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Federal Department of the Environment, Transport,
Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech Division

Interim report dated 26.03.2025

BIENE Battery Manager

Cost and benefit-optimized control of batteries on rail vehicles

Source: ©Markus Halder 2025

Date: 26.03.2025

Location: Bern

Publisher:
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech
CH-3003 Bern
www.bfe.admin.ch

Subsidy recipients:
Bern University of Applied Sciences
Aarbergstrasse 46, 2503 Biel/Bienne
www.bfh.ch/en/research/research-areas/energy-storage-center/

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SFOE contract number: SI/502595-01

Zusammenfassung

Das Projekt BIENE (BatterIEschwarm im BahnstromNEtz) konnte den Nutzen eines zentralen Batteriemanagements für die anstehende Elektrifizierung von Diesel-Schienenfahrzeugen in der Schweiz aufzeigen (BAV, 2022). Die vorgeschlagene Lösung soll auf ersten Batteriefahrzeugen pilotiert werden.

Ziel des zentralen Batteriemanagements ist, eine ausreichende Batteriekapazität für die nächsten Einsätze sicherstellen, ein möglichst batterieschonendes Laden zu ermöglichen und das Asset-Management hinsichtlich einer Optimierung der Lebenszykluskosten der Batterien zu unterstützen. Zudem sollen energiewirtschaftliche und netzdienliche Chancen genutzt werden. Das Pilotvorhaben ermöglicht, erprobte und fundierte Anforderungen für zukünftige Batteriefahrzeuge zu definieren und unterstützt einen effizienten Technologieträgerwechsel von fossilen Energien zu einer klimaneutralen Fahrzeugflotte.

Im Rahmen des Projektes konnten die technischen Voraussetzungen für ein skalierbares, zentrales Batteriemanagement geschaffen werden. Fahrzeuge der beiden Pilotflotten wurden mit einem Bordrechner ausgestattet und die Datenpipeline zur Batteriemanagement-Plattform aufgebaut. Wesentliche Vorarbeiten zur Entwicklung der beiden zentralen Plattform-Module «Asset-Management-Cockpit» und «Batteriemanager» erlauben eine nutzerorientierte Entwicklung. Die über das «Asset-Management-Cockpit» gesammelten und verfügbaren Daten sind nicht nur für die Überwachung der Batterien in den Fahrzeugen wichtig, sondern auch als unverzichtbare Grundlage für 2nd Life Anwendungen. Ladealgorithmen für eine batterieschonende Ladung konnten auf einer Simulationsumgebung getestet werden und sind nun bereit für eine Anwendung auf den Pilotfahrzeugen. Gleichzeitig wurden die methodischen Voraussetzungen entwickelt, um die Wirkung der optimierten Ladealgorithmen auf die Batteriealterung ausweisen zu können. Im Batterielabor der BFH läuft seit November 2024 ein entsprechender Alterungstest mit vergleichbaren Zellen als «Physical Twins» der Fahrzeugbatterien.

Um sicherstellen zu können, dass zukünftige Batteriefahrzeuge mit der Batteriemanagement-Plattform verbunden werden können, müssen entsprechende Anforderungen bereits in der Fahrzeug-beschaffung berücksichtigt werden. Dafür konnte ein Anforderungsdokument entwickelt und in laufenden Beschaffungsprojekten berücksichtigt werden (Halder et al., 2025).

Résumé

Le projet BIENE (BatterIEschwarm im BahnstromNEtz) a pu démontrer les avantages d'une gestion centralisée des batteries pour l'électrification prochaine des véhicules ferroviaires diesel en Suisse (BAV, 2022). La solution proposée consiste à mettre en œuvre un programme pilote sur les premiers véhicules alimentés par batterie.

L'objectif principal du battery management system est de garantir une capacité de batterie adéquate pour les opérations ultérieures, de faciliter la charge optimisée en fonction de l'âge et d'aider à la gestion des actifs afin d'optimiser les coûts du cycle de vie des batteries. En outre, le système vise à tirer parti des possibilités de desserte du réseau.

Grâce à ce projet pilote, nous pouvons établir et valider les exigences pour les futurs véhicules à batterie, en favorisant une transition technologique efficace des combustibles fossiles vers un parc de véhicules à impact réduit sur le climat. Les résultats de cette initiative contribueront non seulement à faire progresser la technologie des batteries, mais joueront également un rôle essentiel dans l'engagement de la Suisse en faveur de solutions de transport durables et écologiques.

Dans le cadre du projet, les spécifications techniques pour un système scalable et centralisé de gestion des batteries ont été établies. Les véhicules des deux flottes pilotes ont été équipés avec un ordinateur de bord et un pipeline de données vers la plateforme de gestion des batteries a été mise en place. Un travail préliminaire significatif sur le développement des deux modules centraux de la plateforme, ‘Asset Management Cockpit’ et ‘Battery Manager’, ont permis un développement orienté vers l’utilisateur. Les données collectées et disponibles via l'Asset Management Cockpit ne sont pas seulement importantes pour surveiller les batteries des véhicules, mais constituent également une base indispensable pour les applications de deuxième vie. Des algorithmes de « battery-friendly charging » ont été testés avec the simulation computationnelles et sont prêts à être utilisés dans les véhicules pilotes. Parallèlement, une méthode pour pouvoir démontrer l'effet des algorithmes de charge optimisés sur le vieillissement des batteries a été développée. Pour prouver les effets du Battery Manager, le laboratoire de batteries de la BFH effectue depuis novembre 2024 des tests de vieillissement avec des cellules qui servent comme « Physical Twins» des batteries des véhicules.

Les applications de seconde vie de la batterie peuvent varier considérablement et, en fonction de leur objectif, différentes évaluations doivent être considérées, notamment en ce qui concerne les données à enregistrer. Pour que les futurs véhicules à batterie puissent être connectés à la plateforme de gestion de la batterie, les spécifications correspondantes doivent déjà être prises en compte lors de l'acquisition des véhicules. Un document sur les spécifications a été préparé à cette fin et pris en compte dans les processus d'acquisition en cours (Halder et al., 2025).

Summary

The project BIENE (BatterIEschwarm im BahnstromNEtz) successfully demonstrated the advantages of a centralized battery management system for the imminent electrification of diesel rail vehicles in Switzerland (BAV, 2022). The proposed solution involves implementing a pilot program on the initial battery-powered vehicles.

The primary objective of the central battery management system is to ensure adequate battery capacity for subsequent operations, facilitate age-optimized charging, and assist in asset management to optimize the life cycle costs of the batteries. Moreover, the system aims to leverage grid-serving opportunities.

Through the pilot project, we can establish and validate requirements for future battery vehicles, fostering an efficient technological transition from fossil fuels to a climate-neutral vehicle fleet. The findings from this initiative will not only contribute to the advancement of battery technology but will also play a pivotal role in supporting the commitment to sustainable and eco-friendly transportation solutions.

As part of the project, the technical requirements for a scalable, centralised battery management system were created. Vehicles in the two pilot fleets were equipped with an onboard computer and the data pipeline to the battery management platform was established. Significant preliminary work on the development of the two central platform modules ‘Asset Management Cockpit’ and ‘Battery Manager’ allows for user-orientated development. The data collected and available via the Asset Management Cockpit is not only important for monitoring the batteries on the vehicles, but also as an indispensable basis for 2nd life applications. Charging algorithms for battery-friendly charging were tested in a simulation environment and are now ready for use in pilot vehicles. At the same time, the methodological requirements were developed to be able to demonstrate the effect of the optimised charging algorithms on battery ageing. A corresponding ageing test with comparable cells as ‘physical twins’ of the vehicle batteries has been running in the BFH battery laboratory since November 2024.

To ensure that future battery vehicles can be connected to the battery management platform, corresponding requirements must already be considered during vehicle procurement. A requirements document has been developed for this purpose and considered in ongoing procurement projects (Halder et al., 2025).

Contents

List of abbreviations

Abbreviation	Definition
API	Application Programming Interface
AVG	Average
BMP	Battery Management Platform
BTC	Bahntechnik Center, Railway Technology Centre of SBB Infrastructure at Hägendorf
DoD	Depth of Discharge
DoC	Depth of Charge
EAP	Enterprise Analytics Platform from SBB
EFC	Equivalent Full Cycles
GSM-P	Global System for Mobile Communication, Public
HDBSCAN	Hierarchical Density-Based Spatial Clustering of Applications with Noise (data clustering algorithm)
LMLS	Lastmanagement-Laststeuerung, power demand management control system
MVP	Minimum Viable Product
MQTT	Message Queuing Telemetry Transport (network protocol)
RUL	Remaining Useful Life
SF	Stress Factor
SoH	State of Health
SoR	State of Resistance
SoC	State of Charge
RhB	Rhaetian Railway, Rhätische Bahn
RTE	Regelwerk Technik Eisenbahn, Railway Technology Regulations from VöV (Swiss Public Transport Association)
SBB	Swiss Federal Railways, Schweizerische Bundesbahnen
TCMS	Train Control & Management System
UPS	Uninterruptible Power Supply System
VRLA	Valve-Regulated Lead-Acid battery
VPN	Virtual Privat Network

1 Introduction

1.1 Background information and current situation

The Swiss Federal Railways (SBB), Rhätische Bahn (RhB) and other railway companies in Switzerland are embarking on a significant technological shift, transitioning from diesel-powered rail vehicles to battery-powered ones. This transition is motivated by the desire to achieve a more sustainable and environmentally friendly rail operation.

Currently, there is just a limited number of battery electric railway vehicles in operation. Experiences with the first vehicles have highlighted several challenges:

- Traction batteries make up a significant share of the total costs of a rail vehicle and therefore have a major impact on the life cycle costs. Active **asset management**, based on operational data and support tools such as battery models is essential to optimize the service life of the battery. However, know-how and experience in managing the asset “traction battery” is very limited today. In addition, monitoring developments in battery performance and the exploration of second-life applications have not been integrated into current practices at Swiss railways.
- Current charging strategies rarely take **battery-friendly charging** into account, although this would often be possible from an operational point of view**.** The batteries are charged independently of the expected use. By default, they are always charged up to maximum SoC. However, a high SoC increases the calendrical ageing of the batteries. The rail power grid can provide high charging currents for charging via overhead lines. If charging is consistently carried out with unnecessarily high currents, cyclic battery ageing increases.
- Battery storage systems tend to be oversized for many missions due to several reasons: a uniform vehicle fleet is normally procured for different requirements - the battery is then oversized for less demanding missions. Furthermore, vehicles may be delivered with a large reserve capacity, which is gradually released as the battery ages to fulfil the mission profiles even with increased aging according to given guarantees. As it is the case for RhB battery shunting locomotives the reserve capacities are blocked in the first years and cannot be used. This reduces **operational flexibility** if a higher battery capacity is required for particularly demanding missions.
- The traction energy that can be stored on battery-powered vehicles is much lower than on diesel vehicles. Dispatchers and users of battery-powered vehicles must therefore pay particular attention to ensuring that the vehicles are sufficiently charged for the next mission. The currently still very limited charging infrastructure at railway sidings poses a particular challenge. Vehicle users need a decision support to prioritize which vehicle to charge first. At present, vehicle users do not have any tools at their disposal with which they can **check** charging needs and operational readiness and actively **influence the charging process**.
- The BIENE study has highlighted potential benefits of **grid services** using the flexibility of a future battery swarm in the railway power grid. With the existing power demand management platform from SBB Energy (Lastmanagement-Laststeuerung LMLS), the foundations have been laid. However, this has so far been used to influence thermal loads, but not to control batteries. For batteries to be connected to the load control system, the necessary technical requirements must be created, and appropriate interfaces defined.
- Experience from the power demand management program with heaters has shown that retrofitting vehicles to connect them to a central management platform is much more expensive than already defining requirements when procuring the vehicles.
  However, there is currently no proven and coordinated **requirements** document for connecting battery rail vehicles to a battery management platform.

Specific solutions are available on the market for individual aspects of the named challenges. This is especially the case for condition monitoring of batteries that support asset management. SBB's Center of Competence Energy Storage has compiled a market overview and selected the battery monitoring solution from PowerUp for a two-year pilot phase. Alternative providers are for example Twaice, Batterylog, Accure Battery Intelligence, Voltaiq or Volytica Diagnostics. These solutions, which are independent of battery system manufacturers, usually offer a web-based platform for battery monitoring. In addition, some battery manufacturers also offer software tools for analyzing battery data. Depending on the solution, the focus can be on health status and retaining useful lifetime prediction, the topic of safety and anomaly detection or on options for fleet analysis and deployment optimization. They each require specific battery data. Existing monitoring solutions on the market are financed by annual license fees based on installed capacity or number of vehicles. In addition, there are lower fees for the onboarding of new battery systems. The solutions offered are used in particular in the field of stationary battery storage or electromobility. The annual license costs are high and the functionalities are often not tailored to the minimum requirements of a railroad operator.

There are also various software solutions for demand-side management on the market. However, as described in the BIENE study, these do not fulfil the requirements for use in the SBB traction electricity network. The existing V2G solutions for road battery-powered vehicles are not transferable to the application for specific use cases in the rail power grid. Specific features of the traction current grid include charging and discharging during the journey, communication via vehicles and not via charging points, and short-term discharging of batteries to cover peak loads in the seconds range, as opposed to 15-minute average values for load management in the 50 Hz grid. (BAV, 2022).

A combined solution that not only allows battery monitoring via unidirectional communication between the vehicles and a central platform, but also optimises battery charging for mobile consumers depending on the expected mission profile and enables the use of swarm batteries as reserve power plants in the traction power grid, is not yet available on the market. The centralised battery management platform planned as part of the project is intended as a pilot version to demonstrate the feasibility and benefits of such a solution.

1.2 Purpose of the project

The purpose of the project is to support the electrification of the rail diesel fleet by supporting key players in the process: vehicle producer, owner, dispatcher and user as well es energy provider as sketched in Figure 1.

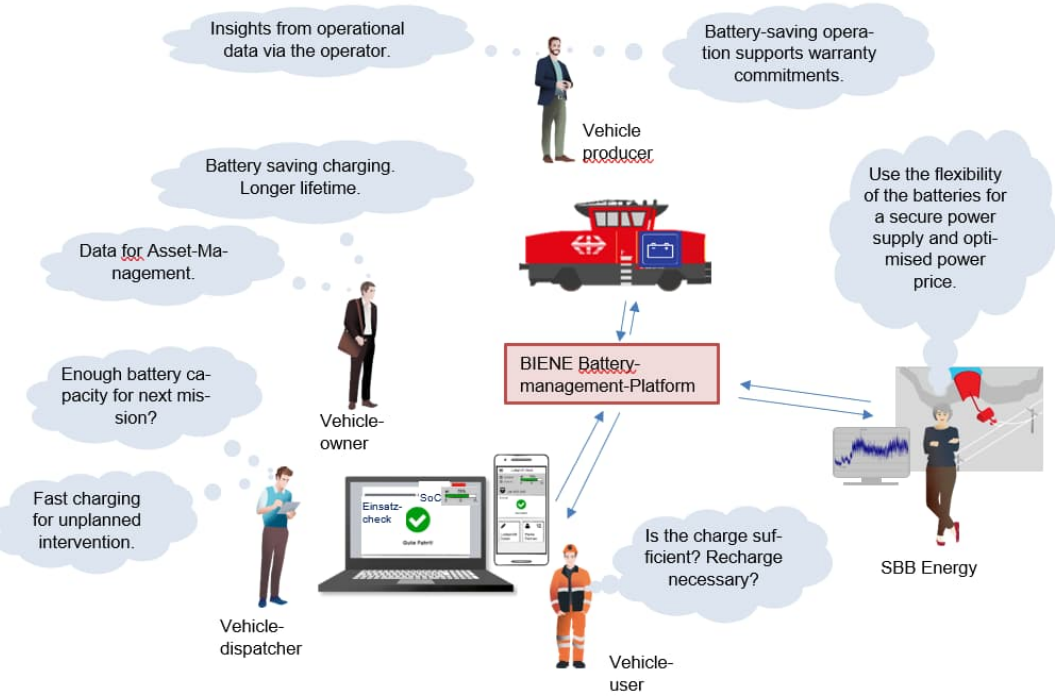


Figure 1: Users and stakeholders of the BIENE Battery Manager and their expectations

The project should provide a solution to the challenges named in chapter 1.1 as follows:

- **Asset management:** Vehicle resp. battery asset owners should be supported by a dedicated digital cockpit with relevant information about battery state, critical impacts, or remaining lifetime. Battery experts should be empowered to easily access important battery parameters for detailed analyses.
  To prepare for possible second-life usage of traction batteries, concepts and requirements must be worked out.
- **Battery-friendly charging:** The vehicle usage in railway business to some extent follows planned schedules. Historical data can be used to forecast the energy requirements for upcoming mission profiles. The battery manager should be able to calculate an optimum charging profile for the next mission profile and send it to the vehicle. Charging power as well as target SoC are key optimisation parameters for an extended battery service life.
  The pilot project is intended to demonstrate the effect of optimized charging strategies on ageing compared to current standard charging strategies.
- **Operational flexibility:** The battery manager influences the state of charge to maximise battery life. However, it should also enable vehicle users to utilise the full battery capacity in a targeted and uncomplicated manner when it is needed for operational reasons.
- **Check and influence the charging process**: Vehicle users are to be supported in ensuring that their battery-powered vehicles are ready for the next service. Available charging windows and different service profiles should be easily customisable.
- **Grid services:** By connecting the BIENE battery manager to the power demand management platform (LMLS) from SBB Energy the technical feasibility of value-cases such as power peak shaving and energy provision in overload situations should be proven.
- **Requirements for vehicle procurement**: As a precondition for nationwide implementation, the requirements for future battery vehicle procurement projects are to be specified to assure

standardised interfaces for connecting the vehicles to a central battery management platform. Further framework conditions that support the overall system optimization, such as contractual issues, regulations, and financing are to be identified.

The central battery management pilot system will be a software tool within SBB's digital zone, with communication interfaces and a user interface cockpit. The pilot will involve the Tafag “Hocharbeitsbühne” battery vehicles from SBB Infrastructure and the Geaf 2/2 shunting locomotives from Rhaetian Railway (RhB), equipped with the pilot BIENE battery manager.

1.3 Objectives

The project aims to address several issues related to the electrification of the rail diesel fleet in Switzerland. To achieve this, the project sets out the following measurable objectives:

1. Increase the usable lifetime of battery systems used for rail application thus minimizing the total CO_2-footprint and maximize the use of resources of lithium-ion battery systems during the lifetime. We expect a lifetime increase of 10-15% in the first life operation compared to a strategy without optimal charging and central management. Adding second life applications will further decrease the CO_2 footprint.
2. Dynamic integration of the rail vehicles traction batteries in the SBB grid. Connecting the pilot vehicle to the SBB power demand management platform so that the value cases described in BIENE (cover power peaks, protecting weak grids, …) can be realised.

The reduction of downtimes for battery vehicles is a further qualitative goal that is expected to be achieved by operating a central management system but cannot be quantified easily. However, the central management and the recorded data from the battery operation in a statistical frame, will help to have fast troubleshooting and fault reparation but most importantly will help the sector to move from a preventive maintenance scheme to a predictive maintenance or on-demand maintenance scheme.

Throughout the duration of the project, the verification of these goals will be carried out using a combination of simulation and measurements on the pilot system. Specifically, the increase in lifetime will be demonstrated by simulating the expected degradation with and without the central battery management system. After the first year of operation on the pilot vehicle, a comparison will be made between the measured and the estimated state of health (SoH) obtained through simulation. These results will highlight the benefits of the forecasted mission profile, optimized charge strategy, and central asset management, all of which contribute to ensuring optimal operating conditions for the battery system.
The goal of meeting the needs of all players involved, especially the vehicle dispatchers and users can also be cited as a very important, indirect goal for the above-mentioned project objectives.
The BIENE Battery Manager can become more successful as a sector project if more and more players start to benefit from it.

2 Description of facility

Core element of the pilot facility will be the central BIENE Battery Manager platform. As sketched in Figure 2, the already existing pilot vehicles will be equipped with an onboard computer including router to communicate with the BIENE platform using existing communication infrastructure of SBB. Adjustments must be made on the train control system TCMS for the interface to the BIENE gateway and router as well as on the communication platform. Furthermore, an interface to the exiting power demand management platform from SBB Energy (Lastmanagement-Laststeuerung LMLS) will be realised.

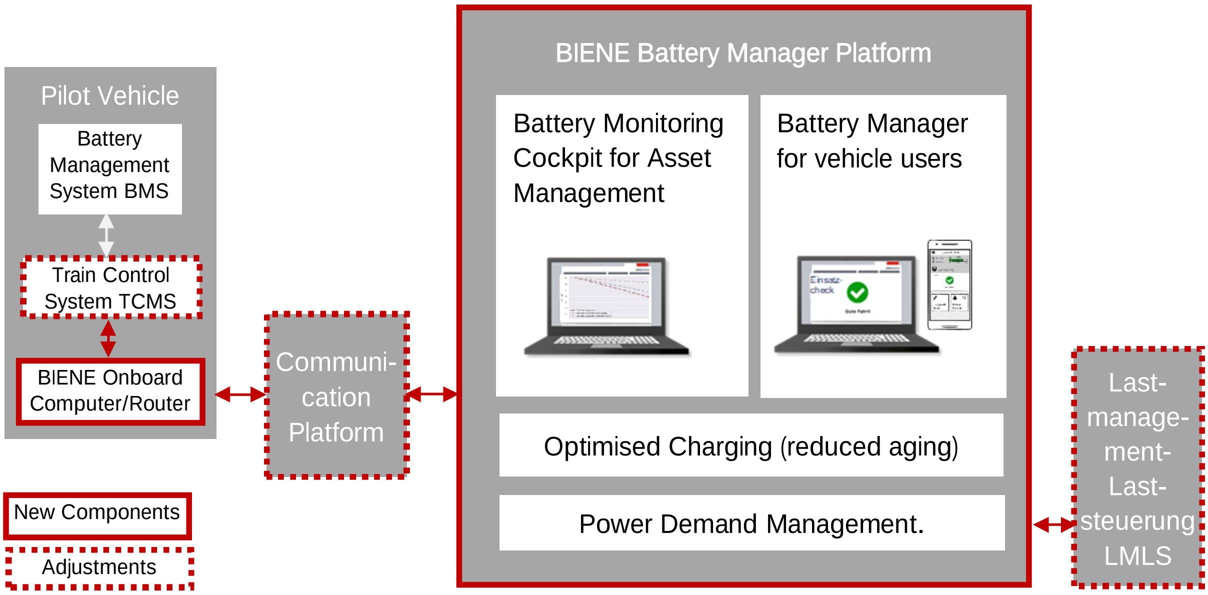


Figure 2: Components of the BIENE pilot facility on vehicle- and landside.

Key features of the BIENE battery management platform are described in chapter 4.3. The components for the communication from vehicle to ground and the characteristics of the pilot vehicles are presented in the following chapters.

2.1 Communication Vehicle to Ground

As part of the pilot project, a communication solution had to be selected that could fulfil the requirements derived from the needs of the users. The solution should also be scalable for later use on future battery fleets deployed by SBB and other railways.

After the evaluation of possible alternatives, routers and gateways have been chosen that are already in use for the existing SBB Passenger Traffic vehicle platform and have proven themselves in railway operations. The gateway chosen in the beginning was the Duagon Gateway 504, as router the model Hirschmann OWL LTE M12 was used for a secured VPN tunnel to the SBB network. In the meantime, however, it has become clear that these two devices are obsolete at SBB and that further security requirements make it necessary to choose another on-board computer with an integrated router. The choice fell on the railway-compatible Syslogic IPC-RSL82J19-R152E device as the successor to a device also used by SBB Passenger Transport for their vehicle platform. All Tafag XTas “Hocharbeitsbühnen” from SBB Infrastructure are in the meanwhile equipped with this new onboard computer, the remaining Rhaetian Railway Geaf 2/2 shunting locomotives are scheduled to be equipped until April 2025.

An interface to the train control and management system (TCMS) was programmed for the two pilot vehicles, the Geaf 2/2 and the Tafag XTas. This allows information to be read from the local battery management system (BMS) and from the vehicle, and target values to be sent to the BMS after a plausibility check on the TCMS. The data is received via GSM-P and processed on land by an MQTT broker. This is connected to SBB's Kafka integration bus via a connector. The data is stored and processed in a Snowflake database on SBB's Enterprise Analytics Platform (EAP). The plan is to realise the active control of battery charging and discharging on an SAP Hana platform, on which SBB's existing power demand management control system (Lastmanagement-Laststeuerung LMLS) has already been deployed (see Figure 3).

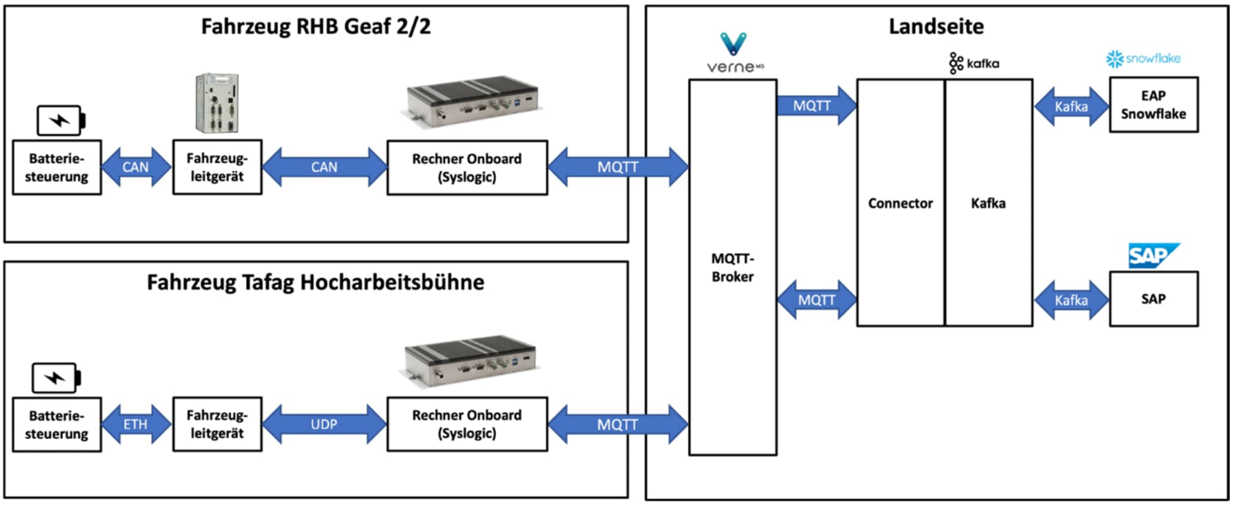


Figure 3: Communication components for the BIENE Battery manager project

The first devices were programmed in the laboratory in 2023 and initial end-to-end connection tests were carried out between a TCMS device and the landside data broker before the devices were installed on a Tafag “Hocharbeitsbühne” vehicle and a Geaf 2/2 shunting locomotive at the end of 2023. A successful data ingest into the SBB Enterprise Analytics Platform (EAP) was realised in January 2024. From then on first data streamed from the pilot vehicles every second were available for analysis purposes and for the planned asset management cockpit. In addition, the RhB's existing TREDIS diagnostic system was utilised for analysis purposes in a first step.

2.2 Pilot vehicles

Although different procurement projects for battery driven rail vehicles are ongoing, yet there are not many vehicles in operation that could serve as pilot vehicles.

At SBB first experiences are taken with the XTas “Hocharbeitsbühne” since 2022. This vehicle can be charged by already existing electrant / distributor boxes beside the tracks with 400 V AC / 32 A or 64 A. If no electrant is available and batteries must be charged, an onboard diesel generator can be used as fallback option. However, the vehicle does not have a pantograph for power supply via overhead lines. The vehicle is not able to drive to a construction site on its own. It must be hauled by a traction vehicle. On the construction side it can move with up to 20 km/h with its own traction engine.

RhB already uses shunting locomotives with traction batteries on board since 2020. Under overhead lines, the vehicles can be supplied with power via a pantograph and travel at a maximum speed of 80 km/h. On non-electrified tracks, they can operate at up to 40 km/h in battery mode. The vehicles can theoretically also be charged via a plug. In practice, however, they are always charged via overhead line.

Table 1: Pilot vehicle fleets

Vehicle	Geaf 2/2	XTas 14m Hocharbeitsbühne
Picture		
Vehicle owner	RhB	SBB Infrastructure
Year built	2020	2022
Vehicle manufacturer	Stadler Bussnang AG	Tafag AG
Weight	30 t	37.2 t
Number of vehicles	7	5
Usage	Shunting, used by teams in Landquart, Thusis, Chur, Untervaz, Ilanz, Davos. Max. speed in battery mode: 40 km/h.	Maintenance of overhead lines. Traction for self-driving up to 20 km/h. Work movement with extended platform: 5 km/h.
Power supply	Via pantograph, plug or battery	Via plug or battery or diesel generator
Batteries	5 x Eforce 31.08 kWh Sum: 155.4 kWh Li-Ion NMC	4 x Akasol 15 OEM 50 PRC, 33 kWh Sum: 132 kWh Li-Ion NMC

3 Procedures and methodology

General procedures and methodologies are described below for connecting pilot vehicles, for achieving efficient and user-oriented software development and finally for proving the impact of the BIENE battery manager especially on battery aging.

3.1 Vehicle connection to the central BIENE platform

A basic prerequisite for centralised battery monitoring and control is the connection of the vehicles to the central BIENE platform. The following methodological principles were defined to ensure that the planned sector solution can be used on a broad basis and can utilise synergies:

- A manufacturer-independent, non-proprietary system by the vehicle operators can reduce dependence on different vehicle suppliers and utilise cross-fleet synergies.

- A pragmatic solution can be chosen for the pilot, but its scalability to the entire fleet must be guaranteed.
- The requirements for communication to and from the vehicle are described in a standard requirements document, which serves as a reference for future vehicle procurement projects (Halder et al. 2025).

IT security is to be guaranteed by complying with SBB's IT requirements. Related to IT security several security mechanisms have been implemented to ensure that no external access (from the public Internet) is possible:

- No public IP address: The router does not have a public IP address. Internet access is via a CGN (Carrier Grade network address translation (NAT)), which means that the address cannot be accessed from outside. All communication must be initiated by the router.
- Forced virtual private network (VPN) communication: The router only allows VPN connections. As no incoming connections are possible through the CGN, the VPN tunnel must always be established by the BIENE computers.
- Stateful firewall on the computer: A stateful firewall is implemented on the BIENE computers, which only allows required outgoing connections. All external connections are blocked.

With regard to safety requirements, the shore-side signals must be regarded as a suggestion on the vehicle. The vehicle must retain technical sovereignty at all times. This means limiting the values to the minimum and maximum. In addition, the suggestion may only be implemented if all environmental conditions like temperatures are suitable. If an incorrect value is sent from somewhere, this may only have an influence within the correct value range.

3.2 Methodology for software development

The feasibility of the envisioned solution depends largely on whether users can use it to fulfil their needs. Vehicle owners will only connect their vehicles to the platform if they benefit from battery monitoring and extended battery life. Vehicle users will only use the software and enter the necessary information if the software helps them to ensure a sufficient charge for and during the next mission. SBB Energie will only invest in further development and operation of the software if it can utilise the flexibility of the swarm batteries in the railway power grid. It is therefore crucial to consistently consider the needs of the user groups from the outset. In terms of methodology, we are guided by established innovation management principles:

- In terms of customer-centred innovation, it is important to find the intersection of what users want, what is technically feasible and what is economically viable.

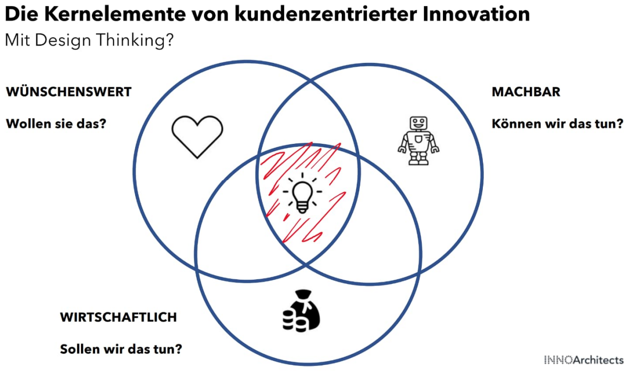


Figure 4: The core elements of customer-centred innovation (Source: InnoArchitects, Bern)

- The solution is developed iteratively in a "learn-build-measure" cycle. The first step is to find out the needs of potential users of the BIENE battery manager via interviews. On this basis, initial user stories are sketched, and rapid prototype versions are created. This allows us to test and measure whether the needs can be met. Only when we have learnt enough about the needs, requirements for a possible IT implementation will be defined.

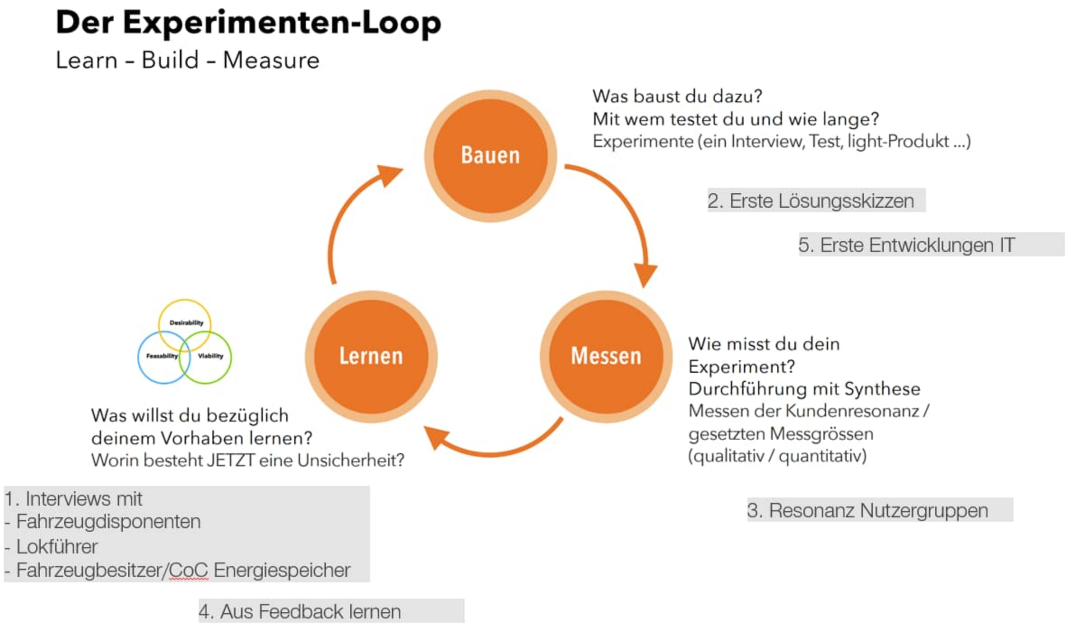


Figure 5: The Experiment Loop (Source: InnoArchitects, Bern, applied to BIENE project (grey boxes))

- The platform is developed according to agile principles. The aim is to create as much added value as possible within the limited resources available. The definition of a minimum viable product (MVP) ensures that features that are essential for users are developed. Once these have been implemented, additional features can be prioritised for additional implementation in close consultation with the users of the platform. The defined MVP functionalities are described in chapter 4.3.2.

3.3 Methodology for impact analysis on battery aging

To scientifically demonstrate the benefits of the battery management system, a physical twin experiment will be conducted, and the results will be combined with the simulation outputs of the Open-Sesame aging model. The physical twin concept involves creating a real-world counterpart that mirrors the characteristics and behaviours of the targeted system, in this case, the battery management system. This entails defining a typical power usage profile (charge and discharge) and testing it in a controlled environment. The degradation impact of this typical profile will be compared with an optimized one (charging optimization), with this power profile comparison being the sole variable. The benefit of the project will be directly demonstrated.

To ensure reliable results, each test will be conducted with multiple cells. This approach enhances the reliability and applicability of the data, considering the natural variability in cell performance.

The results of this activity will not only confirm the advantages of battery management systems in slowing battery aging but will also provide crucial information for fine-tuning the Open-Sesame mechanism to specific cells characteristics. This dual outcome not only validates the effectiveness of the proposed system but also lays the groundwork for optimizing and applying it to different battery cells.

For completeness, three distinct tests will be conducted, comparing their outcomes to clearly prove the benefits of different management strategies.

- First Case: This scenario utilizes the current cell conditions at SBB and RhB, which include voltage limits, hence capacity limitations. The implemented strategy involves charging the battery as soon as possible under constant power conditions until it reaches the maximum allowable SoC. This test aims to showcase the effects of capacity constraints on battery degradation, replicating the current implementation in real-case scenarios.
- Second Case: In this test, the battery voltage is fully unlocked, removing any capacity restrictions while employing the same charging strategy as in the first case. This scenario serves as a reference to evaluate the impact of unrestricted capacity on battery degradation when no optimization strategy is applied, offering a baseline for comparing both restricted and optimized usage conditions.
- Third Case: Contrasting with the second scenario, this test implements an optimized charging and usage strategy with no capacity restrictions to assess the benefits of strategic battery management in minimizing degradation.

These scenarios will help in understanding the trade-offs and benefits of different battery usage strategies, contributing to the optimization of the battery management system for diverse conditions.

4 Activities and results

4.1 Model-based support for battery assessment (WP1)

As part of work package 1, the Open Sesame model is to be prepared in such a way that it can be used as a supporting tool in the preliminary design phase. The selection of the Open-Sesame model is based on its ability to achieve a favourable balance between accuracy and computational efficiency. The aim is to support the preliminary design of a battery system by being able to simulate the dimensioning based on a defined application profile. In addition, it should provide insight into the most critical ageing parameters of the battery storage system in use and provide initial key performance indicators for the economic efficiency calculation.

To achieve this, several features have been defined that are to be added to the Open-Sesame model. The implementation of the features aims to make Open-Sesame more aligned with the specific requirements of the project. Several features and extra outputs have been selected for implementation, including:

a) Visualization of degradation factors
b) Verification of Open-Sesame's prediction accuracy
c) Implementation of oversize protection on ageing
d) Analysis of input profiles
e) Visualizing segments of higher degradation within the usage profile
f) Incorporation of economic indicators

These additions are helpful to make Open-Sesame a more effective tool for the project's battery assessment needs, providing a clear and purpose-driven approach improves its utility for WP3.3.

<u>Open-Sesame model accuracy</u>

During the initial phase of this work package, the accuracy of Open-Sesame's predictions is being checked. This is being done by comparing the model's forecasts with experimental results. This helped understand how reliable Open-Sesame is for NMC cells, whether the model is tuned or not. It also prompts a deep dive into the code and improving the code structure.

The validation of computational results through comparison with experimental data is standard practice, and Open-Sesame is no exception. In this case, the validation process relies on the utilization of two distinct experimental datasets. It's crucial to notice that these datasets were generated under controlled conditions within a protected environment, lending credibility to the assumption that simulating identical tests with the same environmental constraints is valid.

Following the validation process, the results obtained post-adjustment of the initial cell conditions, commonly sourced from a datasheet (referencing SoH degradation, Voltage range, Nominal Capacity, Nominal Energy, and Internal resistance factor), led to a maximum relative error of 10% (Figure 36 in the Appendix), contingent on the specific test case. This alignment between simulated and experimental outcomes underscores the accuracy of Open-Sesame under the given conditions and without any tuning procedure.

$$e_{rel_{max}} = \left| \frac{x_{exp} - x_{sim}}{x_{exp}} \right|_{max}$$

Upon fine-tuning the model with measurements obtained from the tested cell, having refined the stress factor (SF) according to the specific cell characteristics, the accuracy estimation of the SoH model experienced a significant enhancement. The maximum relative error was reduced to 4% signifying a substantial improvement in the model's predictive capabilities, effectively capturing the SoH degradation with precision across a range of temperatures, DoD, AVG SoC, and C-rate[1] (Check Figures in the Appendix for more details). This iterative refinement not only increases the precision of the model but also represents a crucial step towards establishing a more robust and adaptable computational framework.

This activity was specifically conducted for NMC cells and validated using two different datasets. The utilization of multiple datasets not only provided a comprehensive assessment of the model error but also served as a foundation for defining a crucial turning point for subsequent activities. More details about the Open-Sesame validation and its applications can be found in the document published on Aramis (IEA ES TCP Task 32, 2023).

Total Cost of Ownership (TCO)

The TCO is a critical measure for understanding the financial implications of battery system degradation and monitoring the ongoing costs associated with this asset throughout its lifecycle. The calculation of TCO includes both direct costs, such as acquisition and maintenance, and indirect costs, including recycling and estimating the residual value.

TCO calculations are complex, particularly when estimating the residual value of the battery. This complexity is due to the non-linear degradation of the cell's capacity and internal resistance, represented by the SoH and SoR, which are significantly influenced by different usage patterns.

Forecasting the RUL of the battery is a key aspect to define the residual value of the cell. The degradation behaviour of a battery features a 'Knee-point,' which indicates a drastic change in the rate of degradation and marks the approach toward the end of life. The timing of reaching this point can vary significantly based on the battery’s past usage, thus affecting the calculation of the residual value.

For this reason, the TCO is calculated using the following equation:

[1] The C-rate describes the charging and discharging current in relation to the nominal capacity of the battery. 1C means that the battery is fully discharged within one hour.

$$C_{battery} = C_{acquisition} + C_{maintenance} + C_{recycling} - C_{residual\ value}$$

1) $C_{acquisition} = Specific\ energy\ cost\ * nominal\ energy$
2) $C_{maintenance} = specific\ maintenance\ costs\ * energy\ throughput$
3) $C_{recycling} = (C_{fees} + C_{recy}) * Weight_{material} + C_{facility} - Price\ * Weight_{recoverd}$
4) $C_{res.} = C_{acqu}[1 - (\Delta SoH_{cyc} * SF_{cap,cyc} + \Delta SoH_{cal} * SF_{cap,cal} + \Delta SoR_{cyc} * SF_{res,cyc} + \Delta SoR_{cal} * SF_{res,cal})]$

Equation 1: TCO calculation

Equation 1: TCO calculationEquation 1 expresses the TCO as a function of evolving degradation parameters (ΔSoH and ΔSoR) and stress factors (SF) that aggregate the effects of past usages. These stress factors consider all past usage in the form of stress factors combined and weighted based on the EFC for cyclic aging or time for calendar aging. Due to the aging of the cell, the power profile experienced by the cell in one usage scenario may differ in another, affecting the calculated residual value. Furthermore, constraints are included to ensure that past usages cannot reduce the value of the cell by more than 20% from its related degradation.

Besides the implementation of the TCO, a new version of Open-Sesame has been uploaded that includes new outputs and a reshaped code structure. Additionally, a publication detailing all the steps and developments has been submitted for review. Last but not least, an additional version calculating the optimal size of the battery as a function of the power needs has been developed.

4.2 Second-Life readiness (WP2)

The importance of lithium-ion batteries in public transportation is steadily increasing. The variety of applications in which batteries are used is growing and new perspectives are also opening up for the use of second-life batteries. To what extent could an operator extend the cycle of a battery storage system in their own company by using disused batteries for a second application?

4.2.1 Objective

The aim of the Second-Life readiness work package is to clarify whether lithium-ion batteries used by public transport operators could also be used in a second application in the same company after their initial use in the vehicle. The aim of the work package is to identify the conditions under which this would be possible and what challenges would exist.

The aim is to identify which requirements must be incorporated into the procurement and operation of the initial application to enable 2nd life. In addition, possible 2nd-life applications within SBB will be identified and their requirements described. The next step is to discuss how the transition from the first to the second application can take place.

The time horizon until the first battery storage systems from rail vehicles could be used as second-life battery storage systems within SBB is long. However, the conceptual considerations that have already been made can help to make second-life easier later or to test second-life battery storage from other sources today.

4.2.2 Life cycle concept @SBB

Lithium-ion batteries will become established at SBB over the next few years, particularly in rail vehicle applications. The current diesel-powered shunting and construction site vehicles will gradually be replaced by pantograph-battery hybrid vehicles. Last-mile batteries will be used on SBB Cargo's new mainline locomotives. Battery storage systems will also replace the current diesel generators on rail wagons, which require a power supply to operate machines such as cranes or lifting platforms on the wagons. On construction sites, battery storage systems are mainly used in small applications (hand-held devices, small energy supply units, etc.). The fleet of road vehicles is gradually being converted to electric vehicles. For possible second-life applications at SBB, the disused battery storage units of rail vehicles in particular are likely to be considered in future.

The life cycle concept of batteries at SBB is shown in Figure 6. The battery life cycle begins with the sustainable procurement strategy for battery storage systems. The initial course can already be set at the procurement stage to make a later transition from the first to the second life and the subsequent use in the second life as efficient as possible. The new EU Battery Regulation is suitable for defining sustainability requirements in procurement.

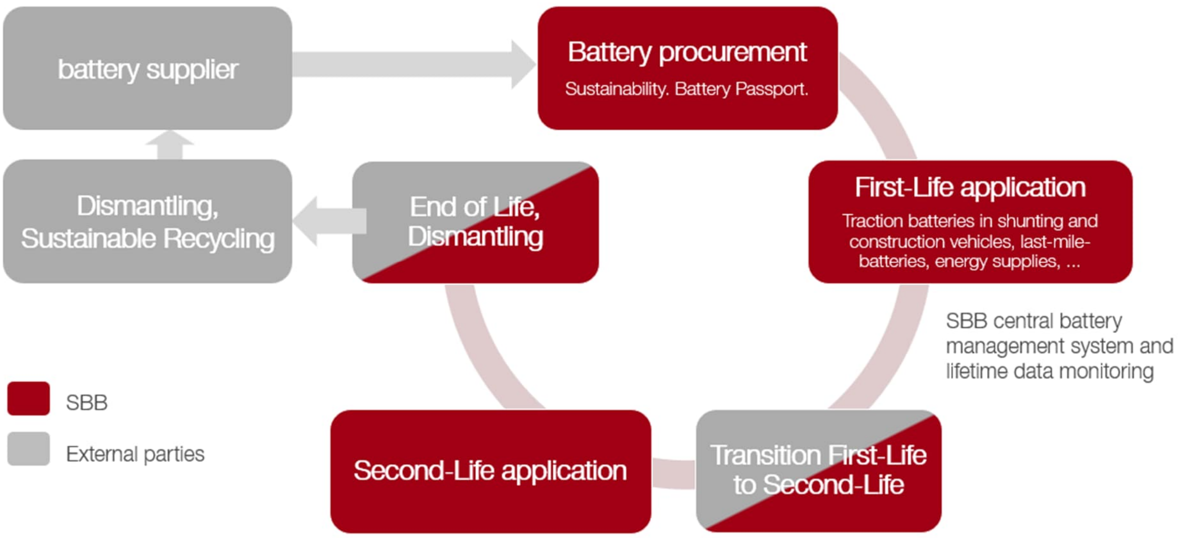


Figure 6: Life cycle concept of SBB batteries.

This is followed using the battery storage system in the initial application. The asset management system implemented via BIENE makes it possible to track battery use over the entire life cycle. An understanding of the battery's previous mode of operation and knowledge of accelerated ageing processes or possible damage is a key advantage for a subsequent second use of the battery.

If the battery storage system can no longer provide the battery capacity or power required for use due to ageing processes, the battery storage system can be put to secondary use. Depending on the cell technology used, this is expected to happen after around ten to eighteen years for rail vehicles.

The transition from the initial application to the second-life application could be carried out by an external partner or, if SBB has the necessary skills, by SBB itself. Challenges and general recommendations for the transition from the first to the second application, or the construction of a second-life battery storage system, are discussed in Chapters 4.2.4 and 4.2.5. It should be emphasized that a second-life battery storage system will only be used in an application if a remaining service life in years or cycles and a certain level of safety can be quantified for the product.

There are many conceivable uses for second-life battery storage at SBB. However, the business case must be assessed individually in each case. The service required over the remaining service life must be considered. Second-life battery storage systems are likely to be used in the stationary sector in particular due to their reduced energy density and lower performance.

The expansion of the second-life battery storage system could also be carried out either by an external partner or by SBB itself. The disused battery storage system can then be dismantled and fed into a high-quality recycling process.

4.2.3 Framework conditions for second-life applications@SBB

Both the experience gained from previous procurement projects with battery storage for traction or energy supply and the requirements placed on stationary battery storage at SBB result in fixed framework conditions. A process that is intended to transfer batteries within a company from primary to secondary use must fit into these framework conditions. These requirements for the process and the second-life application are listed below:

1. The cell technology or battery supplier is not specified in the vehicle procurement for good reasons. SBB will have a variety of battery cell technologies such as NMC, LFP, LTO and others in use.
2. The variety of systems and subsystems such as packs or modules will be even greater due to the different battery manufacturers and constant further development - a wide variety of formats, electrical connections and data interfaces.

   The two points - 1. and 2. - increase the complexity of the transition from the first-life to the second-life application and reduce the possibilities for simple scaling of individual second-life application fields.
3. Processing first-life batteries into second-life batteries requires know-how. Dismantling the systems into individual modules, categorizing these modules according to performance and reassembling them into a second-life product has many advantages. For example, badly aged or damaged battery modules can be specifically sorted out. However, this procedure is time-consuming: More effort is required for testing, it is more time-consuming overall and requires a higher level of employee specialization. This could be realized with the help of an external partner.

   A process in which the conversion of the first-life battery storage system into a second-life product is to take place internally at SBB must be less complex. The battery systems would then not be dismantled and reassembled down to module level, but probably only at pack level. This simplifies the process but also leads to a reduced quality of the second-life product. The smallest units (packs) would probably have a usable battery capacity of around 20-30 kWh and weigh between 150 and 400 kg.
4. A project manager will only consider a second-life battery storage system for his application if he receives a kind of guarantee about the remaining service life in years and reliability, as well as the level of safety for the product. Second-life battery storage systems must therefore be categorized according to safety level and remaining service life.
5. The costs of converting the battery storage system into a second-life product suitable for the required application must be borne internally.
6. The second-life batteries could be used in a wide variety of places within SBB. Since in many cases there will be hardly any know-how about second-life batteries, process support and corresponding documentation and, if necessary, training are required.

4.2.4 Considerations and challenges for second life applications by BFH

Batteries often reach their end of life not solely due to capacity fade but because of imbalances between individual cells, which lead to uneven performance and accelerated degradation. Weak balancing strategies during operation exacerbate this issue, as some cells consistently overcharge or over discharge, stressing them further and reducing the overall pack efficiency. Regular cell voltage balancing, either through passive or active balancing techniques, is crucial to maintain pack health and maximize its lifetime. Incorporating more effective balancing strategies in the Battery Management System (BMS) can mitigate these imbalances, ensuring better cell utilization and delaying the onset of failure.

Severe imbalances are often rooted in differences in internal resistance (IR), which can arise from manufacturing variability, poor quality control, or uneven aging. Variations in IR cause non-uniform current distribution during charging and discharging, accelerating degradation in weaker cells. Additionally, the absence of adequate thermal management can exacerbate these imbalances. Cells operating at different temperatures degrade unevenly, further widening the performance gap between cells in a pack. Without intervention, this compounding effect results in premature end-of-life conditions for the battery pack. Thus, strategies to extend battery life and improve second-life potential must include robust balancing mechanisms, regular monitoring of IR and cell temperatures, and improved thermal management systems. For second-life applications, identifying and replacing cells with significantly higher IR or weaker performance can help restore balance and ensure the battery operates efficiently in its new application. Determining when to transition a battery from first to second life requires a comprehensive evaluation of technical, economic, and operational factors. The primary technical indicator is the battery's State of Health (SOH), with thresholds typically set around 70-80% of the original capacity. Below this range, the battery may not reliably meet the demands of its original application but could still serve less intensive roles, such as stationary energy storage. A key consideration is the battery's degradation behaviour, **particularly the proximity to its knee point**, where capacity fade and internal resistance growth accelerate. Batteries nearing this point are less suitable for second-life applications, as their remaining useful life (RUL) is too short to justify repurposing costs.

The knee point in a battery's degradation curve is the point where capacity or resistance begins to degrade at an accelerated rate, indicating the onset of rapid aging. Identifying this point is crucial for second-life applications, as batteries nearing the knee point have a significantly reduced remaining useful life (RUL) and are less viable for repurposing. To detect the knee point, monitor capacity retention curves over cycles and employ methods like piecewise linear regression or curve-fitting algorithms to pinpoint where the slope changes significantly. Alternatively, use incremental capacity analysis (ICA) to detect subtle changes in battery performance linked to aging mechanisms. Monitoring metrics like the rate of resistance growth and capacity fade can also help predict proximity to the knee point. The knee point is critical for decision-making because it marks the transition from gradual degradation to failure-prone conditions. Investing in repurposing a battery close to or beyond this point is inefficient, as its remaining lifetime will be too short to justify the cost of testing, reconfiguration, and integration into second-life systems. Therefore, second-life applications should focus on batteries with sufficient remaining capacity and stability, ensuring long-term reliability and economic feasibility. To make informed decisions, operational data from the battery’s first life—such as cycle count, depth of discharge, and thermal history—should be analysed to predict degradation trajectories and estimate remaining performance. Functional testing, including capacity checks and impedance measurements, is essential to assess current health and ensure safety. Economic feasibility must also be evaluated by comparing repurposing costs, such as disassembly and reconfiguration, against the potential benefits and revenues of a second-life application. Batteries in relatively uniform condition can often be repurposed as full systems, while heavily degraded or uneven packs might require module-level reconfiguration (that is generally more expensive). Keeping track of module uniformity in terms of voltage and temperature can be achieved via data monitoring as presented below with the Statistical Data Frame elaborated by BFH. Ultimately, the decision to transition is based on aligning the battery’s remaining capabilities with the demands of the second-life application and ensuring the investment is justified by the projected lifetime and performance. Reliable traceability of first-life data and predictive modelling can enhance decision-making and maximize the value of second-life systems.

4.2.5 General recommendations

Recording operational data (e.g. current, voltage, temperature, cycle count, and depth of discharge) improves precision in assessing the viability of second-life systems. While detailed data can enhance knee point prediction and state-of-health (SOH) estimation, the cost of storage and processing must be weighed against its benefits. Key reasons to record operational data include:

- Improved Predictive Accuracy: Advanced models require operational data to precisely estimate remaining useful life (RUL) and degradation trajectories.
- Customized Second-Life Suitability: Detailed usage history helps match batteries to specific second-life applications, optimizing performance.
- Cost-Effectiveness: Accurate data helps avoid repurposing batteries nearing the knee point, saving costs in testing and integration.

However, if recording all operational data is too resource-intensive, focus on key parameters like cycle count, average temperature, and maximum depth of discharge. These provide a strong balance between utility and feasibility (statistical approach like SDF can be a feasible option).

In the following an example is given by considering the RhB locomotive real time data that BFH received (Figure 7). We started by analysing the evolution of main important signals available in the dataset like voltage, current, temperature, SOC, charge. By looking at voltage and current signals, the cycles were divided by charge (green) and discharge (red) events such that information on cycles could be extracted.

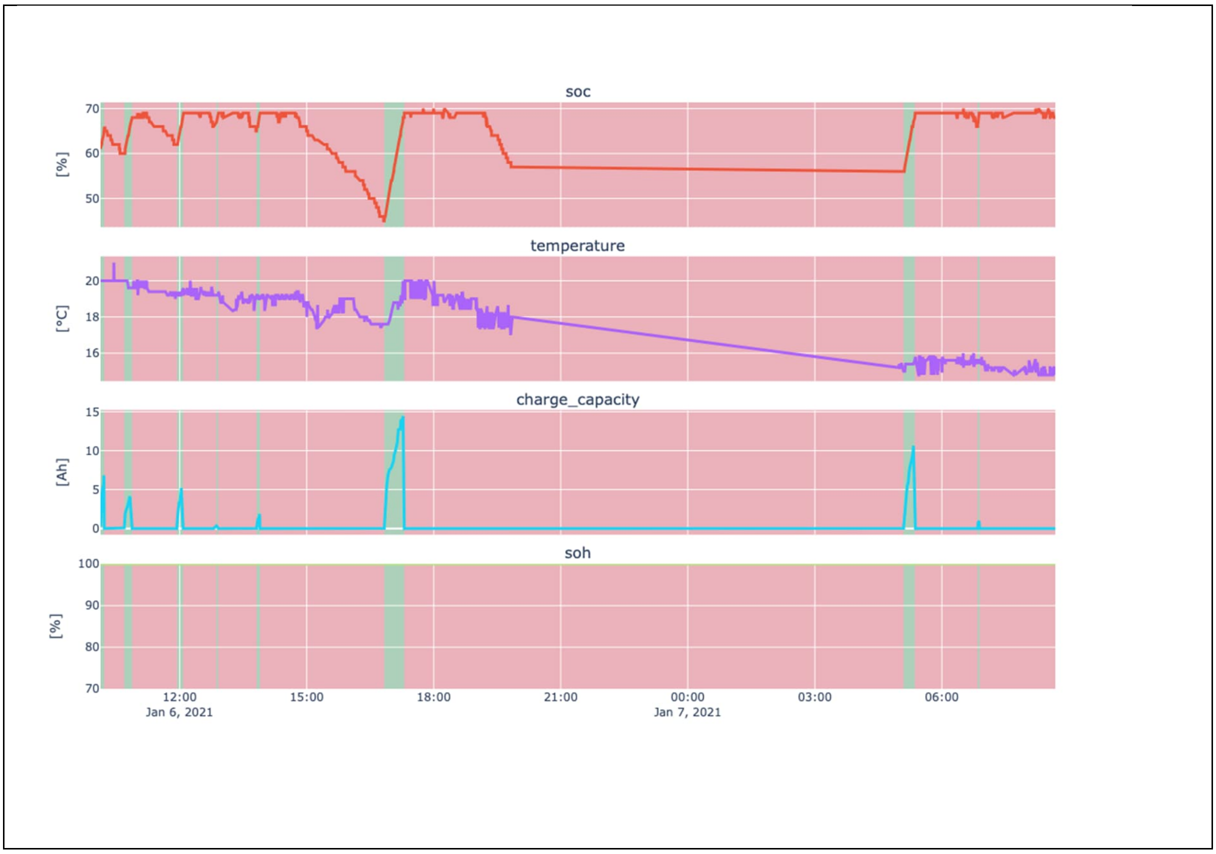
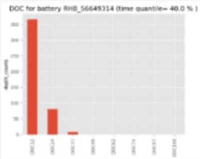
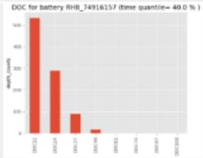
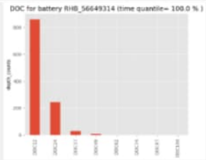
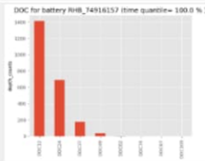
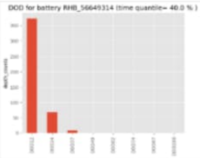
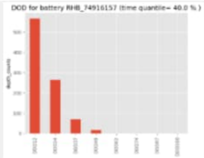
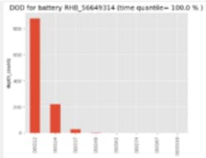
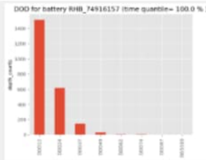
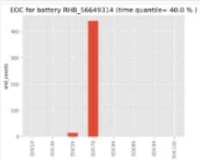
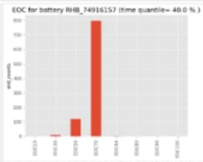
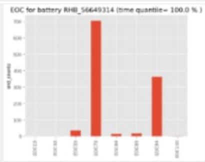
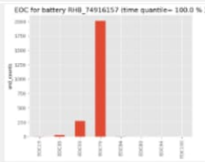
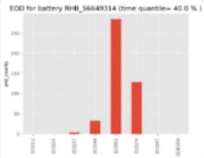
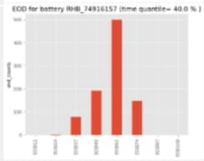
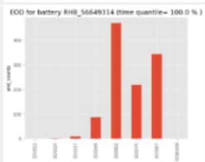
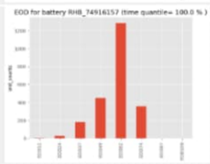
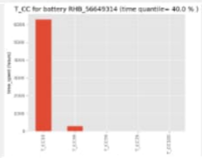
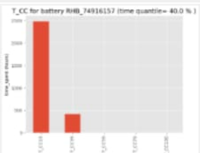
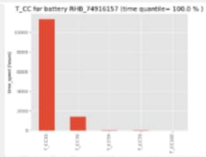
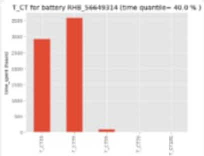
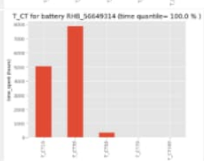
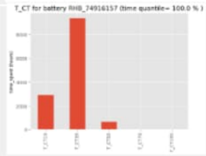
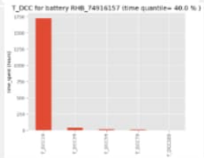
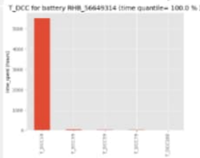
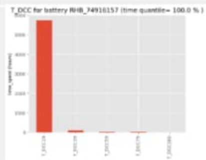
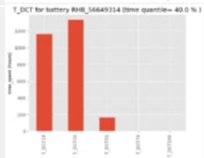
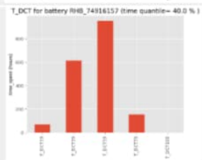
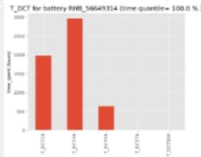
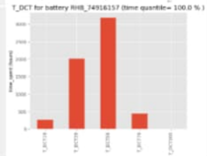


Figure 7: Time domain signals, identification of charge (green) and discharge (red) periods.

From these data, statistical information could be extracted. The BFH statistical data frame (SDF) is computed and visualized as in Figure 8.

	40% quantile		100% quantile	
	Low usage battery	High usage battery	Low usage battery	High usage battery
DOC Depth of Charge (SOC end charge – SOC beg charge)				
DOD Depth of Discharge (SOC end discharge – SOC beg discccharge)				
EOC SOC at end of charge				
EOD SOC at end of discharge		 10/02/2025		

	40% quantile		100% quantile	
	Low usage battery	High usage battery	Low usage battery	High usage battery
T_CC Time spent at charge current level X				
T_CT Time spent at temperature level X during charge				
T_DCC Time spent at discharge current level X				
T_DCT Time spent at temperature level X during discharge				

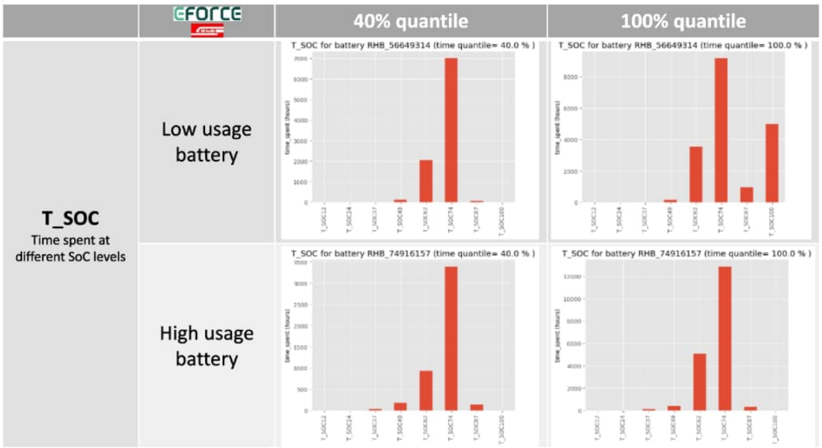


Figure 8: Examples of statistical data frame outputs. X-axis label refers to the indicators reported in Table 2

At the moment the parameters included in the BFH SDF are reported in the tables below:

Table 2: Statistical Data Frame (SDF) tables.

Number of hours							
Discharge current	Charge current	Regenerative current	Bidirectional (Grid) current	Operation Temperature	Temperature during charge	Temperature during discharge	Temperature during regeneration
T_DC_X	T_CC_X	T_REGC_X	T_BDIG_X	T_OP_X	T_CT_X	T_DT_X	T_REGT_X
0-20%	0-20%	0-20%	0-20%	0-20%	0-20%	0-20%	0-20%
20-40%	20-40%	20-40%	20-40%	20-40%	20-40%	20-40%	20-40%
40-60%	40-60%	40-60%	40-60%	40-60%	40-60%	40-60%	40-60%
60-80%	60-80%	60-80%	60-80%	60-80%	60-80%	60-80%	60-80%
80-100%	80-100%	80-100%	80-100%	80-100%	80-100%	80-100%	80-100%

Number of counts
Shochs events
SE_X
0-20%
20-40%
40-60%
60-80%
80-100%
>100%

Consumption information	Name	Unit
Total Wh charge	ET_CH	[Wh]
Total Wh discharge	ET_DH	[Wh]
Total Wh regenerative	ET_REG	[Wh]
Total Ah charge	CT_CH	[Ah]
Total Ah discharge	CT_DH	[Ah]
Total Ah regenerative	CT_REG	[Ah]
Cycle count	CC	[-]

Number of counts (Number of times)					Number of hours		
SOC at the end of charge	SOC at the end of discharge	DOD	DOC	SOC average	SOC level	Difference between max-min cell voltage**	Difference between max-min cell temp.**
EOC_X	EOD_X	DOD_X	DOC_X	SOC_A_X	T_SOC_X	D_VMM_X	D_TMM_X
100-95%	100-87.5%	100-87.5%	100-87.5%	100-87.5%	100-87.5%	100-87.5%	0-20%
94-90%	87.5-75%	87.5-75%	87.5-75%	87.5-75%	87.5-75%	87.5-75%	20-40%
89-85%	75-62.5%	75-62.5%	75-62.5%	75-62.5%	75-62.5%	75-62.5%	40-60%
84-80%	62.5-50%	62.5-50%	62.5-50%	62.5-50%	62.5-50%	62.5-50%	60-80%
79-60%	50-37.5%	50-37.5%	50-37.5%	50-37.5%	50-37.5%	50-37.5%	80-100%
59-40%	37.5-25%	37.5-25%	37.5-25%	37.5-25%	37.5-25%	37.5-25%	
39-20%	25-12.5%	25-12.5%	25-12.5%	25-12.5%	25-12.5%	25-12.5%	
19-0%	12.5-0%	12.5-0%	12.5-0%	12.5-0%	12.5-0%	12.5-0%	

It is essential to understand how a battery has been used when estimating its State of Health (SOH), as SOH is strictly dependent on operating conditions such as temperature, charge/discharge rates, and depth of discharge. Moreover, knowing how the battery will be operated in the future is equally

important, as this allows for assessing the expected degradation over time and predicting its remaining useful life under specific usage scenarios.
The aging mechanisms and performance requirements in a first-life application (e.g. electric vehicles) may differ significantly from those in a second-life application (e.g. stationary energy storage). Understanding the battery's past operating conditions helps estimate its remaining capacity and reliability, while anticipating future usage conditions ensures a more accurate prediction of degradation trends and suitability for second-life deployment.

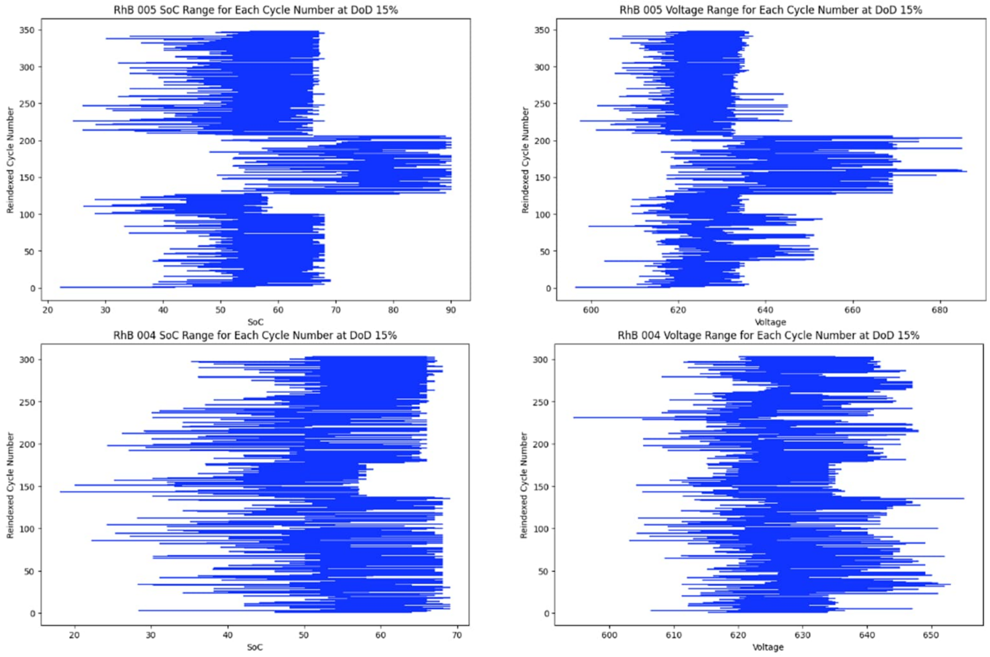
It is also essential to determine whether the battery is better suited for energy-intensive applications (e.g., stationary storage) or power-intensive applications (e.g., fast charging or grid frequency regulation). In second-life applications, repurposing a battery with an inappropriate energy to power ratio for a given use case could lead to inefficient performance and accelerated degradation.
Regarding safety, there are specific requirements that must be considered, especially during the transition from first to second life. These include:

- Thermal Management: Second-life applications may operate under different cooling conditions, affecting thermal stability.
- Electrical Safety: Aging increases internal resistance, which can lead to localized heating and higher risks of thermal runaway.
- State of Health and Reliability: Degradation mechanisms from first-life use must be well understood to ensure safe operation in second-life applications.

If the battery's operation is determined by the provider rather than the user, several challenges arise in accurately estimating State of Health (SOH) and predicting future degradation. One major difficulty is limited data access, as the provider may not share detailed information on charge/discharge cycles, temperature variations, or past usage patterns, making it harder to track degradation mechanisms. Additionally, uncertainty in usage conditions complicates predictions, since changes in operational strategies - such as increasing charge rates or modifying depth of discharge - can significantly alter aging behaviour. This lack of control also impacts future aging predictions, as assumptions must be made about how the battery will be used, introducing uncertainty in remaining useful life (RuL) estimations. From a safety and warranty perspective, there is a risk that improper operation, such as excessive cycling or poor thermal management, could lead to premature failures, raising concerns about reliability and liability. Furthermore, when considering second-life applications, the absence of detailed first-life operational data makes it difficult to assess whether the battery is suitable for reuse. To mitigate these challenges, advanced monitoring techniques, machine learning-based diagnostics, and probabilistic modelling can help infer missing information and provide more robust SOH and RuL estimates, even when full control over battery operation is not available.

In principle with real time data and SDF it will be possible to keep track on how the battery is operated and possibly make estimation of SOH. At BFH SOH estimation using dQ/dV analysis has been developed for the Circubat project. This is a powerful technique that identifies changes in battery capacity by analyzing differential capacity curves derived from voltage and charge data. This method is particularly useful for detecting shifts in electrochemical processes, such as lithium plating, loss of active material, or electrode degradation, making it a valuable diagnostic tool. However, applying dQ/dV analysis in real-time scenarios presents several challenges. First, data resolution and noise can significantly impact accuracy, as real-world current and voltage measurements are often affected by sensor limitations, fluctuations, and external disturbances. Additionally, incomplete charge/discharge cycles in practical applications - where batteries rarely undergo full charge/discharge due to operational constraints - limit the availability of stable data needed for precise dQ/dV extraction (see example of RhB). Another difficulty arises from temperature variations, which shift voltage responses and complicate the interpretation of dQ/dV peaks, potentially leading to incorrect SOH estimations.

Finally, the computational burden of real-time analysis must be considered, as extracting and interpreting dQ/dV curves on embedded systems or cloud platforms requires efficient data processing algorithms. Addressing these challenges requires advanced filtering techniques, adaptive algorithms that compensate for temperature effects, and machine learning approaches to enhance the robustness of real-time SOH estimation. This is especially evident in the RhB case, where the battery's voltage window defined in the Battery Management System (BMS) is influenced by the vehicle provider (Stadler) rather than controlled by the operators (RhB). As a result, the available voltage range, from which dQ/dV analysis can be extracted, varies Figure 9 , making it difficult to extract consistent and comparable features over time and further complicating SOH tracking. A key advantage of BIENE project is that it anticipates these issues upfront, ensuring that data requirements are clarified during the procurement phase. While this approach cannot fully guarantee that all challenges, such as strict adherence to BMS limits, proper data recording, and consistent operating conditions will be resolved, it significantly improves the chances of obtaining usable data for more reliable SOH estimation and long-term monitoring.



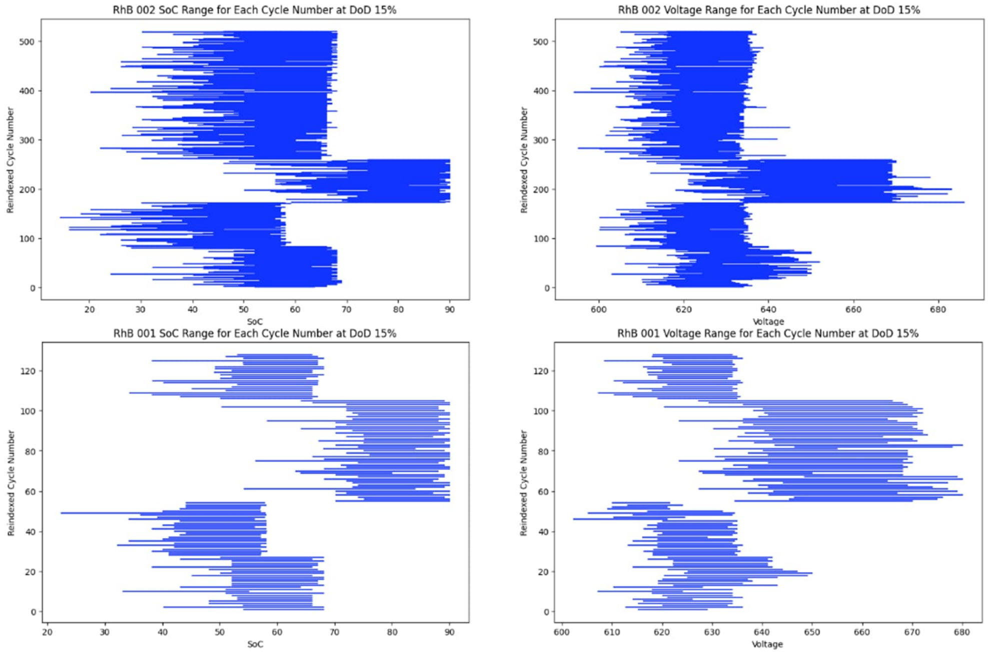


Figure 9: Voltage ranges

4.2.6 Procurement

BIENE vehicle specification document

In vehicle procurement projects, target requirements are defined with regard to modularity. The energy storage system should be designed in exchangeable units and be able to be exchanged by SBB to increase or decrease the battery capacity or for maintenance. In order to give the vehicle and battery manufacturers the necessary leeway, this requirement was not specified in more detail or defined as a mandatory requirement. The requirement was defined, among other things, to make it easier to pursue the possibilities for second life at a later date.

As described in chapter 4.3.7 a catalogue of requirements was drawn up for the BIENE project, which can be used to incorporate the requirements of the circular economy for vehicle batteries into future procurement projects (Halder et al., 2025). The specification document defines requirements for the most transparent and sustainable production and procurement of battery storage systems. In addition, the data parameters and their temporal resolution and accuracy are defined, which are necessary for monitoring the batteries in the first use and for the transition to the second use.

Alternative procurement model: Product as a Service or Battery as a Service

Alternatives to the traditional procurement of battery storage systems were investigated. The SBB Center of Competence Energy Storage together with the Center of Competence Circular Economy investigated the suitability of the “Product as a service” (PaaS) purchasing model for battery storage systems (Battery as a service).

The assessment was carried out on the basis of a screening criteria template for PaaS procurement created by Prozirkula. The suitability of a battery storage system installed as a traction battery in a locomotive as a PaaS was assessed.

The assessment is based on different areas, for each of which points are awarded. The results of the study are as follows:

Assessment: Potential of today's market

There are currently no or few PaaS offerings in the battery storage sector. Market maturity is at prototype level. Offers are not yet fully developed and rarely include more than maintenance services and end-of-life replacement. Possibilities to include further services are conceivable. In addition, the current battery storage market is very dynamic, and the leaps in optimization and growth are large. The product will not achieve “stability” in the near future. Cell chemistries, technologies and design are developing rapidly. The leaps in development have also been great in recent years, and experience with the product is still being built up on the manufacturer side in some cases. In the field of electromobility, this can be seen in the area of guaranteed ranges. A few years ago, ranges of 60,000 km were guaranteed. The guarantees were quickly adjusted to 100,000 km, 150,000 km and more, and guarantees for years of use are already being given. The product is developing rapidly, and with the existing level of establishment, lifetimes and risks often cannot yet be estimated with the accuracy that would be necessary for a PaaS offering. This risk is also charged in the form of a premium price in business models such as PaaS. This speaks against battery as PaaS.

Assessment: Future market potential

There are not yet any major providers of battery storage services. The market is currently still very much in flux and the pressure to innovate is high. There are larger manufacturers who are trusted to offer PaaS services or who are currently developing them. However, the application in the rail vehicle sector is a niche application, and development in this direction is expected to be very delayed. The possibilities for bundling SBB demand with other users are very limited.

Assessment: Product potential

After initial use at SBB, there is still a high residual value of the battery storage system - both for second-life applications and the pure material value. This speaks against PaaS. The product characteristics (modularity, use of individual components) speak in favor of PaaS. The product application speaks against PaaS due to low expected maintenance and repair costs and strong product evolution.

Assessment: Potential Economy & Organization

Battery storage promises low operating costs and the need to outsource this is low - especially since maintenance personnel are already available at SBB, competencies can be expanded quickly. There are some outsourced services that SBB could also provide, but which could also be outsourced and purchased, such as training, evaluation and optimization services. However, outsourcing also means losing some of the know-how. There is little potential to outsource jobs, as few jobs are involved while the system is running. There is further potential for optimization through PaaS in the area of modularity and the transfer to second-life applications. Overall, there are more points against PaaS than in favour of it. One argument in favour of PaaS is the potential to reduce the burden on the investment calculation and thus smooth cash flows.

Assessment: Ecology potential

Based on the previous chapters, the potential of ecology clearly speaks in favour of PaaS. High residual value, possible general overhaul or remanufacturing, modularity and suitable options in product design.

Assessment: Risks Operation

Battery storage on rail vehicles is a central element of rail operations. When considering an outsourced service such as Product as a Service, this leads to high safety risks and risks for rail operations. The reliability of the batteries and, if necessary, prompt service options are highly relevant to the success of rail operations. In addition, they enable the use of synergy effects within rail operations, which would be diminished by a PaaS. A reduced utilization rate and early replacement with a poorer eco-balance would be conceivable. It is not clear to what extent the risks of the safety-critical product battery could be eliminated in PaaS contracts.

Conclusion

The final assessment revealed that the battery product offers potential for such a sales model. However, neither the market nor the products are currently at the necessary level in the railway environment - this is in particular due to the novelty of the technology and the speed and dynamism of product developments. PaaS for battery storage is not being pursued further at the moment.

4.2.7 Potential Second-Life applications @SBB

As part of this project, possible second-life applications at SBB were investigated. In a first step, a general overview of possible use cases and likely relevant requirements was created. This overview is presented below:

Applications traction current network 16.7 Hz

Energy compensation vis-à-vis Swissgrid
The electricity costs for large consumers are based on both energy consumption and maximum peak power. For SBB Energie, the highest monthly quarter-hourly power consumption across all frequency converters determines the power price charged to Swissgrid. Another cost driver is unplanned deviations from agreed energy procurement or energy supply for 15 minutes at a time. A grid balancing controller therefore ensures the operational compensation of possible forecast errors. Stationary batteries could be included in the available balancing pool.

Parameter	Description
Storage dimensioning	Power battery (MW/MWh), energy requirement over several minutes to compensate for forecast errors in quarter hours and to reduce the maximum monthly quarter-hour output.
Technical requirements	Number of load peaks and predictability requires analysis. High state of charge required. Low installation costs. Integration in grid balancing controller of SBB Energie required.
Necessary reliability	Low. Failure would result in higher electricity costs.
Necessary security level	Low to medium-high. Depending on location.
Scalability	Many locations throughout Switzerland. Very good scalability. Total capacities in the range of several MWh.
Synergy opportunities	Depending on the regularity and occurrence of load peaks.
Estimation of benefit	Not an economically viable operation but should be seen as complementary for systems with other priority benefits. Benefit assessment necessary in the overall context of available flexible production resources such as hydro plants and energy industry framework conditions.

Cutting short load peaks
Breaking extreme load peaks in the traction current grid, preventing additional import requirements via frequency converters. Currently, load peaks in winter in particular; in the future, due to increasing air conditioning requirements, it is assumed that summer load peaks will become increasingly relevant for dimensioning.
In addition to dimensioning the required frequency converter output, cutting short load peaks can reduce the hydro reserves to be held in reserve and thus give retailers more degrees of freedom.

Parameter	Description
Storage dimensioning	Power battery in the MW range. High power requirement, comparatively low energy requirement, as load peaks are only a few seconds long.
Technical requirements	Short-term discharge in the seconds to minutes range. A few hundred times a year. This could cover previously unmanageable peaks in summer - like thermal load management for heating systems in winter. Integration into load management. High state of charge required. Higher installation costs.
Necessary reliability	High, as relevant for dimensioning.
Necessary security level	Medium-high to high.
Scalability	
Synergy opportunities	In addition to peak load cutting with heaters and vehicle batteries by connecting to the SBB load control system.
Estimation of benefit	NPV for dispensing with a total of 80 MW of converter capacity by 2035 by switching off the heating load during peak loads: CHF 20-25 million (saved investments and LCC costs) To be seen as a supplementary use case. No economic operation, but to be understood as supplementary for systems with other priority benefits.

<u>Replacement emergency power systems UPS</u>
One-to-one replacement of stationary emergency power systems (UPS) at the end of their service life with standardized racks or similar.

Parameter	Description
Location	Stations, substations, control centers, safety systems, ...
Storage dimensioning	Dependent on current emergency power systems. Normally energy battery.
Technical requirements	Almost no cyclical ageing. 1:1 replacement of current UPS, therefore specific requirements regarding connection options. Specific requirements regarding voltage, if applicable. Only power output, state of charge 100 %.
Necessary reliability	High reliability, redundancies are planned if necessary
Necessary security level	Depending on location. Stationary. Medium-high to high.
Scalability	Many locations throughout Switzerland. Very good scalability. Individual capacities in the 1-50 kWh range, total capacities in the range of a few MWh.
Synergy opportunities	None.
Estimation of benefit	Compare with current costs for UPS.

Other possible applications:

- Support for the overhead contact line during substation conversion work: When substations are converted, it is often “only” possible to rely on the emergency power supply capability of the overhead contact line system. A transportable battery container could be used to provide additional power to the FL grid.
- Prevention of voltage dips in weakly connected regions: Weakly connected regions that are supplied solely via the overhead line and are relatively far away from surrounding substations experience voltage dips due to the loads. Voltage could be supported with a storage system at the node.

- Emergency power supply for a tunnel system: In the event of an incident, it must be possible to evacuate all trains in the tunnel. Evacuation of all trains can be guaranteed with the help of storage.
- Buffer storage could help to reinforce a transmission line for as long as expansion work is delayed by objections, for example. Containers with batteries could be placed at the end points of weak transmission lines to cover the peak load. In phases with low power consumption, such as at night, these could be recharged.

Applications 50 Hz network

Peak load management
The electricity costs for large consumers are based on both energy consumption and maximum peak power. The maximum 15-minute power peak is used for this purpose. Electricity costs can be reduced in the 50 Hz grid through peak load management.

Parameter	**Description**
Location	Industrial plants, larger sites with higher individual load peaks, GBT, RBCs, BTC, ...
Storage dimensioning	Location-dependent, dependent on grid operator and power prices. Power battery, power requirement defines system size, the greater the load peaks are to be cut, the greater the energy requirement.
Technical requirements	Few load peaks per month. Predictability good, 15 min values. Only power output. Few cycles per year (< 100). High state of charge required. Low installation costs.
Necessary reliability	Low. Failure would result in higher electricity costs.
Necessary security level	Low to medium-high. Dependent on location. Stationary.
Scalability	Many locations throughout Switzerland. Very good scalability. Individual capacities in the range of 50-300 kWh, total capacities in the range of several MWh.
Synergy opportunities	Depending on the regularity and occurrence of peak loads. Prioritization of peak load management is high. Synergy possibilities: PV self-consumption optimization, reactive power compensation, ...
Estimation of benefit	Estimated at around CHF 100 per kW and year.

Self-consumption optimization
The aim of self-consumption optimization is to temporarily store the electricity produced during the day via photovoltaics at the SBB site in a battery. The share of own consumption in PV production is to be increased, with discharging often taking place in the evening and at night.

Parameter	**Description**
Location	Larger sites with PV: industrial plants, office locations, RBCs, BTC, ...
Storage dimensioning	Location-dependent, depending on installed PV and existing consumption. Energy battery.
Technical requirements	For private customers, 220 full cycle equivalents per year are assumed. Requires battery control/adjustment to forecast. State of charge varies throughout the day across the entire range. Low installation costs.
Necessary reliability	Very low. Failure would result in higher electricity costs.
Necessary security level	Low to medium-high. Dependent on location. Stationary.

Scalability	Many locations throughout Switzerland. Dependence on PV installation and PV owner. Very good scalability. Individual capacities in the range of 50-200 kWh, total capacities in the range of several MWh.
Synergy opportunities	Peak load management, power factor correction, ...
Estimation of benefit	Simple rough calculation depending on purchase price and PV feed-in tariff. To be clarified,

Swissgrid ancillary services

System services include the procurement of control power and the use of control energy. In this way, Swissgrid permanently balances the difference between production and consumption and ensures the stability of the electricity grid. Primary control power, secondary control power, voltage maintenance, compensation for active power losses, black start and island operation capability.

Parameter	**Description**
Location	Connection to medium-voltage grid
Storage dimensioning	Power battery. Individual capacities in the range of 500-5000 kWh, total capacities in the range of several MWh possible.
Technical requirements	Prequalification by Swissgrid. Few cycles per month. No predictability of use. State of charge 50 % for positive and negative control power, otherwise 100 %. Higher installation requirements for black start or island operation capability.
Necessary reliability	High. High conventional penalties.
Necessary security level	Low to medium-high. Dependent on location. Stationary.
Scalability	Very good scalability.
Synergy opportunities	High prioritization, synergy difficult to achieve.
Estimation of benefit	Remuneration models have changed in recent years and need to be updated.

Buffer storage

At locations where the grid connection would have to be expanded for further consumption or feed-in, a stationary battery storage unit could be used instead to buffer the load and distribute it better over the existing connection. This could prevent or delay the expansion of the connected load.

Parameter	**Beschreibung**
Location	Depending on expansion requirements Grid connection
Storage dimensioning	Depending on location. More likely to be an energy battery.
Technical requirements	Replacement necessary in the event of failure, therefore higher requirements for service life and reliability. Future development must be considered, otherwise it is a temporary solution at best.
Necessary reliability	Very high. Connection is undersized.
Necessary security level	Low to medium-high. Dependent on location. Stationary.
Scalability	Rather few locations. Low scalability. Individual capacities in the 20-200 kWh range.
Synergy opportunities	None.
Estimation of benefit	Rather low, copper is usually cheaper.

Other possible applications:

- Replacement of emergency power systems UPS: See “Replacement of emergency power systems UPS” under “Applications for traction current network 16.7 Hz”

4.2.8 Second life application: BTC peak load management

The use of a 2nd-life battery storage system at the Hägendorf railway technology centre (Bahntechnik Center, BTC) to optimise self-consumption and for peak load management has been examined in detail. Energy consumption and load peaks in 15-minute resolution, photovoltaic feed-in and energy and power prices were analysed to determine the optimum battery storage capacity in terms of economic efficiency. The results show a slightly positive business case for a battery storage system with a storage capacity of approx. 60 kWh. Optimising self-consumption turned out to be of little interest, as the planned PV system has already an expected self-consumption rate of up to 97%. The more interesting area of application is peak load management, as the BTC - like many other workshops - has individual high load peaks with a corresponding influence on the price of energy from the 50 Hz grid. We secured financing for a pilot project and are in the process of procuring a second-life battery storage system.

4.3 BIENE battery management platform (WP3)

4.3.1 User needs

The first few months of the project were used to define user needs and expectations. To this end, targeted interviews were conducted with people from the user groups of vehicle owners or battery asset managers, vehicle dispatchers and vehicle users (train drivers, team leaders). In each case, the general conditions and needs of the interviewee, as well as derived findings and requirements for a BIENE battery manager were recorded.

After an initial round of interviews, typical use cases of a battery manager were outlined in the form of user stories and could thus be further honed with the users.

Examples of such user stories are “planning of charging”, “request fast charging” or “warning when battery is not charging”. The central user story “planning of charging” is presented here in detail as an example. It represents the needs of the fictitious team leader Martin, who must ensure that all the battery vehicles he uses are sufficiently charged for the next shift (see Figure 10).

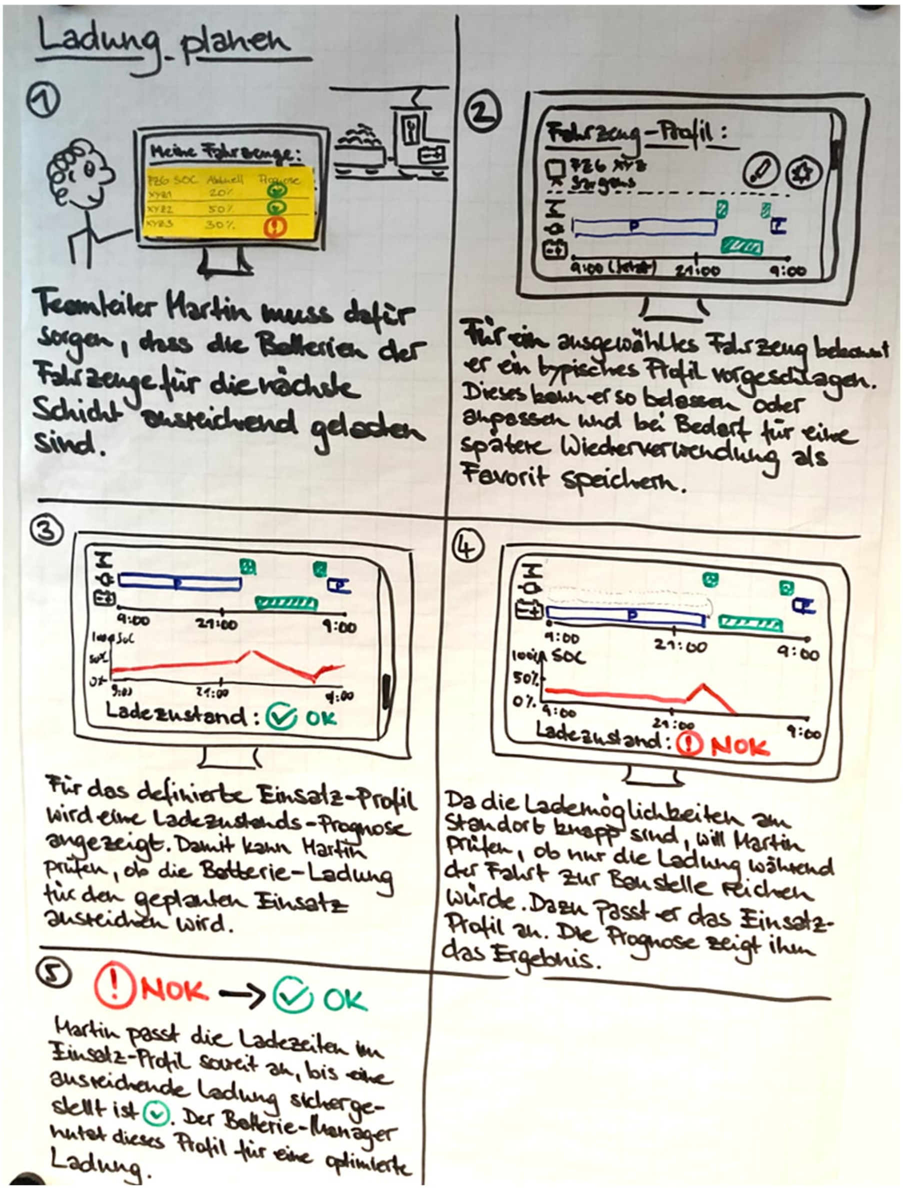


Figure 10: User Story “Planning of Charging”

He wants to use the BIENE Battery Manager to ensure that each vehicle currently in use in his team is sufficiently charged for the next mission:

(1) In the BIENE Battery Manager software, he can select his vehicles and see in an initial overview whether the charge will be sufficient with the currently defined charging and deployment profiles.

(2) He selects an individual vehicle, checks the vehicle profile for the next 24 hours and adjusts it if necessary. In the example shown, it is planned that the vehicle will be charged via the plug until the start of the next shift at 23:00, then it will travel to the construction site for half an hour under overhead contact line and can also be charged with higher power via the railway grid during the journey. From 23:30 to 05:00 it is in battery mode on the construction site, at 05:00 in the morning the team travels back to the depot for half an hour and the battery is then charged again via the plug.

He can adapt this profile according to the current planning and save it as a typical “favourite” profile for later reuse.

(3) The battery manager calculates the expected energy requirement in battery mode from comparable operations in the past, considering the temperature forecast, and can use the specified charging time to calculate whether the charge will be sufficient for the planned operation. Team leader Martin is shown the expected charge status curve of the battery and, in this example, a confirmation that the mission will be feasible.

(4) The battery manager can now help him to check other missions or charging strategies. In this example, he checks whether the current state of charge would be sufficient even without recharging via the plug during the day, as the plug charging options at the location are scarce. To do this, he moves the bar from "Plug charging" to "Parking in battery mode" by 23:00. The battery manager shows him that the short charge during the journey to the construction site would not be sufficient for the following night shift in battery mode.

(5) Martin must now adjust the charging strategy until the vehicle is sufficiently charged. For example, by charging for a minimum time via the plug or charging the vehicle earlier and longer via the overhead line with a higher available charging power.
The battery manager then uses the defined profile and calculates an optimised charging profile on this basis. The calculated target charging current is sent to the vehicle fully automatically by the battery manager and the charging process is monitored.

After this user story was confirmed by several users, the first mock-ups for a possible user guidance were created. Figure 11 shows the screenshot of a clickable mock-up for the selection of vehicles at the team location, corresponding to image (1) in the user story. Figure 12 shows the one for defining a loading profile as in step (2) above.

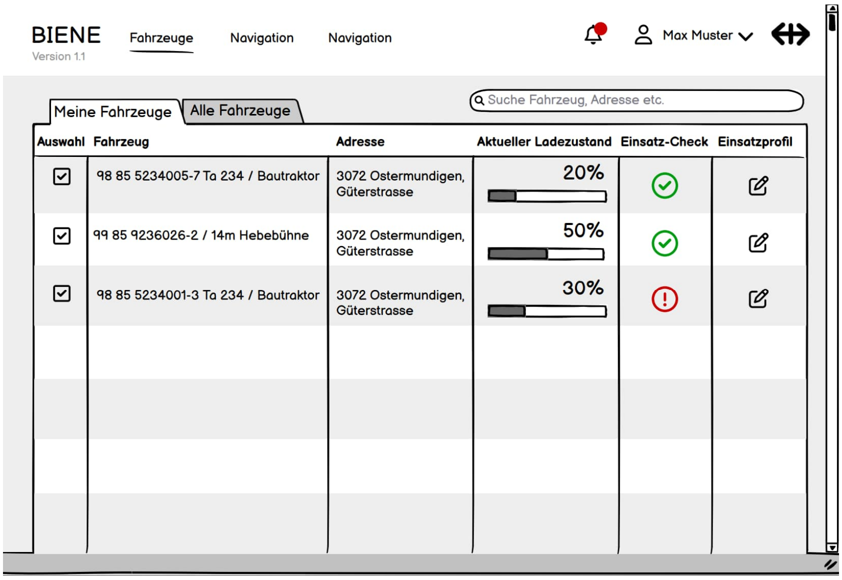


Figure 11: Mock-up Screenshot “Vehicle selection”

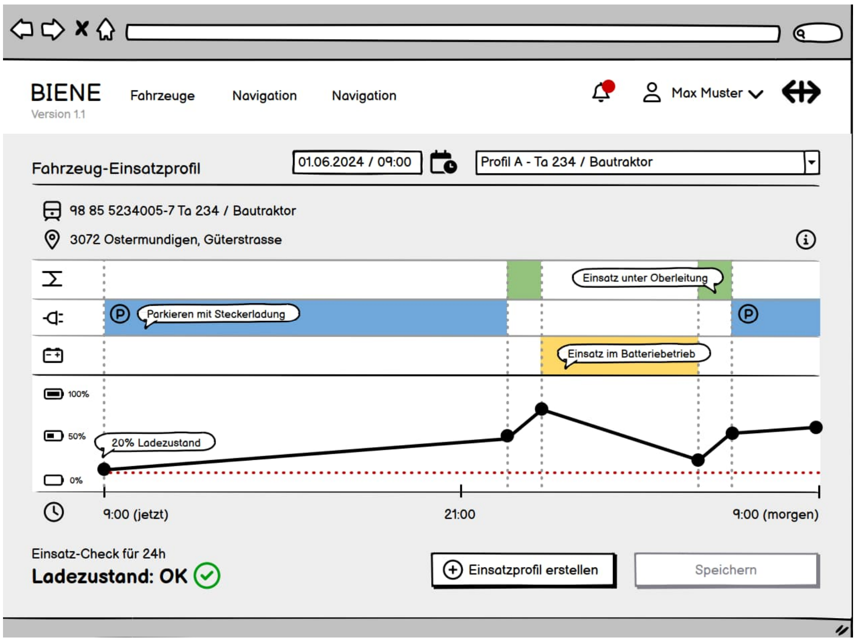


Figure 12: Mock-up Screenshot "Vehicle Profile"

The next step was to adapt the BIENE simulator, which had already been created as part of the previous BIENE study (BAV, 2022), to the user requirements tested here.
The BIENE simulator can be used to create a charging profile. With the stored and modifiable vehicle parameters, the tool automatically checks whether the application is feasible and adjusts the target state of charge (SoC) and the charging power for battery-friendly charging.

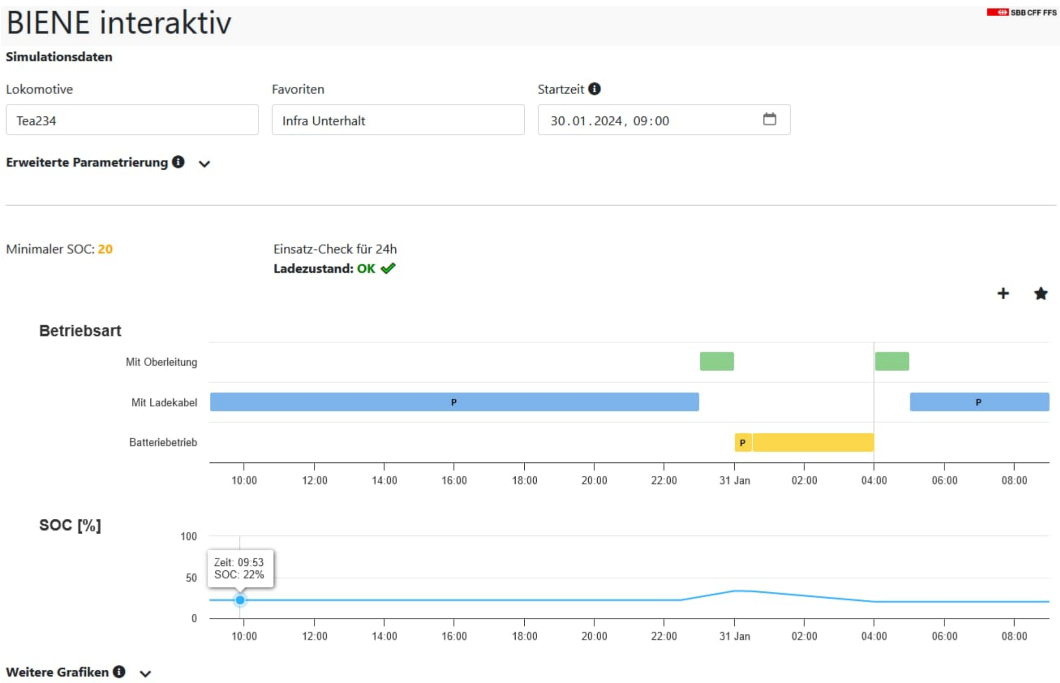


Figure 13: Screenshot BIENE Simulator for Profile «Night-time Maintenance» (optimised profile)

4.3.2 Minimum Viable Product (MVP)

Based on the evaluation of the user needs and expectations, deliverables in the sense of a Minimum Viable Product (MVP) of the BIENE battery manager were defined. This MVP should be achieved as a minimum result within the framework of the pilot project and allow the work to be focused accordingly. Additional functionalities will only be developed if they bring additional benefits and can be realised within the project budget.

Table 3: Description of MVP Features for the Analysis Tool and Asset Management Cockpit

Deliverables: Analysis Tool and Asset Management Cockpit

Features MVP	**Benefits**
Data from the traction battery and the vehicle are logged to the SBB Cloud at regular intervals (1/sec analogue to battery manager requirements). Data will be in accordance with a standard parameter list to be defined.	
Asset Management Cockpit. • Display of warnings, alarms or error messages. • Display of State of Health of the battery. • Display of relevant battery data and ready-made analyses (graphics, tables, etc.) in an asset management dashboard. • Link to relevant documents such as service contracts, guarantees, data sheets, procurement contracts, … Documentation/instructions for interpreting and handling the cockpit information.	For persons responsible for the battery storage system or vehicle asset (do not have to be battery experts): • Enables management of the traction battery asset: maintenance/ replacement planning, recognition of systematically critical states, … Are supported in their work with appropriate documentation. Particularly relevant for the first battery vehicles, as there is little experience to date.
Analysis Tool: • Customised analysis functions and visualization according to the needs of a small number of power users (project staff, CoC energy storage). • Export option for further processing of the data in other tools, e.g. export of performance profiles for SoH forecast in Open Sesame.	For battery experts: • Enables uncomplicated access to all battery data with a standardised solution. • Fast visualisations and analyses for specific, individual questions on vehicle and battery use, environmental influences, ageing, warranty conditions, etc.

Nice to have (2nd Priority):

- Application Programming Interface (API) to existing system landscape.
- Display of Remaining useful lifetime.

Table 4: Description of MVP Features for the Battery Manager

Deliverable: Battery Manager

Features MVP	**Benefits**

Software solution with front end for users (vehicle dispatcher and vehicle operator) on PC and app for mobile devices:
• Enables selection of the vehicles relevant to the user (e.g., all vehicles at the team location)
For selected vehicle:
• Enables a mission profile check: can the planned mission be driven with the installed battery and intended charging option? Display of the current state of charge (SoC) of the battery and the expected SoC curve.
    • Allows a vehicle profile to be defined for at least the next 24 hours: Time in battery mode (operation and standstill), under catenary (operation and standstill) and/or connected to charging station via plug.
    For construction vehicles, the prognosis time horizon should be a week, as detailed work plans are typically made for the same period.
    • The expected energy demand during battery usage varies according to the location and outside temperature. The values are calculated by experts based on analyses of previous vehicle deployments.
    • The battery manager reports back whether the mission is feasible according to the specified vehicle profile.
• If, contrary to the planned vehicle profile, the vehicle is not connected to the charging infrastructure, an automatic message is sent via a channel to be defined (SMS, e-mail) to a group of persons defined for each vehicle and/or location.
	For vehicle users (vehicle dispatching centrally and in teams, vehicle operators):
	• Are enabled to check the feasibility of planned deployments depending on the available charging options.
	• Can drive more demanding missions that require faster charging or higher charge states than compared to a situation with fixed parameterisation of vehicle and battery as is the case today. System automatically adapts charging to the desired use and reports back if not possible.
	• Are informed via warnings or alarms if the operation is jeopardised and can react (e.g., connect vehicle to overhead line or charging station or adjust operation profile).

• The battery manager automatically calculates a battery-friendly charging profile by adjusting the charging current and target SoC for the defined vehicle profile. If the battery temperature is outside the optimum range, the charging current is derated. • The resulting charging current is sent to the vehicle as a suggestion at 1 Hz until the target SoC for a defined power profile is reached. If communication is interrupted, the charging current sent is retained until the target SoC is reached. If the vehicle does not receive a setpoint value for the charging current for more than one hour, the vehicle should use a default value of 0.25 C up to a SoC of	For vehicle owners: • Age-optimised management of the traction battery.

100% of the usable capacity. • Existing power demand control functionalities in the railway grid (cutting load peaks, load reduction in the event of overload) can be tested with batteries (stop charging or discharging when feasible on the vehicle in the event of load peaks and overload).	For SBB Energy: • Use as a reserve power plant.
• Operators of the battery management platform can retrieve information on the operation of the software (availability, software and communication faults, connected vehicles). • Documentation and material for educational purposes.	For operators of the software: • Receives operating data and can react to faults.

Nice to have (2nd Priority):

- Display of warnings / alarms for battery operation with immediate relevance for vehicle users (e.g., defects, critical temperature). Requires a classification of messages with respect to urgency, importance and addressee, which is challenging since every BMS delivers a proprietary set of messages.
  Critical warnings are also displayed on the vehicle itself, therefore the added value of displaying it via the battery manager has to be weighted related to additional implementation costs.
- Automatically calculated energy demand forecast in battery mode depending on location and temperature forecast from historical data.
- Automatically generated vehicle profile (time linked to charging infrastructure, in battery mode) from historical data with the option to adjust this manually.
- Control of the charging of several vehicles on a train being connected by a power line or at the same location: smart power demand management if power capacity is limited or energy prices for plug charging in the 50 Hz grid are power-dependent.
- Additional benefits for the power grid:
  - Smooth out the load profile: If there is enough time for charging, the battery manager controls charging in a grid-friendly manner (charging at minutes 26 and 56 with systematic low power demand instead of minutes 11 and 41 with power peaks in the grid).
  - Market-orientated charging - coupling with future energy trading systems...

Table 5: Description of MVP Features Tools for sector-wide implementation.

Deliverable: Tools for sector-wide implementation

Features MVP	Benefits
• Documentation of requirements for vehicle procurement including parameter list with precise definition of the format. • Proof of impact on lower ageing/LCC costs, user support and energy-economic benefits. • Concept for sector-wide implementation incl. Communication.	For all railway companies that procure battery-powered vehicles: standardised requirements, use synergies. For all stakeholders who need arguments in favour of using the BIENE sector solution.

4.3.3 Power profile forecasting (WP3.1)

The core input for defining an optimization strategy, forecasting mission profile energy consumption, and predicting battery pack aging is the power profile. Therefore, in the context of WP3.1, the objective is to predict the energy requirements for the mission profile of a specific vehicle. Another objective of this activity is to establish a reference discharging and charging profile that represents the standard usage of the locomotive.

As a methodological basis to predict energy demand in battery mode general approaches to mathematically describe vehicle missions and the influence factors on the energy balance have been studied at the beginning of the project. Preliminary conclusions are: Since it is difficult to predict power exactly in dependence of space and time, the preferred way forward will probably be to determine specific energy per time or per distance for different classes as well as separately forecasting temperature related energy demand for thermal management consumers (see Table 6).

Table 6: Energy Classes and their main dependencies as basis for energy demand forecasts

Specific Energy	**Classes**	**Main dependence on**
Energy for traction and auxiliaries / time	▪ For standby ▪ For different work activities (shunting, maintenance…) at different places with different conditions (topography, shunting demand, …)	Time
Traction energy / gross ton-km	▪ For different vehicles and ▪ different train configurations	Mass Distance Altitude
Energy for thermal management / time	▪ Air conditioning for people ▪ Thermo-management for batteries	Time and ambient temperature

Like current diesel vehicles, forthcoming battery-powered rail vehicles will predominantly serve for shunting and construction site tasks. Given Switzerland's fully electrified main railway network, battery-operated vehicles will not be deployed for long-distance journeys. Consequently, the demand for traction energy relies more on operational time than on distance travelled. In addition, monitoring and forecasting operational time is comparatively simpler for estimating energy needs than estimating tonne-kilometres covered.

For a minimum viable product (MVP) of the battery manager (see chapter 4.3.2) distributions of these specific energy uses can be derived from the analysis of operational data. Based in sampled, typical profiles of standby and activity per type of vehicle resp. type of work, the energy needed can then be estimated. The distributions of the specific energies will allow to give a range of estimates of energy use. In close exchange with the vehicle users an acceptable level of uncertainty has then to be defined to assure uninterrupted operation. For the MVP the expected specific energy demand for the different classes will have to be calculated and manually stored in the parameters of the battery manager. Furthermore, the vehicle user resp. dispatcher must define the expected times of the vehicle in different modes (see chapter 4.3.2).

In a later stage, when statistics become better because fleets of vehicles with batteries become bigger, machine learning can be applied to arrive at more precise specific energy distributions that can be used automatically for a forecast. Depending on how regularly the vehicles are used, it is also conceivable to automatically predict the complete vehicle profile with the respective times in the various modes.

To define a standard profile, power profiles of the Tafag vehicle used for construction work have been analyzed using machine learning clustering methods with the following learnings:

- The data pipeline architecture has a not negligeable impact on the results.
- Full-day's activities are poorly correlated.
- Event based analysis has been chosen – Event extraction activities gave good results: Power profile, energy needs and time occurrence of each event.
- Energy flow clustering analysis provided more effective results than power profile time series analysis.
- Density-based clustering algorithm, HDBSCAN gives good results for time series clustering, it will be used for the upcoming clustering activities.
- Several metrics have been tested and compared (time series distance definition).
- Results can be used to derive standard profiles that can be used for impact analysis on battery aging as described in chapter 3.3.

The initial input for this study was the recurrence of similar daily activities at specific locations, which directed our analysis toward recognizing patterns and clustering different types of work. Despite the poor correlation observed in full-day activities (Figure 14), the extraction and clustering of specific events during battery mode operations demonstrated good correlation results for events occurring close to the same location and with similar durations.

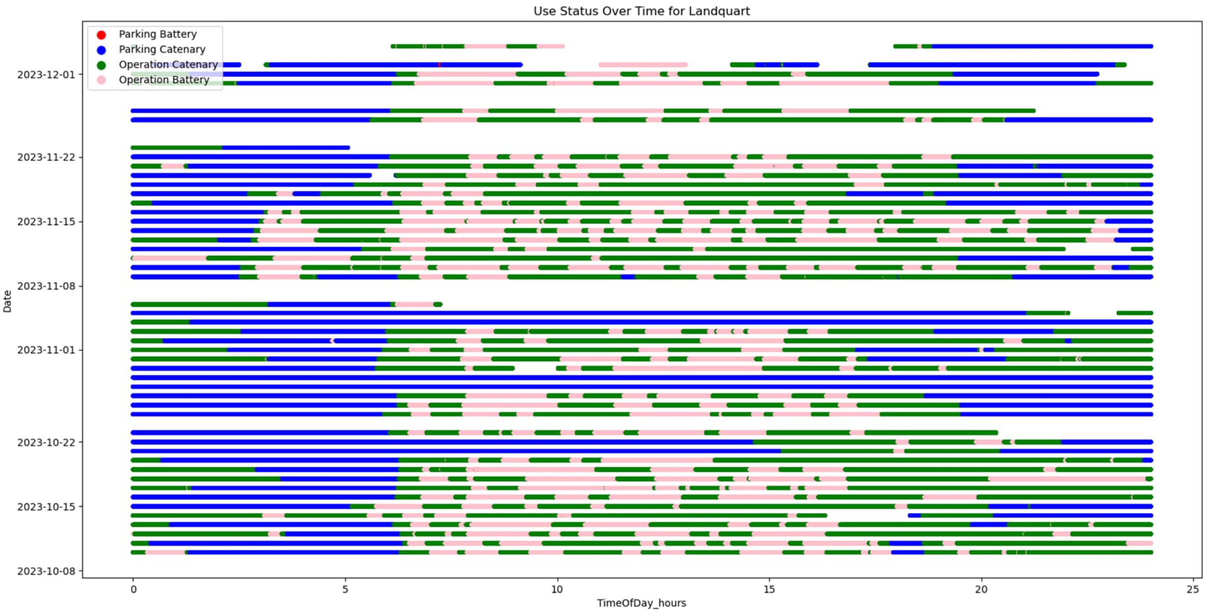


Figure 14: Landquart daily activities (vehicle 20606)

The variability of "hidden" variables within the system, such as the weight carried by the locomotives, the number of wagons being shunted per time or the varying slopes of the railways around a specific location, significantly influenced the outcomes. This influence was evident through noticeable variability in certain results and was further confirmed by practical experiences we gathered during our visit to the locomotive team in Landquart. As a result, the duration of battery mode operation and, to a lesser extent, ambient temperature, emerged as the primary variables impacting the results (Figure 15).

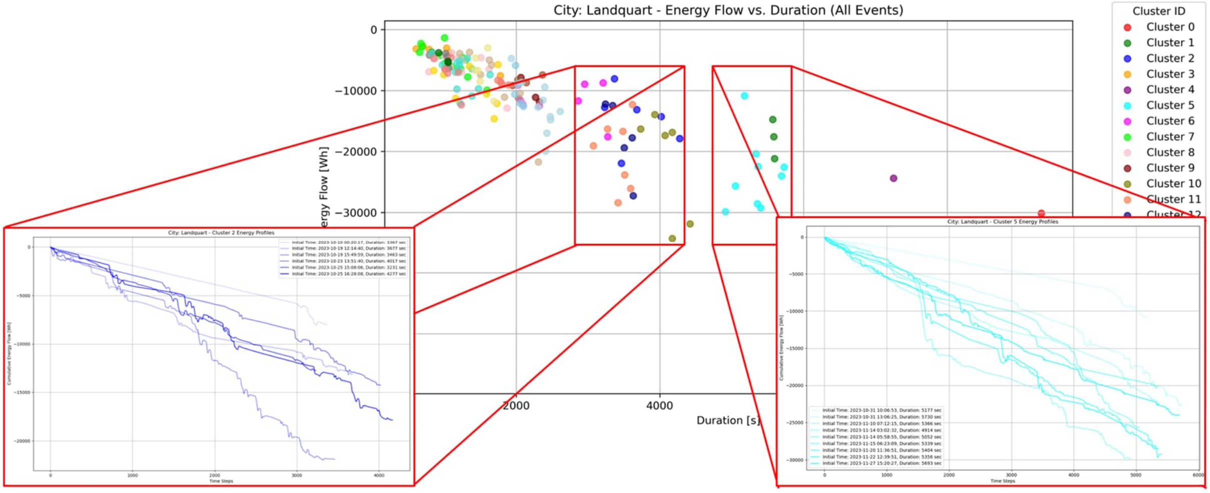


Figure 15: Clustering results based on event length and ambient temperature (Landquart, vehicle 206006)

These insights led us to consider one of two potential solutions: either creating a synthetic profile based on specific usage and then defining an energy needs profile and its associated power profile based on the clustering outcomes or adopting a statistical approach using an existing profile that possesses representative characteristics suitable for subsequent analysis.

The simplest method for forecasting the energy consumption of the next service is to take the duration of a shift, estimate the percentage of pure battery operation (characterized by non-connection of the pantograph to the feeder line) and to use a percentile value from a distribution of the measured energy use per time, data taken from logfiles (for a specific task by a specific vehicle).
Taking a low percentile value for energy use per unit time gives less energy reserve for a certain shift than choosing a high percentile value in the range of e.g. 75 to 90%.

The following diagrams show examples of possible distributions of energy consumption per minute (Figure 16 and Figure 17). The example from Thusis (Figure 17) shows that these distributions can have a long tail. This means that there are a few outliers with particularly high energy requirements. It would therefore be too optimistic to take the median value for the specific energy consumption. However, since the operating times in battery mode are usually longer than just a few minutes, the forecast quality can be increased by averaging over a longer period. The majority of outliers are then averaged out.

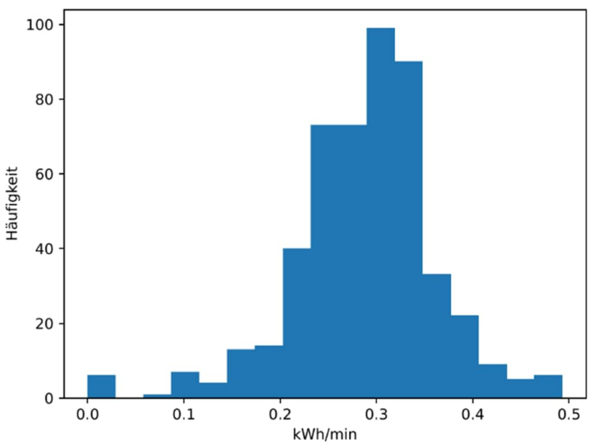


Figure 16: Energy use per Minute of a RhB Geaf shunting locomotive at Landquart.

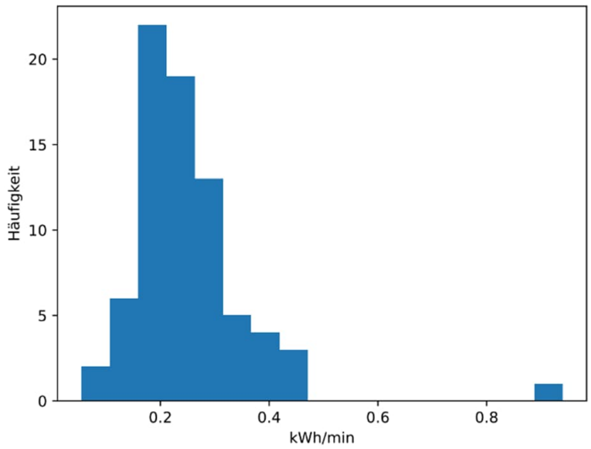


Figure 17: Energy use per Minute of a RhB Geaf shunting locomotive at Thusis.

While the energy requirement for traction dominates in the RhB locomotive, a stronger dependence on the ambient temperature was observed in the Tafag elevated work platform. Figure 17 shows a clear increase in hourly energy consumption at colder temperatures, although a wide variation is still visible.

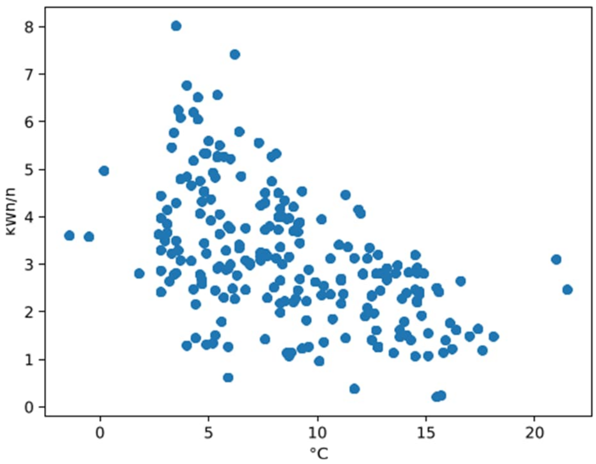


Figure 18: Hourly energy use of a Tafag Hocharbeitsbühne (no driving, no pressurized air compression) in dependance of the ambient temperature (Vehicle 14).

For an energy consumption forecast as a basis for charge optimization in the BIENE Battery Manager, it is therefore recommended that the ambient temperature is also considered. In particular, the use of the ambient temperature for forecasting energy demand is state of the art for energy companies.

4.3.4 Optimal charging (WP 3.2)

A major potential benefit of the BIENE battery manager is the ability to increase the lifetime of the batteries through optimised charging. General rules for battery-friendly charging are presented below before the optimisation algorithms developed as part of the project are described.

General rules for battery-friendly charging

If a vehicle profile is known, rules for battery-friendly charging derived from ageing models can be applied. Figure 19 lists the stress factors considered in the Open Sesame model. The following general rules for the BIENE Battery Manager can be derived from this:

- The target state of charge SoC should be kept as low as possible. This means that, depending on the expected use, charging should only take place as late as possible and then only as far as necessary.
- The charging power resp. the C-rate should be reduced as much as possible. The lower limit is a minimum charging capacity, above which losses increase significantly due to poorer efficiency of the respective vehicle components.
- The battery should be operated in a temperature range that minimizes ageing as much as possible. The local BMS protects the battery from extreme temperatures (by switching off current at elevated or very low temperatures), whereas the battery manager will also be able to reduce the charging power at temperatures that are still permitted but are stressful for the batteries, provided there is sufficient charging time.
  In the future, lowering battery temperature during standby or before events of high power use of the battery could reduce ageing even further. But e.g. the Geaf shunting locomotive cannot yet be put into a “sleeping mode” with lowered battery temperatures, like e.g, +10° rather than in between 25° and 30° degrees Celsius.
- Stress factors on the battery, in particular temperatures and depth of discharge (DoD), can be monitored with the battery manager and operational or design measures can be derived.

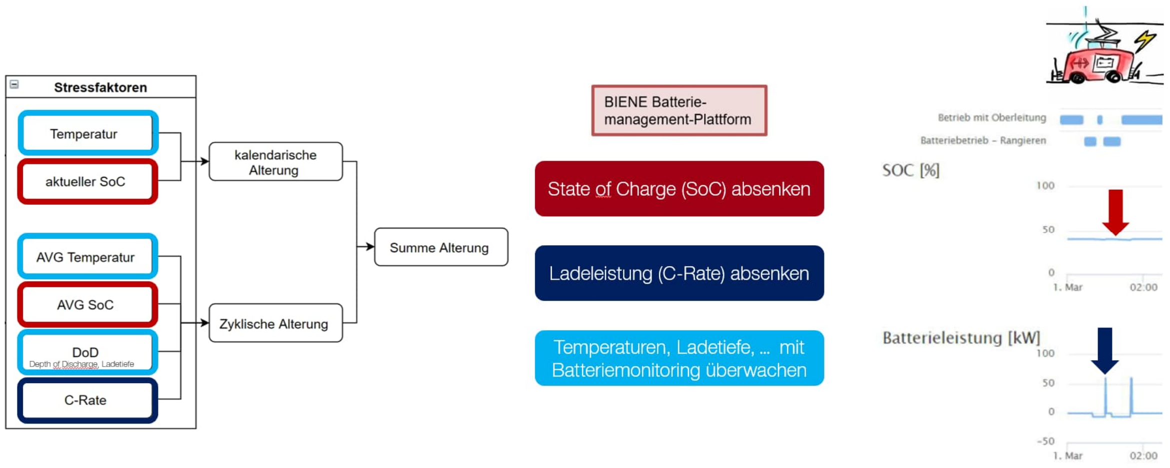


Figure 19: Battery ageing stress factors and rules for the battery manager (BAV 2022)

These rules for minimising battery ageing have been implemented in a simple form in the BIENE simulator. The simulator can therefore already be used to apply and test strategies for optimising the charging profile for specific applications.

The effect of the charging optimisation can be seen by ticking the boxes under "Optimisation". The battery manager then applies the selected rules for battery-friendly charging: Reduce charging power and lower SoC and "just in time" charging to stay as long as possible in a lower state of charge.

The example of a typical shunting cycle of a battery shunting locomotive in Landquart shows the effect of optimisation. Figure 20 shows the charging profile without optimisation as it is currently practised. As soon as the vehicle is under overhead contact line, it is fully charged with 75 kW. In the SoC diagram, 100 % corresponds to a capacity of 90 kWh. Although a larger battery was installed on the vehicle, its available capacity was limited to 90 kWh.

Figure 21 shows the SoC curve and the battery capacity for the same vehicle profile with battery-saving charging. The charging power was greatly reduced and only charged to such an extent that the definable minimum SoC of for example 20 % is always maintained as a reserve. It is easy to see that, in the case of a longer period under overhead contact line, charging only takes place before use. In this example, no charging takes place until 01:25 a.m. and only then is the battery sufficiently charged with the defined minimum power of 18 kW for the next use.

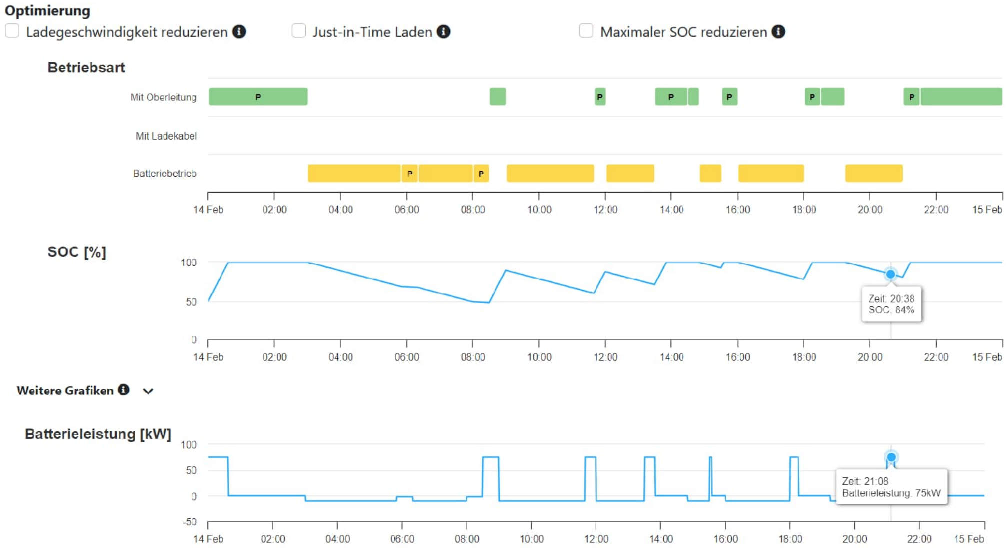


Figure 20: Screenshot BIENE-Simulator shunting in Landquart without optimisation.

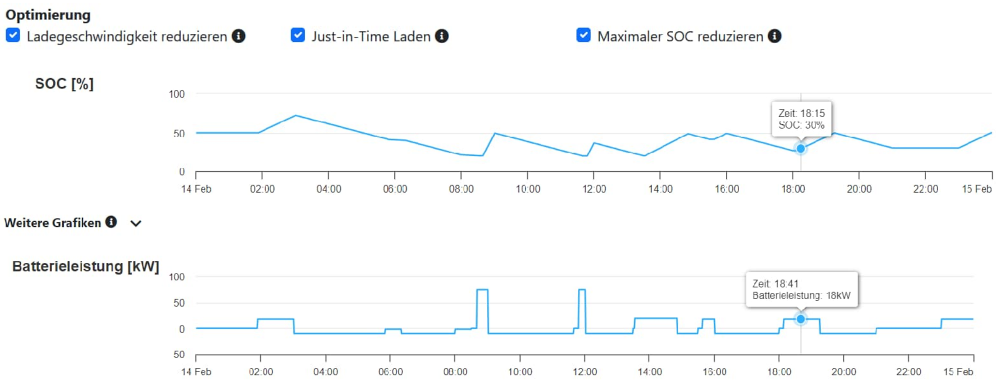


Figure 21: Screenshot BIENE-Simulator shunting in Landquart with optimisation.

A first version of the "optimisation" had been programmed in the simulator at the beginning of the project. During the project, the weighting of the rules among each other is to be further fine-tuned using ageing models.

Charging algorithms ANNA and OLGA

Prototypes for two algorithms were developed. The algorithms address two different applications of battery vehicles.

The first scenario is a standard use case for infrastructure rail vehicles at SBB: These vehicles are typically used for one or multiple shifts on a construction site, followed by a period without usage. During the shifts the vehicles must operate autonomously, i.e. without external power supply. In between the shifts there might be charging infrastructure available, depending on the construction site. It can also happen that the vehicle has to be transferred back to the depot to charge there. For the disposition of the vehicles and planning of the construction intervals it is highly valuable to know how many work shifts can be completed before the battery of the vehicle has to be recharged. This is what the optimised charge-planning algorithm (OLGA) provides: For a given planning interval (usually seven days) the algorithm plans the state of charge (SoC) curve in accordance with the user input. Based on the SoC at the beginning of the planning interval it computes an optimal trajectory of the SoC. It makes sure that the SoC never falls below a given minimum and respects the vehicle's maximum charging speed. At the same time, the algorithm tries to keep the SoC low whenever possible to reduce battery aging while avoiding high charging powers. Based on this plan the vehicle operators can schedule the vehicle usage. For example, the disposition manager can check whether the planned use of the vehicle on a construction site is feasible, or if the vehicle needs to be driven/shunted to a location where it can be charged. To this end the user can try different usage patterns and directly see their effect on the SoC trajectory of the vehicle. The battery management platform assists the users in planning their shifts by showing the capabilities of the vehicle, regarding its battery capacity and recharging needs. During longer breaks, e.g. when the vehicle is parked for a few days in between two construction missions, the algorithm’s aim is to keep the SoC low and to charge the battery just in time before the next usage of the vehicle.

The second use case is typical for vehicles like shunting locomotives, that can operate in catenary mode as well as in battery mode. These vehicles will usually do some of their work on rails without an overhead powerline, in the remaining time they can use the pantograph to obtain energy for their operations and to charge the battery. Today, battery electric locomotives often charge their batteries as soon as they are connected to the catenary with some default power, regardless of the vehicle’s current SoC. In many cases this is unnecessary because the amount of energy needed for the upcoming operations is far smaller than the capacity of the battery. Often it would be possible to reduce charging power, only charge to a smaller SoC or even not to charge the battery at all. This way, the charging power and the SoC could be lowered in many cases, reducing the aging of the battery. The goal of the adaptive recharging algorithm (ANNA) is to automatically recharge the battery during an active shift. Based on user inputs (duration of the shift and percentage of time in battery mode), ANNA continuously evaluates if and how much the battery should be recharged. This happens automatically, without any user interaction required during the shift. The algorithm works with the user input and also adapts the suggested charging power based on the data collected so far during the active shift.

The target image for the interaction of the two algorithms ANNA (Adaptive Reload Algorithm) and OLGA (Optimized Load Planning Algorithm) in the context of BMP is shown in the following Figure 22.

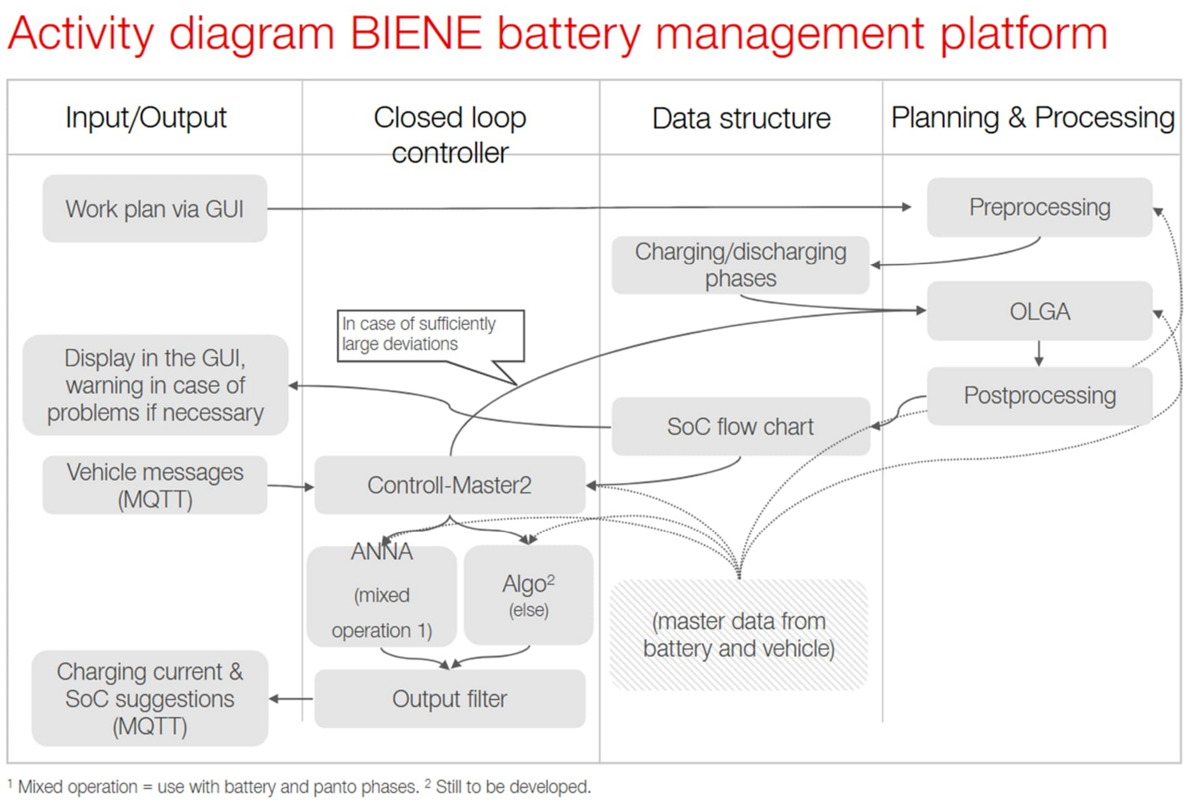


Figure 22: Draft of a diagram showing the control algorithm of the battery management platform.

The functionalities of the BMP are divided into two areas.

One is the closed-loop controller, which is in constant contact with the vehicle. This takes over the monitoring of the vehicle and exchanges data with the vehicle at a defined frequency (e.g. 1 Hz). In particular, the closed-loop controller makes suggestions regarding the actual charging current.

These are based on the second area of the BMP: The load planning is recalculated in the event of new user input and sufficiently large deviations between the plan and reality (OLGA). The charge planning results in a target state of charge and, if applicable, a target charging current for each moment of the planning period. Based on this plan and the live data from the vehicle, the closed-loop controller calculates suggestions for charging current and SoC that are sent to the vehicle.

ANNA is part of the closed-loop controller, responsible for charging suggestions during mixed operation (operations that include both battery operation and operation via panto/catenary). OLGA takes over the load planning, which results in a planned SoC progression for the planning period. It should be noted that the prototype developed focuses on optimisation and that the pre- and post-processing of the data still needs to be developed further.

ANNA

The adaptive recharging algorithm (ANNA) creates suggestions for recharging the vehicle during a shift. ANNA works as a closed-loop controller, adaptively adjusting the charging currents to the current vehicle status. ANNA is particularly relevant for cargo locomotives and similar vehicles that are equipped with a battery but can also draw energy (usually from the overhead line) during operation to recharge the battery and are not permanently dependent on battery power.

ANNA must fulfil the following requirements in order of importance:

- ✓ The vehicle must always remain operational, i.e. the load must be sufficient for the remaining operation, and the minimum load level should not be undercut if possible.
- ✓ Keep charging power as low as possible.
- ✓ Keep the overall charge level of the battery as low as possible.

The core idea of ANNA is to suggest a charging current every second based on user input for the current shift and live data from the vehicle. Specifically, the user is required to provide an estimate of the operating time and an estimate of the percentage of the time spent in battery mode in advance. The vehicle transmits its current charge status every second and indicates whether it is currently able to charge (e.g. panto voltage available).

When calculating a charging current suggestion, the algorithm considers the current status of the vehicle and the previous progress of the current shift. To do this, the algorithm is initialised at the start of the shift according to the user input. During the shift, the algorithm reacts to the current state of charge (SoC) every second and makes charging current suggestions if charging is possible.

Specifically, the algorithm uses the following parameters to calculate the suggested charging current: There is a predicted "total SoC consumption". The difference between this forecast and the measured SoC is included in the proposal of an optimal, that is, ageing-minimizing charging current. Furthermore, the calculation is based on the distance between the measured SoC and the reserve SoC, as well as the difference between the estimated and measured time share in battery operation. These three so-called "covariates" are standardised, transformed, multiplied by weights and then added together. The result is the suggested charging current in the form of a C-rate.

ANNA was implemented as a prototype in Python. To test the algorithm, simulations were carried out using log data from RhB Geaf vehicles. The behaviour of the vehicle is simulated according to the log data. The vehicle is loaded in the simulation according to the ANNA suggestions and the resulting performance and SoC profiles are recorded. These recordings provide information on whether the algorithm has recharged enough energy during the work shift so that the operation could have been carried out. Based on this simulation, the log data from seven Geaf vehicles over a period of nine months was used to identify the most demanding applications for the battery. The parameters of the algorithm were adjusted so that all operations would have been driveable when using ANNA.

The performance profiles of selected shifts were evaluated by Open Sesame. The aim was to prove the ageing reduction of ANNA by comparing the battery ageing during charging and discharging according to the original profiles, which are today implemented locally in the Geaf shunting locomotive.

OLGA

The optimised charge planning algorithm (OLGA) generates a plan for the SoC progression over a period of e.g. seven days based on user input in advance. The user (or by default) defines operating shifts and pauses that could be used for charging. An estimate of the battery percentage is given for each operating shift (e.g. 70% if the user expects that approx. 70% of the operation will take place in battery mode and 30% under catenary). The value can also be set to 100 %, which means that no overhead line or charging option is available (e.g. for the Tafag “Hocharbeitsbühne”, which can only be charged via plug when stationary during breaks). For the charging pauses, the power at which charging can take place must be specified (e.g. in the form of a "plug" or "panto" specification). This information is used to calculate an optimised plan for the SoC process. The algorithm has three main objectives:

- ✓ The average state of charge should be kept low.
- ✓ Fast charging, i.e. high charging power, should be avoided by anticipatory charging. A higher state of charge may be accepted in return.
- ✓ If possible, a vehicle should always be parked with an (adjustable) minimum charge level. This increases operational flexibility, e.g. for short-term on-call assignments.

Load planning consists of the pre- and post-processing of the input and output data, as well as the optimisation algorithm (OLGA). The focus of development was on the optimisation algorithm. The pre- and post-processing of the data and the visualisation of the results were only implemented rudimentarily for test purposes.

The load planning procedure is as follows (see diagram below): The user entries are transferred to a shift/pause table. Based on this table, the expected energy requirement is determined for each line of the table and, from this, the change in the state of charge (delta SoC) is derived. Based on the user input and the specific energy requirements, a so-called "naive solution" is determined, a charging plan that has not yet been optimised. The actual optimisation then consists of the determination of constraints and bounds to be fulfilled and a cost function to be minimised, which maps the main objectives of the algorithm formulated above. The mathematical (numerical) solution to the optimisation problem is found using a suitable optimisation library (in the Python prototype, this is the SciPy library). The object of the optimisation is the state of charge at the end of each charging phase. An SoC charge-process plan is then created in post-processing from the result of the optimisation and the user input.

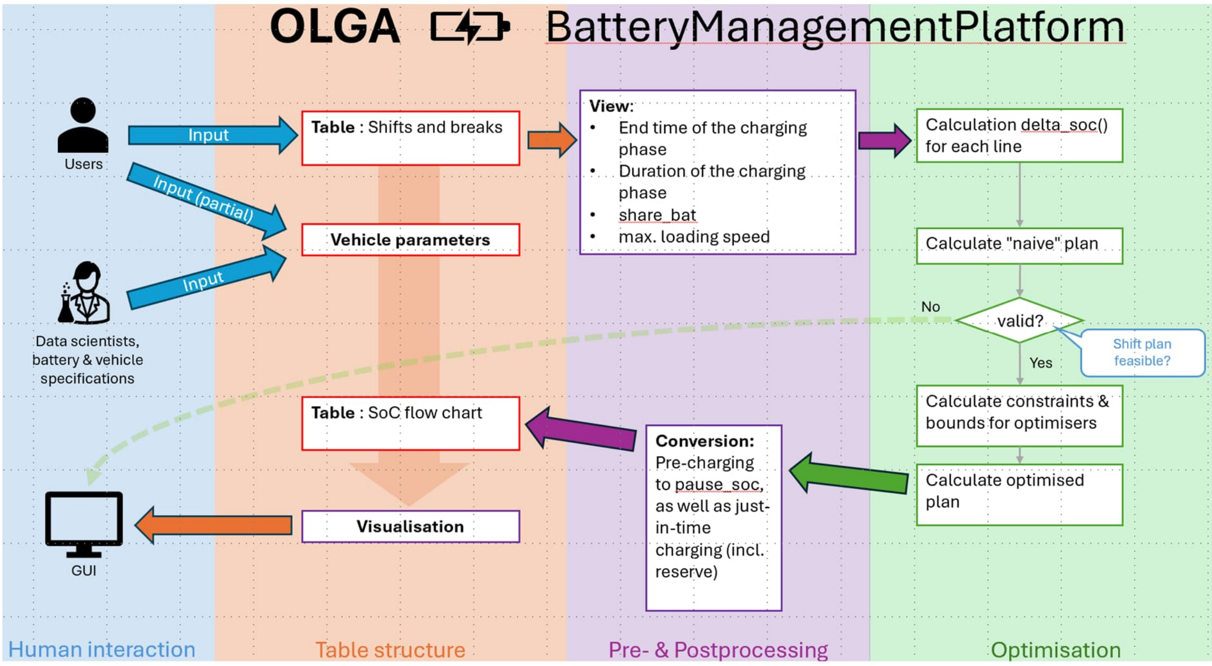


Figure 23: Draft of the process to arrive at an optimal plan for charging over a period of several days (called OLGA).

The individual optimisation steps are described in more detail below.

Delta SoC:

To carry out charge-planning using the optimisation algorithm, the amount by which the battery is discharged must be calculated for each discharge phase (the so-called delta SoC). When used in mixed operation (battery and panto), the converted energy does not necessarily correspond to the change in the SoC: Due to recharging, the difference in the state of charge between the start and end of a shift can be small, even though significantly more energy has been converted from the battery (potentially more than once the total battery capacity). It is therefore not sufficient to simply multiply the shift duration, battery percentage and energy consumption per time as an estimate for the delta SoC. Instead, an algorithm is used to determine a suitable delta SoC depending on the battery share and shift duration. To quantify the battery share and shift duration, these are standardised and each transformed with a logistic function. The result is a value between 0 and 1, with high battery shares and long shift durations corresponding to high values. The larger of the two values is used and Delta-SoC is determined according to this value as a proportion of the maximum possible capacity (max_soc - min_soc).

Naive solution:

OLGA requires an initial value from which the optimisation starts. For this purpose, the problem must be solved "naïvely". In the following, the term "naïve" solution refers to the solution x that merely keeps the SoC as low as possible over the planning period but does not pay attention to the lowest possible charging currents.

The approach for the naïve solution is to calculate "backwards". This means that, based on an SoC at the end of the planning period, it is determined for each charging phase how much could be charged at maximum charging power. This results in an SoC for the end of each charging phase; taken together, these SoCs form the naïve solution.

Cost function

The core of the algorithm is the minimisation of a non-linear cost function under certain constraints. The aim of OLGA is to suggest valid charge states. As the consumption phases are fixed, as is the difference in the state of charge between the start and end of each consumption phase (delta Soc), OLGA can only influence the SoC at the end of each charging phase resp. at the start of each shift. OLGA should therefore determine an optimum SoC for the end time of each charging phase so that the cost function is minimised. At the same time, the conditions described below (constraints and bounds) must be fulfilled.

The cost function is a weighted sum of three partial cost functions. These three partial cost functions represent the objectives of the algorithm defined above:

- ✓ The time integral over the SoC should be minimised.
- ✓ The sum of the squared charging powers should be minimised.
- ✓ The sum of the differences between the target states of charge and the specified limit, provided that the respective target state of charge is less than the limit.

Bounds and constraints

The conditions to be fulfilled by the charge states are divided into bounds and constraints.

Bounds are upper and lower limits between which the load states must lie. The SoC must be smaller than the maximum authorised SoC for the vehicle or battery. It must be greater than the planned reserve plus the expected consumption for the next use.

Constraints are dependencies between different load states. Two successive states of charge cannot be arbitrarily far apart due to the specified maximum charging power. The constraints ensure that the maximum charging capacity is considered in the charging planning.

Constant Voltage Phase

If the battery has a high state of charge, charging can only take place at a reduced charging power. In the constant-voltage phase (CV phase), the battery is charged at a constant voltage rather than a constant current. As the battery voltage increases, the amperage and therefore the charging power decreases, and charging takes correspondingly longer. This fact must be considered in the charge planning. For this purpose, an exponentially decreasing charging power is assumed in OLGA. The SoC from which the CV phase begins is one of the parameters with which OLGA is initialised, as is the curvature of the exponential power reduction. These parameters can (or must) be set according to the battery or the BMS.

Application Examples

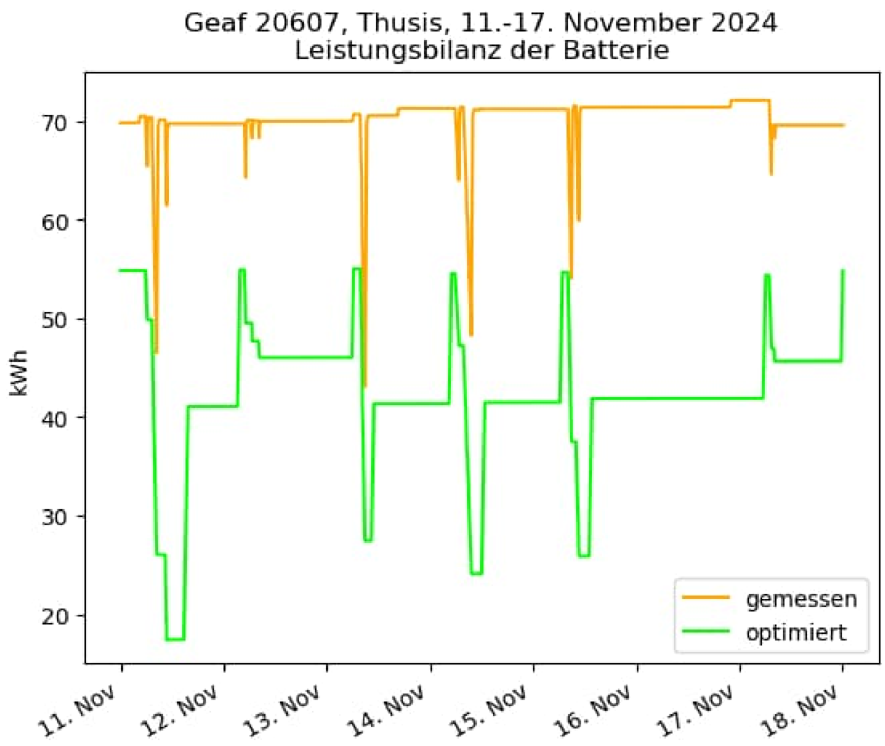


Figure 24: Geaf 20607 from Thusis (11 - 17 November 2024), OLGA only, no adaptive recharging by ANNA.

This is an example of how the OLGA algorithm optimises the SoC of a Geaf vehicle. The Geaf shunting locomotive based in Thusis is an interesting example for the OLGA algorithm: At this location the locomotive is not used very much in battery mode. Under the current regime, the battery is always recharged back to full, as soon as the vehicle is connected to the overhead powerline (orange curve). In this case, the OLGA algorithm creates a plan for the SoC over a period of one week (green curve). Based on the user input it was determined that the battery should be charged to 55 kWh every morning (except on Saturday morning, November 16, since there were no planned vehicle uses for that day). At the end of each shift, the battery is charged to 42 kWh. It remains there until it is charged up shortly before the next planned shift. This leads to a lower average SoC. By always charging up to a certain level (42 kWh here) the algorithm ensures that there is a certain level of flexibility, in case the vehicle needs to be used earlier than planned. On November 12 and November 18, the battery usage was smaller than expected and the SoC never fell below 42 kWh. Thus, the battery did not get recharged until just before the next shift.

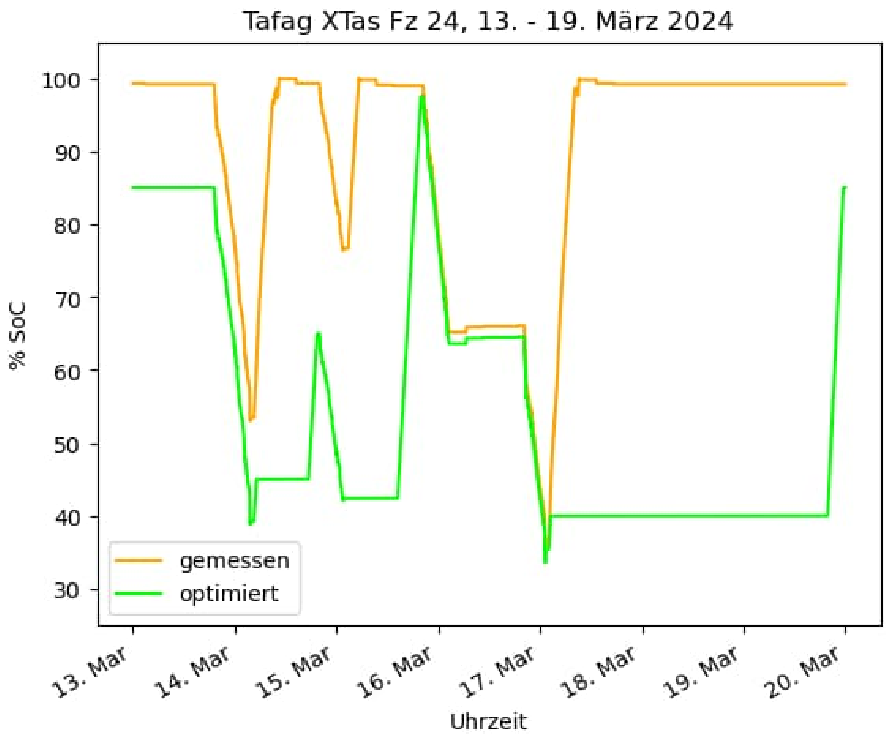


Figure 25: Tafag XTas 24 (13 - 19 March 2024), OLGA only (it cannot be recharged during operation anyway).

This graph shows the SoC trajectory of a Tafag XTas vehicle. Here, the OLGA algorithm performs very similar to the above example of the Geaf in Thusis. The Tafag vehicle is used on construction sites, very often during the night. In this example the vehicle is parked (and charged) during the day. Again, the orange curve shows how the vehicle is currently recharged, always up to 100 % SoC, whereas the green curve shows the optimised SoC curve as suggested by OLGA. Again, we see how the algorithm keeps the SoC low (around 40 %) during periods without activity. The battery is only charged up as much as needed for the next shift and charging only begins shortly before the next work shift.

A key feature of this example is the fact that the battery can (for some reason) not be recharged on March 16. The OLGA algorithm “knows” this from the user input and charges the battery accordingly: On March 14 it only charges the battery to around 65 % SoC, since it can be recharged again after the work shift. On March 15 however, the battery is charged to almost 100 %. This way, the battery contains enough energy for the two following shifts. Since there are no planned vehicle usages during the second half of the week, the algorithm keeps the SoC at 40 % until right before the end of the planning period. Based on the assumption that the vehicle usage follows a weekly pattern, the vehicle should then be charged again. However, as the week progresses, the user will input the usage for the following week and the plan can then be continuously adapted according to the upcoming usages.

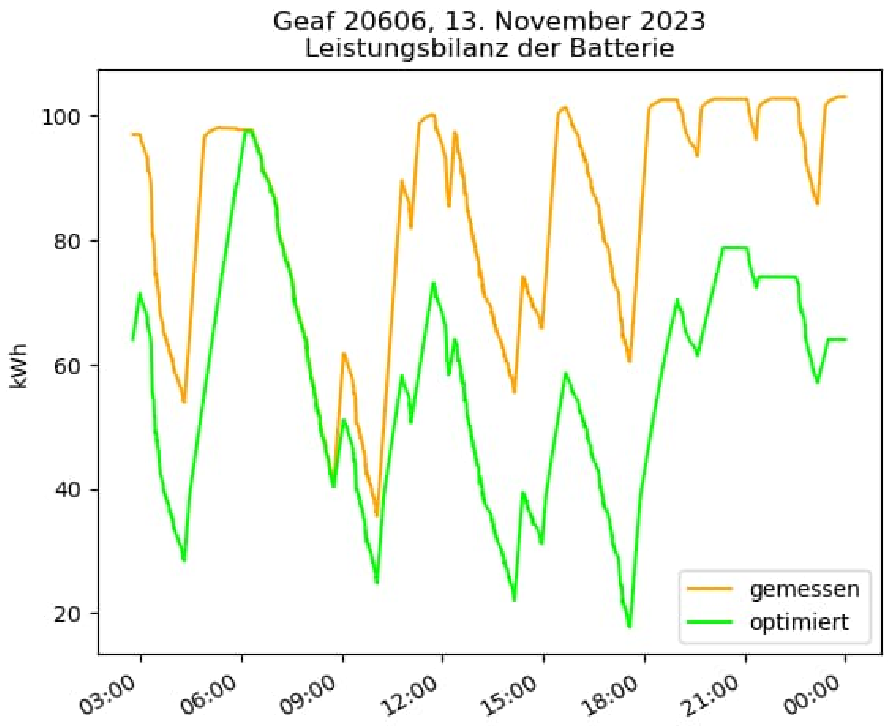


Figure 26: Geaf 20606 from Landquart (13.11.2023), adaptive recharging by ANNA

This example shows how the ANNA algorithm influences the charging of the Geaf vehicle over the course of one day. In orange the data that was collected on the vehicle is shown. The green curve is the optimized SoC trajectory according to ANNA. At the beginning of the day the algorithm charges the battery rather quick and to a high SoC. This is due to the uncertainty of what will happen throughout the course of the day. Towards the end of the day, the battery is not charged all the way up anymore, e.g. around 20:00, the algorithm stops charging at 80 kWh, and around 21:00 it stops at 75 kWh. The logic behind this is simple: The algorithm expects that there cannot be too much activity left in the short remaining time of this shift, so it does not need to charge too much.

It can be observed that the green curve generally has a steeper slope (in the charging periods) when the SoC is low, while the curve slope gets smaller once the battery has been charged for a while. This is ANNA's work: A low SoC requires fast charging. Once the SoC is high enough, there is no need to charge fast anymore, or even no need to charge at all (like towards the end of the shift, or day respectively). This allows a lower average SoC over the course of the shift, and significantly lower charging powers during almost all the charging phases.

Physical Twin activities

Considering that one of the main goals of this project is to demonstrate the effects of optimized, smart usage of battery locomotives, experimental tests are being conducted in the BFH laboratory on 6 real cells (177Ah NMC prismatic Westart cells at 25°C) to validate the results of our approach. Before deciding which profile to run on the real test cells, several profiles were analysed and simulated using the Open-Sesame model to forecast and quantify the expected improvement, the profile was chosen such that within a reasonable testing time of 2 years, the tests could show significant results for the 3 scenarios. The selected profile (Figure 27) illustrates the comparison between the current and optimized profiles. During the discharge phase, due to the imposed energy needs of the mission profile, no intervention can be made, thus the blue and orange lines representing the power profiles overlap, indicating same discharge behaviours that include regenerative braking, shown by negative values and single positive peaks due to the braking. The differences between the two profiles become apparent during the charging phase, which is represented by constant positive values of power.

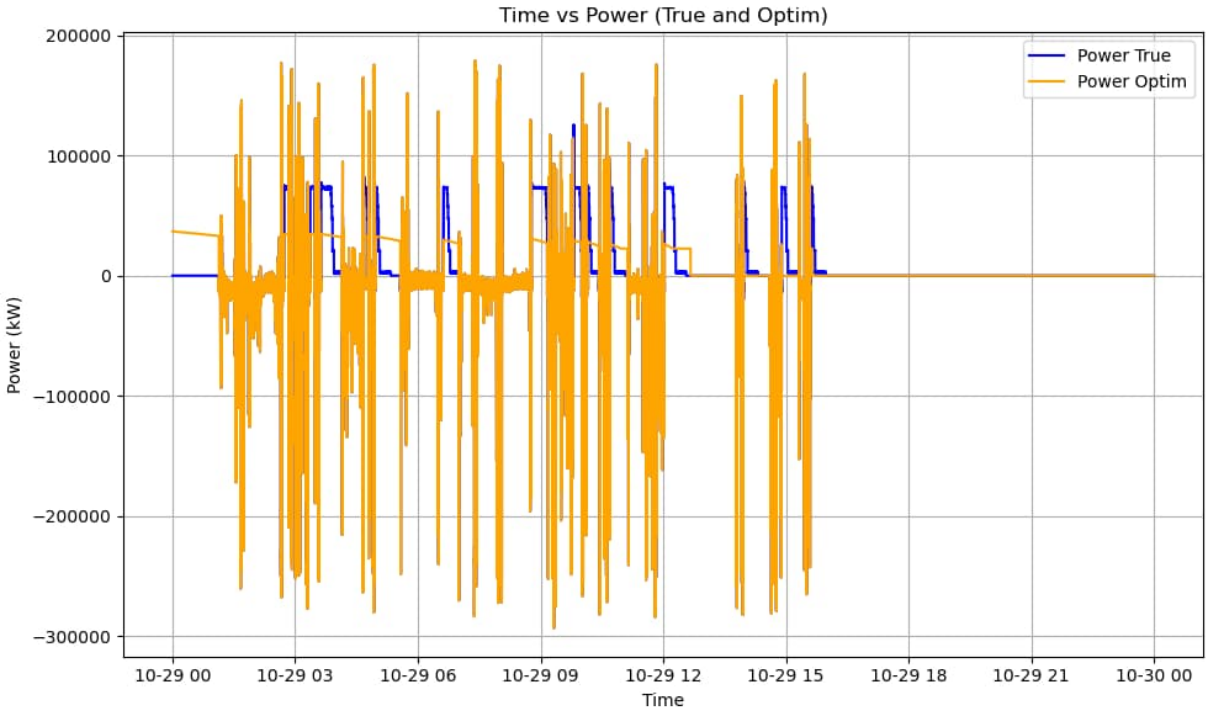


Figure 27: Power profile comparison (original vs optimized).

The varying charging approaches lead to different SoC, observable on the left sides of subsequent images (Figure 28, Figure 29, Figure 30).

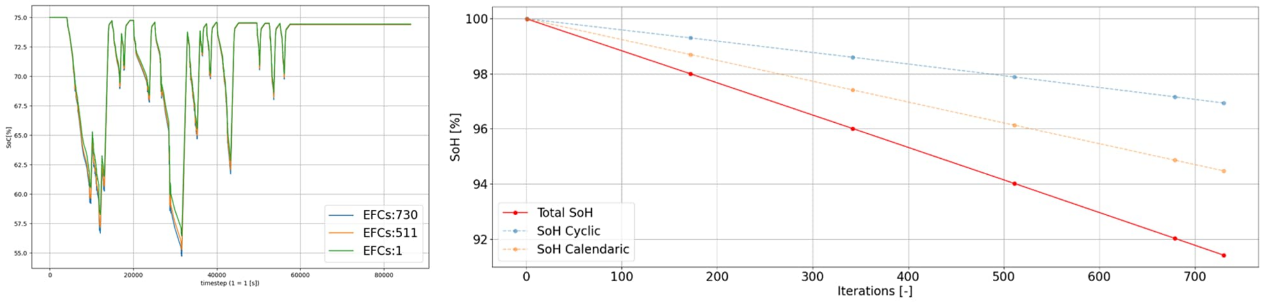


Figure 28: Open-Sesame simulation output of the original profile with SBB SoC limitations

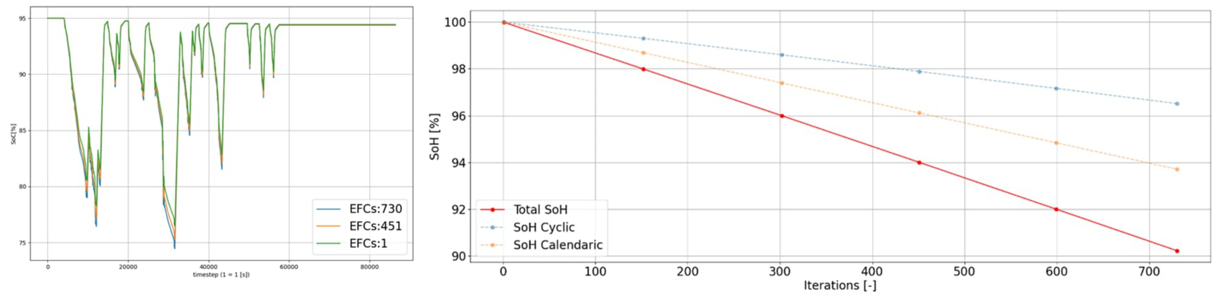


Figure 29: Open-Sesame simulation output of original profile without SoC restrictions

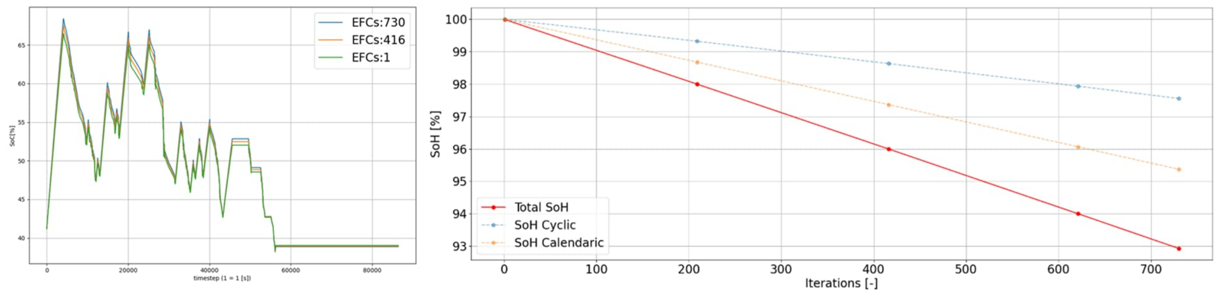


Figure 30: Open-Sesame simulation output of optimized power profile

According to these simulations, after approximately two years of testing, leads to a degradation of the non-optimized profile of 8.6% ΔSoH (Figure 28), while the optimized profile shows a reduced degradation of 7% ΔSoH (Figure 30). This improvement of 1.6 ΔSoH represents a 19% reduction in degradation, proving the significant benefits of this optimization strategy. The reference case (Figure 29) shows how the SBB algorithm would impact the battery degradation if there were no SoC limits, and how a simple change of initial SoC can reduce the aging of 14%.

4.3.5 Battery asset management support (WP 3.3)

Objective and scope of asset management

The traction battery of a rail vehicle is an expensive individual component with 1'000-2'500 CHF/kWh which also maintains a high value over lifetime. As these components will be present in large numbers at SBB by 2040, there is also a high total value within the overall fleet. The systems are digital and already provide a lot of data that can be used for asset management and operational optimisation.

There are monitoring solutions on the market from a wide range of providers with different focuses. In future, SBB will have a wide variety of battery systems with different cell technologies from different manufacturers. The aim is to be able to track the data from the various battery systems centrally in one monitoring system, not in several. The use of existing solutions quickly becomes very expensive due to the annual licence costs incurred. Furthermore, the existing solutions only fulfil the requirements to a limited extent, or they offer additional features that are not required.

The aim of this work package is to develop an asset management tool for the vehicle battery asset. This should support the asset manager in always monitoring the asset, ensuring operation and maintenance, optimizing operating processes, prolonging service life of the battery, supporting strategic decisions.

Asset management is understood to mean the following:

- Management of the "vehicle battery" asset (usually traction batteries) over its entire life cycle, once in operation at SBB.
- Monitoring and ensuring the safe and optimal operation of the asset; also supporting operations.
- Disclosure of faults and having tools for initial fault analysis.
- Monitoring of guarantees that were contractually negotiated in the procurement phase.
- Forward-looking (predictive) processing of information on the condition of the asset, e.g., for predictive replacement planning or fault detection.

Subject areas such as procurement and disposal are upstream and downstream processes; storage must be considered separately.

Concept for implementation via web interface

Asset management is primarily mapped via a comprehensive web interface. However, individual parts can also be implemented in outsourced applications. Figure 12 shows the current concept regarding asset management functionalities.

When calling up the asset management tool or web interface, a fleet overview could serve as an entry point. This provides information on the number of battery systems, number of vehicles per vehicle type, installed and usable capacities, fault and alarm messages, average state of health (SoH), ...

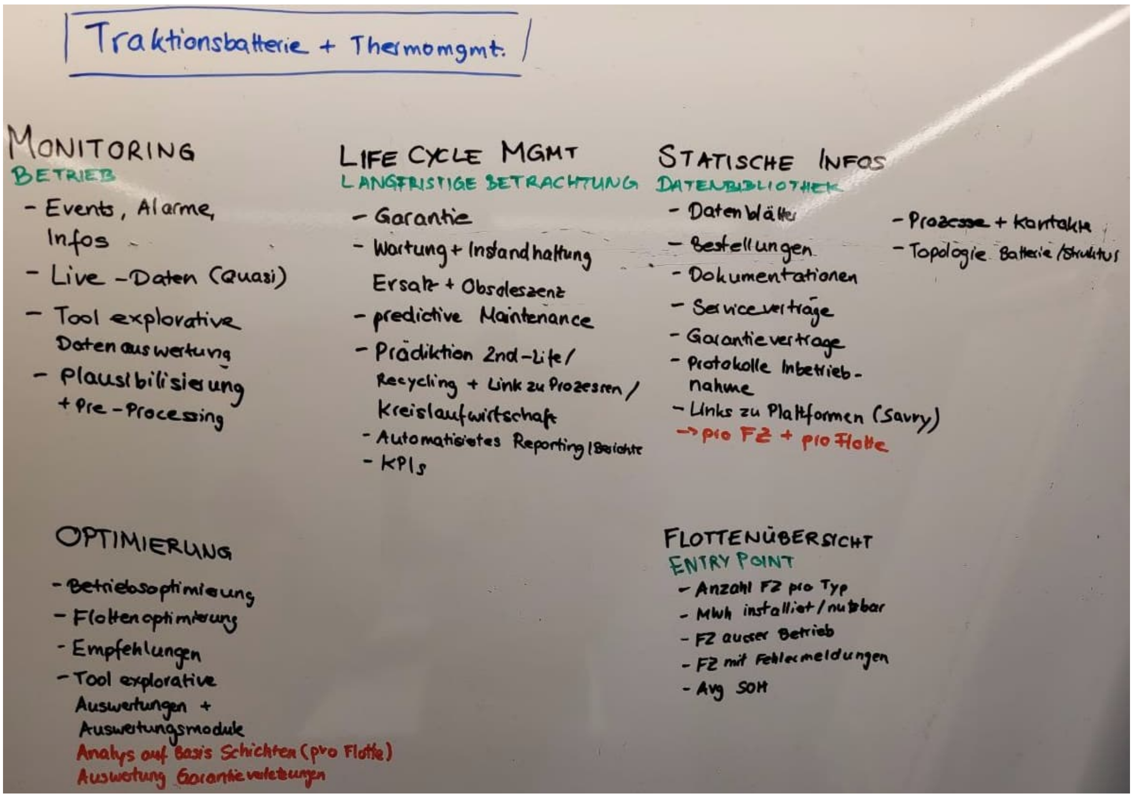


Figure 31: Asset Management Concept.

Another component of asset management is the monitoring of operations. Live data or quasi-live data is uploaded here and visualized in predefined graphics in a quick overview. This includes events, alarms and fault messages, power, temperature and SoH curves, quick evaluations of battery usage and other parameters.

Static information such as data sheets, contract documents, warranty, maintenance and service agreements, logs and documentation are stored in a data library.

In the Life Cycle Management component, quick analyses and evaluations can be carried out for data that is relevant for the long-term management of the asset. This includes analyses of maintenance and servicing as well as replacement, warranty compliance, retaining useful lifetime of the battery and prediction of usability in a 2nd life application and other key performance indicators (KPIs).

Battery data from the SBB Cloud could be made available in an optimization tool for analyses and more complex programming or visualizations. This enables individual fleet analyses and operational optimizations, explorative evaluations, and the derivation of recommendations.

Pilot phase battery monitoring of an external service provider

SBB's Center of Competence Energy Storage has compiled a market overview and selected one battery monitoring solution for a pilot test phase. The cloud-based provider acquires daily battery operation records from SBB. These records come from the five battery-electric Tafag-locomotives also used as a pilot-vehicle for the BIENE project.

The main KPIs highlighted within the dashboard are:

- SoH (State of Health): The SoH provided is based on fundamental electrochemistry. Therefore, it is possible to compare with the SoH value provided by the battery supplier through the Battery Management System and gain experience regarding the divergence and the trustworthiness of the SoH estimate provided by the manufacturer. The resolution of the SoH is at module level.

- RUL (Remaining Useful Lifetime): This metric provides a useful indicator for the long-term planning. Furthermore, the system can detect the so-called knee-point (a certain point of the lifetime of the battery after which the deterioration progresses at an accelerated pace).
- Alerting System: Overuse conditions such as over-/under-temperature, over-voltage, under-voltage, over-current as well as cell-imbalance and lithium plating generation are monitored. An alarm log on the monitoring dashboard notifies safety issues, giving its root cause and level of criticality.
- Performed battery cycles, split by operation mode (battery in charging, discharging or resting mode).

4.3.6 Using flexibility as reserve power plant (WP 3.4)

Primary focus at the beginning of the project was to be able to support vehicle users with the first battery vehicles and to establish effective battery monitoring and support asset management. The use of battery vehicles as a reserve power plant will only become relevant once the battery swarm with larger vehicle fleets are deployed. The technical feasibility of using the flexibility of the batteries will be tested during the 2nd half of the project.

The strategy of using batteries as additional flexibility in the traction current grid was confirmed by the SBB Energie management team in November 2024. Now that the first stage of the power demand management programme launched at SBB in 2015 has been successfully implemented to cut extreme load peaks by temporarily blocking heating systems, the programme is to be expanded in the second stage, which has now been launched. Figure 32 shows the target image for 2030 for the second stage of the programme. The plan is to use batteries for all three fields of action: Control overload, cutting load peaks and smoothing the load profile.

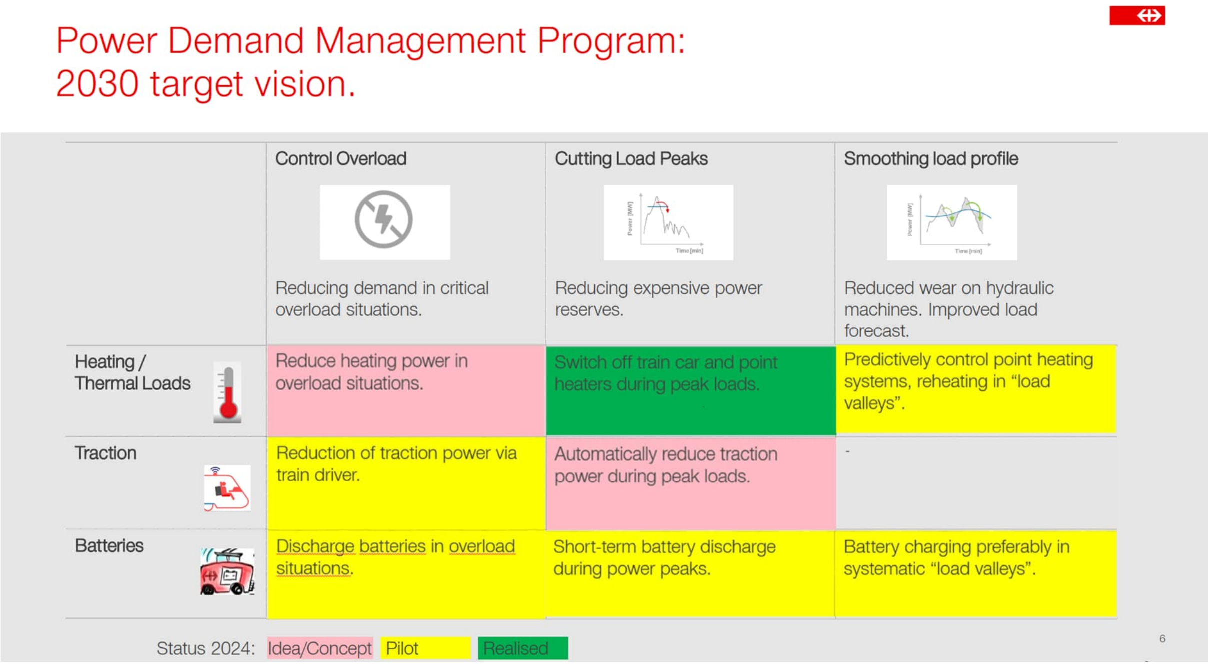


Figure 32: Target image 2030 of the 2nd stage of SBB's power demand management program.

4.3.7 Fleet-wide implementation (WP4)

Important prerequisites must be met for fleet-wide implementation. Firstly, it is important to ensure that the necessary requirements for connecting to the battery management platform are met as early as possible when the vehicles are procured. In addition, the roles and tasks for all participants and stakeholders must be clarified and agreed so that the necessary organisational requirements can be established.

Vehicle specifications

Several procurement projects for battery-powered rail vehicles are currently running or in preparation. The necessary requirements must be defined so that these vehicles can be connected to a central battery management platform in the future.

A standard requirements document was therefore created as part of the project, which can be used for future procurement projects (Halder et al., 2025). The requirements described in this document relate to the current state of knowledge on the development and operation of a centralised battery management platform. As during this project new findings are to be expected, the document will have to be updated on an ongoing basis. The document should also serve as a basis for subsequent standardisation, e.g., as a set of rules for the RTE railway technology regulations. In an initial exchange with the Swiss Association of Public Transport (Verband öffentlicher Verkehr, VöV), the latter clearly signalled its willingness to support the BIENE concept as an industry solution and to examine the standardisation of procurement requirements as an RTE standard.

The project team liaised with those responsible for the procurement projects to ensure that the requirements are considered. This was especially the case for the procurement projects for new maintenance vehicles of SBB Infrastructure in the Project Hyperion and EULE, for new locomotives of SBB Cargo for long distances transport with battery range extenders for last mile services. Furthermore, requirements have been taken into account in procurement projects of BLS infrastructure and RhB.

Experience to date has shown that some procurement project managers were initially reluctant to include additional requirements. These always represent an additional challenge in projects that are usually under time pressure and have a tight budget. It was important to demonstrate the advantages of the concept for all those involved and to deal openly with the uncertainties that still exist. The management's support for an entrepreneurial solution was certainly also helpful.

It also became clear that vehicle suppliers needed more in-depth background information in order to be able to categorise additional requirements. The BIENE concept not only foresees sending data from the battery or vehicle to the central platform but also transferring target values for battery charging from the central battery manager to the vehicle. To ensure secure transmission, security requirements must be taken into account, target values on the vehicle must be checked for plausibility and an appropriate data architecture must be in place on the vehicle. In addition, the vehicle must be able to transfer energy from the battery to the DC link and feed it back into the overhead line when parked and while travelling.

In order to ensure good interaction between the vehicle and the battery management platform, a deeper understanding of the BIENE concept is also necessary on the part of the vehicle manufacturer. The experience gained in the BIENE Battery Manager pilot project and in the first battery vehicle projects will be very helpful in developing and consolidating a common understanding for a successful industry solution.

Roles and responsibilities of stakeholders

Successful sector-wide implementation of the BIENE concept in Switzerland will depend heavily on whether a suitable organisational form can be found for all parties involved.

The aim must be to find an optimal solution for the sector, considering the interests and requirements of the parties involved in a balanced manner.

The bachelor's thesis “Vehicle2Bahnstromnetz - Von der Konzeption zur Umsetzung / Vehicle2Rail-traction-grid - from conception to realisation”, which was supervised as part of the pilot project, examined various implementation options (Trick, 2024).

The BIENE concept provides a holistic solution with three major value propositions:

- Flexibility for the traction current network

- Battery monitoring

- Charging optimisation/ageing optimisation.

Alternatively, variants were described in which individual components are dispensed with or, where possible, purchased externally (see Figure 33).

	Flexibilität für Bahnstromnetz	Batteriemonitoring	Ladeoptimierung und Alterungsoptimierung
Variante 1 Brachenlösung: Biene als Brachenlösung von SBB Energie	SBB Energie / Branchenlösung		
Variante 2 Hybrid : SBB Energie fokussiert auf Lastmanagement und Lademanagement – Beschaffung Batteriemonitoring	SBB Energie	Extern eingekauft	SBB Energie
Variante 3 Flex-Monitoring: SBB Energie fokussiert auf Lastmanagement – Beschaffung Batteriemonitoring und Verzicht auf Lademanagement	SBB Energie	Extern eingekauft	Verzicht
Variante 4 Flex only: SBB Energie fokussiert auf Lastmanagement – Verzicht auf Batteriemonitoring und Lademanagement	SBB Energie	Verzicht	Verzicht
Variante 5 Monitoring only: keine SBB Entwicklung - Beschaffung Batteriemonitoring Verzicht auf Lademanagement	Verzicht	Extern eingekauft	Verzicht

Figure 33: Implementation variants for the use of battery flexibility, battery monitoring and charging optimisation (Trick, 2024).

Benjamin Trick (2024) analysed the costs and benefits of these implementation options based on rough assumptions and supplemented them with qualitatively described aspects. In addition, he assessed potential acceptance risks by comparing the characteristics of the variants with the needs of key stakeholders.

As outlined in Figure 34, the BIENE concept with a comprehensive sector solution clearly offers the best cost-benefit ratio as with the lowest implementation risk. The main reason for this is that the BIENE concept as a sector solution allows synergies to be utilised and provides value propositions for all parties involved. If individual elements are omitted, the overall benefit is significantly lower. If battery monitoring is purchased externally, the costs increase due to the lack of synergies in the overall solution.

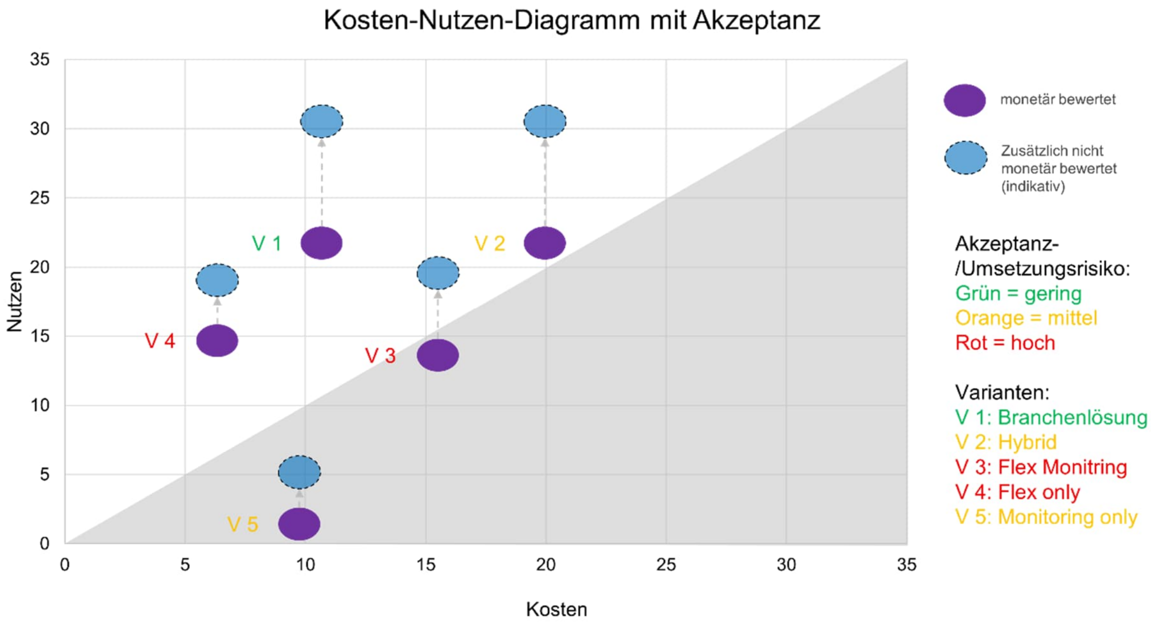


Figure 34: Cost-benefit diagram with acceptance risk for different implementation variants (Trick, 2024).

These results confirm the BIENE concept, which envisages making the functionalities of the BIENE Battery Manager available as a service, with SBB Energy benefiting from the flexibility of the vehicle batteries in return. The conditions under which this flexibility may be utilised must be agreed with the vehicle owners, with one important criterion being that the operational flexibility for vehicle owners must not be restricted. An exception to this is the use of swarm batteries as a reserve power plant in extremely rare emergencies to prevent an interruption in the traction power supply.

However, SBB Energy will not be in a position to finance hardware on the vehicles or communication from the vehicles to the land side. This will be the responsibility of the vehicle owners. At the same time, they can also use the technology for other applications, such as the transmission of operating times for energy-optimised stabling or as a possible option for central vehicle diagnostics. A further synergy is currently being examined in collaboration with the Pantoguard project, the objective of which is to prevent damage to pantographs and overhead contact lines by automatically lowering the pantograph as soon as the electrified area is left.

The Passenger Division of SBB has considerable experience with systems for communication between vehicles and the landside, having been involved in such projects for many years. The vehicle platform (APFZ) team is responsible for the provision of hardware solutions, together with the corresponding communication pipelines and the services required to support them. These systems are utilised for the provision of customer information and video surveillance, amongst other applications. The current power demand management system also employs this communication channel for the transmission of trigger signals to the vehicles. Consequently, a current investigation is underway to ascertain the feasibility of extending these services to the Cargo and Infrastructure Divisions, with a view to their utilisation with future battery-powered vehicles.

Figure 35 outlines a possible implementation model with agreements between SBB Energy and the vehicle owners, as well as the necessary requirements between vehicle owners and vehicle suppliers.

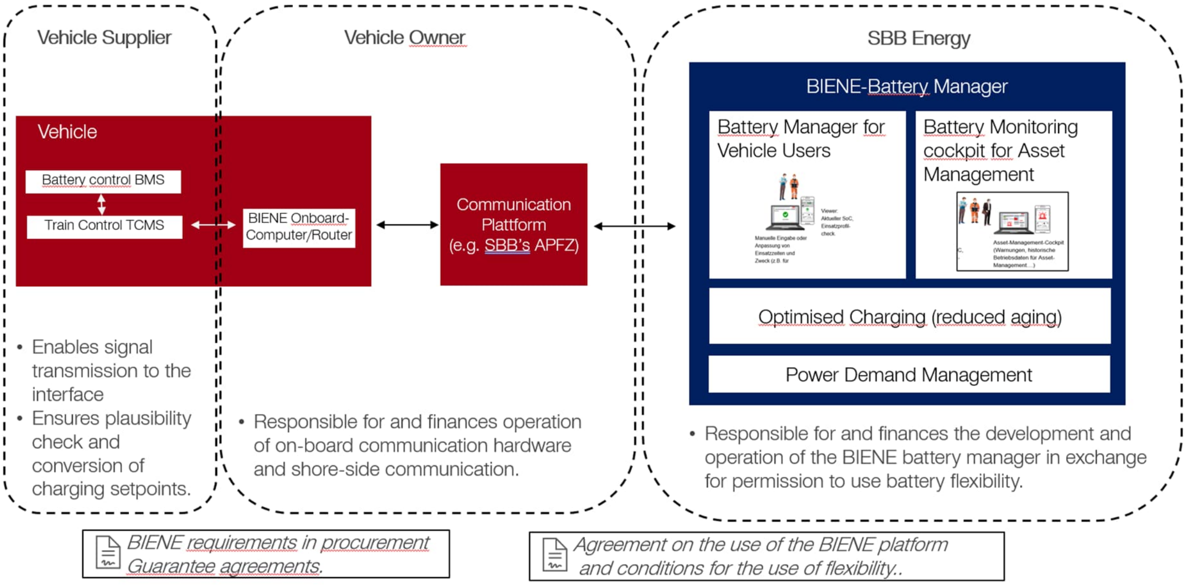


Figure 35: Proposal of Roles and Responsibilies for the BIENE Battery Manager

This model is designed to provide a non-discriminatory service also to vehicle owners not affiliated with SBB. It facilitates connectivity for these railway companies with their vehicle communication systems, enabling integration with the central BIENE battery manager platform via a secure interface.

5 Evaluation of results to date

The project results in the individual work packages can be evaluated as follows:

In Work Package 1 (WP1), important prerequisites were created in the Open Sesame model for a simulation of battery ageing. Stress factors for the NMC battery technology available on the ‘high work platform’ pilot vehicle, for example, were refined. A total cost of ownership (TCO) model was integrated in Open Sesame. To be able to demonstrate the effect on battery ageing by applying the BIENE algorithm not only in the model, a ‘physical twin’ was designed in the battery laboratory. The ageing test in the lab has been running since October 2024. Compared to the previous work plan, updates to the model for LTO batteries are still missing.

The activities for 2nd life opportunities (WP2) focused on identifying the key data to be stored for making informed decisions before transitioning a battery from first to second life. This involved evaluating how SOH could be estimated based on available data while ensuring that recorded variables also provided meaningful insights from a safety perspective.

An important prerequisite for the pilot of the battery management platform is a functioning data connection to the pilot vehicles. All SBB Infrastructure's Tafag XTas ‘Hocharbeitsbühnen’ are now equipped with an on-board computer, and the remaining Rhaetian Railway Geaf 2/2 shunting locomotives are expected to be equipped by April 2025.

The reason for the delay in equipping all pilot vehicles was the need to replace the communication hardware used due to obsolescence. In the meantime, data from the RhB's TREDIS diagnostic system could be used to analyse the RhB fleet.

To forecast energy consumption in battery mode, energy consumption data for typical operations was analysed depending on influencing factors and the average consumption per time was derived for pilot vehicles (WP3.1).

Possible vehicle planning tools were evaluated but were not deemed suitable for direct connection as part of the pilot project. In an initial version, the battery manager will be dependent on the manual input of usage profiles. User requirements were evaluated, and mock-ups developed to ensure acceptance of the battery manager in operation. For operations with frequent changes between battery and panto mode, only the working shift times and the percentage in battery mode are entered. An initial test of possible user inputs made it possible to simulate the charging strategies developed for the specified mission profiles. A first version of the battery manager is thus available on a simulation platform but is yet not tested end-to-end with the pilot vehicles (WP 3.2).

Initial drafts of an asset management cockpit were developed on SBB's Enterprise Analytics Platform. A data pipeline from the pilot vehicles to a powerful central database was established for this purpose. In preparation for this, the user needs of future asset managers were and are being analysed and comparable tools on the market evaluated (WP 3.3).

Utilising the flexibility of batteries to generate business value was confirmed as an important strategic step by SBB Energie. A strategic target vision for 2030 was defined and agreed by the SBB Energie management board (WP 3.4).

Various implementation models were evaluated for a sector-wide introduction and the optimum ‘sector solution’ model was outlined based on the given framework conditions (WP 4).

To ensure that future battery vehicles can be connected to a central battery management platform as efficiently as possible, the necessary interfaces and functionalities on the vehicles must be considered at the procurement stage. To this end, a generic specification was developed that could be used in the current procurement projects of SBB, BLS and RhB.

6 Next steps

Now that the foundations have been laid in the first two years of the project, it was possible to build on this basis and further develop the functionalities of the BIENE Battery Manager and prove their impact especially on battery lifetime.

The next steps planned were:

- WP1: Open-Sesame now features a reshaped structure that enhances its speed, with additional outputs and plots for a more comprehensive analysis overview. The results from the digital twin and various applications will offer further insights for potential improvements. The next steps include enhancing the program through performance optimization, integrating new outputs, and seeking new datasets to validate other chemistries. These enhancements will increase the resilience of the program and, consequently, improve the quality of analyses and comparisons.
- WP2: Several considerations and challenges for second-life applications have been addressed. A practical example has been illustrated, and the key metrics to monitor have been outlined. WP2 will be completed with more details about a planned pilot for use of a 2nd-life battery storage system at the Hägendorf railway technology centre.
- WP3: The next steps involve the equipping of the remainder of the RhB fleet's pilot vehicles with communication hardware, with connectivity to be established over the coming months. Further development of features for the Analysis Tool and Asset Management Cockpit on SBB’s Enterprise Analytics Platform is also planned, alongside ongoing monitoring of the batteries on these pilot vehicles.

End-to-end testing of optimized charging algorithms on the pilot vehicles will be conducted. Additionally, the impact of these algorithms on battery service life will be evaluated in the battery laboratory to quantify aging effects and refine aging models.

Furthermore, several value cases for the electricity grid will be assessed, with the most promising identified for grid support applications.

- WP4: Consideration will be given to the generic specifications for a connection to the battery management platform in current and future vehicle procurement projects. The specifications will be refined based on the findings. Further elaboration of an implementation model for a sector-wide solution will also be undertaken. In addition it will be examined which elements of centralised battery management could be transferred to other non-rail domains such as buses and what challenges are seen in doing so.

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IEA ES TCP Task 32, 2023, Open Sesame – Modelling of energy storages for simulation/optimization of energy systems, Link.

8 Appendix

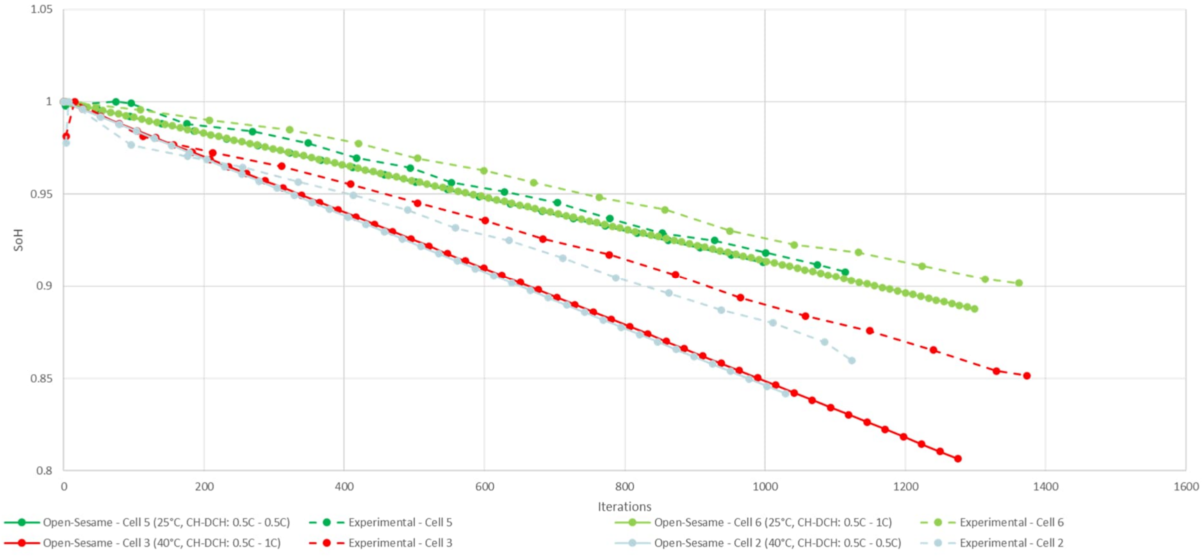

Figure 36: Dataset 1 - Open-Sesame validation activity, no-tuning

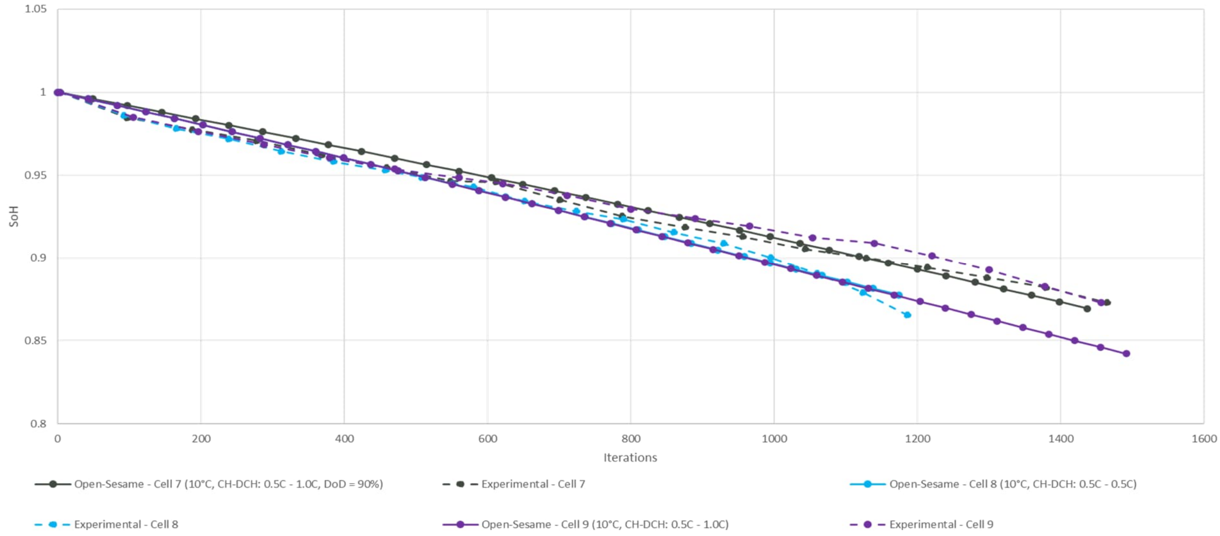

Figure 37: Dataset 1 - Open-sesame validation activity (T = 10°, different condition comparison), tuned

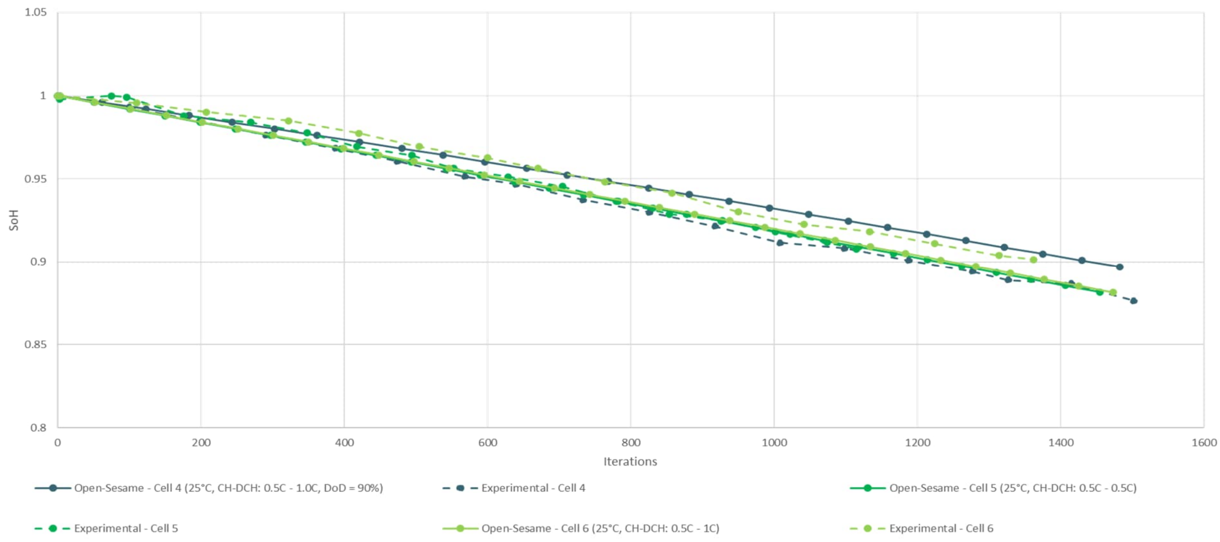

Figure 38: Dataset 1 - Open-sesame validation activity (T = 25°, different condition comparison), tuned

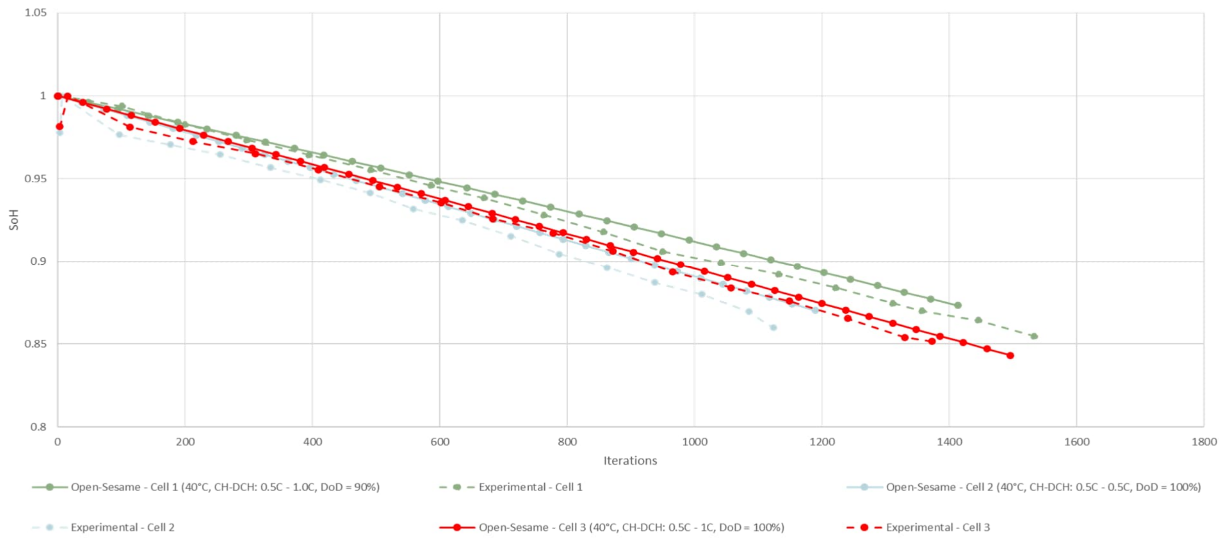

Figure 39: Dataset 1 - Open-sesame validation activity (T = 40°, different condition comparison), tuned

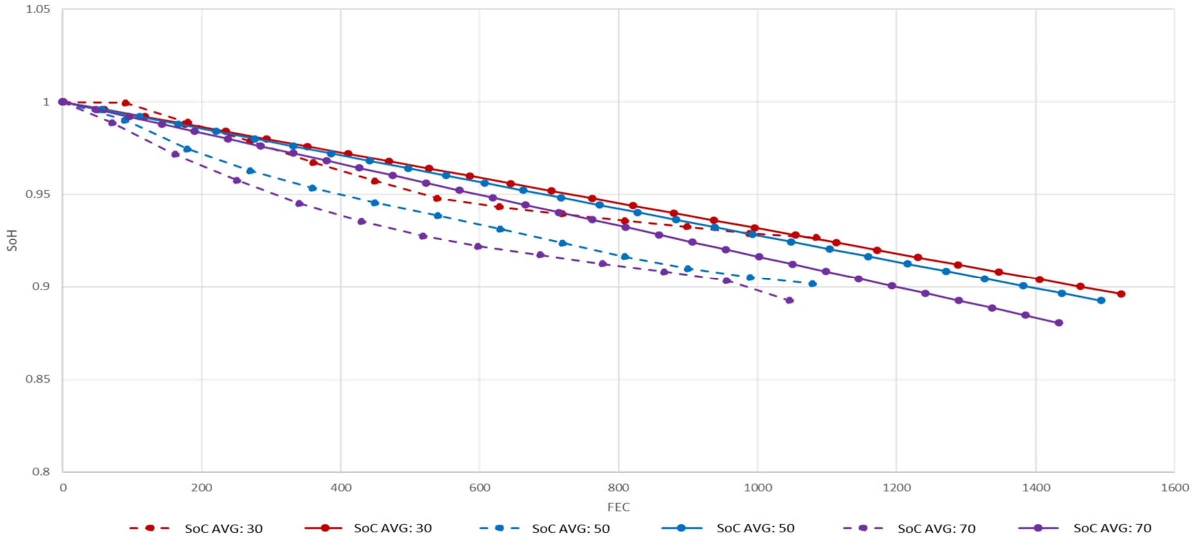

Figure 40: Dataset 2 - Open-sesame validation activity (AVG SoC comparison), tuned.

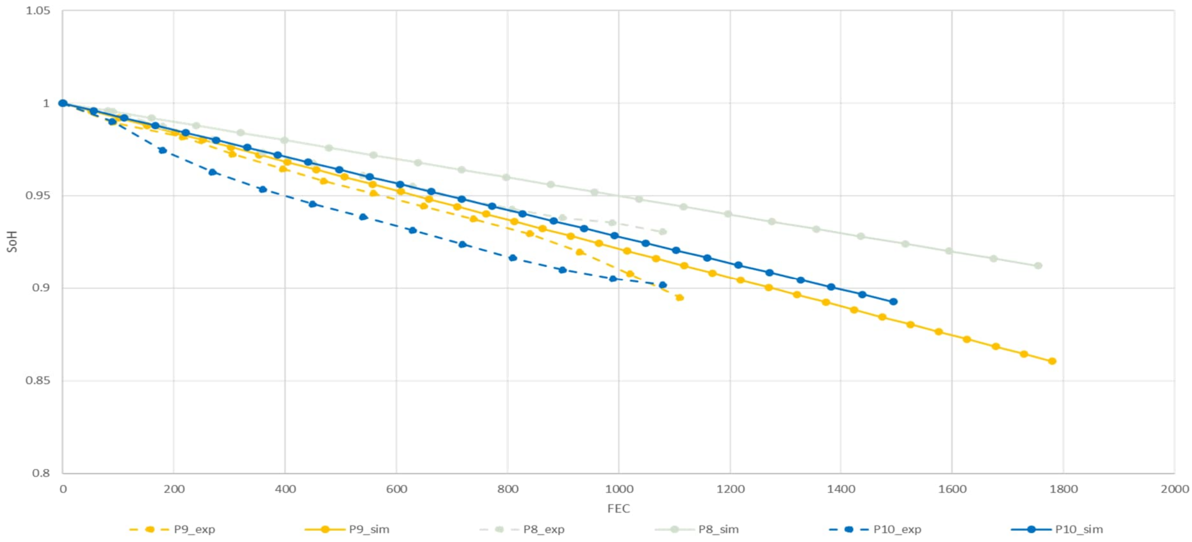

Figure 41: Dataset 2 - Open-sesame validation activity (T comparison), tuned.

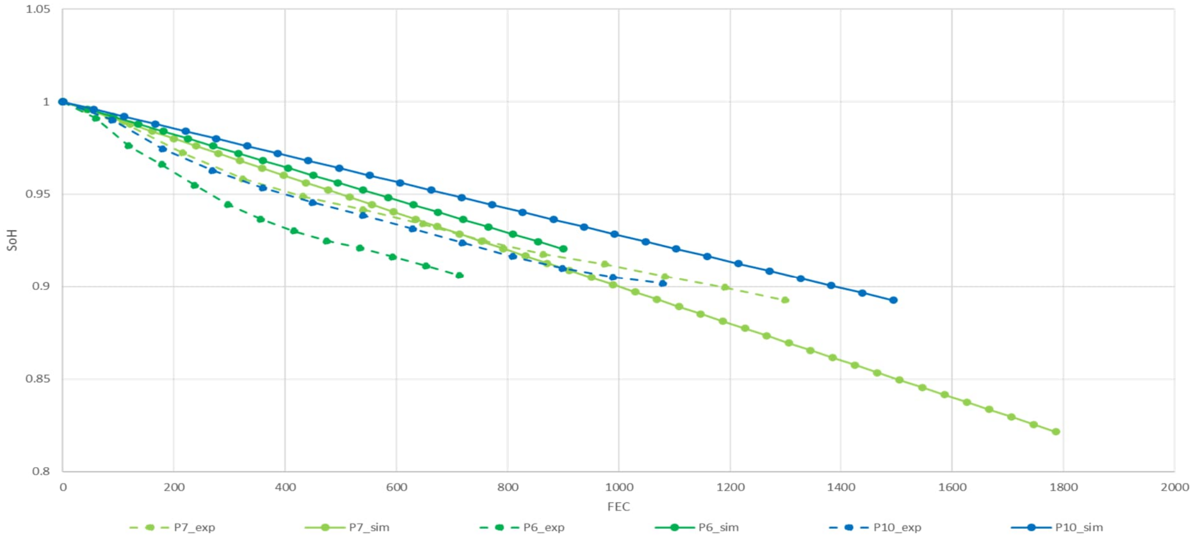

Figure 42: Dataset 2 - Open-sesame validation activity (C-rate comparison), tuned.

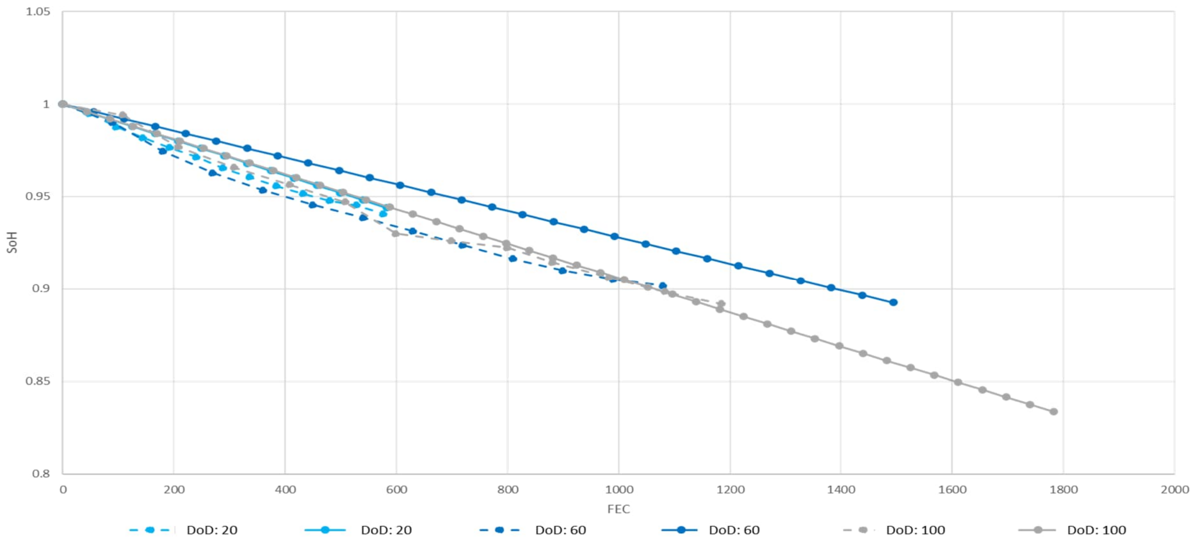

Figure 43: Dataset 2 - Open-sesame validation activity (DoD comparison), tuned.

9 Project progress (confidential)

9.1 General project status and budget

As described in Chapter 5, the project is generally on track with some delays in fully equipping the pilot vehicles with the communication platform as well as in developing an end-to-end pilot platform for controlling battery charging and the asset management cockpit.

Table 7 summarizes the financial expenses sustained to date from SBB, RhB, and BFH. The SBB expenses total CHF 949’103, which include hours costs (Table 8) and part of the pilot vehicle installation expenses (CHF 155’951). RhB expenses amount to CHF 45’640, covering working hours (Table 11) and the remaining pilot vehicle costs (CHF 20’000). Lastly, BFH has sustained costs of CHF 297’817, primarily from working hours (Table 9). To date, the total SFOE contribution used stands at CHF 474’002.5, representing the 37% of the total expenses. It covers the costs from BFH and the pilot vehicle communication. This is slightly higher than the initial projected 31% (CHF 535,000 of CHF 1,750,200).

It is to be expected that SBB as well as RhB will have slightly higher costs in 2025 and 2026 and compensate for the slightly smaller contribution in the last two years. At SBB more effort will be needed for IT development of the battery manager and asset management cockpit to catch up on the delays. RhB will have extra efforts to equip the rest of their Geaf fleet and to accompany the pilot.

Table 7: Costs summary according to project application and actual financial project status (last table)

Timetable for distribution of project costs and financing of costs

Show the annual distribution of the total costs incurring for each project partner and their financing contribution (sources: cash and in-kind contributions from partners, SFOE contribution, third-party funds). In-kind contributions include labour and material contributions. Give the source of any third-party funds (cantons, building owners, foundations, associations, etc.)

Timetable for distribution of project costs among project partners according to project application

Cost centre (institution)	2023 - 2024	2025	2026	Total*
SBB incl. Communication Vehicle/Hardware	1'173'200	656'000	586'000	2'415'200
Rhätische Bahn (RhB)	108'000	31'000	19'000	158'000
Berner Fachhochschule (BFH)	444'000	242'000	190'545	876'545
Total*	1'725'200	929'000	795'545	**3'449'745**

Timetable for distribution of financing of project costs by project partners, SFOE and third parties according to project application

Source of financing (institution)	2023 - 2024	2025	2026	Total*
SBB	1'053'200	631'000	581'096	2'265'296
Rhätische Bahn (RhB)	98'000	26'000	14'000	138'000
Berner Fachhochschule (BFH)	64'000	32'000	30'545	126'545
SFOE contribution**	**535'000**	**200'000**	**184'904**	**919'904**
Third-party funds (state source here)				
Third-party funds (state source here)				
Total*	1'750'200	889'000	810'545	**3'449'745**
%SFOE contribution	**31%**			

Actual financial project status

Expenses	2023 - 2024	Compared to budget	
SBB incl. Communication Vehicle/Hardware	949'103	- 224'097	-19%
Rhätische Bahn (RhB)	45'640	- 62'360	-58%
Berner Fachhochschule (BFH)	297'817	- 146'183	-33%
Total	1'292'560	- 432'640	-25%
Costs covered by SFOE	474'002.50	395'109	37%

* The grand total must concur with the sums of the internal and external project costs (folder "Internal costs for staff" and "Equipment and exter

** The final payment must amount to at least 20% of the total SFOE contribution (Art. 23, para. 2 SuG)

*** Pilot Vehicles communication expenses will be covered by SFOE contribution (deducted from SBB-IT and RhB contributions)

SFOE budget is coming directly to BFH, invoiced amount over the past 2 years has been 535'000 CHF. Over this budget, BFH and pilot vehicle communication cost have been covered.

The following tables show in detail the cost covered by BFH for the pilot vehicle communication (Table 8), for BFH working hours (Table 9) as well as for SBB (Table 10) and RhB (Table 11).

Table 8: BFH financial report for pilot vehicles

Kostenart	Kostenartenbeschr.	RefBelegnr	BuchDatum	Belegdatum	PSP-Element	Bezeichnung	BWähr	Wert/BWähr	TWähr	Wert/TWähr	Men..	GME	PersNr	Gegenkonto	GKontBezeichnung
400001	Materialbeschaffungen	500414909	04.10.2024	04.10.2024	R.012523-20-IEMX-02	routers for pilot vehicles	CHF	25,295.40	CHF	25,295.40				2139479	Rail Diagnostics GmbH
400001							**CHF**	**■ 25,295.40**	**CHF**	**■ 25,295.40**					
400004	Dienstleistungen von Dritten	500356977	02.06.2023	02.06.2023	R.012523-20-IEMX-01	BIENE communication vehicle interface	CHF	39,822.10	CHF	39,822.10				2139479	Rail Diagnostics GmbH
		500359542	22.06.2023	22.06.2023	R.012523-20-IEMX-02	Biene externe Leistungen	CHF	9,625.15	CHF	9,625.15				2140280	Tafag AG
		500362125	01.07.2023	30.06.2023	R.012523-20-IEMX-01	communication interface Biene	CHF	10,484.60	CHF	10,484.60				2139479	Rail Diagnostics GmbH
		500363004	28.07.2023	28.07.2023	R.012523-20-IEMX-01	communication vehicles	CHF	7,374.75	CHF	7,374.75				2139479	Rail Diagnostics GmbH
		500366554	01.09.2023	01.09.2023	R.012523-20-IEMX-01	communication interface pilot vehicles	CHF	7,730.15	CHF	7,730.15				2139479	Rail Diagnostics GmbH
		500369631	02.10.2023	02.10.2023	R.012523-20-IEMX-01	Roman September	CHF	7,907.85	CHF	7,907.85				2139479	Rail Diagnostics GmbH
		500375926	03.11.2023	03.11.2023	R.012523-20-IEMX-01	coomunication interface pilot vehicles	CHF	6,397.40	CHF	6,397.40				2139479	Rail Diagnostics GmbH
		500379500	04.12.2023	04.12.2023	R.012523-20-IEMX-01	pilot vehicles communication	CHF	3,642.95	CHF	3,642.95				2139479	Rail Diagnostics GmbH
		500388033	01.02.2024	12.12.2023	R.012523-20-IEMX-01	tafag 2024	CHF	9,490.75	CHF	9,490.75				2140280	Tafag AG
		500389231	06.03.2024	06.03.2024	R.012523-20-IEMX-01	pilot vehicles	CHF	8,745.30	CHF	8,745.30				2139479	Rail Diagnostics GmbH
		500418159	05.11.2024	05.11.2024	R.012523-20-IEMX-01	communication pilot vehicles	CHF	11,950.45	CHF	11,950.45				2139479	Rail Diagnostics GmbH
		500425771	20.12.2024	20.12.2024	R.012523-20-IEMX-01	communication pilot vehicles	CHF	27,484.45	CHF	27,484.45				2139479	Rail Diagnostics GmbH
400004							**CHF**	**■ 150,655.90**	**CHF**	**■ 150,655.90**					
664001	Reisespesen	500368908	27.09.2023	27.09.2023	R.012523-20-IEMX-01	Eforce Visit	CHF	54.60	CHF	54.60				2141542	Priscilla Caliandro
664001							**CHF**	**■ 54.60**	**CHF**	**■ 54.60**					
664004	Repräsentationskosten	500368907	29.09.2023	29.09.2023	R.012523-20-IEMX-01	Conference V2X	CHF	180.00	CHF	180.00				2133060	Andrea Lucas Corti
664004							**CHF**	**■ 180.00**	**CHF**	**■ 180.00**					
							CHF	**■■ 176,185.90**	**CHF**	**■■ 176,185.90**					

Table 9: BFH working hours financial report

Name	h	h-Satz	Summe
Priscilla Caliandro	164.5	95	15’628
Bruno Lemoine	10.68	80	854
Andrea Corti	3104.32	80	248’346
Joel Wooden	344.11	65	22’367
Samuel Zgraggen	159.8	65	10’387

Table 10: SBB financial report

Name	Organisation	Hauptaufgaben	Stunden h	Stundensatz CHF/h	Eigenleistung CHF
Markus Halder	SBB Energie	Co-Projektleitung Epic-Owner IT-Entwicklung, Stakholdermgmt.,…	402 1061	CHF 160 CHF 120	CHF 64.320 CHF 127.320
Andreas Fuchs	SBB Energie	Lösungskonzeption, PO IT-Entwicklung	810	CHF 120	CHF 97.200
Steffen Wienands	SBB CoC Energiespeicher	Batteriemodell, 2nd-Life, Asset-Management Batterien (WP1, WP2, WP3.3)	517	CHF 120	CHF 62.040
Maria Kaninia	SBB CoC Energiespeicher	Datenanalyse, Asset-Management Batterien, Batteriemodell	196	CHF 120	CHF 23.556
Ueli Kramer	SBB CoC Energiespeicher	Asset-Management Batterien, Koordination SBB intern.	67	CHF 120	CHF 8.040
Roger Kocher	SBB CoC Energiespeicher	Anforderungen Fahrzeugbeschaffung	130	CHF 120	CHF 15.600
Francois Nzale	Trainee SBB Energie	Konzept Einsatzprofilprognose	630	CHF 100	CHF 62.976
Oliver Schulz/Goran Maric	SBB IT	IT-Architektur	250	CHF 120	CHF 30.000
Brian Lynderup	SBB IT	Entwickler, SAP Hana	200	CHF 120	CHF 24.000
Raimund Feldmann, Ali Eyertas	SBB IT	Organisation IT-Entwicklung (Release Train Engineer und Scrum Master)	50	CHF 120	CHF 6.000
Ralf Kowatsch	SBB IT, DG Analytics	Aufbau Datapipeline, Support Maria Kaninia	30	CHF 120	CHF 3.600
Matthias Thoma, Sepp Stark,…	APFZ, DSO ROS	Kommunikation Fzg-Zentrale	30	CHF 120	CHF 3.600
Sibylle Trenck	SBB IT	UX / Nutzeranforderungen	30	CHF 120	CHF 3.600
Flächenmitarbeiter SBB	SBB Infra & Cargo	Angabe Nutzeranforderungen in Interviews, Feedback Userstories, Simulationstest,…	40	CHF 120	CHF 4.800
Benjamin Trick	SBB PP-F-UHR	Variantenanalyse für Implementierung (WP. 4)	100	CHF 120	CHF 12.000
Roland Schäfer	SBB Energie, Datanalytics	Unterstützung Aufbau Datenprodukt	50	CHF 120	CHF 6.000
Jannis Pomsel	SBB CoC Energiespeicher	WP2: 2nd-Life	112	CHF 100	CHF 11.180
Janos Dudey	SBB ENergie	Algorithmus Lademanager	801	CHF 100	CHF 80.100
Elio Wanner	SBB Energie	BIENE Simulator	106	CHF 100	CHF 10.600
				SUMME SBB Stunden	**CHF 656.532**
Auftrag Raildiagnostics (Roman Tschai		Engineering Kommunikationshardware und Datapipeline		2023	CHF 74.250
				2024	CHF 62.370
				SUMME Externer Auftrag	**CHF 136.620**
				SUMME SBB	**CHF 793.152**

Table 11: RhB financial report

Name	Organisation	Hauptaufgaben	Stunden h	Stundensatz CHF/h	Eigenleistung CHF
Danilo Dorrizi	RhB	Coordination for RhB work	20	CHF 160	CHF 3.200
Daniel Zurbrügg	RhB	Engineering Work on RhB Loco, TReDIS data,…	137	CHF 120	CHF 16.440
Renato Hirsiger	RhB	Vehicle Procurement,…	40	CHF 120	CHF 4.800
Martin Vital	RhB	User needs Planner and Driver	10	CHF 120	CHF 1.200
				SUMME Rhb	**CHF 25.640**

9.2 Status of work packages

Chapter 5 describes the current results compared to the original work plan. In general, the project is well on schedule, with a certain delay in fully equipping the pilot vehicles with the communication platform. The development of an end-to-end pilot platform for controlling battery charging and the asset management cockpit in work package 3 is also delayed, but the most important preliminary work has been completed and provides a good basis for the next steps.