ADVANCING CIRCULAR PUBLIC TRANSPORT

Circular economy pilot experiences and solutions for public transport operators

Interreg
CENTRAL EUROPE

Co-funded by
the European Union

CE4CE

Imprint

Project
CE0100250 CE4CE - Public Transport Infrastructure in Central Europe – facilitate transitioning to circular economy

Contact
Leipziger Verkehrsbetriebe (LVB) GmbH/ Leipzig Public Transport Company,
Address: Georgiring 3, 04103 Leipzig, Germany
Web: https://www.l.de/verkehrsbetriebe/
E-mail: CE4CE.Verkehrsbetriebe@L.de

Financed by
Interreg Central Europe Programme
Web: https://www.interreg-central.eu/

Authors
Danijel Hojski, Marjan Lep, Vlasta Rodošek (University of Maribor, Slovenia)

Contributors
Stefan Röll, Conrad Jentzsch (Leipzig Public Transport Company, Germany), Jan Röhl (Kruch Railways, Austria), Liliana Donato, Sara Biffi (ATB Bergamo, Italy), Gabriele Grea (Redmint Impresa Sociale scrl, Italy), Dominika Kowalkowska (PKA Gdynia, Poland), Agnieszka Szmelter-Jarosz, Marcin Wolek (University of Gdansk, Poland), Németh Zoltán Ádám, Gábor Jéga-Szabó (SZKT Szeged, Hungary), Mitja Klemencic (Municipality of Maribor), Alexandra Scharzenberger, Marta Woronowicz (trolley:motion association, Austria), Laura López, Ana-Maria Baston (Rupprecht Consult, Germany), Nikolett Csörgő (Mobilissimus Kft, Hungary)

Layout and design
Danaja Dvornik (@_studio_kai_)

Date of publication
April 2026

About the CE4CE project

The CE4CE project empowers circular economy system thinking for actors in public transport from Central European countries to reduce waste and create value along new life cycles of infrastructure and rolling stock. To do so, CE4CE jointly develops solutions that increase knowledge and capacities for the sector, help reduce barriers and costs, and initiate the development of new services and skilled jobs, as well as strategies and action plans that improve policy development, learning and exchange on the regional and transnational level.

CE4CE aims at bringing circular economy principles into the public transport sector and, thus, reduce waste, increase efficiency in the sector and improve the ecological footprint of public transport.

Figure 1: CE4CE partners during a joint discussion on solutions and action plans in 2025. Credentials: The CE4CE consortium.

Table of contents

List of Abbreviations

Abbreviation	Definition
AETE	Avoid - Extend - Transform - Enable
BESS	Battery Energy Storage System
CAN-BUS	Controller Area Network Bus
CE4CE	Circular Economy for Central Europe
DC	Direct Current
EFS	Energy Flow Simulation
GNSS	Global Navigation Satellite System
IMC	In-Motion Charging
KPI	Key Performance Indicator
PV	Photovoltaic
RES	Renewable Energy Sources

List of Abbreviations of partners

Abbreviation	Definition
LVB	Leipziger Verkehrsbetriebe, Germany
KRUCH	KRUCH Railway Innovations, Austria
TM	trolley:motion, Austria
ATB	Azienda Trasporti Bergamo, Italy
REDMINT	Redmint Impresa Sociale, Italy
SZKT	Szeged Transport Company, Hungary
MOBILISSIMUS	Mobilissimus, Hungary
PKA	Public Transport Bus Operator in Gdynia, Poland
MOM	Municipality of Maribor, Slovenia
UG	University of Gdańsk, Poland
UM	University of Maribor, Slovenia
RUPPRECHT	Rupprecht Consult (consultant to LVB), Germany

Executive summary

The CE4CE project supports the transition towards circular economy practices in public transport systems in Central Europe by translating circular economy principles into practical pilot actions and transferable solutions addressing infrastructure and rolling stock life cycles. Through real-life experimentation and solution development, CE4CE contributes to reducing waste, preserving value and creating new circular value chains in public transport.

Within the project, public transport authorities, operators and other stakeholders jointly developed and tested pilot actions and solutions that increase sectoral knowledge and capacities, help reduce implementation barriers and costs, and enable the development of new services, skills and circular business models. By focusing on concrete applications under real operating conditions, CE4CE supports improved resource efficiency, reduced environmental impacts and the long-term sustainability of public transport systems.

The pilots and solutions presented in this handbook build on co-creation, pilot testing and peer review processes. They demonstrate circular practices such as life-time extension, reuse, repurposing and remanufacturing of assets, as well as enabling mechanisms including digital tools, platforms and business models that support uptake across the public transport sector.

CE4CE was implemented by a transnational partnership reflecting a whole value-chain and system perspective, comprising public transport authorities and operators, municipalities, industry and research organisations from six Central European countries. The involvement of associated partners and international networks further supported communication, knowledge exchange and the wider transfer of project results.

This handbook documents and disseminates the key pilot actions and solutions developed within CE4CE, providing practical insights and guidance for stakeholders seeking to apply circular economy principles in public transport contexts.

The handbook is structured as follows:

Chapter 2

introduces the conceptual and methodological framework of the CE4CE approach, including the AETE model and its relevance for circular economy implementation in public transport.

Chapter 3

presents the CE4CE pilot actions together with the corresponding solutions, highlighting how practical experiences were translated into transferable and uptake-oriented outputs.

Chapter 4

synthesizes the key lessons learned across all pilots and solutions, identifying common success factors, challenges, and implications for replication.

Chapter 5

provides implementation guidance, including practical steps, key considerations, and risk factors for deploying CE4CE solutions, and concludes with an outlook on future applications and scalability.

Figure 2: CE4CE consortium at the final project meeting in Maribor, March 2026. Copyright: University of Maribor.

1. Introduction

Main objective of the CE4CE project

The main objective of the CE4CE project is to enable public transport authorities and operators to move from linear asset management approaches towards circular, life-cycle-oriented models. By addressing technical, organisational and market-related barriers, CE4CE supports the preservation of value, reduction of waste and more efficient use of resources across public transport infrastructure, vehicles and related assets.

To achieve this, CE4CE combines pilot implementation with the development of uptake-oriented solutions that can be transferred and adapted beyond the project partnership.

Project partnership

CE4CE is implemented by a transnational partnership bringing together public transport authorities and operators, municipalities, research institutions and solution providers from several Central European countries. This diversity enables testing and development of circular economy approaches in different operational, organisational and regulatory contexts, while fostering mutual learning and exchange across regions.

Scope of this handbook

The goal of this handbook is to document, structure and present the pilot actions and solutions developed within CE4CE. It focuses on how circular economy principles have been tested in practice and how the resulting solutions can support uptake by public transport organisations.

The handbook is intended as a practical reference document for public transport authorities, operators, policymakers and other stakeholders interested in implementing circular economy approaches. It provides structured descriptions of pilots and solutions, highlights lessons learned and supports transferability and replication in other contexts.

2. CE4CE Structure of Pilots and Solutions

Within CE4CE, pilot actions and solutions are organised and presented according to **three thematic activity clusters** defined within the project. These activity clusters reflect distinct circular economy challenge areas in public transport and provide the common framework within which project outputs were developed.

Each activity cluster comprises both **pilot actions and its corresponding solutions**. Pilot actions are implemented as practical interventions under real operating conditions and serve to test approaches, generate empirical evidence and identify technical, organisational and market-related challenges. Based on the experience, results and insights generated through pilot implementation and joint development processes, **each pilot is directly linked to one corresponding solution**, which consolidates the pilot findings into a transferable and uptake-oriented output.

The four thematic areas covered in this handbook are:

- **A.1: Development of the CE4CE Circularity Compass and Knowledge Platform for public transport**, including a structured circularity assessment framework, a web-based knowledge platform and an online second-hand and match-making market supporting collaboration and information sharing across public transport life-cycle actors.

- **A.2: Development of joint digital solutions to enable and accelerate circularity in public transport**, including a common analytical framework and pilots on predictive maintenance and e-corridor simulation.

- **A.3: Development of solutions to preserve value and reduce waste of public transport infrastructure**, addressing reuse of infrastructure components and second-life applications of energy-related assets.

- **A.4: Facilitation of the take-up of solutions to preserve value and reduce waste of vehicles and rolling stock**, focusing on remanufacturing, reuse and market-oriented mechanisms.

The activity-based structure allows readers to easily navigate between pilot actions and solutions within the same thematic area and supports a clear understanding of how CE4CE outputs contribute to the implementation of circular economy principles across different segments of public transport systems.

2.1. Linking CE4CE activities to the AETE life-cycle framework

The CE4CE activities and their associated pilot actions and solutions are aligned with the **AVOID-EXTEND-TRANSFORM-ENABLE (AETE)** life-cycle framework for circular economy adoption in public transport. This framework supports the systematic identification of where and how circular value can be created or preserved across different life-cycle stages of public transport assets.

Each CE4CE activity primarily addresses specific **AETE action fields**, while also contributing to enabling conditions across the system. The pilots implemented under each activity therefore operationalise circular economy principles by targeting concrete life-cycle stages such as use, maintenance, reuse, refurbishment or repurposing.

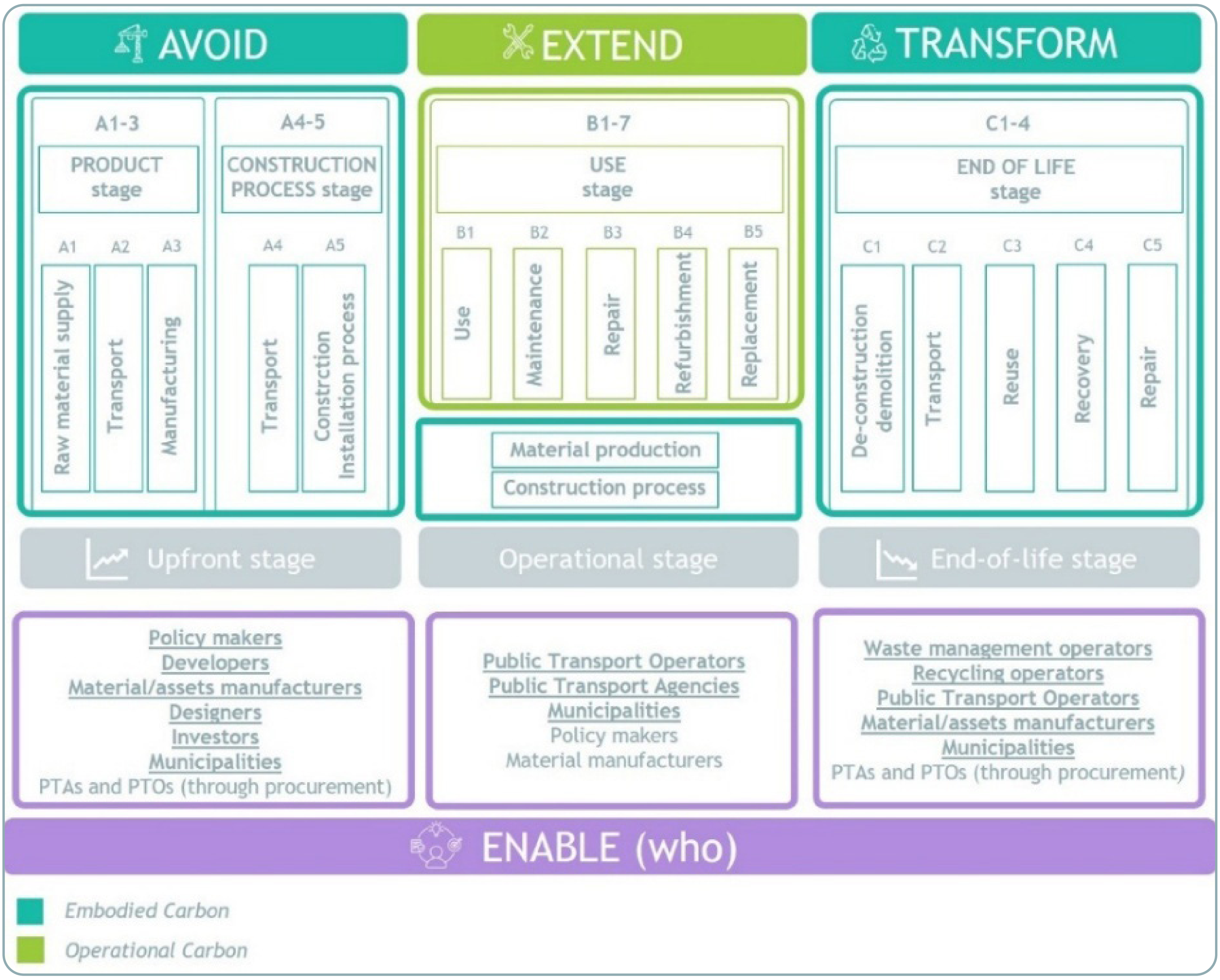


Figure 3: Adapted PTI Life-cycle-based on EN15978 version

A.1: Developing the CE4CE Circularity Compass and Knowledge Platform for Public Transport

This activity primarily addresses the ENABLE dimension of the AETE framework. By developing and testing the CE4CE Circularity Compass and the associated Knowledge Platform, it establishes the systemic and organisational preconditions necessary for circular economy uptake in public transport.

The Circularity Compass pilot supports **ENABLE** by providing a structured **assessment methodology** to identify circularity gaps and design new life-cycle value chains. It facilitates strategic reflection, stakeholder engagement and informed decision-making.

The Knowledge Platform and the online second-hand and match-making market further strengthen ENABLE conditions by promoting knowledge exchange, information sharing and collaboration between life-cycle actors. At the same time, the matchmaking platform indirectly supports **EXTEND – reuse and remanufacturing** by enabling market mechanisms for second-life components and refurbished assets.

This activity therefore provides the horizontal foundation upon which the more technically oriented pilot actions and solutions are built.

A.2: Digital solutions to enable and accelerate circularity in public transport

This activity primarily addresses the **ENABLE** dimension of the AETE framework. Through digital tools for predictive maintenance, simulation and business planning, it creates the conditions required to support AVOID and EXTEND actions across infrastructure and rolling stock life cycles. Predictive maintenance pilots contribute in particular to the **EXTEND – maintenance and repair** stages by enabling early intervention, reducing failures and extending asset lifetimes. Simulation of e-corridors and energy flows supports **AVOID** by informing better planning decisions and avoiding over-dimensioning of assets.

A.3: Solutions to preserve value and reduce waste of public transport infrastructure

This activity is mainly positioned within the **EXTEND** and **TRANSFORM** dimensions of the AETE framework. Pilots focusing on the re-use of trolleybus switches directly address **EXTEND – reuse**, preserving embedded material and energy by keeping infrastructure components in service beyond their first use phase. The pilot implemented in Maribor, analysing the application of used batteries for powering fast chargers, addresses **EXTEND – repurposing**, as batteries are reassigned from their original traction function to a new use as stationary energy storage. At the same time, this activity contributes to **TRANSFORM**, as it prepares the ground for new life-cycle value chains and end-of-first-life management strategies.

A.4: Facilitation of the take-up of solutions to preserve value and reduce waste of vehicles and rolling stock

This activity primarily addresses **EXTEND – refurbishment and reuse**, as well as **ENABLE**. The pilot on tram control unit remanufacturing focuses on extending the functional life of vehicle components through redesign and refurbishment. The associated solution, an online second-hand and match-making platform, strengthens **ENABLE** conditions by supporting information sharing, market creation and collaboration between life-cycle actors, which are prerequisites for scalable reuse and remanufacturing practices.

Overall, the CE4CE activities demonstrate how different **AETE action fields are addressed in a complementary manner** across public transport systems. While individual pilots may focus on specific stages such as maintenance, reuse or repurposing, their combined effect contributes to a systemic transition from linear asset management towards circular, life-cycle-oriented public transport systems.

An overview of the thematic activity clusters and the corresponding pilot-solution pairs are provided in Table 1, which summarises the relationships between pilot actions, solutions and the partners involved.

Activity	Pilot	Solution	Solution trpe	Primary AETE action
A.1 Development the CE4CE Circularity Compass and Knowledge Platform for Public Transport	P.1 Circularity compass for public transport - assessing circularity gaps and designing new value chains to increasing resource efficiency	S.1 CE4CE Circular Public Trans-port Knowledge Platform	Digital platform / knowledge hub	ENABLE - System knowledge & collaboration
		S.2 Online second-hand and match-making market for used parts, products and information-sharing	Digital marketplace / matchmaking tool	EXTEND - Reuse / Remanufacturing enablement
A.2 Development of joint digital solutions to enable and accelerate circularity in public transport	P.2 & P.3 Digital infrastructure and vehicle optimisation through predictive maintenance	S.3 Modules for predictive maintenance of infrastructure and rolling stock	Monitoring system / digital solution	EXTEND - Maintenance / Repair
	P.4 Simulation of an e-corridor and energy flows to simulate circular scenarios for electrification upscaling (bus lane, electric supply and in-motion charging)	S.4 Circular business planning tool for electrified public transport fleets and infrastructure	Planning tool / decision-support tool	AVOID - Upfront planning / system optimisation
A.3 Development of solutions to preserve value and reduce waste of public transport infrastructure	P.5 Demonstrate the feasibility to re-use trolleybus switches	S.5 Definition of uptake criteria to re-use trolleybus switches	Methodology / decision framework	EXTEND - Reuse
	P.6 Analysis of used battery applications to store renewable energy for powering a fast charger as an example for strategic orientation towards circularity	S.6 Transferable business models for second-life use of traction batteries as stationary storage	Business model / implementation framework	EXTEND - Repurpose
A.4 Facilitation of take-up of solutions to preserve value and reduce waste of vehicles and rolling stock	P.7 Design for tram control units within tram remanufacturing	Promotion and scaling supported through S.2 Online second-hand and match-making market		EXTEND - Refurbishment / Remanufacturing

Table 1: Overwiev od CE4CE pilots and corresponding solutions by activity.

3. CE4CE Pilots and Solutions

Pilot actions constitute a core implementation element of the CE4CE project. They translate circular economy concepts, methods and tools into concrete applications under real operating conditions, enabling public transport authorities, operators and other stakeholders to test approaches, assess feasibility and generate practical experience.

The pilots implemented within CE4CE serve multiple purposes. They provide empirical evidence on the technical, organisational and economic implications of circular economy practices, support learning across partners, and reduce uncertainties related to implementation and uptake. At the same time, pilot actions act as a bridge between strategic objectives and solution development, generating the insights and data required to consolidate pilot experience into transferable and scalable solutions.

Within CE4CE, pilot actions focus on a set of defined **pilot focus topics**, reflecting the main circular economy leverage points addressed by the project across public transport infrastructure and rolling stock life cycles:

- Circularity assessment and design of new life-cycle value chains
- Predictive maintenance of public transport infrastructure and rolling stock
- Digital simulation of electrified public transport corridors and energy flows
- Re-use of public transport infrastructure components
- Second-life use of traction batteries as stationary energy storage
- Remanufacturing and reuse of rolling stock components

These focus topics are addressed through **seven pilot actions**, implemented by public transport authorities and operators in different Central European cities:

- A pilot on the **Circularity Compass for public transport**, coordinated by the trolley:motion association (with support from Rupprecht Consult), developed and tested a structured assessment tool to identify circularity gaps and design new value chains to increase resource efficiency. The pilot included the development of a web-based interface and practical application within the project partnership.
- In **Leipzig**, Germany, the local public transport operator LVB implemented a pilot on **predictive maintenance**, applying digital condition monitoring to selected infrastructure and rolling stock assets to test data-driven maintenance approaches and support life-time extension.
- In **Bergamo**, Italy, a similar **predictive maintenance pilot** was implemented by ATB in a different operational context, allowing comparison of methodologies, data requirements and organisational conditions across networks.
- In **Gdynia**, Poland, public transport operator PKA implemented a pilot on **simulation of electrified public transport corridors** to analyse energy flows and assess circular electrification scenarios, including in-motion charging and bus lane electrification.
- In **Szeged**, Hungary, public transport operator SZKT implemented a pilot demonstrating the **re-use of trolleybus switches**, focusing on extending the service life of heavily used infrastructure components and reducing material waste.
- In **Maribor**, Slovenia, Municipality of Maribor - MOM analysed the **second-life use of traction batteries** as stationary energy storage to support renewable-powered fast charging infrastructure, exploring technical feasibility and integration aspects.
- In **Szeged**, SZKT also implemented an additional pilot addressed the **remanufacturing and redesign of tram control units**, aiming to extend component lifetimes and enable reuse through adapted design and information-sharing.

While pilot actions focus on testing and validating approaches in real operational environments, solutions represent consolidated, uptake-oriented outputs developed based on pilot implementation and joint analytical work

Solutions translate pilot experience into **structured tools, methodologies, criteria and business models** that can be transferred, replicated and scaled in other public transport contexts. Each solution is linked to one or more pilot actions within the same thematic activity area and builds on empirical evidence, stakeholder feedback and iterative refinement processes.

For each activity area, pilot actions are described together with their corresponding solutions, highlighting the pathway from testing and validation to consolidation and transfer.

3.1. Activity A.1: Development of the CE4CE Circularity Compass and Knowledge Platform for Public Transport

Although this activity does not formally belong to the work package *"Demonstrate how public transport can become circular"*, the Circularity Compass was implemented and validated through a pilot-like testing process. The tool was developed and subsequently tested with public transport stakeholders through workshops, surveys and validation exercises involving operators, authorities, researchers and industry representatives. These activities allowed practical verification of the methodology and refinement of the tool based on real operational feedback. The Circularity Compass therefore represents a technical pilot and solution supporting the transition towards circular public transport systems, even though organisationally it is located in the project's methodological work package rather than the demonstration work package.

3.1.1. Pilot P.1: Circularity Compass for public transport

Short description of the pilot

The Circularity Compass pilot was developed to address a key challenge in the transition towards circular public transport systems: the lack of practical tools that help organisations understand where and how circular economy principles can be integrated into everyday operations and strategic planning.

While circular economy concepts are increasingly discussed in the transport sector, public transport authorities and operators often lack structured approaches for translating these principles into concrete actions. The Circularity Compass therefore aims to provide a practical orientation tool that helps organisations assess their current circularity practices and identify opportunities for improvement across the public transport system.

The objective of the pilot was to develop and validate a methodology that allows public transport stakeholders to evaluate circular economy practices across the life cycle of infrastructure, vehicles and energy systems. Unlike infrastructure or technology pilots implemented within CE4CE, the Circularity Compass represents a knowledge-based solution designed to enable circular transition through better system understanding and decision-making.

The Circularity Compass solution

The Circularity Compass is an online self-assessment tool available through the CE4CE knowledge platform. It provides a structured framework that allows public transport organisations to evaluate circular economy practices across different components of their systems.

The assessment covers four key areas of public transport systems: fleets, including vehicles and batteries; infrastructure; energy systems; and governance, which includes organisational and enabling conditions. By addressing these areas together, the tool reflects the systemic nature of circularity in public transport.

The framework follows the circular lifecycle logic Avoid – Extend – Transform – Enable (AETE). In practice, this means that organisations are guided to reflect on how they can reduce resource consumption through better planning and procurement, extend asset lifetimes through maintenance and refurbishment, transform assets through reuse or repurposing, and establish the organisational conditions needed to support circular implementation.

At the core of the tool is a structured self-assessment survey covering key lifecycle stages, from manufacturing and procurement to operation, maintenance and end-of-life management. The results provide a clear overview of current circularity practices and highlight areas where organisations can further develop circular strategies and solutions.

10 R-principles for circular public transport systems

Figure 4: Adaptation of the 10R circular economy principles for public transport systems.

Resources needed

The implementation of the Circularity Compass primarily requires organisational and analytical resources. It relies on stakeholder involvement, expert facilitation and access to operational knowledge within public transport organisations.

The testing phase was carried out through workshops, expert consultations and self-assessment surveys involving public transport operators, authorities and researchers. This collaborative process ensured that the tool reflects real operational conditions and is applicable across different organisational contexts.

Expected results/benefits

The Circularity Compass enables public transport organisations to identify circularity gaps, assess their readiness for circular economy adoption and explore potential improvement areas across the public transport lifecycle.

By structuring complex information into a clear assessment framework, the tool supports awareness raising and strategic planning. It helps organisations better understand how circular economy principles can be applied in practice, particularly in areas such as infrastructure management, fleet operations and energy systems.

Figure 5: The CE4CE Circularity Compass online self-assessment tool interface.

Scalability and future development potential

The Circularity Compass provides a scalable framework supporting the transition towards circular economy practices in the public transport sector. As an awareness and self-assessment tool, it helps organisations identify circularity gaps and prioritise actions related to infrastructure, fleets and energy systems.

The results of the assessment can serve as a starting point for more detailed analyses, such as lifecycle assessments, circular procurement strategies or resource efficiency planning. At the same time, the further development and practical relevance of the tool depend strongly on the active involvement of stakeholders and the continuous contribution of sector knowledge and experience.

With sustained stakeholder input, the Circularity Compass can evolve into a broader knowledge and benchmarking platform supporting circular transition in public transport systems.

3.1.2. Solution S.1: Circular Public Transport Knowledge Platform

Short description of the solution

The CE4CE Knowledge Platform is an online knowledge hub designed to support the transition towards circular economy practices in the public transport sector. It provides a structured digital environment where public transport stakeholders can access tools, best practices, methodologies and learning materials related to circularity in transport systems.

The platform addresses a key challenge identified during the project: knowledge related to circular public transport solutions is often fragmented and difficult for practitioners to access. By centralising relevant resources and linking them with practical project results, the platform supports capacity building, knowledge exchange and the wider uptake of circular solutions.

The platform is publicly accessible at: https://circularity4publictransport.eu/

Solution objectives

The main objective of the CE4CE Knowledge Platform is to strengthen the capacity of public transport stakeholders to implement circular economy principles. In practice, the platform acts as a centralised entry point where users can access circular economy tools and resources, explore practical examples and tested solutions, and better understand how to address identified circularity gaps. It supports knowledge transfer across the sector while helping organisations navigate available approaches and implementation pathways.

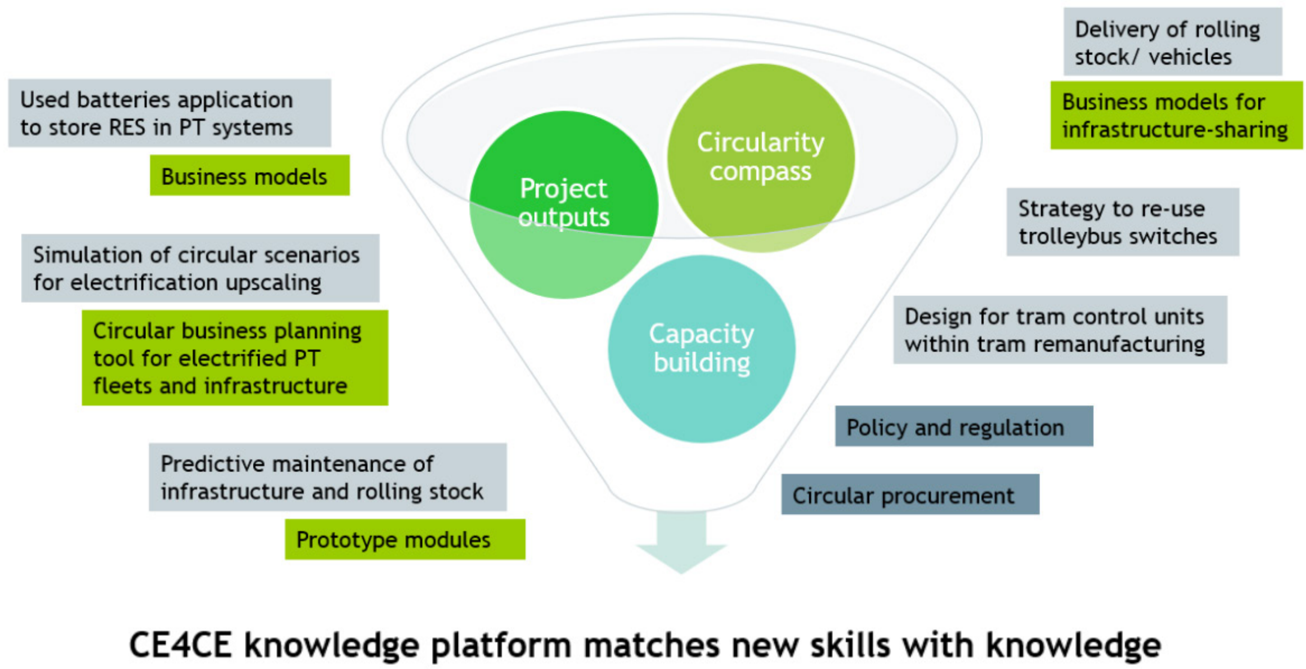


Figure 6: Conceptual structure of the CE4CE Knowledge Platform connecting circular solutions, tools and capacity building.

Core concept of the solution

The CE4CE Knowledge Platform was developed in parallel with the **Circularity Compass**, which acts as a self-assessment tool for evaluating circular economy practices in public transport organisations.

The two solutions are conceptually linked:

- the **Circularity Compass** enables organisations to assess their circularity performance and identify improvement areas
- the **Knowledge Platform** provides the resources, tools and examples that help address the identified gaps

In this way, the platform connects **assessment results with practical implementation support**.

The concept of the platform is based on the **10R principles of the circular economy**, adapted to the public transport context. These principles guide the organisation of knowledge resources across key public transport system components such as infrastructure, vehicles, energy systems and governance.

The Knowledge Platform is structured into five main components:

1. **Competence Map** – identifies the key skills and knowledge required for implementing circular economy principles in public transport.
2. **Circularity Compass** - an online self-assessment survey allowing organisations to evaluate their circularity status.
3. **Best Practices** – a collection of case studies demonstrating circular solutions in the sector.
4. **Knowledge Hub** – a repository of tools, guidelines, reports and methodologies supporting circular planning, operation and maintenance.
5. **Matchmaking Forum** – a planned digital marketplace enabling exchange of spare parts and equipment between public transport organisations.

Through this structure, the platform connects **circularity assessment, knowledge resources and practical solutions**, creating a comprehensive support environment for organisations implementing circular public transport systems.

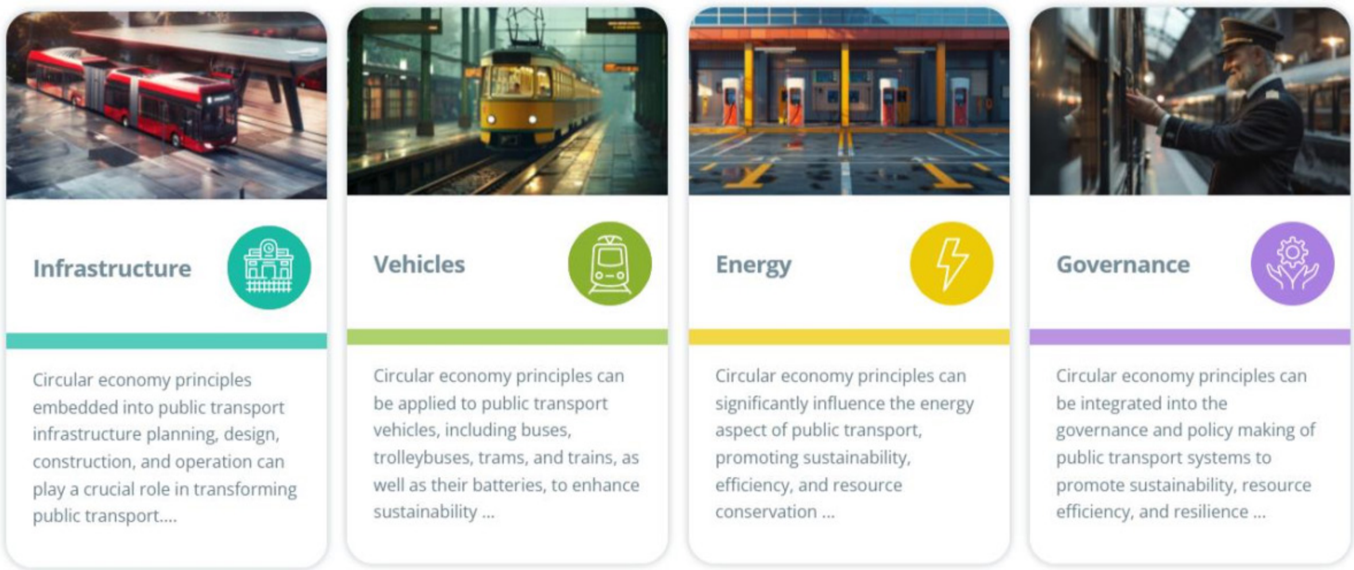


Figure 7: Main competence areas of the CE4CE Knowledge Platform: infrastructure, vehicles, energy and go-

Conclusion of the solution

The CE4CE Knowledge Platform provides a structured and scalable environment supporting the transition towards circular public transport systems. By linking assessment (Circularity Compass), knowledge resources and practical solutions, it enables stakeholders to move from awareness to implementation. Its long-term value depends on continuous content development, stakeholder engagement and integration with sector initiatives, allowing it to evolve into a central reference point for circular economy practices in public transport.

3.1.3. Solution S.2: Online Second-hand and Match-making Market

Short description of the solution

The solution introduces a digital matchmaking platform that enables public transport stakeholders to exchange information on used vehicles, spare parts and infrastructure components, supporting their reuse and remanufacturing.

Developed as a functional module of the CE4CE Knowledge Platform, the solution complements its knowledge and capacity-building role by providing a practical tool for identifying and realising circular use cases. It addresses the lack of structured exchange mechanisms in the sector, where reuse opportunities are often missed due to limited visibility and fragmented communication.

The matchmaking forum is publicly accessible at:

https://circularity4publictransport.eu/matchmaking-forum/

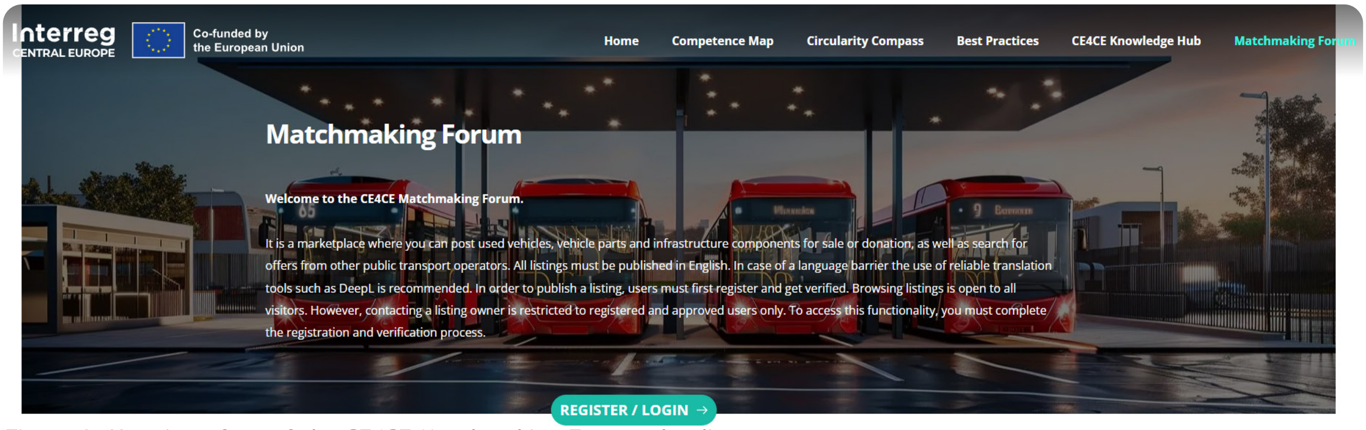


Figure 8: User interface of the CE4CE Matchmaking Forum - landing page.

Solution objectives

The main objective of the solution is to enable structured exchange of used assets across the public transport sector and increase the visibility of reusable components.

By improving information flow and supporting connections between operators, authorities and suppliers, the platform contributes to reuse and remanufacturing practices, reduces premature disposal of assets and strengthens collaboration within the sector.

Core concept of the solution

The solution is based on a **digital matchmaking forum** that connects supply and demand for used public transport assets. Its functioning follows a simple process:

1. organisations publish offers or requests for vehicles, components or infrastructure elements
2. users search and filter listings based on relevant criteria
3. interested parties establish contact via the platform

The platform acts as an **information-sharing and matchmaking tool**, not a transactional system. By reducing information gaps and increasing transparency, it creates the conditions for reuse and remanufacturing practices to scale within the sector.

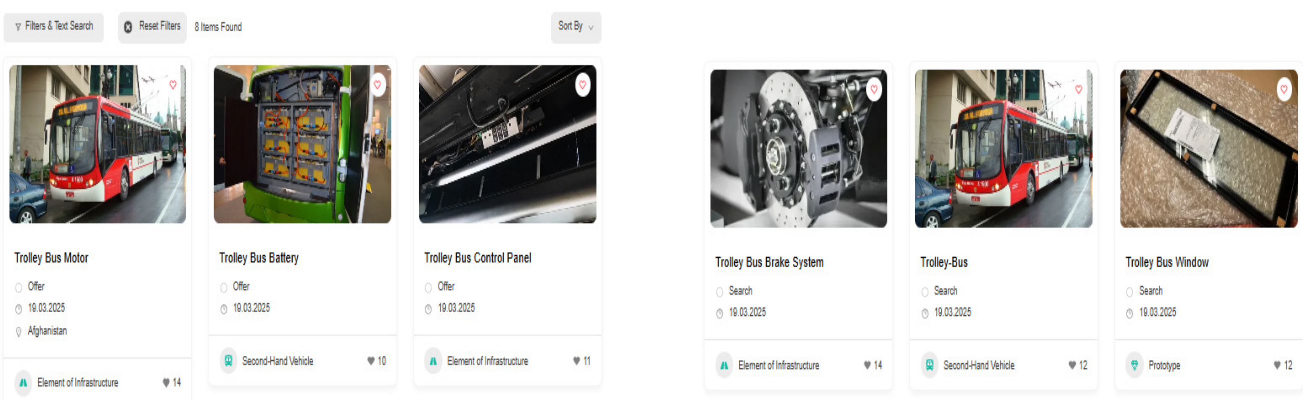


Figure 9: Example listings in the CE4CE Matchmaking Forum for used vehicles, components and infrastructure elements.

Conclusion of the solution

The Matchmaking Forum represents a practical enabling tool that supports circular economy implementation by facilitating reuse and extending the lifecycle of public transport assets. Its effectiveness increases with broader participation, as a higher number of users improves visibility and matching opportunities.

With continued stakeholder engagement and further development of functionalities, the platform has the potential to become an important mechanism for supporting circular value chains in public transport.

3.2. Activity A.2: Development of Joint Digital Solutions to Enable and Accelerate Circularity in Public Transport

This activity focuses on the application of digital tools to support circular and resource-efficient management of public transport infrastructure and rolling stock. It explores how data-driven monitoring and simulation can improve maintenance practices, infrastructure planning and operational efficiency across the system life cycle.

Three pilots were implemented under this activity in Leipzig, Bergamo and Gdynia. The pilots in Leipzig and Bergamo test predictive maintenance through digital condition monitoring, while the Gdynia pilot applies digital twin modelling and energy flow simulation to support planning of electrified public transport corridors.

The results and experience from these pilots form the basis for the development of a joint solution providing modular digital tools for predictive maintenance and circular planning of public transport systems, presented in the following section.

3.2.1. Pilot P.2: Digital Infrastructure and Vehicle Optimisation through Predictive Maintenance (Leipzig, Germany)

Short description of the pilot

This pilot focuses on the implementation of predictive maintenance approaches for public transport infrastructure and rolling stock through the use of digital condition monitoring. Implemented by Leipziger Verkehrsbetriebe (LVB) in Leipzig, the pilot aims to shift from reactive and time-based maintenance towards data-driven, predictive maintenance to extend asset lifetimes, reduce unplanned failures and minimise resource-intensive interventions.

Three tram vehicles were equipped with sensors, cameras and laser systems to monitor tracks and overhead lines along 14 km of Line 1 during regular operation. The collected data is analysed to detect early signs of wear and enable targeted maintenance actions, while energy consumption monitoring was also explored.

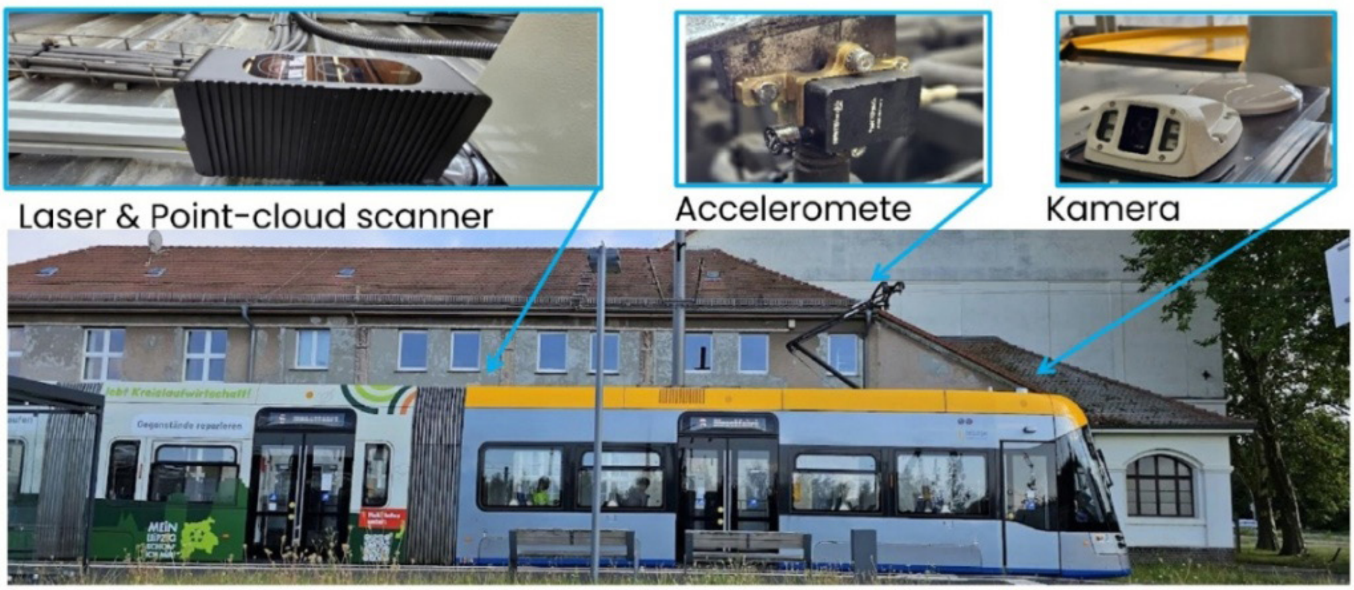


Figure 10: Part of the installed vibration monitoring system on the trams (PantoHealth)

Resources needed

Implementation required sensor systems, data processing infrastructure and analytical software, combined with coordination between the operator, technology providers and project partners. Additional efforts included staff training, workflow integration and compliance with railway standards and certification procedures for deployment under real operating conditions.

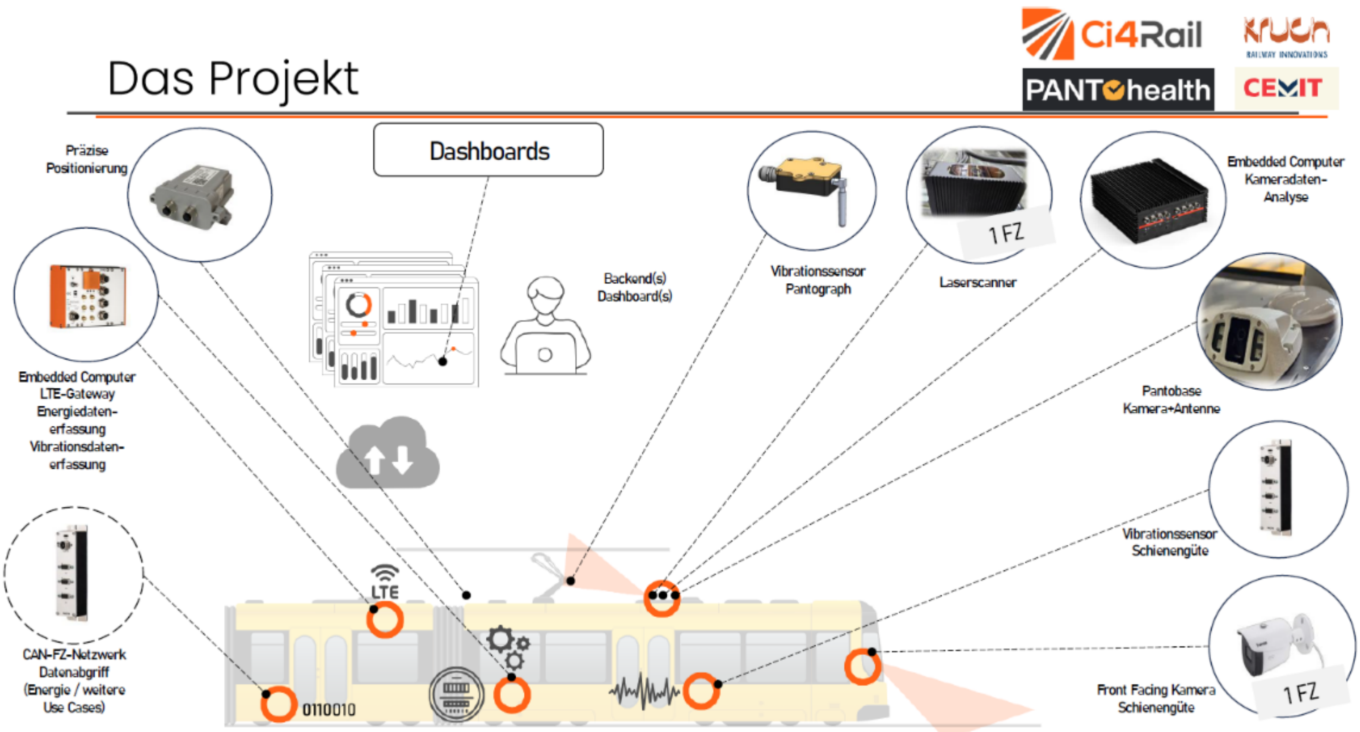


Figure 11: Overview of the predictive maintenance monitoring set-up implemented in the Leipzig pilot

Evidence of success

The pilot confirmed that continuous vehicle-based monitoring is feasible and effective under real operating conditions (June 2024 – February 2025), enabling early detection of infrastructure defects.

Eight critical overhead line points were identified, including two adjusted section insulators, while eight track fault areas were detected, including three previously undetected broken rails; ten locations were inspected and corrective actions implemented.

The results led to updates of maintenance plans in sections with accelerated deterioration and improved data reliability through integration of a direct CAN-BUS interface for energy monitoring.

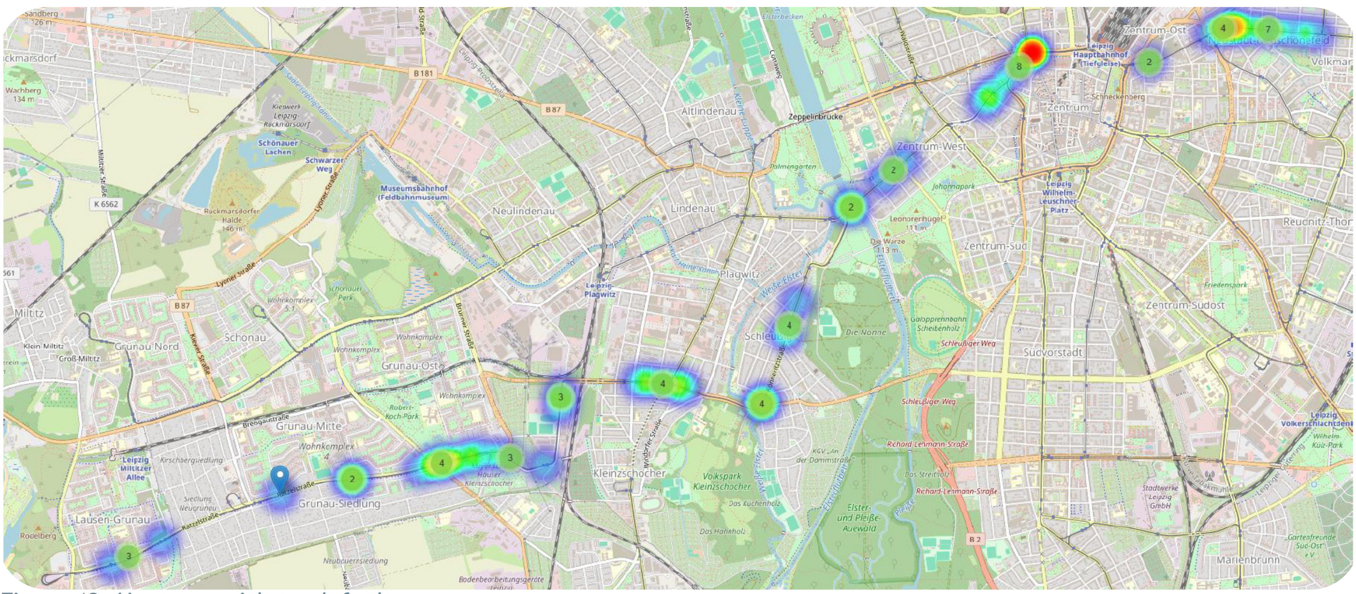


Figure 12: Heatmap with track fault areas.

Challenges encountered

Several challenges were encountered during implementation. These included the integration of new sensor systems into existing vehicles, ensuring data quality and reliability, and addressing limitations of existing energy metering systems. In particular, inaccurate legacy energy data required the identification of alternative data sources and the integration of additional interfaces to access vehicle energy data directly.

Operational challenges related to installation during ongoing service, coordination between multiple service providers and the need to meet strict railway certification requirements were addressed through phased implementation, close coordination and iterative testing.

Potential for learning and transfer

The pilot demonstrates strong transfer potential due to its modular approach and the use of vehicles as monitoring platforms, enabling scalable deployment without dedicated inspection equipment.

Key lessons include the importance of data quality, phased deployment and integration of analytics into maintenance processes. The approach supports circular economy principles by enabling early intervention, extending asset lifetimes and improving resource efficiency.

3.2.2. Pilot P.2: Digital Infrastructure and Vehicle Optimisation through Predictive Maintenance (Bergamo, Italy)

Short description of the pilot

This pilot focuses on predictive maintenance of tram infrastructure and rolling stock through digital condition monitoring and simulation tools. Implemented by Azienda Trasporti Bergamo (ATB) in cooperation with KRUCH Railway Innovations, it aims to improve infrastructure reliability and optimise energy use within the network.

A tram vehicle in daily operation was equipped with a modular sensor system, including GNSS modules, acceleration sensors, cameras, CAN-bus interfaces and onboard edge-computing devices. The system enables continuous monitoring of pantograph-overhead line interaction and real-time data collection. In parallel, a digital twin of the tram power supply network was developed to simulate energy flows and analyse different operational scenarios.

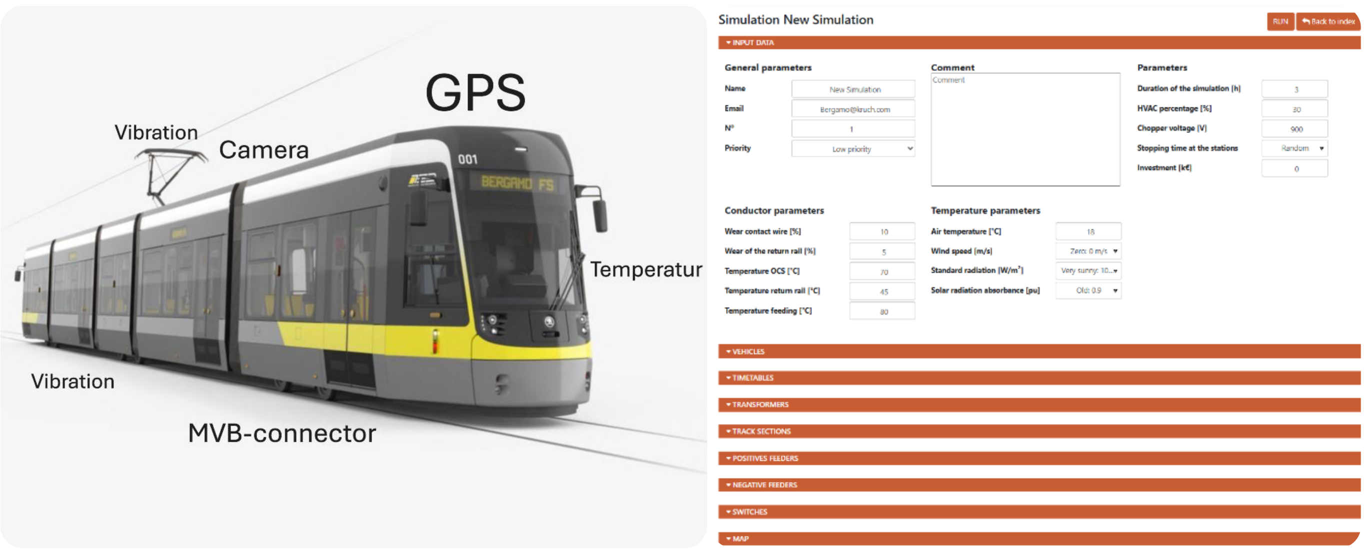


Figure 13: Sensor-based monitoring system and digital simulation tool used in the Bergamo predictive maintenance pilot.

Resources needed

Implementation required modular sensor systems, onboard computing units, communication infrastructure and data analysis tools. In addition, a simulation environment based on MATLAB and SIMULINK/SimPowerSystems was developed to model the tram network and its electrical supply system. The pilot also required coordination between ATB, KRUCH and other stakeholders, including system calibration, staff training and integration into maintenance and asset management processes.

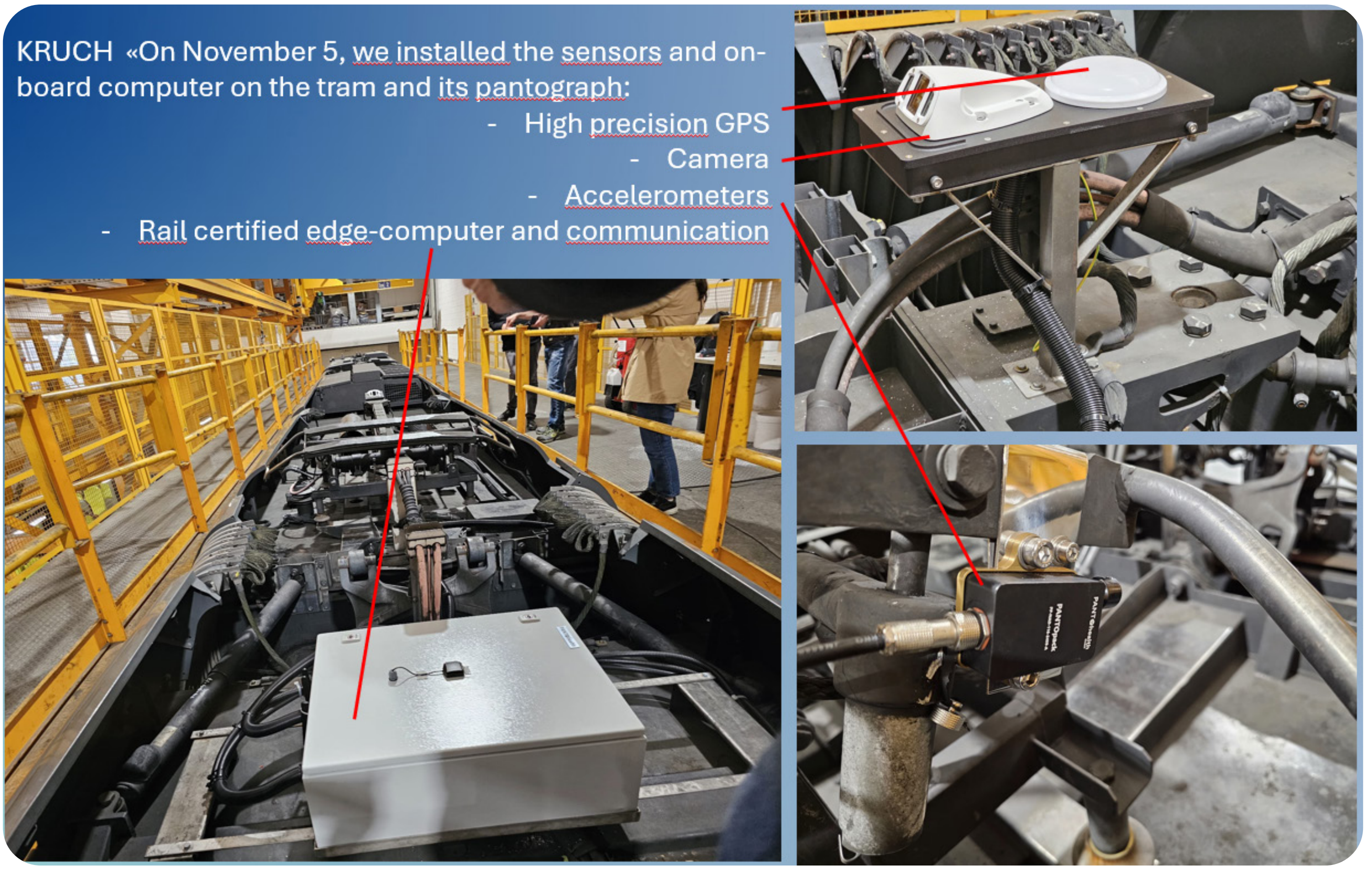


Figure 14: Sensor system installed on the tram pantograph for monitoring the interaction between vehicle and overhead contact line.

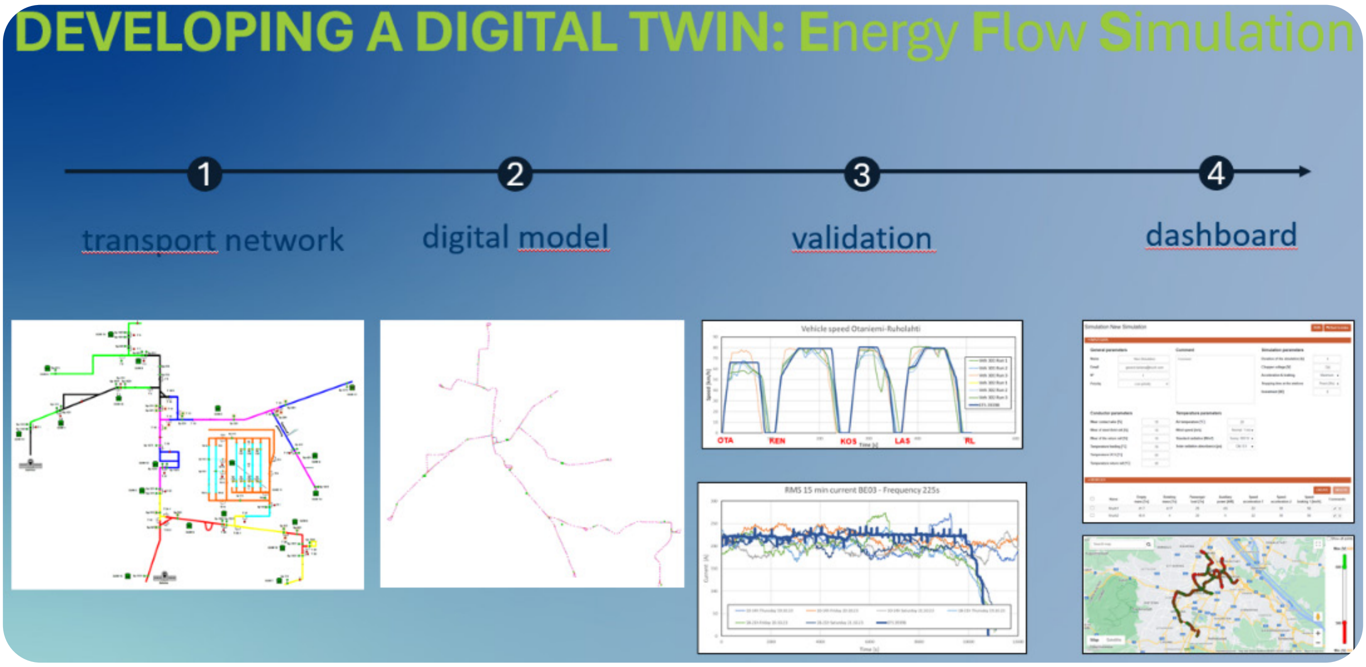


Figure 15: Digital twin modelling and energy flow simulation used to analyse operational and energy scenarios in the Bergamo tram network.

Evidence of success

The pilot confirmed that combining real-time monitoring with simulation supports predictive maintenance and energy optimisation. The monitoring system was installed on tram vehicle #004 operating on the T1 line, enabling continuous data collection every 1-3 seconds, including position, speed and energy consumption parameters.

The system detected irregular pantograph-overhead line interactions and identified locations with increased wear risk. In parallel, a digital twin of the tram network was developed and used to simulate multiple operational scenarios, analysing energy consumption, recuperation potential and system performance.

Overall, the pilot demonstrated that integrating monitoring data with simulation tools improves decision-making and supports more efficient infrastructure and energy management.

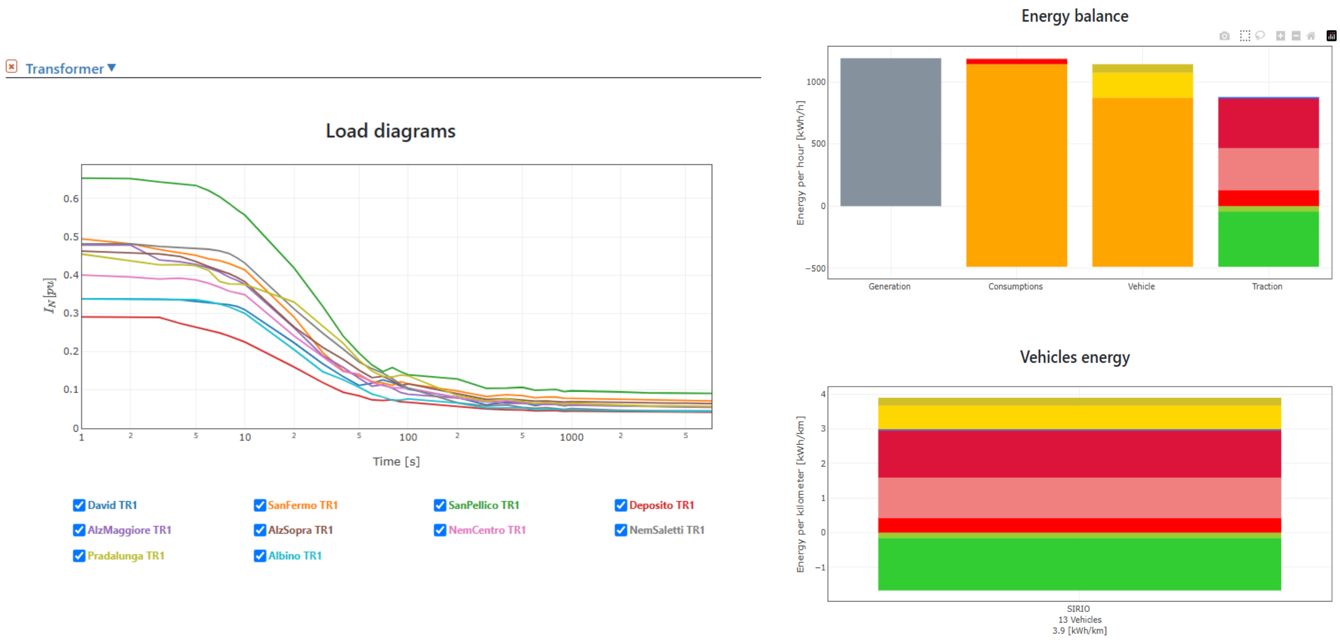


Figure 16: Energy flow simulation results used to analyse transformer loads and optimise energy consumption in the Bergamo tram system.

Challenges encountered

Challenges included integration of sensor systems into existing vehicles and ensuring reliable data transmission in urban environments. Calibration and configuration adjustments were required to improve sensor accuracy and communication stability.

Additional complexity arose from integrating real-world monitoring data with simulation models, requiring continuous validation and coordination between project partners.

Potential for learning and transfer

The pilot demonstrates strong transfer potential, particularly for small- and medium-sized tram systems. Its modular monitoring setup and separation of data collection, analysis and simulation enable flexible adaptation to different networks.

Key lessons include the importance of pre-testing modular systems, combining monitoring with simulation, and ensuring close cooperation between operators and technology providers. The approach supports circular economy principles by extending asset lifetimes and improving system-level resource efficiency.

3.2.3. Solution S.3: Modules for Predictive Maintenance of Infrastructure and Rolling Stock

Short description of the solution

This solution provides a modular framework for predictive maintenance of public transport infrastructure and rolling stock based on continuous, vehicle-based condition monitoring. It builds on pilot implementations in Leipzig and Bergamo, combining infrastructure monitoring, energy data analysis and simulation into a transferable approach.

The solution supports the transition from reactive and time-based maintenance towards data-driven asset management, enabling earlier detection of defects, more targeted interventions and improved operational reliability.

Solution objectives

The solution aims to enable continuous monitoring of infrastructure and vehicle condition, detect early-stage defects and support timely maintenance interventions.

By improving data availability and decision-making, it contributes to extending asset lifetimes, reducing material-intensive repairs and increasing overall resource efficiency.

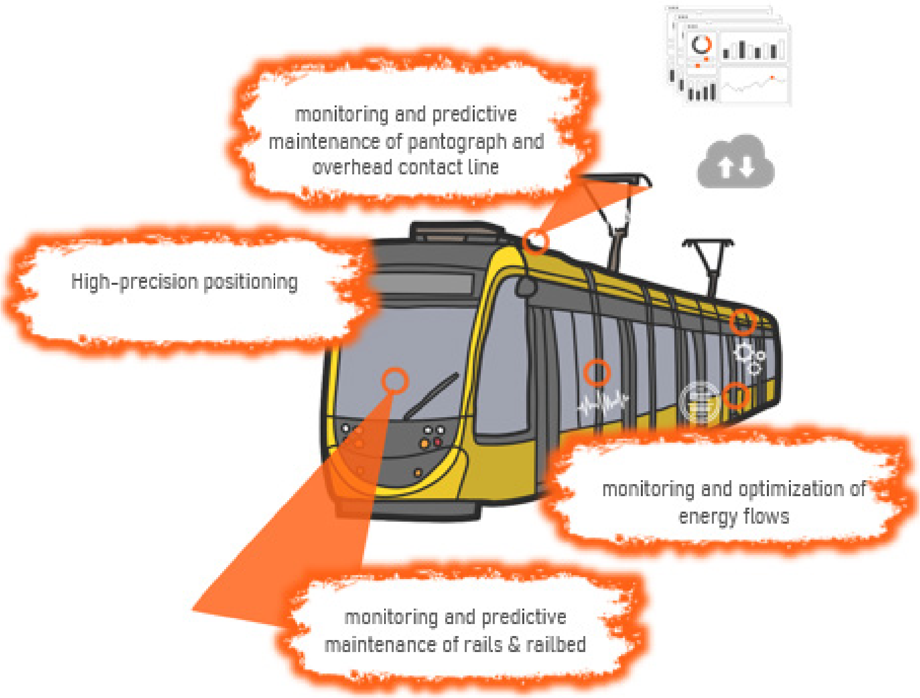


Figure 17: Scope of predictive maintenance applications in public transport systems.

Core concept of the solution

The solution is based on a modular monitoring chain integrating data collection, processing and decision support into existing maintenance workflows. Sensors and monitoring systems installed on vehicles collect data during regular operation, which is processed and analysed to detect anomalies and identify degradation patterns.

The results are integrated into asset management systems through georeferencing and visualised via dashboards, supporting prioritisation of maintenance actions. The system operates as a continuous loop linking detection, validation and intervention, enabling predictive, condition-based maintenance.

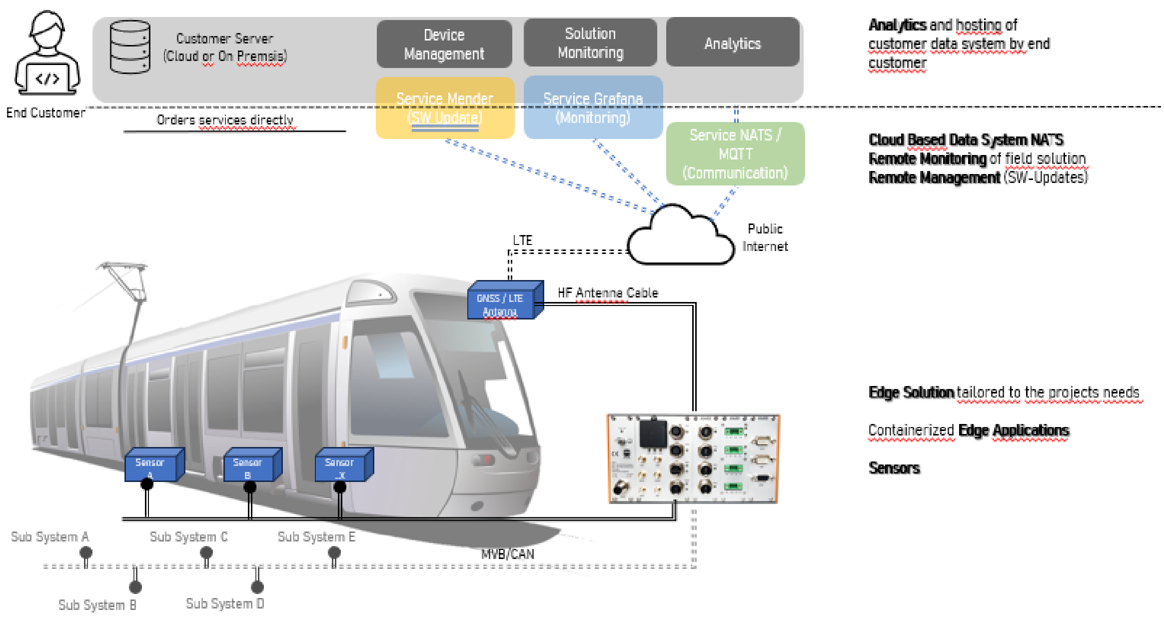


Figure 18: End-to-end architecture of the predictive maintenance system from data acquisition to analytics and monitoring.

Implementation insights

Implementation highlighted that data quality, stable data pipelines and system integration are critical for usable results. Automated detections require validation through field inspections, while modular architecture enables flexible deployment across different systems.

Organisational readiness is also essential, as predictive maintenance introduces new workflows and roles, and its value increases when integrated with existing asset management and planning processes.

Transferability potential

The solution demonstrates strong transfer potential for operators managing rail-based infrastructure and rolling stock. Its modular approach allows gradual implementation and adaptation to different networks, vehicle types and organisational contexts.

By enabling early intervention and lifecycle-oriented asset management, the solution supports circular economy principles, particularly in extending asset lifetimes and improving resource efficiency.

The solution primarily contributes to the **EXTEND - maintenance and repair** stage by enabling early intervention and extending asset lifetimes.

3.2.4. Pilot P.4: Simulation of Electrified Public Transport Corridors and Energy Flows (Gdynia, Poland)

Short description of the pilot

This pilot focuses on the use of digital modelling and simulation tools to support circular and resource-efficient electrification planning in public transport systems. Implemented in Gdynia by the public transport operator PKA Gdynia in cooperation with the University of Gdańsk (UG) and the technology partner Kruch Railway Innovations, it aims to enable data-driven decision-making for infrastructure investments, vehicle technologies and operational strategies.

A digital twin of the Western Corridor was developed using the Energy Flow Simulation (EFS) tool. The model integrates operational data such as fleet characteristics, service frequencies and energy consumption, allowing simulation of different electrification scenarios, including battery electric buses, trolleybuses with in-motion charging (IMC) and hybrid configurations.

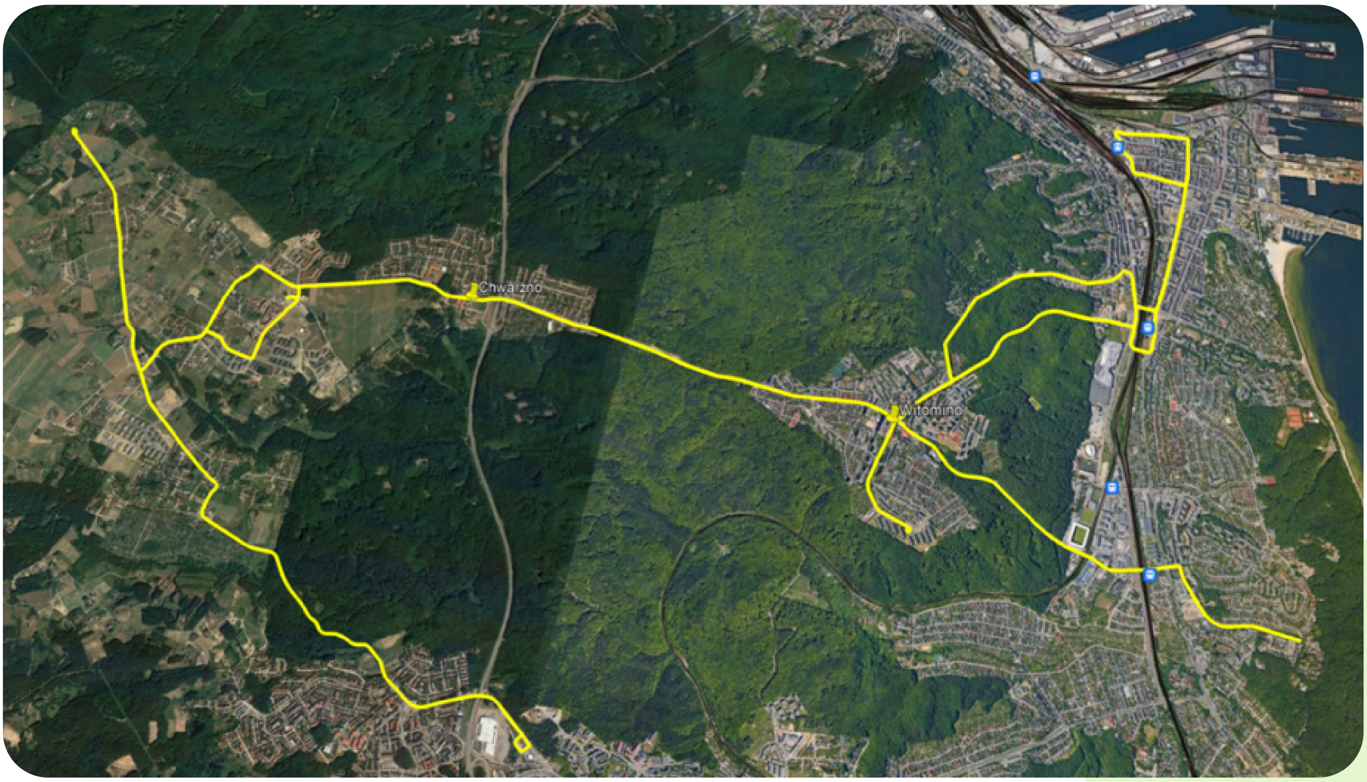
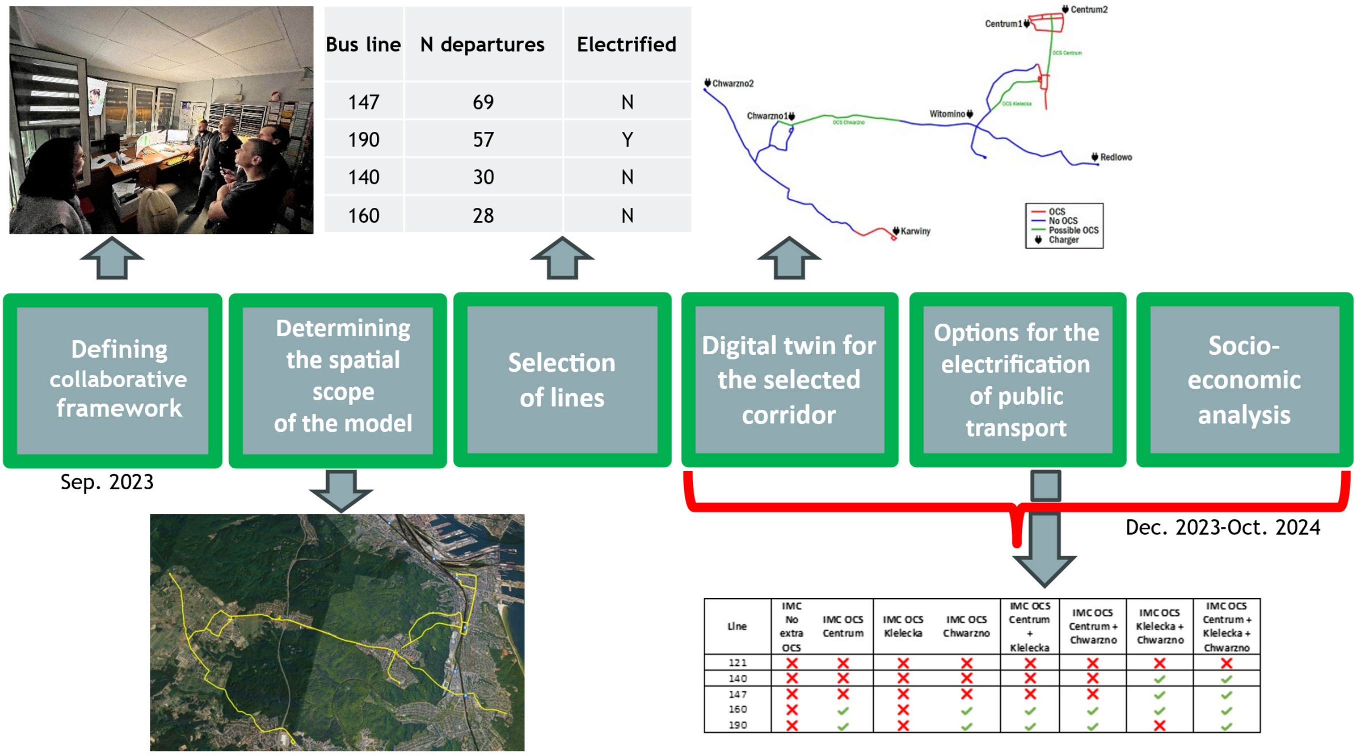


Figure 19: The spatial layout of the Western Corridor in Gdynia.

Resources needed

The pilot required modelling tools, operational data and close cooperation between transport operators, researchers and technology providers. Key resources included the EFS simulation environment and detailed input data such as vehicle schedules, energy consumption parameters and traffic conditions.

Institutional coordination was essential to ensure realistic modelling assumptions and validation of results, including involvement of the operator, municipal authorities and infrastructure stakeholders.



Bus line	N departures	Electrified
147	69	N
190	57	Y
140	30	N
160	28	N

Line	IMC No extra OCS	IMC OCS Centrum	IMC OCS Kielecka	IMC OCS Chwarzno	IMC OCS Centrum + Kielecka	IMC OCS Centrum + Chwarzno	IMC OCS Kielecka + Chwarzno	IMC OCS Centrum + Kielecka + Chwarzno
121	✗	✗	✗	✗	✗	✗	✗	✗
140	✗	✗	✗	✗	✗	✗	✓	✓
147	✗	✗	✗	✗	✗	✗	✓	✓
160	✗	✓	✗	✓	✓	✓	✓	✓
190	✗	✓	✗	✓	✓	✓	✗	✓

Figure 20: Development process of the Energy Flow Simulation (EFS) model for the Gdynia Digital Twin.

Evidence of success

The pilot demonstrated that digital simulation can effectively support electrification planning and infrastructure optimisation. A digital twin of the corridor was successfully developed and validated using real operational data from bus line 190.

More than 110 electrification scenarios were simulated, comparing battery electric buses, IMC trolleybuses and hybrid approaches. The analysis showed that IMC operation requires targeted infrastructure extensions, while certain lines, such as line 190, can operate without additional overhead infrastructure.

The results also highlighted that battery electric bus operation may require a higher number of vehicles compared to IMC solutions, and confirmed that traffic conditions significantly influence energy consumption, vehicle requirements and system costs.

Line	E-bus base	E-bus extra	IMC No extra OCS	IMC OCS Centrum	IMC OCS Kielecka	IMC OCS Chwarzno	IMC OCS Centrum + Kielecka	IMC OCS Centrum + Chwarzno	IMC OCS Kielecka + Chwarzno	IMC OCS Centrum + Kielecka + Chwarzno
121	✓		✗			✓		✓	✓	✓
140	✗	✓ +2	✗	✗	✗	✓	✓	✓	✓	✓
147	✗	✓ +3	✗	✓	✓	✓	✓	✓	✓	✓
160	✗	✓ +2	✗	✓	✓	✓	✓	✓	✓	✓
190 Loop	✗	✓ +3	✓	✓			✓	✓		✓
Total vehicles	26	36	26	26	26	26	26	26	26	26
Total chargers	7	7								
Extra Substations				1	1	2	2	3	3	4
Extra OCS km				1,51	1,54	3,12	3,05	4,63	4,66	6,17

Figure 21: Example of simulation results comparing different electrification scenarios, showing vehicle energy balance and

Line	Vehicles	IMC without OCS		IMC with extra OCS in Centrum		IMC with extra OCS in Chwarzno		IMC with extra OCS in Kielecka		IMC with extra OCS in Centrum and Chwarzno		IMC with extra OCS in Centrum and Kielecka		IMC with extra OCS in Chwarzno and Kielecka	
		SOC [%]	Battery [h]	SOC [%]	Battery [h]	SOC [%]	Battery [h]	SOC [%]	Battery [h]	SOC [%]	Battery [h]	SOC [%]	Battery [h]	SOC [%]	Battery [h]
121	3	20	1,4	20	1,4	49	>10	20	1,4	48,9	>10	20	1,4	49,1	>10
140	7	20	1	20	1	59,4	>10	20	2,7	59,8	>10	24,2	>10	64,2	>10
147	7	20	4	31,6	>10	66,4	>10	40,9	>10	68,8	>10	41,5	>10	71,1	>10
160	3	20	2	41	>10	67	>10	52	>10	68,8	>10	51,9	>10	78,8	>10
190Loop	6	54	>10	60,1	>10	54,7	>10	55,1	>10	60,3	>10	60,3	>10	56,1	>10

Figure 22: Comparison of electrification scenarios showing operational feasibility of different vehicle technologies and infrastructure configurations.state-of-charge feasibility after 10 hours of operation.

Challenges encountered

Challenges mainly related to data integration and modelling. Operational data from different sources (traffic, operations and energy) required harmonisation, which initially slowed the modelling process.

Further complexity arose in modelling battery degradation and lifecycle performance, as well as in accurately representing traffic conditions, which required iterative calibration of the model and inclusion of elements such as traffic signals.

These challenges were addressed through iterative model refinement and validation using real-world data.

Potential for learning and transfer

The pilot demonstrates strong transfer potential for cities planning electrification of public transport systems. The digital twin approach allows comparison of multiple scenarios before committing to infrastructure investments, supporting more efficient and informed decision-making.

Its modular structure enables adaptation to different urban contexts, provided that sufficient operational data are available. The approach supports circular planning by optimising resource use, reducing unnecessary investments and improving system-level efficiency.

3.2.5. Solution S.4: Circular Business Planning Tool for Electrified Public Transport Fleets and Infrastructure

Short description of the solution

This solution provides a structured planning tool supporting public transport operators and authorities in designing and comparing electrification scenarios using circular economy principles. It builds on the Gdynia pilot, where digital twin modelling and energy flow simulations were used to assess different electrification strategies. The solution translates these experiences into a transferable, KPI-based framework that connects circular objectives with practical planning and investment decisions.

Solution objectives

The solution aims to support evidence-based planning of electrified public transport systems and improve consistency in scenario evaluation. By translating circular economy objectives into measurable indicators, it enables comparison of electrification options, improves transparency of assumptions and supports integration of fleet, infrastructure and energy planning.

Core concept of the solution

The solution is based on a KPI-driven planning workflow supported by a structured selection and configuration process. It enables users to define relevant indicators, set targets and compare different electrification scenarios using a consistent framework.

The approach treats fleet, infrastructure and energy systems as an integrated planning domain, linking technical performance, energy use and circularity outcomes to support informed decision-making.

In operation, the tool supports a structured workflow:

selection → configuration → scenario analysis → comparison → decision support

The solution treats fleet, infrastructure and energy systems as a single planning domain, where energy acts as the system backbone influencing performance, costs and circularity outcomes.

Implementation insights

Implementation showed that data availability and quality are critical and often require combining multiple sources. Standardised KPI definitions and clear governance, including ownership and update procedures, are essential for consistent use.

A gradual approach is recommended, starting with a core KPI set and expanding over time, while ensuring alignment with existing planning and reporting processes.

Transferability potential

The solution demonstrates strong transfer potential for public transport operators planning fleet electrification.

It can be applied across different system types and adapted to local conditions, including energy mix, infrastructure constraints and operational requirements.

By supporting consistent scenario comparison and lifecycle-oriented planning, the solution contributes to more efficient resource use and informed investment decisions.

The solution primarily contributes to the **AVOID - upfront planning and system optimisation** stage by enabling more informed and consistent decision-making.

3.3. Activity A.3: Development of Solutions to Preserve Value and Reduce Waste of Public Transport Infrastructure

This activity focuses on extending the lifecycle of public transport infrastructure components and energy-related assets through reuse and repurposing approaches. It addresses circular economy principles at the infrastructure level by exploring how existing components and materials can remain in service beyond their original operational context.

Two pilot actions were implemented within this activity. In Szeged, the pilot examined the feasibility of reusing trolleybus switches to extend the service life of critical infrastructure components and reduce material waste. In Maribor, the pilot analysed the repurposing of second-life traction batteries as stationary energy storage to support electric bus charging infrastructure.

Together, these pilots demonstrate practical approaches to preserving value embedded in public transport infrastructure and related assets, while reducing resource consumption and supporting more circular asset management practices. The experience gained through these pilots forms the basis for the development of transferable solutions presented in the following sections.

3.3.1. Pilot P.5: Re-use of Trolleybus Switches (Szeged, Hungary)

Short description of the pilot

This pilot focuses on the practical application of circular economy principles through the reuse of trolleybus infrastructure components. Implemented by Szeged Transport Company (SZKT), it demonstrates how components that are no longer optimal for high-intensity operation can be reused in parts of the system with lower operational demand.

Within the pilot, four high-speed overhead switches from the operational network, originally installed between 2005 and 2014, were replaced with new equipment and subsequently reused in the depot. This approach extended the service life of existing components while improving reliability in both the network and depot infrastructure.

Figure 23: Trolleybus overhead switch used in the Szeged network.

Resources needed

The pilot required relatively limited technical resources, as the work primarily involved replacement and relocation of existing infrastructure components within the trolleybus system. Implementation relied on internal capacities of SZKT, including infrastructure maintenance teams, traffic operations and logistics units. Coordination was needed to manage installation works and temporary service adjustments, as well as cooperation with local authorities during short road interventions.

Figure 24: Installation of a trolleybus switch by the SZKT maintenance team.

Evidence of success

The pilot successfully demonstrated that reuse of infrastructure components can improve reliability while reducing investment needs. Four new switches were installed in the main network, while four reused switches were deployed in the depot, improving infrastructure performance at eight locations.

The replacement reduced failures in high-frequency sections and eliminated issues with outdated depot switches, while avoiding unnecessary procurement of additional equipment and reducing material waste.

The pilot successfully demonstrated that circular reuse of infrastructure components can improve operational reliability while reducing investment needs. Key results achieved during implementation include:

Challenges encountered

Challenges were mainly related to coordination and integration within the existing infrastructure system. Variations in supporting elements such as masts and foundations required adjustments during installation. Additional effort was needed to organise temporary traffic arrangements and ensure safe integration of reused components into the system.

Potential for learning and transfer

The pilot demonstrates a simple and transferable circular approach applicable to many public transport systems. Infrastructure components removed from high-intensity network sections can often be reused in lower-demand environments such as depots.

By systematically identifying such opportunities, operators can extend asset lifetimes, reduce investment costs and minimise material waste, supporting more efficient and circular infrastructure management.

3.3.2. Solution S.5: Definition of Uptake Criteria for Re-use of Trolleybus Switches

Short description of the solution

This solution provides a transferable framework for the circular reuse of trolleybus overhead switches in public transport systems. It builds on the experience from the Szeged pilot and translates the practical approach into a set of uptake criteria that can be applied by other operators.

The solution introduces a cascade reuse model, where infrastructure components removed from high-intensity network sections are redeployed in locations with lower operational demand, such as depots. This approach extends asset lifetimes, reduces waste and improves cost efficiency in infrastructure renewal.

Solution objectives

The solution aims to support public transport operators in implementing circular infrastructure management practices.

It focuses on extending the operational life of infrastructure components, reducing material consumption, improving investment efficiency and maintaining reliability and safety through structured reuse approaches.

Core concept of the solution

The solution is based on matching infrastructure components to different levels of operational intensity within the network. Components removed from high-frequency network sections may no longer meet strict reliability requirements but can still function effectively in lower-demand environments such as depots. This leads to a two-tier infrastructure approach, distinguishing between high-intensity operational areas and lower-intensity service environments. By aligning component condition with operational requirements, operators can extend asset lifetimes while maintaining system performance.

Implementation insights

Implementation shows that successful reuse depends on proper condition assessment and compatibility with existing infrastructure elements such as masts, wiring and foundations. Effective coordination between maintenance and operations is required during installation, while systematic identification and tracking of reusable components is key to scaling the approach.

Transferability potential

The solution demonstrates strong transfer potential for operators managing trolleybus or tram infrastructure. Similar conditions exist in many systems, where infrastructure operates under different intensity levels across networks and depots.

By integrating operational intensity into asset management, operators can systematically identify reuse opportunities, reduce costs and extend infrastructure lifecycles, supporting circular economy principles.

The solution therefore contributes to the **EXTEND - reuse** stage of the circular economy framework in public transport infrastructure management.

3.3.3. Pilot P.6: Second-life Use of Traction Batteries as Stationary Energy Storage for Renewable-powered Fast Charging (Maribor, Slovenia)

Short description of the pilot

This pilot explores the use of second-life lithium-ion batteries as stationary energy storage to support electric bus charging infrastructure. Implemented by the Municipality of Maribor with support from the University of Maribor, it focuses on improving energy efficiency while extending the lifecycle of traction batteries.

At the Vzpenjača terminal station, a 150 kW fast charger supports electric bus line G6, which operates on a 7.7 km route with frequent short charging events. To optimise energy use, a battery energy storage system (BESS) based on repurposed batteries was integrated into the charging infrastructure, acting as a buffer between the grid, renewable sources and charging demand.

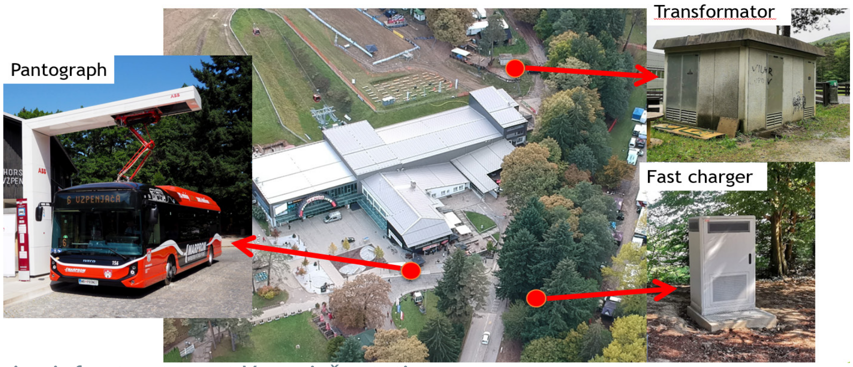


Figure 25: Current charging infrastructure at Vzpenjača station.

Resources needed

The pilot required integration of a second-life battery storage system with a capacity of 136 kWh, combined with an 80 kW hybrid inverter and integration with an existing 150 kW DC fast charger. The system also included monitoring and control components, as well as a small photovoltaic installation. The BESS is connected in a **parallel hybrid configuration**, allowing simultaneous power supply from the grid and the storage system during bus charging events.

Implementation required coordination between municipal authorities, research partners and technical providers, as well as compliance with safety and regulatory requirements for battery systems.

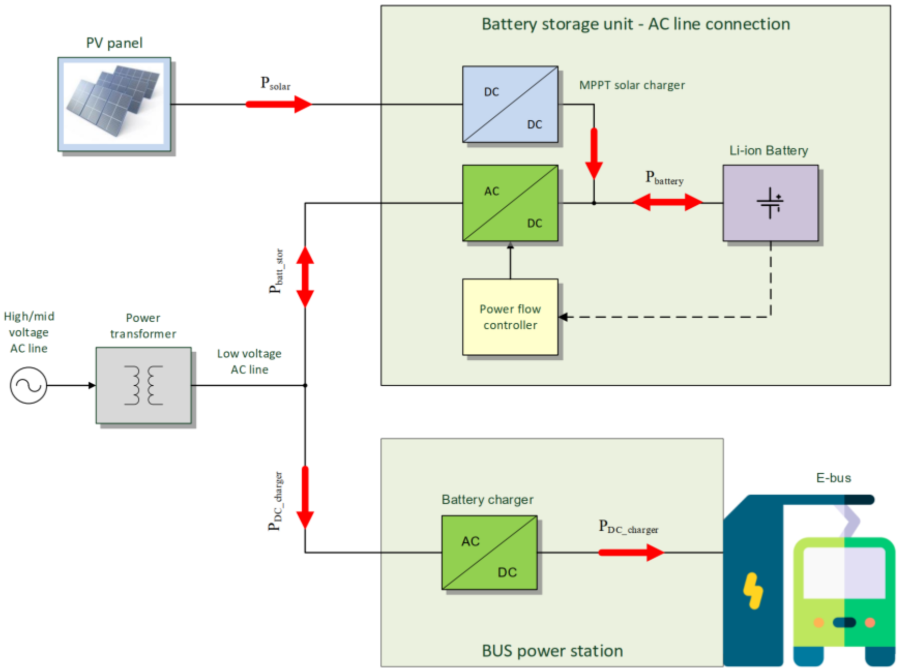


Figure 26: Technical diagram of parallel configuration of BESS integration Source: University of Maribor.

Evidence of success

The pilot confirmed the technical feasibility of integrating second-life batteries into charging infrastructure. The system supports annual charging demand of approximately 145,000 kWh, with daily consumption around 400 kWh and peaks up to 650 kWh, while individual charging sessions last around 5 minutes with 8–14 kWh transferred.

The BESS enabled peak load reduction of around 25 kW and demonstrated hybrid operation between grid and storage. Integration of photovoltaic generation further supported energy flexibility and reduced grid dependency.

Overall, the pilot showed that second-life battery storage can improve energy management and extend battery lifecycles within public transport systems.

Figure 27: Key components of the BESS system: PV panels, inverter and second-life battery pack.

Challenges encountered

Challenges included limited standardisation of second-life battery integration, compatibility between battery modules and inverter systems, and ensuring thermal stability and fire safety.

Additional issues related to sourcing suitable batteries, regulatory requirements and limited market experience were addressed through careful system design and cooperation with specialised experts.

Potential for learning and transfer

The pilot demonstrates strong transfer potential for cities expanding electric bus infrastructure. Second-life battery storage can support peak load management, improve energy flexibility and enable better integration of renewable energy sources.

The modular nature of BESS solutions allows adaptation to different contexts, supporting circular economy principles by extending battery lifecycles and improving resource efficiency.

3.3.4. Solution S.6: Transferable Business Models for Second-life Use of Traction Batteries

Short description of the solution

This solution provides a transferable framework for the use of second-life traction batteries as stationary energy storage in public transport charging infrastructure. It builds on the Maribor pilot and translates its technical and operational experience into business models and implementation conditions that can be applied in other contexts.

The solution supports circular economy principles by extending battery lifecycles before recycling, while also improving energy management, reducing peak electricity demand and supporting integration of renewable energy sources.

Solution objectives

The solution aims to help public transport operators and authorities implement second-life battery storage as part of electrified transport infrastructure.

It focuses on extending battery lifecycles, improving charging flexibility, reducing peak demand, supporting renewable energy integration and creating economically viable approaches for second-life battery applications.

Core concept of the solution

The solution is based on integrating second-life battery energy storage systems between the electricity grid, renewable energy sources and charging demand. In this role, the battery system acts as a flexible energy buffer that supports peak shaving, load shifting and renewable energy use.

Its practical application depends on the alignment of three dimensions: technical integration, energy management strategy and economic and regulatory conditions. Rather than offering a single fixed model, the solution provides a flexible framework that can be adapted to local infrastructure, load profiles and market conditions. While peak shaving alone provides limited benefits, combining storage with tariff optimisation and renewable energy integration significantly improves overall performance.

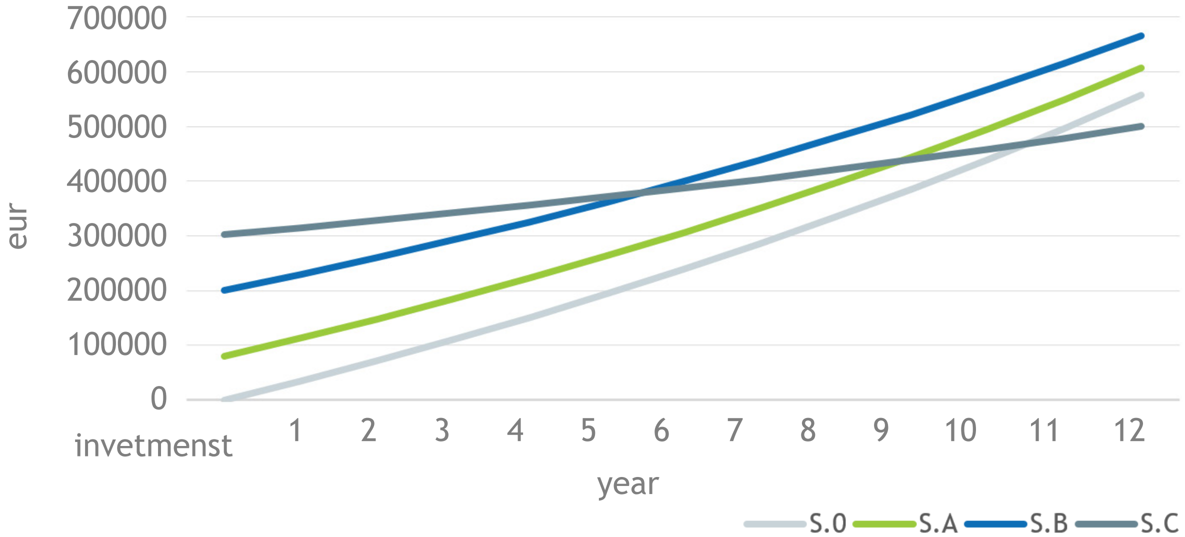


Figure 28: Comparison of cumulative electricity costs across different energy management scenarios.

- S.0: Baseline (no storage): full reliance on grid electricity
- S.1: Peak shaving: reduction of short-term power peaks with limited economic return
- S.2: Tariff optimisation: shifting energy use to lower-cost periods, improving cost efficiency
- S.3: Renewable integration: combining storage with RES to reduce grid dependency and maximise long-term value

Implementation insights

Implementation showed that compatibility between battery modules, inverter systems and charging infrastructure is a key condition for success, while safety requirements and system architecture must be considered from the start.

The business case depends strongly on system size, load profile, electricity tariffs and grid constraints. Peak shaving alone offers limited return at small scale, while combining storage with renewable energy integration significantly improves long-term value.

Transferability potential

The solution demonstrates strong transfer potential for public transport systems undergoing electrification. Many cities face similar challenges related to charging demand, grid constraints and future battery management.

Second-life battery storage offers a practical way to address these issues simultaneously, and can be applied at opportunity charging stations, depots or mobility hubs. In this way, the solution supports both circular economy objectives and more flexible energy management in public transport systems.

The solution primarily contributes to the **EXTEND - repurpose** stage of the circular economy hierarchy by enabling cascading use of traction batteries before their final recycling.

3.4. Activity A.4: Facilitation of Take-up of Solutions to Preserve Value and Reduce Waste of Vehicles and Rolling Stock

This activity focuses on extending the lifetime of rolling stock components through refurbishment, remanufacturing and improved information sharing across the public transport sector.

The pilot implemented in Szeged demonstrates the redesign and remanufacturing of an obsolete tram door control unit, enabling continued operation of ageing Tatra tram vehicles. By replacing a critical electronic component that is no longer available on the market, the pilot illustrates how targeted component redesign can preserve the operational value of existing rolling stock.

The experience gained through the pilot is linked to the development of a digital second-hand and match-making platform, which supports information exchange and collaboration between public transport actors to facilitate reuse and remanufacturing of vehicle components.

3.4.1. Pilot P.7: Remanufacturing and Redesign of Tram Control Units to Enable Component Reuse (Szeged, Hungary)

Short description of the pilot

This pilot focuses on extending the operational lifetime of tram vehicles through the redesign and remanufacturing of a critical electronic component. Implemented by Szeged Transport Company (SZKT), it addresses the issue of obsolete door control units used in Tatra T6A2 and KT4D-ME tram fleets, which are no longer available on the spare parts market.

To mitigate this risk, a new, parameterizable and diagnosable control unit was developed using modern components. The unit was designed to be compatible with both tram types and to integrate with existing door systems, enabling continued operation of ageing vehicles without the need for premature replacement.

Figure 29: Tatra tram vehicles (KT4D and T6A2 types) operating in Szeged.

Resources needed

Implementation required technical analysis of existing systems, development of new hardware and diagnostic software, and establishment of a controlled testing environment.

Additional efforts included certification by an accredited body, regulatory approval for operation and production of an initial batch of replacement units, supported by close cooperation between internal teams and external partners.

Figure 30: Controlled test environment used for functional testing of the newly developed door control unit.

Evidence of success

The pilot successfully developed and deployed a replacement control unit compatible with two tram types. A total of 99 original units were identified as critical components across 28 vehicles, and an initial batch of 40 new units was manufactured and installed.

The solution eliminated spare-parts obsolescence for a key component, secured continued operation of the fleet and introduced diagnostic functionality supporting improved maintenance and fault detection.

Figure 31: Newly manufactured door control unit installed in a tram vehicle.

Challenges encountered

The main challenge was the approval process for a newly developed safety-critical electronic component, as regulatory procedures were not clearly defined and required extensive coordination with certification bodies. Additional complexity involved ensuring compatibility with different tram systems and defining technical specifications suitable for long-term operation.

Potential for learning and transfer

The pilot demonstrates a transferable approach to addressing spare-parts obsolescence in ageing rolling stock. Many cities operate similar tram fleets and face comparable challenges.

The methodology—identifying critical components, redesigning replacements and obtaining certification—can be replicated by other operators, supporting circular maintenance strategies and extending vehicle lifetimes.

The approach primarily contributes to the **EXTEND** dimension of the AETE framework, particularly through refurbishment and remanufacturing of rolling stock components.

4. Lessons learned

Several key themes emerged across the CE4CE pilots, reflecting how circular solutions perform in practice under different operational conditions.

Data and system integration

Predictive maintenance pilots demonstrated that the effectiveness of digital solutions depends strongly on data quality and system integration. In Leipzig, continuous vehicle-based monitoring enabled early detection of infrastructure defects but also revealed the need for stable data pipelines and validation through field inspections. Similarly, simulation-based approaches showed that harmonisation of data from different sources is a prerequisite for reliable modelling and decision support.

Extending asset lifetimes through reuse and remanufacturing

Pilots focusing on infrastructure and component reuse highlighted the potential of extending asset lifetimes. In Szeged, the reuse of trolleybus switches showed that components removed from high-intensity network sections can be effectively redeployed in lower-demand environments. A similar principle was applied in the remanufacturing of tram control units, where redesign enabled continued operation of ageing vehicles despite spare-part obsolescence.

System integration and value creation in energy applications

Energy-related pilots demonstrated that the value of circular solutions increases with system integration. In Maribor, second-life battery storage showed limited benefits when used only for peak shaving, but significantly higher value when combined with renewable energy integration and flexible energy management. This highlights the importance of considering circular solutions as part of broader system optimisation rather than standalone interventions.

Organisational readiness and implementation processes

Across all pilots, successful implementation depended on coordination between multiple stakeholders and integration into existing operational structures. Phased implementation approaches, starting with pilot testing and followed by gradual scaling, proved effective in managing technical and organisational complexity.

These insights are summarised in the table below.

Area	Key Lessons
Technical & data	• Successful solutions depend on compatibility with existing infrastructure and systems, particularly in legacy environments. • Reliable implementation requires high-quality and harmonised data, supported by stable data pipelines. • Modular system design enables scalable deployment and flexible integration.
Operational	• Implementation requires coordination across organisational functions and integration into existing workflows. • Early stakeholder involvement significantly reduces risks and facilitates implementation. • Phased approaches enable testing, validation and gradual scaling.
Economic	• Circular solutions typically require upfront investment but generate value over longer time horizons. • Economic performance depends on system scale, integration level and operational context. • A significant share of value is created through indirect benefits such as reliability and efficiency.
Circular economy insights	• The greatest potential lies in extending asset lifetimes, reuse of components and repurposing of energy-related assets. • Circular strategies often follow a cascade logic across different use contexts. • A life-cycle perspective is essential to capture full value.
Transferability	• Solutions based on modular and adaptable approaches show the highest transfer potential. • Transfer depends on local organisational, technical and regulatory conditions. • Knowledge sharing and clear documentation support replication.

Table 7: Overview of cross-cutting lessons learned.

5. Implementation checklist and key aspects

Building on the lessons learned presented in Chapter 4, this chapter provides practical guidance for the implementation of CE4CE solutions in different local contexts. It translates the identified insights into actionable steps, key success factors and risk considerations to support stakeholders in deploying circular economy approaches in public transport systems.

The guidance is intended for public transport operators, authorities and other stakeholders seeking to adapt and implement CE4CE solutions, considering local technical, organisational and economic conditions.

5.1. Key aspects for successful implementation

Implementing CE4CE solutions requires addressing a set of key aspects that determine feasibility, effectiveness and scalability. These aspects reflect practical requirements identified through the pilot actions and solution development processes.

Successful implementation depends on ensuring compatibility with existing infrastructure and systems, particularly in legacy environments, as well as on the availability of reliable and well-structured data. At the same time, organisational readiness plays a key role, including coordination across departments, stakeholder involvement and the ability to integrate new approaches into existing workflows.

Economic viability must be considered from a lifecycle perspective, considering both direct and indirect benefits, while regulatory requirements and approval procedures may influence implementation timelines and solution design. In addition, solutions should be designed with scalability and transferability in mind, allowing adaptation to different operational and institutional contexts.

5.2. Implementation checklist

Table 9 provides a structured step-by-step approach to support the implementation of circular economy solutions in public transport systems, from initial assessment to scaling and integration into standard operations.

Step	Focus
Step 1: Initial assessment	• Identify circular economy opportunities in infrastructure, vehicles and energy systems • Analyse current asset lifecycle management practices • Define priority areas for intervention
Step 2: Feasibility analysis	• Assess technical feasibility of selected solutions • Evaluate data availability and system requirements • Analyse economic viability and potential benefits • Identify regulatory constraints
Step 3: Solution design	• Define technical concept and system architecture • Select appropriate technologies and partners • Develop implementation plan and timeline • Define performance indicators
Step 4: Implementation	• Deploy solution in a controlled pilot environment • Monitor performance and collect data • Engage operational staff and stakeholders • Adjust system based on feedback
Step 5: Evaluation and optimisation	• Analyse pilot results and performance data • Identify improvements and optimisation potential • Validate economic and operational benefits
Step 6: Scaling and transfer	• Develop scaling strategy within the organisation • Adapt solution to other contexts or locations • Share knowledge and lessons learned • Integrate solution into standard operations

Table 9: Step-by-step implementation checklist.

5.3. Common risks and mitigation measures

The implementation of circular economy solutions in public transport systems involves a set of common risks related to data, technology, organisational capacity and regulatory conditions.

One key challenge concerns the availability and quality of data, as incomplete or inconsistent data can limit the effectiveness of digital tools and evidence-based decision-making. This requires early assessment of data availability, along with validation procedures and the establishment of reliable data management processes.

Technical incompatibilities with existing infrastructure and legacy systems may also affect implementation. These challenges can be addressed by adopting modular and flexible system designs that allow gradual integration into existing environments without requiring extensive system changes.

Regulatory requirements and approval procedures may influence implementation timelines, particularly for innovative or safety-critical solutions. Early involvement of regulatory authorities is therefore important to clarify requirements and reduce the risk of delays.

Organisational capacity constraints, including limited expertise or resources, can further affect implementation. These risks can be mitigated through capacity building, targeted training and the allocation of adequate resources to support implementation and operation.

Finally, stakeholder engagement plays a critical role in successful implementation. Limited involvement or misalignment between stakeholders can hinder progress, while continuous communication and early engagement support coordination, acceptance and effective implementation.

Risks	Mitigation measures
Lack of data or poor data quality	Early data assessment and validation
Technical incompatibility	Modular system design
Regulatory delays	Early involvement of regulators
Limited organisational capacity	Capacity building and training
Low stakeholder engagement	Continuous stakeholder communication

5.4. Conclusions and outlook

The CE4CE handbook demonstrates how circular economy principles can be translated into practical applications within public transport systems. Through pilot actions implemented in different operational contexts, the project has generated valuable experience on how to preserve value, reduce waste and improve resource efficiency across infrastructure, vehicles and energy systems.

The solutions presented in this handbook build on this experience and provide structured, transferable approaches that can support public transport authorities and operators in implementing circular practices. Together with the cross-cutting lessons learned, they offer both strategic orientation and practical guidance for transitioning from linear to circular asset management.

The checklist presented in this handbook provides a structured approach that can be adapted to different public transport contexts and circular solutions. Continued knowledge exchange, stakeholder collaboration and further development of circular business models are essential prerequisites to scale these approaches and support the transition towards more sustainable and circular public transport systems.

6. References

CE4CE project deliverables:

D.1.1.3 The Public Transport Circularity Compass – Results summary with indications for uptake.

D.1.2.2 Report on implementation, testing, evaluation and peer review of the CE4CE Public Transport Circularity Platform.

D.3.1.1 Report on joint requirements, pilot preparation, implementation and evaluation: predictive maintenance in Leipzig and Bergamo, and simulation of an e-corridor in Gdynia.

D.3.1.2 Report on development of joint digital solutions to enable and accelerate circularity in public transport.

D.3.2.1 Report on joint requirements and plan for pilot preparation, implementation and evaluation: re-use of trolleybus switches in Szeged and re-use of second-hand batteries in Maribor.

D.3.2.2 Report on development of solutions to preserve value and reduce waste of public transport infrastructure.

D.3.3.1 Report on joint requirements and plan for pilot preparation, implementation and evaluation.

D.3.3.2 Report to facilitate take-up of solutions to preserve value and reduce waste of vehicles and rolling stock.

CE4CE project output factsheets:

O1.1 CE4CE Public Transport Circularity Compass

O1.2 CE4CE Public Transport Circularity Knowledge Platform

O3.1 Digital infrastructure and vehicle optimisation through predictive maintenance.

O3.2 Modules for predictive maintenance of infrastructure and rolling stock.

O3.3 Simulation of an e-corridor and energy flows to simulate circular scenarios for electrification upscaling.

O3.4 Circular business planning tool for electrified public transport fleets and infrastructure.

O3.5 Demonstrate the feasibility to re-use trolleybus switches.

O3.6 Definition of uptake criteria to re-use trolleybus switches.

O3.7 Analysis of used battery application to store renewable energy for powering a fast charger as example for strategic orientation towards circularity.

O3.8 Develop transferable business models for re-use of batteries to store renewable energy in public transport systems.

O3.9 Design for tram control units within tram remanufacturing.

O3.10 Online second-hand and match-making market for used parts, products and information-sharing.

The CE4CE project (Public Transport Infrastructure in Central Europe - facilitate transitioning to circular economy) empowers circular economy system thinking for public transport actors in Central Europe to reduce waste and create value along new life cycles of infrastructure and rolling stock.

CONTACT US

Leipziger Verkehrsbetriebe (LVB) GmbH/ Leipzig Public Transport Company
Project coordinator: Mr. Stefan Röll
Email: CE4CE.Verkehrsbetriebe@L.de
Project website: https://www.interreg-central.eu/projects/ce4ce/
LinkedIn: https://www.linkedin.com/company/interreg-ce4ce/
YouTube: https://www.youtube.com/@InterregCE4CE
Project knowledge platform: https://circularity4publictransport.eu/