicability, explore suitable concrete tools for implementation and identify issues early.

In BatWoMan, the combination of production data from pilot factories, aided by rigorous studies and investigation concerning raw materials and the batteries' full life cycle provides an ideal testbed for such a demonstrator. The design for the battery dataspace and passport outlined in this paper provides the basis for a flexible, interoperable implementation within the BatWoMan project and fosters knowledge sharing within and beyond the digital passport and dataspace communities.

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