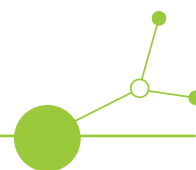


Deliverable D3.1.1

Report on pilot joint requirements,
preparation, implementation and
evaluation

**Pilot: Digital infrastructure and vehicle
optimization through predictive
maintenance in Bergamo, Italy**



Version 1
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Pilot action Bergamo, Italy

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1. Introduction

The CE4CE project supports the transition toward a circular economy in the public transport sector across Central Europe by equipping key stakeholders with the tools, strategies, and knowledge needed to reduce waste and unlock new value along the full life cycle of vehicles and infrastructure. By fostering collaboration between public transport operators, technology providers, researchers, and policymakers, the project aims to dismantle existing barriers, lower implementation costs, and strengthen local capacities for sustainable innovation.

A central element of CE4CE is the implementation of pilot actions that bring circular economy concepts into practice. These pilots serve as living laboratories for the development and testing of digital, operational, and strategic approaches that improve resource efficiency and long-term value retention.

ATB is cooperating with KRUCH Railway Innovations GmbH & Co KG, who is actively involved in several of these pilots, applying its expertise in digital monitoring systems, data analytics, predictive maintenance and energy-flow-simulation systems.

Redmint Impresa Sociale is supporting the partners and local actors in the set up, execution and monitoring of pilot activities, ensuring the engagement of key stakeholders.

TEB (Tramvie Elettriche Bergamasche), tram operator and subsidiary of ATB, has been engaged in the planning and implementation of pilot activities, installing sensors and testing the different components of the system.

The Municipality of Bergamo (Associated Partner) participated in the discussion on the set up and launch of the pilot action, and is informed on its developments during the testing phases, on the results and potential benefits deriving from a broader application of the innovative solutions.

Through this and other initiatives, CE4CE not only demonstrates the feasibility of circular public transport models but also contributes to broader goals such as knowledge transfer, workforce development, and policy innovation. The project's outcomes are expected to guide future investment decisions and support more sustainable and resilient urban mobility systems across the region.

2. NUTS region(s) concerned by the pilot action (relevant NUTS level)

The region covered by the action plan refers to the city of Bergamo in northern Italy. Bergamo is a dynamic and historically rich urban center with a population of approximately 120.000 inhabitants, while the urban agglomeration in the range of urban and sub-urban services like the tramway the population is approximately 300.000. Located in the Lombardy region, one of the most industrialized and densely populated areas in Italy, Bergamo plays an important role in regional mobility and sustainability planning. The city is actively engaged in modernizing its public transport system and implementing innovative, data-driven approaches as part of its Sustainable Urban Mobility Plan (PUMS).

Country (NUTS 0)	IT
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Macroregion (NUTS 1)	
Region (NUTS 2)	ITC4 - Lombardia
Sub-region (NUTS 3)	ITC46 - Bergamo

3. Basic pilot concept

1.1. Aim and purpose

The pilot project in Bergamo focuses

- (1) on enhancing the durability and operational reliability of public transport infrastructure and the rolling stock through the implementation of real-time monitoring and predictive maintenance strategies, and
- (2) on energy optimization through running a big set of simulations on a digital copy of the electric network and by these studying hundreds of possible scenarios and parameter setting and their impact on the most circular use of energy.

1.2. Integration with circular economy principles

In the Bergamo pilot we apply circular economy principles in both sub-projects:

- (1) By “continuous monitoring” we enable the early detection of defects and infrastructure wear => reducing subsequent errors, complete destruction of components and unnecessary repairs and downtimes. Using artificial intelligence (AI) to develop a predictive monitoring system allows for minimally invasive and well-targeted maintenance interventions => getting the maximum out of time and material. The time of useful life of the infrastructure components (e.g. overhead contact line) as well as the rolling stock (e.g. pantograph) is increased, we get “more use” out of the materials (crucial resources like copper and carbon) and create “less waste”. For the data collection, a “standard tram” is used during its daily passenger operation - so no extra vehicles and no extra journeys are needed, extra expenses and energy consumption for monitoring are avoided.
- (2) By building a digital copy of the electric power system of the network and using digital simulation technology (Energy Flow Simulations) to study hundreds of different settings and operation modes, ways to “reuse braking energy in a more efficient way, minimizing the losses” are identified, “energy consumption” of tram operations is reduced and the circularity of transport networks is improved. These results can be achieved quickly, helping to apply improvements early, maximizing the effect of the intervention.

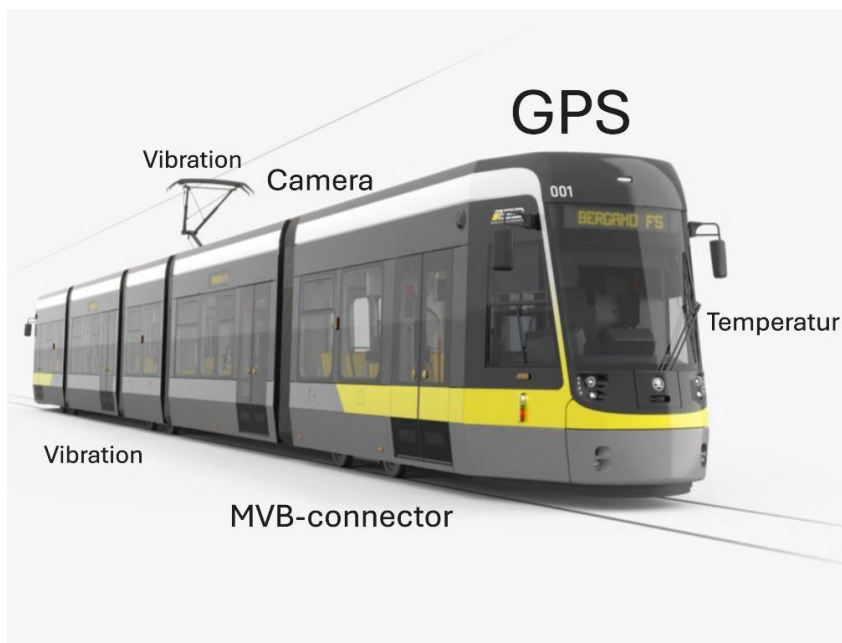
Reliable decision-making: producing clear and trustworthy data to support strategic decisions, helping improve the quality and effectiveness of planning for tram operations and future infrastructure investments, avoiding failure or non-optimal decisions.



1.3. Basic concept of the pilot project

Within the scope of the pilot project, standard tram vehicles - which travel in daily passenger service - are equipped with advanced sensor units, data connectors, edge computers and data modems, that enable continuous monitoring of the overhead contact line, pantograph interface, vehicle data and related structural elements. The collected data is processed using advanced analysis methods and AI tools to identify early indicators of wear, misalignment, or structural degradation. Furthermore, data is compared to EFS simulations run by KRUCH during the preparation phase of the pilot project to ensure consistency and reliability of generated output. This data-driven methodology supports the implementation of timely, condition-based maintenance strategies that prevent minor issues from developing into major failures. As a result, the need for large-scale repairs and material replacements can be significantly reduced, supporting both cost efficiency and infrastructure sustainability.

- (1) By integrating sensor technology, data connectors and edge-computers into tram vehicles, the project enables continuous monitoring of key infrastructure components such as the overhead contact line and pantograph interface, and the rolling stock vehicles themselves. The objective is to develop data-driven analysis methods that facilitate early detection of potential faults. This forward-looking approach aims to replace reactive maintenance practices with predictive systems, ultimately improving operational efficiency, minimizing infrastructure-related interventions, and supporting a more sustainable and low-emission public transport system.



- (2) By modelling a digital copy of the electric network and setting up simulation software based on that model, hundreds of simulations can be performed to optimize the tram operations and find reasons & solutions for potential problems. This helps to improve the use of energy, reduce energy waste and re-use recuperated energy.



Simulation New Simulation RUN Back to index

▼ INPUT DATA

General parameters	Comment	Parameters
Name New Simulation	Comment	Duration of the simulation [h] 3
Email Bergamo@kruch.com		HVAC percentage [%] 30
N° 1		Chopper voltage [V] 900
Priority Low priority		Stopping time at the stations Random
		Investment [k€] 0

Conductor parameters	Temperature parameters
Wear contact wire [%] 10	Air temperature [°C] 18
Wear of the return rail [%] 5	Wind speed [m/s] Zero: 0 m/s
Temperature OCS [°C] 70	Standard radiation [W/m²] Very sunny: 10...
Temperature return rail [°C] 45	Solar radiation absorbance [pu] Old: 0.9
Temperature feeding [°C] 80	

▼ VEHICLES

▼ TIMETABLES

▼ TRANSFORMERS

▼ TRACK SECTIONS

▼ POSITIVE FEEDERS

▼ NEGATIVE FEEDERS

▼ SWITCHES

▼ MAP

1.4. Main activities during the pilot

The pilot project in Bergamo was structured into three main phases: preparation, implementation, and evaluation.

1. Preparation Phase:

In the initial phase, a detailed requirement-analysis was carried out in close cooperation between ATB and KRUCH to define the technical and operational specifications. Based on this, KRUCH selected appropriate sensors and communication components. These were procured, preassembled into modular test units, and functionally tested. The integration of the sensor system into the tram vehicles and the infrastructure – particularly at the pantograph – was planned to ensure seamless operation. In parallel, the data management system was set up by KRUCH and its suppliers, and involved staff were trained in handling the technology and interpreting the collected data.

2. Implementation Phase:

During this stage, sensor systems were installed and activated on one vehicle (tram #004) in Bergamo. Real-time data collection began, with continuous monitoring of operational conditions. The data streams were analysed using custom-developed algorithms to identify patterns and detect anomalies. Initial test runs and calibrations ensured the functionality and precision of the system. A feedback loop between data analysis and operational teams allowed for ongoing refinement of the setup and processing logic. Furthermore, the collected data were compared to EFS (Energy Flow Simulation) scenarios run by KRUCH earlier to validate accuracy and ensure consistency between simulated and real-world performance.

3. Evaluation Phase:

The final phase focused on assessing the overall performance of the system, particularly regarding its potential to enable predictive maintenance in a circular public transport context. Analytical results were documented and reviewed, with special attention to the early detection of infrastructure degradation.



Feedback from stakeholders and pilot partners informed the refinement of methods and tools. Lastly, the scalability of the solution was assessed, with a view toward future application beyond the pilot setting and its integration into broader asset management strategies.

1.5. Alignment with policies and strategies

Local policies and strategies

The pilot project in Bergamo is fully aligned with the city's **Sustainable Urban Mobility Plan (PUMS)**¹, which prioritizes the development of clean, efficient, and inclusive mobility systems. The plan encourages the integration of intelligent technologies to reduce environmental impact, improve the reliability of public transport, and promote a modal shift from private vehicles to collective mobility. By implementing real-time monitoring systems and enabling predictive maintenance, the project directly supports these objectives—ensuring more reliable services, minimizing disruptive repairs, and extending the operational life of infrastructure components.

Furthermore the plan, as well as the city's Climate City Contract² (signed in 2024).

The climate city contract, elaborated in the framework of the NetZeroCities initiative, includes all the activities that the City of Bergamo and its partners will implement towards zero neutrality

In particular, concerning mobility ATB is committed to the following:

- Fleet electrification by 2033
- T2 della Valle Brembana tramway by 2026
- e-BRT (Bus Rapid Transit) Bergamo-Dalmine by 2026

Within this innovation pathway, understanding the potential and benefit of circular solutions in infrastructure management, and in particular of predictive maintenance, is fundamental in order to ensure future sustainability and control over operational costs and resource efficiency during the lifespan of the infrastructural elements. The pilot action applies a systematic approach to transfer predictive maintenance processes and structures into asset management and maintenance.

Challenges:

- Bergamo's topography and historical layout pose constraints on infrastructure renewal, making intelligent maintenance solutions especially valuable;
- The city faces increasing commuter traffic and tourism, requiring scalable and resource-efficient solutions to maintain service quality;
- The investments related to the ecological transition must be durable and sustainable over a long lifespan, extending the life of infrastructure and rolling stock is essential to generate long term positive effects.

¹ https://www.comune.bergamo.it/sites/default/files/2019-03/PUMS-Bergamo_Proposta-di-Piano_v4.pdf

² <https://netzerocities.app/resource-4432>



Regional policies and strategies

Lombardy is among the most urbanized and industrialized areas in Italy, with high mobility demand and environmental sensitivity. The pilot demonstrates how data-based approaches can support cost-effective maintenance and improve long-term resilience of public transport networks.

The project contributes to the strategic goals outlined in the Region's energy and mobility planning documents, particularly those related to digital innovation, emissions reduction, and sustainable infrastructure management.

Concerning the Regional Programme for Mobility and Transport, the pilot action contributes to the following specific objectives:

C) "to develop collective transport in universal form and achieve integration between different modes of transport, specific focus on technological innovation", in particular as measure focused on technological innovations;

G) "transport safety"; interventions on the linear infrastructure components as well as in nodes, on rolling stock, etc.).

Challenges:

- High network load in urban and peri-urban areas creates stress on infrastructure and accelerates wear.
- There is a need for interoperable solutions that can be replicated across multiple municipalities within the region.

National policies and strategies

The project aligns with Italy's National Recovery and Resilience Plan (PNRR), which dedicates significant funding to the digital transformation and ecological transition of public infrastructure. The pilot supports Mission 2 ("Green Revolution and Ecological Transition") and Mission 1 ("Digitalization, Innovation, Competitiveness") by demonstrating how predictive maintenance and sensor-based infrastructure monitoring contribute to both sustainability and technological innovation. Furthermore, the project contributes to the goals of the Strategia Nazionale per lo Sviluppo Sostenibile (2023), particularly in reducing emissions, preserving resources, and improving the efficiency of public services.

Challenges:

- Italy's aging transport infrastructure requires innovative and scalable solutions for modernization without excessive resource consumption.
- Bridging the gap between traditional public service management and digital transformation requires capacity building and demonstrator projects like CE4CE.

European policies and strategies

The pilot action is fully consistent with the European Union's objectives on sustainable mobility, circular economy, and climate-neutral cities. It contributes to the goals of the European Green Deal (2020), the Circular Economy Action Plan CEAP (2020), and the New EU Urban Mobility Framework (2021), by improving the life cycle performance of transport infrastructure, reducing emissions, and fostering digital innovation. The use of AI-based predictive analytics, data-driven decision-making, and modular sensor technology reinforces the EU's ambition to create smart, connected, and sustainable urban systems.



Digitalization is a core enabler of this pilot project. The integration of smart sensors and real-time data analysis lays the groundwork for intelligent maintenance and system optimization. By comparing real-world data with previously run EFS simulations, the project ensures reliable forecasting and supports a shift from reactive to proactive infrastructure management. Furthermore The insights gained are intended to support future integration with local and national digital platforms, contributing to broader smart city objectives in Italy.

4. Key pilot development phases

This section describes the key phases of the pilot, planning steps, activities, and the corresponding results, providing a timeline and an overview of progress. You can include additional supporting materials like maps, dates, or participants' details.

Main milestones of the pilot project	Description	Duration of the stage	Calendar term	Responsible partner
<i>Pilot Design</i>	<i>Defining the overall concept and design of the pilot project, including objectives, scope, and key deliverables. This stage also includes initial planning and resource allocation.</i>		04/2023 - 02/2024	ATB (PP9) KRUCH (PP6)
<i>Stakeholders Engagement and joint development</i>	<i>Engaging key stakeholders through workshops, hackathons, and other meeting forms to gather feedback, validate assumptions, and align expectations.</i>		01/2024 - 03/2024	ATB (PP9) KRUCH (PP6)
<i>Feasibility Study and Preparation</i>	<i>Conducting feasibility studies to assess technical, financial, and operational feasibility. This also includes securing necessary funding and permits.</i>		03/2024 - 05/2024	ATB (PP9) KRUCH (PP6)
<i>Procurement Process(es)</i>	<i>Initiating the procurement process for the goods, services, or equipment required for the pilot project. Includes issuing tenders and selecting vendors.</i>			KRUCH (PP6)
<i>Pilot Implementation</i>	<i>Overseeing the work of the contractors and ensuring that the implementation follows the project plan.</i>			ATB (PP9) KRUCH (PP6)
<i>Operational Launch</i>	<i>Ensuring that all systems are fully functional, providing initial training for</i>			ATB (PP9) KRUCH (PP6)



	<i>users and operators, and solving any initial operational challenges.</i>			
<i>Monitoring and Evaluation</i>	<i>Collecting data and performance metrics to assess the pilot's effectiveness. This stage focuses on the monitoring of the system in real-time and evaluating its performance against objectives.</i>			ATB (PP9) KRUCH (PP6)
<i>Reporting and Documentation</i>	<i>Compiling findings, data, and analyses into comprehensive reports. This includes both interim and final reports to document progress, results, challenges, and lessons learned.</i>			ATB (PP9) KRUCH (PP6)

5. Preparation and technical requirements

Pilot design

At the beginning of the project, several coordination meetings were held between ATB Bergamo and KRUCH to define the pilot's objectives, technical parameters, and implementation strategy. For this purpose, Jan Röhl from KRUCH came for site visits to Bergamo. The core idea was to develop a modular, sensor-based system capable of monitoring key infrastructure components, with a particular focus on the overhead contact line and its interaction with the pantograph during operation. This infrastructure is subject to high mechanical and thermal loads and presents a critical point for wear and failure.

Based on the planning process, it was decided that the sensor system would not be installed initially in the vehicles in Bergamo but rather designed, procured, preassembled, and fully tested in KRUCH's workshop in Vienna. This change was included in a major project modification process and supported by all project partners. It ensured high technical quality and simplified the final installation on-site. The goal of the pilot is to enable early fault detection and support the transition from reactive to predictive maintenance practices. In parallel, the pilot contributes to improving energy efficiency by analyzing the relationship between driving behaviour, pantograph dynamics, and infrastructure performance.

The pilot was implemented in close coordination with ATB's technical units, with whom KRUCH jointly developed the data architecture and analytics tools for infrastructure assessment.

Stakeholder engagement and joint development

Following initial bilateral discussions, KRUCH organized a targeted workshop at its Vienna facility in late 2023, bringing together internal experts, ATB representatives, and system integration partners. The aim was to align on operational needs, discuss sensor design requirements, and finalize the structure of the test units.



The workshop covered:

- Integration strategies for overhead contact line monitoring systems
- Technical specifications and mechanical interfaces for sensor housings
- Selection criteria for edge processing units
- Cable routing, energy supply, and mounting concepts for tramway use

Workshop Outcomes:

- Confirmation of pilot scope and technical setup
- Final design of sensor units and communication interfaces
- Review of certification requirements for infrastructure-side installations
- Outline of testing procedure and installation logistics in Bergamo

Feasibility study and preparation

KRUCH and ATB jointly conducted a feasibility assessment to evaluate the implementation risks and infrastructure conditions. Special focus was placed on the practical integration of the system into ATB's public transport network, given the compact space on vehicle roofs and the specific lay-out of the Bergamo's public transport network. KRUCH also reviewed the electromagnetic environment and vibration conditions that could affect measurement quality.

Technical Evaluations Included:

- Sensor durability under field conditions
- Integration compatibility with ATB's vehicle types
- Functionality of the data acquisition unit and onboard communication system
- Mounting methods compliant with tramway infrastructure constraints

Financial Feasibility

The pilot costs were jointly assessed to ensure compliance with the CE4CE budget structure. This included detailed planning of material procurement, hardware assembly in Vienna, and on-site installation support in Bergamo. Special consideration was given to ensuring modularity and cost-effective replication potential for future applications.

Operational Feasibility

The operational impact of the pilot was thoroughly analyzed. All activities were planned to avoid disruption to ATB's daily transport operations. Since installation was carried out with preassembled units, on-site work was limited to a short intervention period, reducing downtime and resource requirements. ATB maintenance staff was informed and involved in the process to ensure smooth integration.

Securing the necessary approvals

The installation of the sensor modules was carried out in accordance with applicable technical norms and tramway regulations. Although no modifications were made to the core safety systems of the vehicles, KRUCH documented all components and mounting steps in line with railway-specific best practices. Special attention was given to ensuring fire resistance, mechanical safety, and compliance with EN standards where applicable.



6. Implementation phase

Procurement process

As part of the CE4CE pilot project in Bergamo, specific procurement decisions were made to ensure a technically sound and timely implementation of the monitoring solution developed by KRUCH. Unlike in Leipzig, where multiple providers were involved through a structured tender process, the Bergamo pilot relied on a more compact procurement model, based on a direct collaboration between ATB Bergamo and KRUCH Railway Innovations GmbH & Co KG.

Implementation phases

The project was divided into clearly defined phases, covering system design, component procurement, testing, and final installation:

- Phase 0 (Q3 2024):
Finalization of technical specifications and modular design of the sensor units at KRUCH's Vienna workshop.
- Phase 1 (Q4 2024):
Procurement of sensors, computing modules, and communication interfaces, followed by full system assembly and internal testing.
- Phase 2 (Q4 2024 / Q1 2025):
Transport of the fully tested monitoring units to Bergamo and installation on one tram vehicle and selected infrastructure segments. Live testing and trouble shooting.
- Phase 3 (ongoing):
Commissioning, calibration, and start of data collection in live operation.

Procurement and delivery strategy

Given the focused scope and the integrated nature of the solution, a revised procurement and assembly approach was chosen. KRUCH, as CE4CE project partner acquired direct receipt of INTERREG funds for the procurement within a major amendment process and managed the selection and procurement of all technical components. This included:

- GNSS (Global Navigation Satellite System)
- acceleration sensors
- camera units
- power supply units
- on-board-edge-computer
- data connectors to the CAN-bus-system
- communication modules for data transfer

All components were selected based on quality, compatibility with tramway standards, and proven performance in mobile infrastructure environments. Assembly and functional testing were conducted at KRUCH's in-house facility, ensuring readiness before field deployment.



Role of and involvement of project partners

KRUCH Railway Innovations GmbH & Co KG (PP6):

Lead technical partner for system design, procurement, assembly, and pre-deployment testing. Responsible for coordination of sensor integration and data management architecture.

ATB Bergamo (PP9):

Implementation partner and system operator. Provided input on local infrastructure, vehicle availability, and operational integration. Supported installation and local alignment.

Outcome of the procurement process

Thanks to the modular approach and direct collaboration among project partners, all required components were procured, assembled, and tested on schedule. The system was successfully installed without the need for additional public procurement procedures, because the components were procured from the same suppliers as in the pilot-project with LVB, who have been selected within a tendering procedure. All activities were carried out within the scope of the approved CE4CE project plan and financial framework.

This streamlined and partner-driven procurement strategy ensured the technical integrity, legal compliance, and readiness of the pilot system, in alignment with both CE4CE objectives and local operational requirements in Bergamo. A delay caused by the shift of the procurement process for the components from ATB to KRUCH was largely compensated. The final project deadline is not at risk.

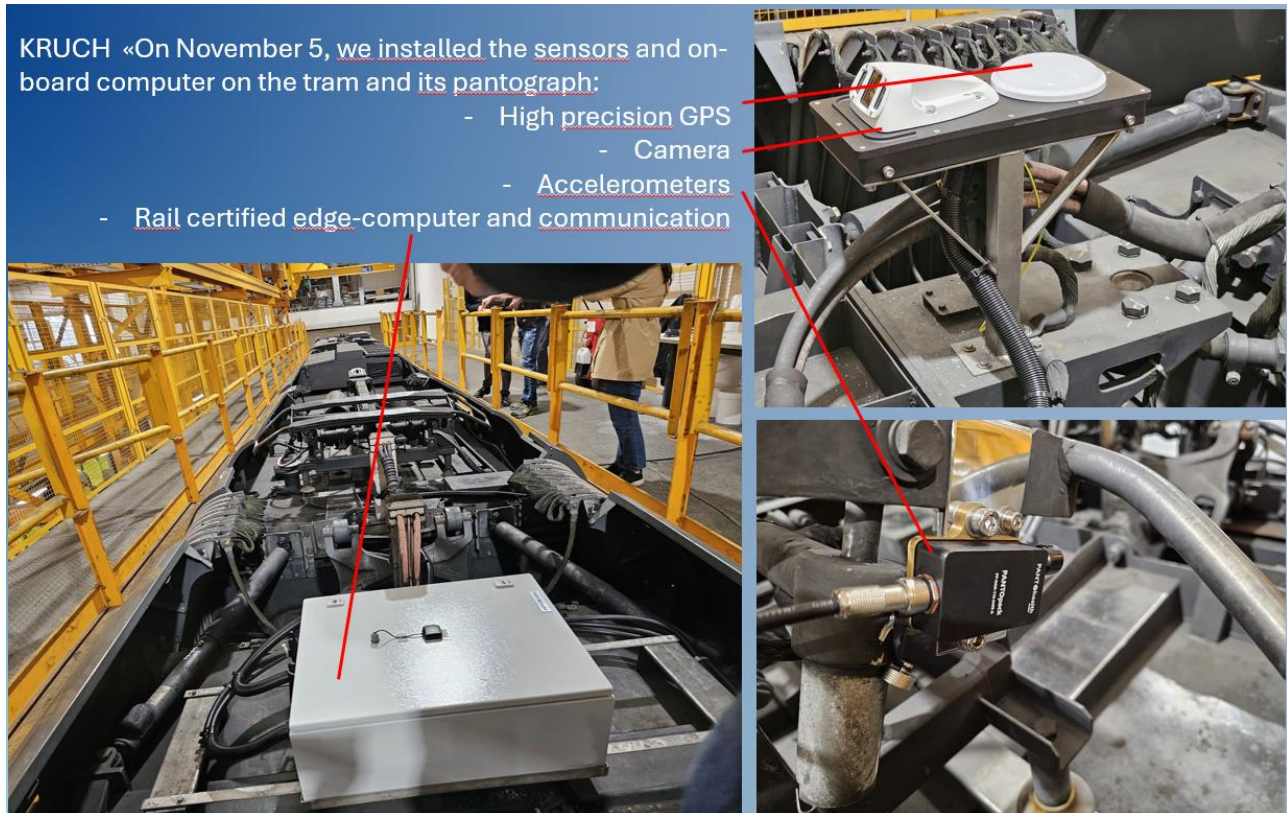
Pilot Implementation

The implementation phase of the CE4CE pilot project in Bergamo included the coordination and execution of all technical and organizational activities necessary to deploy the sensor-based monitoring system developed by KRUCH. The project followed a structured, phase-based approach to ensure that the system was installed, calibrated, and commissioned under real-world conditions in close collaboration with ATB Bergamo.

Sensor and hardware integration

In the initial step, fully preassembled sensor units as listed above were delivered from KRUCH's Vienna facility to Bergamo.

The modular units were mounted on a selected ATB tram vehicle (#004), primarily focused on the pantograph and overhead contact line. Mechanical installation was carried out with minimal intervention to the vehicle structure and did not require permanent modifications.



Software integration and system testing

In parallel with the physical installation, the software platform was configured to receive and process incoming data. The edge devices were connected to internal data loggers and set up to perform initial filtering, event detection, and data compression. Test runs were conducted to verify sensor function, GNSS signal stability, and alignment of camera views.

Calibration procedures included static and dynamic validation of the acceleration sensors, synchronization of time-stamped data across modules, and functional verification of the data pipeline. In addition, measurement data were compared with previously run EFS simulations to ensure consistency between simulation and real-world results.

Project coordination and quality assurance

Implementation activities were coordinated through regular virtual meetings and structured on-site visits. Open technical issues were tracked and operational challenges resolved in real time. ATB's technical team supported installation and integration, while KRUCH led the coordination of software deployment and system tuning.

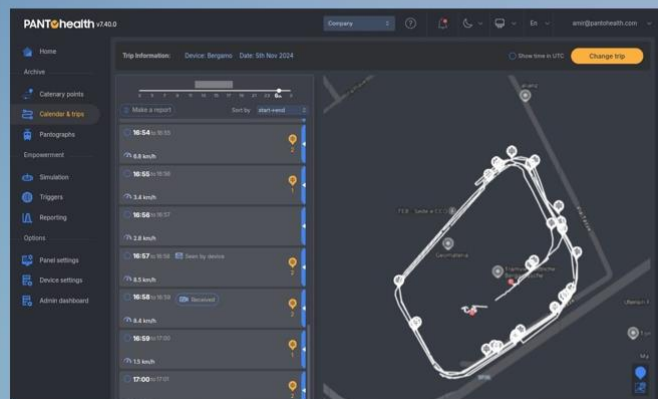
To ensure traceability and regulatory compliance, all system components and their integration steps were fully documented. Although the pilot hardware remains the property of the project partners, it was operated in line with ATB's technical standards and Italian tramway regulations. The pilot system is intended for temporary use under the CE4CE framework and is subject to project-specific operational conditions.

The entire implementation process adhered to relevant international norms, including quality, environmental, and occupational safety standards (e.g. ISO 9001, ISO 14001, ISO 45001, ISO 50001). The strong coordination between partners ensured a smooth rollout and established the foundation for continuous data collection and further analysis during the pilot phase.



First testride

Successful installation, all sensors online

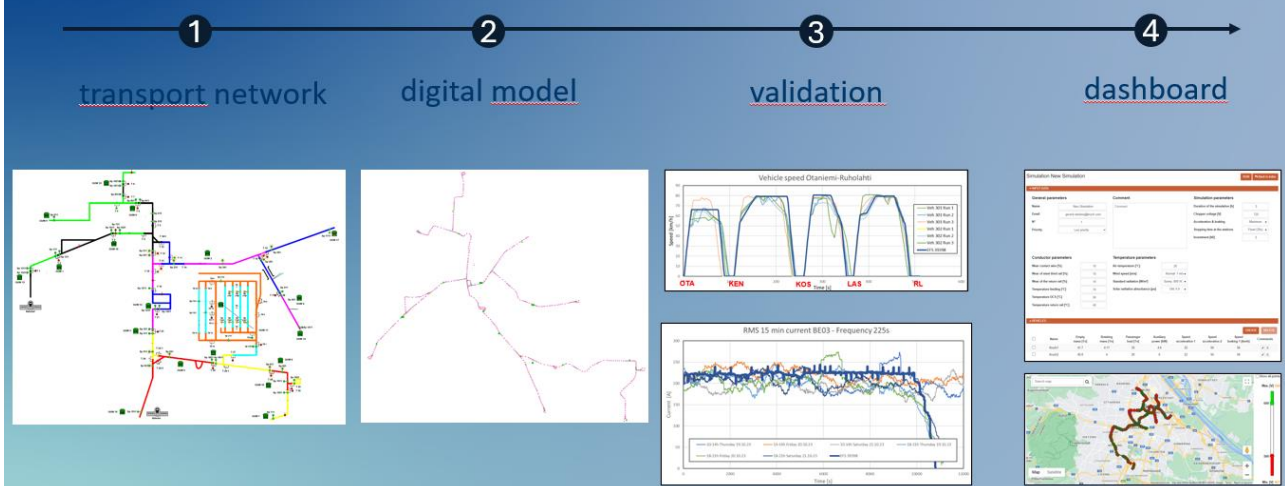


Modelling and deploying the digital twin of the power network

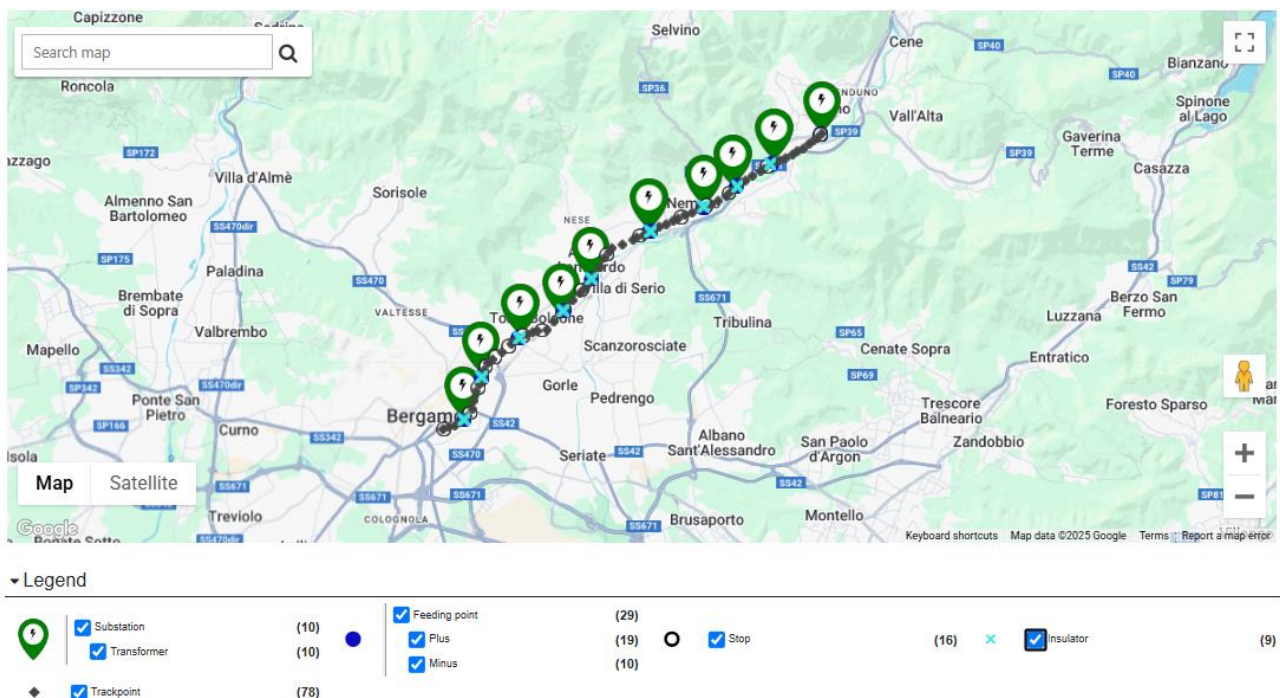




DEVELOPING A DIGITAL TWIN: Energy Flow Simulation



Based on technical documentation (route data, position of stations, building information of the overhead contact line, component lists, electrical diagrams of the substations and the feeding system, and many more) KRUCH with its supplier KRUCH SIDOS modelled a digital copy of the complete line T1 using MATLAB. On top of that model a simulation was created using SIMULINK and SIMPOWERSYSTEMS.





An easy-to-use website was created to offer a graphical user interface for the ATB team. On this website, relevant parameters can be easily adjusted to create countless variations of interesting scenarios. With this simulation tool, ATB and KRUCH can change infrastructure settings, vehicle settings, timetables, electrical switching, and many more.

7. Process evaluation

The operational launch of the CE4CE pilot project in Bergamo followed a structured, step-by-step approach aligned with the technical implementation phases. The objective was to ensure that the monitoring system developed by KRUCH functioned reliably under real-world conditions, that ATB's operational processes were respected, and that all involved staff were adequately prepared for the system's use.

To support the launch, technical teams from KRUCH worked closely with ATB to install and commission the sensor units on a selected tram vehicle. The modular sensor systems had been carefully tested prior to shipment by KRUCH in its Viennese facilities, which minimized the need for on-site adjustments. Nonetheless, fine-tuning and verification steps were carried out during the initial weeks of operation to ensure signal stability, data integrity, and compatibility with operational routines.

Training sessions were held for ATB's maintenance and infrastructure personnel. These covered the safe handling of installed sensor components, the basic operation of the edge computing devices, and the procedures for data access and reporting. Special emphasis was placed on ensuring that the new systems would complement, rather than disrupt, existing maintenance workflows.

During the first phase of operation, KRUCH supervised the system's behaviour in real-time together with its subcontractors Kruch-Sidos, PANTOhealth and CI4RAIL. This included:

- Monitoring sensor output under normal and stress conditions
- Verifying GNSS accuracy in the urban environment
- Evaluating camera image quality and vibration readings
- Ensuring stable data transmission via the onboard communication modules



Any necessary calibrations or configuration changes were performed in coordination with ATB staff. Issues such as environmental signal interference, mechanical vibrations, optimising the camera position, stabilising the voltage source, or cable routing adjustments were promptly addressed through joint troubleshooting.

To maintain continuous coordination, regular update calls and technical check-ins were held between KRUCH and ATB.

The successful start of the pilot under real operating conditions marked an important milestone in the CE4CE project. It confirmed the technical feasibility of using modular, sensor-based systems to enable predictive maintenance and digital monitoring of public transport infrastructure. The launch also laid the foundation for the upcoming evaluation phase, during which the collected data will be analyzed and compared to earlier simulations to assess the system's overall performance and impact.

8. Testing and evaluation phase

Monitoring and evaluation

Following the successful operational launch in early 2025, the Bergamo pilot entered the continuous monitoring and evaluation phase. The objective of this phase was to assess the performance and reliability of the installed sensor system under real operational conditions and to analyse the quality and relevance of the data being collected.

Key components under observation included the overhead contact line, the pantograph interface, and vehicle-infrastructure interaction. The sensor package – consisting of GNSS modules, acceleration sensors, high-resolution cameras, CAN-bus connectors, onboard edge computers, and communication modules – provided continuous streams of data on positional accuracy, vibration patterns, and mechanical anomalies.

Particular attention was paid to:

- Signal stability under varying environmental conditions
- Accuracy of sensor readings in detecting contact irregularities and mechanical disturbances
- Image and video data quality captured by the onboard cameras
- Correct interpretation of collected sensor data by software components and AI
- Comparison of real-world data with previously conducted EFS simulations to validate assumptions

KRUCH worked closely with ATB's infrastructure and operations teams to interpret the incoming data and evaluate the predictive maintenance potential. Preliminary anomalies – such as brief signal losses, irregular pantograph movement, or elevated vibration levels – were identified by the system and assessed collaboratively with ATB's technical staff.

Regular coordination meetings between ATB and KRUCH supported a dynamic feedback loop: findings were reviewed, sensor parameters adjusted, and software refinements implemented where needed. The goal was not only to stabilize technical performance but also to build mutual understanding regarding the interpretation of data and its application in infrastructure planning.

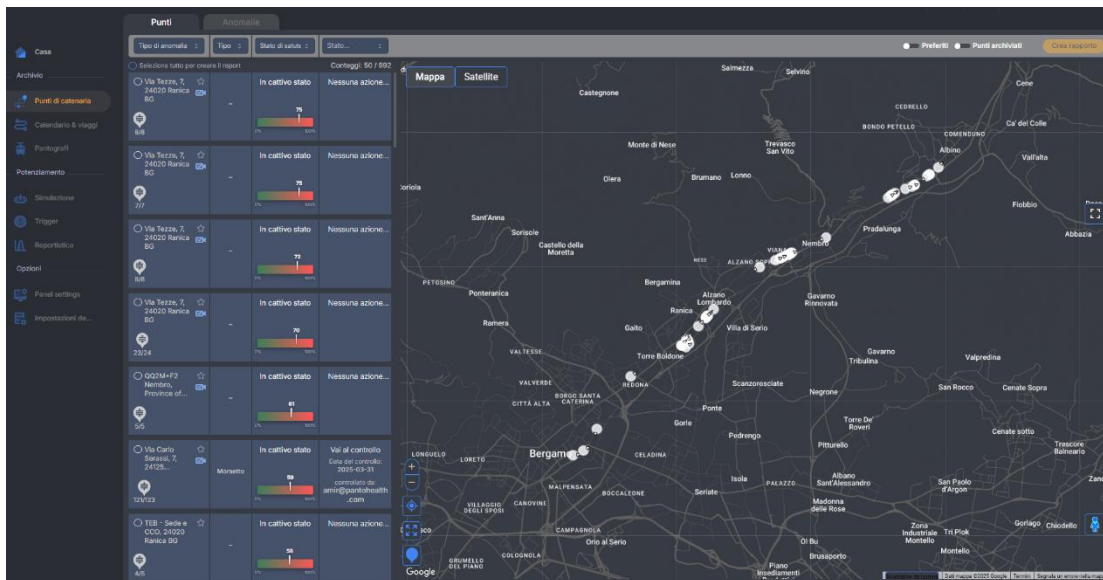
A technical review workshop is planned around the partner meeting in Bergamo scheduled for June 2025 to present interim results, discuss open questions, and outline scenarios for further use of the system beyond the pilot phase. In this setting, project participants will jointly assess the added value achieved and identify potential applications of the solution within ATB's broader asset management strategy.



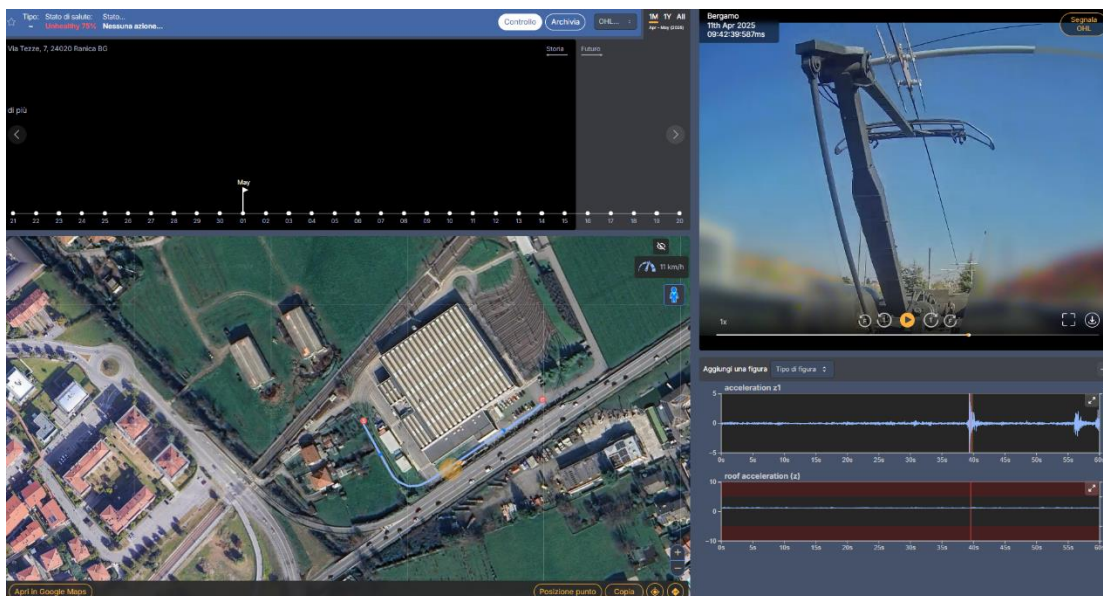
The monitoring and evaluation phase forms the basis for a possible scaling of the solution to other lines or vehicles, both within Bergamo and beyond. The pilot thus serves as a practical test case for implementing digital and circular maintenance practices in public transport systems of similar size and infrastructure typology.

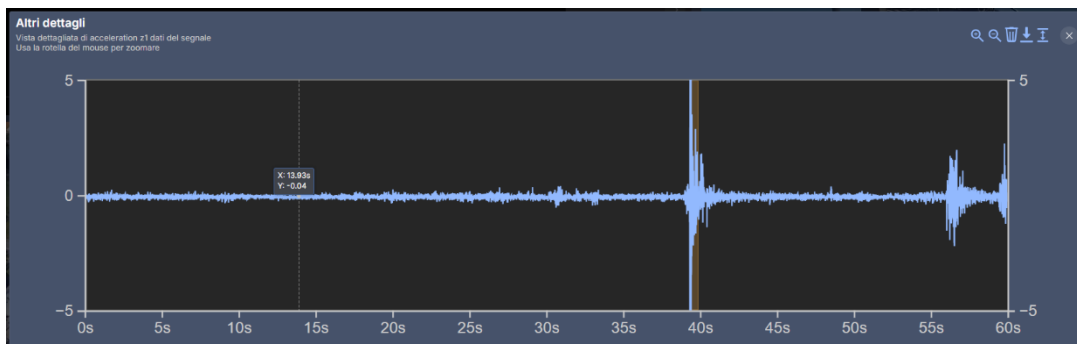
Continuous Monitoring and predictive maintenance of the overhead contact line

Already, specific points in the line with a higher “likelihood of a problem” have been identified and are listed in an online-interface, ranked by their health-status.



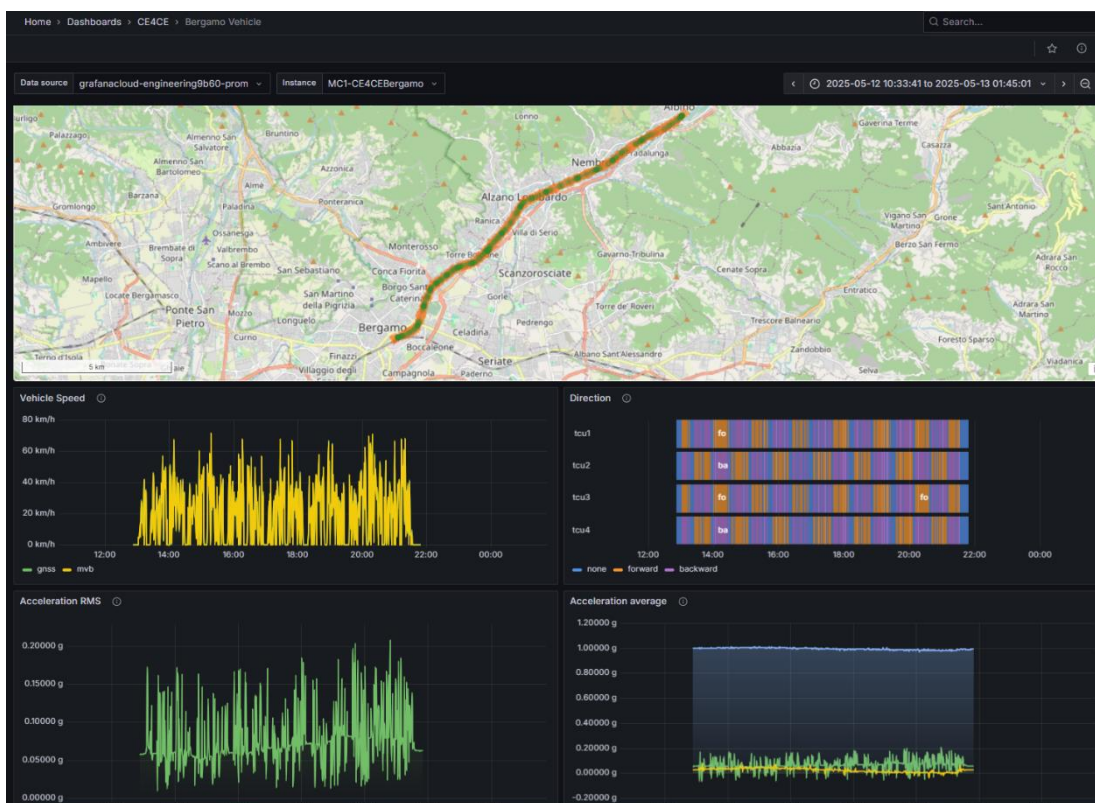
Each point can be studied in detail with its exact position, vibration signal, video feed and additional information.





Continuous energy monitoring and building knowledge of the rolling stock

Every 1-3 seconds a data set is transmitted and the dashboard with all visualisations is refreshed. Like this, position, speed, drivers' controls, accelerations and energy consumption can be monitored.



This data can be used to compare the “real world” behaviour of the trams and the electrical infrastructure with the “theoretical” simulation results. This comparison opens a completely new platform for gaining additional knowledge and identifying potential for improvement of circularity factors.



Energy Flow Simulations on the “digital copy of the tram network”

With the intuitive access to the complex electrotechnical simulation tool, all kinds of scenarios can be analysed:

Simulation v.2025.02

[Download as Excel](#) [Print](#) [Return to index](#)

INPUT DATA

General parameters

Name: v.2025.02
Email: gerard.clariana@kruchsidoss.com
Creation: 2/14/2025 9:41:58 AM
Nº: 1

Comment

Comment

Parameters

Duration of the simulation [h]: 3
HVAC percentage [%]: 30
Chopper voltage [V]: 900
Stopping time at the stations: Random
Investment [k€]: 0

Conductor parameters

Wear contact wire [%]: 10
Wear of the return rail [%]: 5
Temperature OCS [°C]: 70
Temperature return rail [°C]: 45
Temperature feeding [°C]: 80

Temperature parameters

Air temperature [°C]: 18
Wind speed [m/s]: Zero: 0 m/s
Standard radiation [W/m²]: Very sunny: 1000 W/m²
Solar radiation absorbance [pu]: Old: 0.9

VEHICLES

TIMETABLES

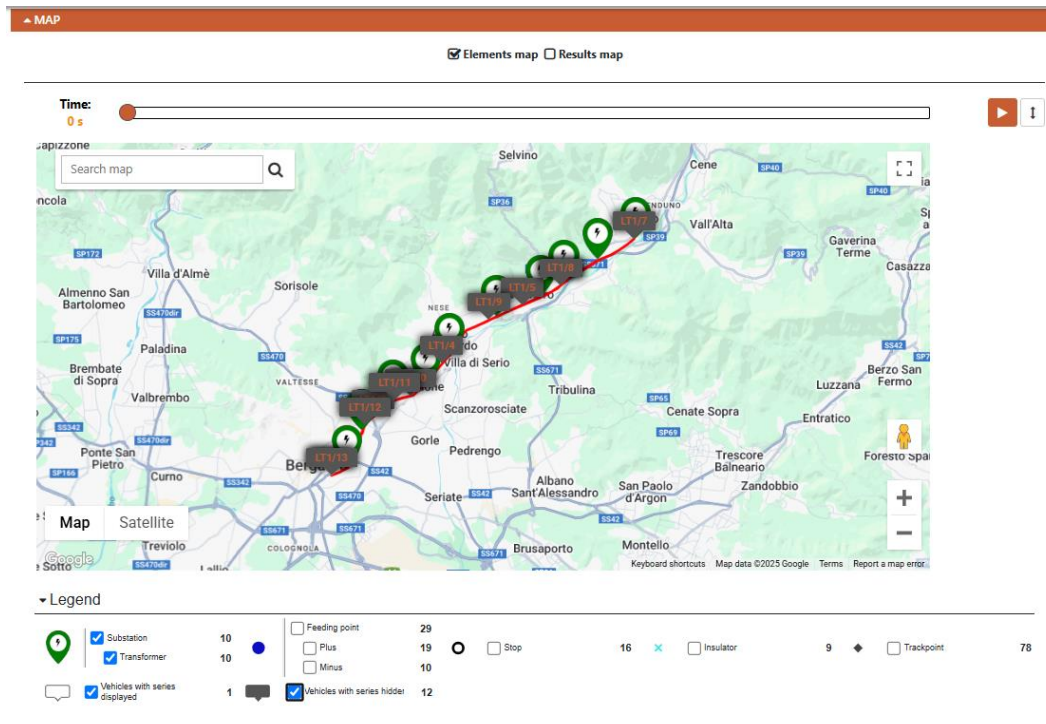
TRANSFORMERS

TRACK SECTIONS

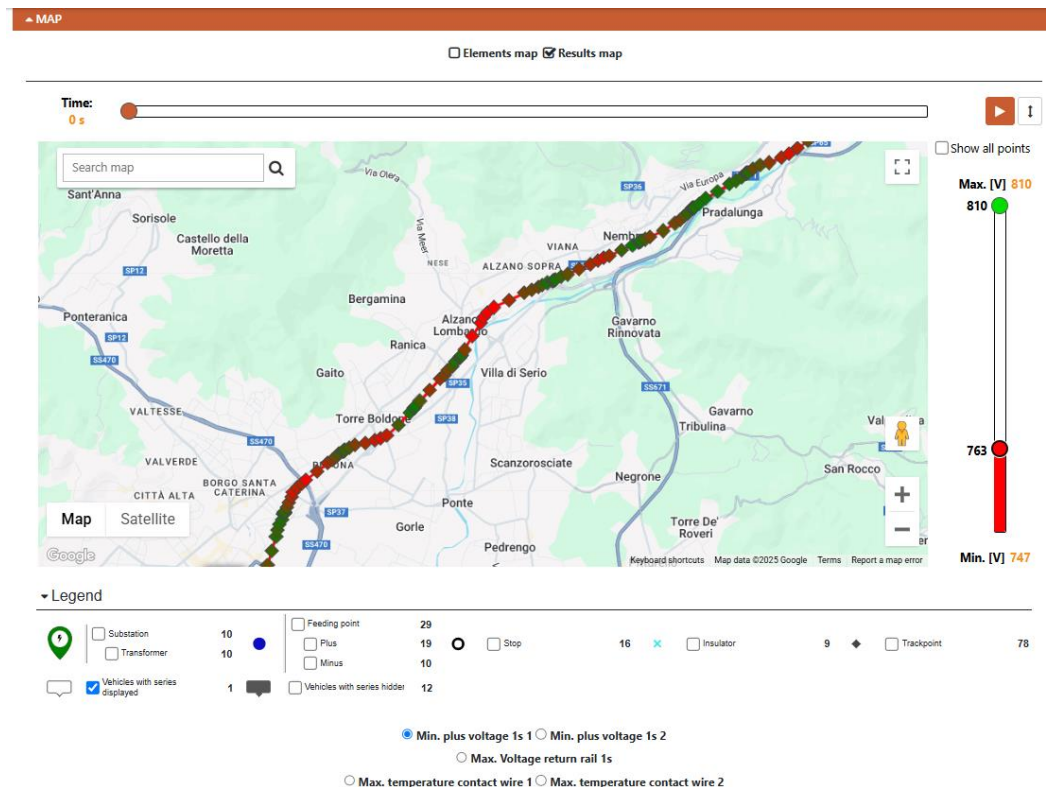
POSITIVES FEEDERS

NEGATIVE FEEDERS

SWITCHES



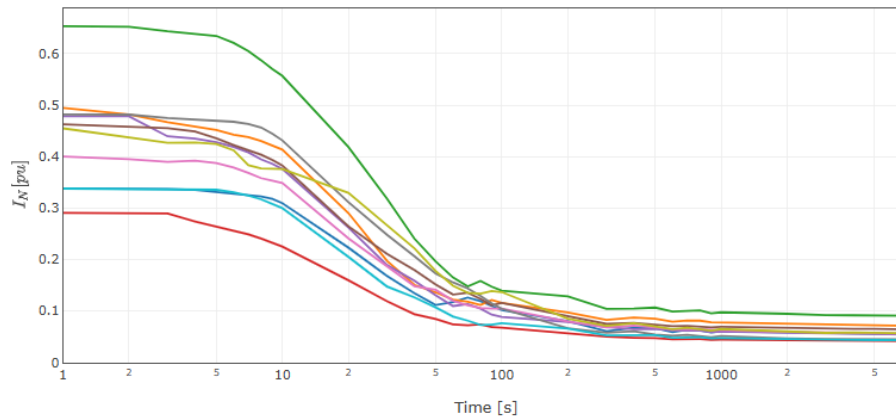
The results can be plotted in a graphical visualisation to easily understand and interpret the situation in the different scenarios. Like this, problems can be identified, solutions can be easily suggested and studied, and effective improvements can be applied with significant effect in daily operation.





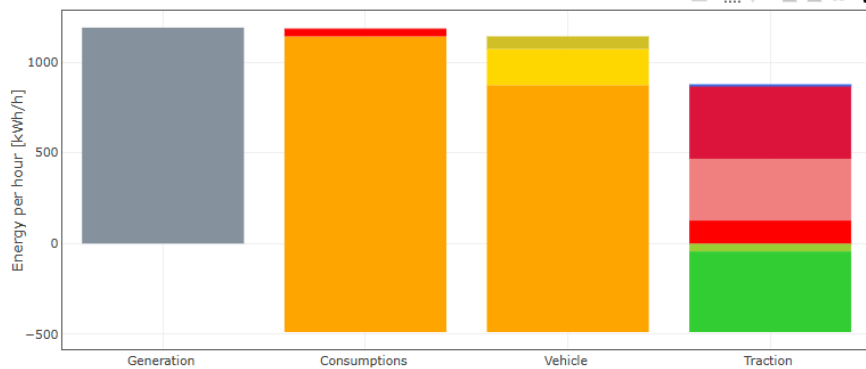
Transformer ▼

Load diagrams

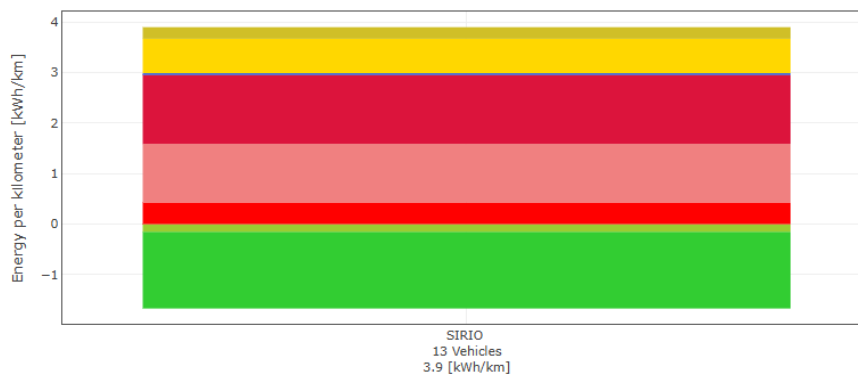


- ✓ David TR1
- ✓ SanFermo TR1
- ✓ SanPellico TR1
- ✓ Deposito TR1
- ✓ AlzMaggiore TR1
- ✓ AlzSopra TR1
- ✓ NemCentro TR1
- ✓ NemSaletti TR1
- ✓ Pradalunga TR1
- ✓ Albino TR1

Energy balance



Vehicles energy





Reporting and documentation

The documentation of project progress and findings is an integral part of the Bergamo pilot. KRUCH has maintained detailed technical records on system design, hardware installation, and data validation procedures. All modifications and integration steps were recorded in compliance with applicable norms and are available for future reference or replication.

The following documentation formats have been applied:

- Status reports submitted as part of CE4CE project reporting
- Technical documentation of sensor configuration and data interface design
- Joint analysis summaries prepared after each coordination meeting with ATB
- Preparation of workshop materials for the upcoming review event in Bergamo

The insights gained during the monitoring phase and consolidated through structured reporting will directly inform the next development stages of CE4CE. These findings contribute not only to technical refinement but also to the strategic integration of predictive maintenance in circular public transport systems.

9. Best practices

As part of the CE4CE pilot project in Bergamo, not only was an innovative predictive monitoring solution developed and implemented, as well as an “energy flow simulation” for electrical studies, but insights from comparable European initiatives were also taken into account. Particular attention was given to good practices in the fields of digital infrastructure monitoring, circular procurement, and predictive maintenance. The pilot in Bergamo demonstrates how modular, sensor-based systems can contribute to extending the life cycle of infrastructure components while supporting broader goals of sustainability and efficiency in public transport.

Examples of good practice from Europe

- **Circular Public Procurement (Italy, EU level):**
In Italy, national guidelines for Green Public Procurement (GPP) promote in accordance with EU-communication 2008/400 the integration of environmental criteria into tenders. These include requirements for energy efficiency, durability, and lifecycle cost considerations. The CE4CE pilot in Bergamo aligns with this logic by emphasizing preventive action and long-term infrastructure resilience.
- **Lifecycle-Based Electrification (Czech Republic, Slovenia)**
Pilot regions in other Interreg projects have implemented electrification projects with strong emphasis on total cost of ownership (TCO) and long-term performance data. The Bergamo pilot similarly highlights the value of long-term asset monitoring to guide investment and operational decisions.
- **Predictive Maintenance in Urban Rail (Austria, Germany)**
Several urban rail operators across Europe are now testing AI-supported condition monitoring for trams and infrastructure. The CE4CE pilot in Bergamo reflects this trend by integrating multi-sensor data and localized processing to detect early anomalies in the pantograph-overhead contact line interface.



CE4CE Pilot in Bergamo - distinctive features

The pilot in Bergamo is characterized by its compact yet high-impact implementation strategy, tailored to the specific conditions of a mid-sized urban transport system. It demonstrates how even modest interventions can significantly improve infrastructure knowledge and maintenance strategies.

Technical Features:

- Modular sensor units assembled and tested in advance
- GNSS, acceleration sensors, and high-resolution cameras
- CAN-bus integration and onboard edge computing
- Data transmission via secure communication modules

Monitoring and Evaluation:

- Real-time detection of vibration patterns and pantograph dynamics
- Visual assessment of contact line conditions
- Validation of anomalies in cooperation with ATB experts
- Comparison of measured data with simulated scenarios (EFS)

Impact on Energy Efficiency and Sustainability:

- Reduced risk of infrastructure failure through early detection
- More efficient use of maintenance resources
- Extended service life of critical components
- Foundations for energy optimization through behavior-based insights

Transferability and Strategic Recommendations

The system's modular and self-contained design allows for easy replication in similar tramway networks, particularly in small and medium-sized cities. Key success factors include:

- Full preassembly and testing before installation
- Clear division between data collection and analysis, preserving flexibility
- Strong coordination with the infrastructure operator (ATB)
- Integration without major intervention in vehicle structure

The CE4CE pilot in Bergamo proves that circular economy principles can be applied not only at the procurement or end-of-life stages, but also within the operational phase of public transport systems. Intelligent usage, condition-based maintenance, and data-informed decisions represent a presently rarely implemented, yet highly effective, pathway toward sustainable urban mobility.

10. Risks and contingency approach

As part of the CE4CE pilot project in Bergamo, a systematic approach was taken to identify, evaluate, and manage potential project risks. The objective was to anticipate technical, operational, and organizational challenges at an early stage and to define effective mitigation strategies in close coordination between KRUCH, ATB and Redmint.



Technical risks

One of the primary technical risks involved the integration of new sensor technology into existing tram infrastructure. To minimize the risk of hardware incompatibility, data loss, or system instability, all components – including GNSS, acceleration sensors, and onboard edge computers – were fully assembled and tested in advance at KRUCH's Vienna facility. The modular design and use of proven components helped reduce complexity during installation. Interfaces with the CAN-bus system were strictly designed as “read only” connections and carefully evaluated to avoid disruption to existing vehicle electronics.

Operational risks

Installing and operating monitoring systems for infrastructure segments during live public transport operations required careful planning to avoid service interruptions. Installation activities were scheduled in coordination with ATB's technical team and were aligned with regular maintenance intervals to reduce operational impact. Additionally, tram drivers and maintenance personnel were informed in advance and trained to handle the new system components installed in an selected pilot test tram safely and effectively.

Organizational risks

Although the project involved fewer external service providers compared to other CE4CE pilots, clear role definitions and consistent communication between KRUCH and ATB remained essential. Regular coordination meetings, shared documentation (e.g. action lists), and direct communication channels ensured that responsibilities were clearly understood, and potential delays avoided.

Financial risks

To avoid budget overruns, all technical and logistical measures were planned and costed in detail in advance. Since KRUCH acted as both system developer and integrator, internal procurement and testing allowed cost control and efficient resource allocation. The pilot remained within the financial scope of the CE4CE project framework and required no additional public tendering or external financing.

Contingency measures

For each identified risk area, KRUCH prepared contingency measures in advance. These included fallback hardware configurations, software reconfigurations in the event of data transfer issues, and alternative installation scenarios to accommodate local conditions. In case of deviations from the original timeline, a flexible installation schedule was in place. Continuous monitoring of technical progress and risk tracking were carried out during regular coordination sessions between KRUCH and ATB.

This structured risk management approach ensured that the pilot could be implemented smoothly and adaptively, even under changing technical or operational conditions. The delay caused by the shift of funds for the procurement of sensor units and devices from ATB to Kuch could be compensated by stringent project management. The lessons learned will inform future replications and scaling of the solution in other public transport environments.

11. Pilot impact and sustainability

Preliminary results from the CE4CE pilot project in Bergamo indicate that the use of sensor-based digital monitoring systems can provide tangible benefits in terms of infrastructure longevity, maintenance efficiency, and operational sustainability. While the full evaluation and data analysis are still ongoing, several initial impacts can already be observed.



Impact on Infrastructure and Operations

Extended lifespan of overhead line components:

Continuous monitoring of the pantograph-contact line interaction enables early detection of wear, alignment deviations, or irregularities in mechanical contact. This contributes to prolonging the service life of overhead wires and pantograph consumables, such as carbon strips.

Early identification of infrastructure anomalies:

Vibration and acceleration data, combined with GNSS positioning and visual inspection via cameras, allow for the timely recognition of unusual movement patterns or potential structural weaknesses. This supports condition-based maintenance and reduces the risk of larger-scale failures.

Reduction of unplanned service interruptions:

By shifting from reactive to predictive maintenance, the system helps prevent acute failures and enables proactive scheduling of repairs. This enhances infrastructure reliability and minimizes disruptions to public transport services.

Improved infrastructure availability:

Preventing cascading damage — such as catenary damage resulting from undetected pantograph issues — leads to fewer downtimes of route sections resulting in less service interruption leading to higher customer satisfaction.

Foundations for energy optimization:

Although direct energy consumption analysis is not a central focus of the Bergamo pilot, the combination of positional data, speed, and pantograph performance lays the groundwork for future applications in energy flow monitoring and efficiency evaluation.

Contribution to the Attractiveness and Sustainability of Public Transport

The pilot in Bergamo demonstrates how relatively low-intrusion digital technologies can enhance the resilience and performance of urban transport systems. The benefits contribute to:

- Greater reliability and safety of service for passengers
- More efficient allocation of maintenance resources
- A measurable reduction in infrastructure-related emissions and resource use

By enabling informed decision-making, prioritization of maintenance, and early fault detection, the system strengthens the role of public transport as a cornerstone of sustainable mobility in medium-sized cities like Bergamo.

At the time of reporting, detailed data analysis and system calibration are ongoing. A comprehensive assessment of the system's quantitative effects will be conducted during the final phase of the CE4CE project and will feed into the consolidated development of the "CE4CE Solutions."

12. Transferability of the pilot action

The modular monitoring solution developed and tested in the CE4CE pilot project in Bergamo demonstrates a high level of transferability to other public transport operators and urban infrastructure systems. The challenges addressed by ATB Bergamo—such as maintaining infrastructure quality, avoiding unplanned service disruptions, and improving the efficiency of maintenance practices—are common across European cities, particularly those with ageing assets and growing operational demands.



The core strength of the Bergamo pilot lies in the use of preassembled, self-contained sensor units that include rail-compatible hardware (e.g., GNSS, acceleration sensors, onboard edge computers) and standard interfaces (CAN-bus, communication modules). The system was designed and implemented in full compliance with applicable norms and operational practices, ensuring that it can be transferred to other vehicles, networks, or infrastructure settings without major redesign or re-certification efforts.

Concrete Transfer Potentials:

Within Bergamo and Lombardy:

The sensor system can be expanded to additional tram vehicles or deployed at fixed infrastructure points such as substations or depots. Its modular nature also allows for integration into regional transport systems operated by other agencies in Lombardy.

To other cities and operators:

The solution is directly applicable to other small and medium-sized tram networks across Europe, particularly in urban environments with similar operational constraints and infrastructure typologies.

To other vehicle types:

The underlying technology platform is adaptable for use in regional rail, trolleybus, and potentially e-bus fleets, especially in contexts where overhead line monitoring or infrastructure-vehicle interaction is a critical factor.

Expansion of use cases:

The collected data and system architecture provide a solid foundation for further use cases, such as real-time condition diagnostics, fault prediction, integration into asset management tools, or linking with energy simulation and optimization platforms (e.g., EFS).

The broader adoption of such solutions offers clear economic and environmental benefits: more targeted maintenance, reduced lifecycle costs, improved service continuity, and better-informed investment planning. The CE4CE pilot in Bergamo therefore not only strengthens digital innovation and operational resilience in local transport but also provides a practical, scalable model for advancing circularity in public transport across Europe.

13. Annexes