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CE4CE

Guidelines for developing circular strategies in the public transport sector

Lessons learned from the CE4CE strategies and action plans

Imprint

Project

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

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List of Abbreviations

Abbreviation	Definition
AI	Artificial Intelligence
BESS	Battery Energy Storage System
BSR	Baltic Sea Region
CCC	Climate City Contract
EN	European Standard
eBRT	Electric Bus Rapid Transit
ESG	Environmental, social and governance
GIS	Geographic Information System
ISO	International Organization for Standardization
KPI	Key Perfromance Indicator
MR.pro®	Maintenance management software/system used by LVB
PV	Photovoltaic
SECAP	Sustainable Energy and Climate Action Plan
SMEA	Strategic Maintenance and Engineering Assessment (methodological reference linked to prioritisation/risk management)
SUMP	Sustainable Urban Mobility Planning
ZEDAS	Railway maintenance and asset management software system

List of project partners

Abbreviation	Definition
LVB	Leipzig Public Transport Company, Germany
PKA	Public Transport Bus Operator in Gdynia, Poland
UG	University of Gdańsk, Poland
SZKT	Szeged Transport Company, Hungary
Kruch	Kruch Railways Innovations, Austria
MOM	Municipality of Maribor, Slovenia
UM	University of Maribor, Slovenia
ATB	ATB Mobility Bergamo, Italy
Redmint	Redmint social enterprise, Italy
Mobilissmus	Mobilissimus Ltd., Hungary
TM	trolley:motion association, Austria
RUPPRECHT	Rupprecht Consult (consultant to LVB), Germany

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Executive summary

The Interreg Central Europe CE4CE project: Public Transport Infrastructure in Central Europe – facilitate transitioning to circular economy[1] , empowered 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 developed 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 aimed 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.

Furthermore, stakeholders from the public transport community cooperated in CE4CE to jointly develop and adapt processes and solutions as key enablers for the integration of circular economy principles, like data sharing concepts, new and innovative procurement guidance, product and business model designs, extended life-cycle assessment, and cost-benefit analysis methodologies.

CE4CE's partnership reflected the whole value chain and transport sector system perspective including 11 project partners from 6 Central European countries, ranging from public transport authorities/operators, industry and research to interest groups. To enlarge this cooperation, associated partners like the international networks ICLEI, UITP and EIT Urban Mobility were strategically involved as advisors to maximise communication outreach and knowledge transfer of project results.

One of the key success factors of the project was the collaboration among project partners, associated partners, external experts and advisors, who jointly developed outputs based on co-creation and peer reviews for take up by the public transport sector in Europe, e.g. pilot actions and solutions such as the CE4CE Circularity Compass self-assessment tool for public transport, the CE4CE Circularity Knowledge Platform, a web-based second-hand marketplace, strategies and pilot actions to increase resource-efficiency and pilots demonstrating use more, reuse and recycle approaches for the public transport sector. Each partner contributed practical experience, pilot activities and technical expertise related to energy systems, infrastructure and rolling stock. Together, they explored lifecycle-based approaches that improve resource efficiency, extend asset lifetimes, optimise energy use and support the transition towards more circular and sustainable public transport systems.

"Leipzig Public Transport Company places a strong emphasis on circularity within the company. Through initiatives like the Interreg CE4CE project, the company managed to take action towards optimizing and digitalising the local public transport services. We are proud to have led a team of specialists from across Central Europe in a common journey to advance on the pathway towards enabling the circular economy principles and mechanisms in the public transport sector. ***And the journey will not stop here!"***

-Stefan Röll, Project Manager CE4CE, Head of Infrastructure at Leipzig Public Transport Company (LVB)-

1 https://www.interreg-central.eu/projects/ce4ce/

1. Introduction to the CE4CE project

The CE4CE project, financed by the Interreg Central Europe programme, empowered 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. CE4CE aimed 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. To do so, CE4CE jointly developed 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.

The public transport sector is currently facing increasing challenges related to infrastructure ageing, operational reliability, cost efficiency, and the transition towards more sustainable and digitalised practices. In this context, the CE4CE activities, namely strategies, action plans, pilots and solutions, aimed to address circularity as a whole and involved aspects such as modernisation of maintenance management processes through the integration of innovative digital tools, predictive maintenance approaches, data-driven decision-making methods, second life of assets and procurement.

This handbook has been developed as a practical reference document to support transport operators, maintenance managers, technical staff, and project stakeholders in understanding and applying the methodologies, tools, and lessons learned throughout the project to translate circular economy principles into a public transport life-cycle logic. It support the knowledge transfer and replication of good practices across other public transport systems and organisations seeking to improve the efficiency, sustainability and circularity of their processes, including planning, procurement, operations, maintenance and end-of-life. It covers the project strategies and action plans developed jointly by the project partnes with contribution of support actors and experts.

For further information on the project pilots and solutions referenced in this document, a different handbook has been developed and is publicly available on the CE4CE project website.

2. Strategies for enhancing circularity in the public transport sector

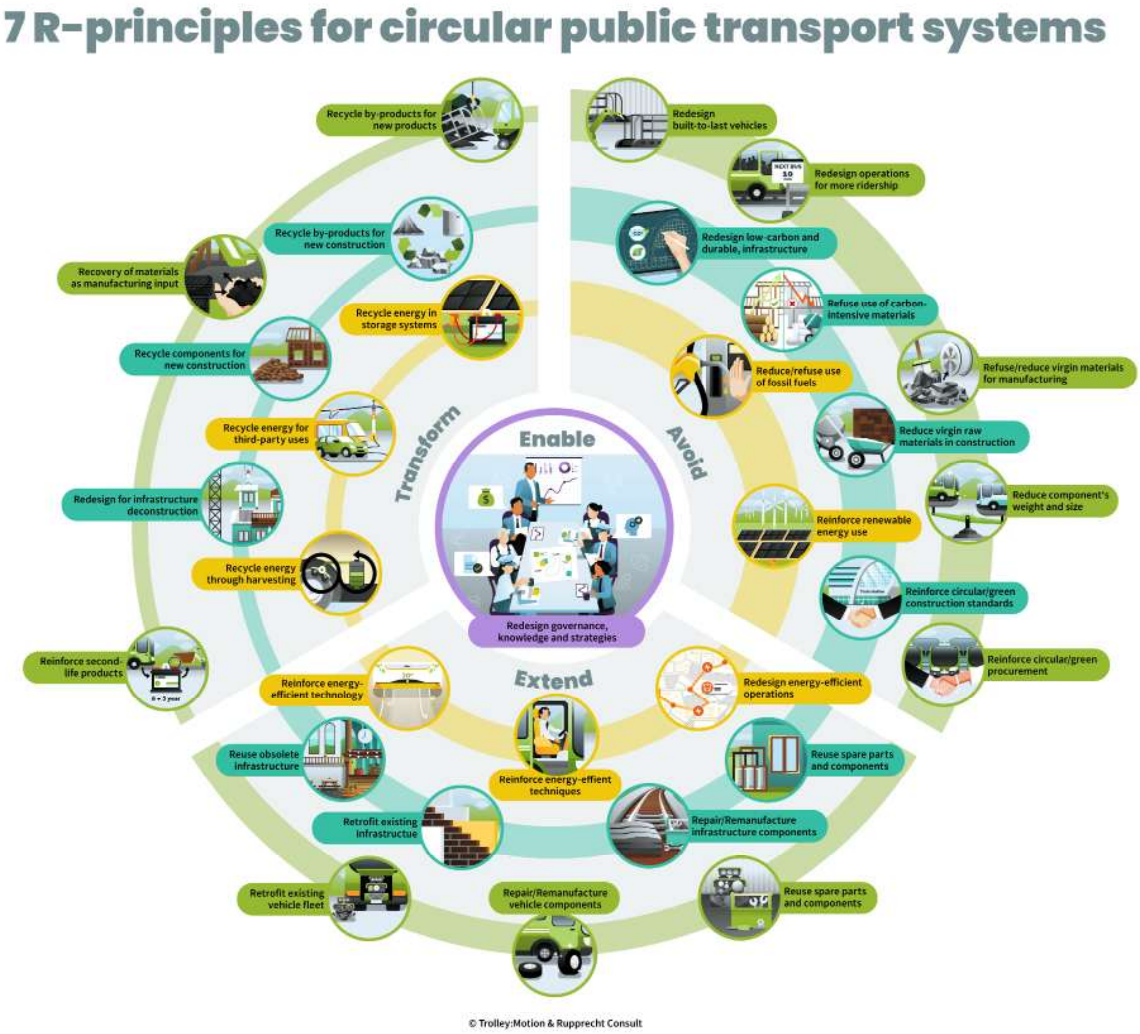

Figure 1. AVOID-EXTEND-TRANSFORM-ENABLE (AETE) Framework. Credits: trolley:motion association

Public transport is widely recognised as the cornerstone of sustainable mobility. However, while its operational emissions are generally lower than those of private transport, significant environmental impacts remain embedded in the life cycles of energy systems, infrastructure and rolling stock. These include not only use of resources and emissions during operational activities, but also embodied energy and emission from the use of raw materials, fossil fuels, and waste generated throughout manufacturing, construction, maintenance and end-of-life stages. In particular, materials such as steel, concrete, copper and critical raw materials used in infrastructure, fleets, and batteries represent both environmental and strategic challenges for European cities and regions.

Traditional linear models based on a take-use-dispose logic are no longer compatible with climate neutrality objectives, resource security, and long-term affordability of public transport systems. Recycling alone, while essential, is insufficient and applied only at the end of the life cycle. The CE4CE strategies therefore adopt the Avoid-Extend-Transform-Enable (AETE) life-cycle model as a common framework for integrating circular economy principles into public transport. Rather than focusing solely on waste management, the AETE approach promotes a systemic perspective that seeks to minimise resource consumption, maximise the utilisation and lifetime of assets, and create the enabling conditions for circular practices across planning, procurement, operation and end-of-life management. Through this framework, circularity becomes a strategic principle guiding decisions throughout the entire lifecycle of public transport systems.

The CE4CE strategies respond to this challenge by translating circular economy principles into concrete, sector-specific approaches for public transport energy systems, infrastructure and rolling stock. They aim to support public transport authorities and operators in moving from isolated circular measures towards systemic, life-cycle-based strategies that reduce waste, optimise resources, and create long-term value.

A common framework: the AETE life-cycle model

All three CE4CE strategies are built on a shared analytical and operational framework: the AVOID-EXTEND-TRANSFORM-ENABLE (AETE) life-cycle model for circular economy adoption.

- AVOID focuses on preventing waste and emissions at source, by refusing unnecessary resource use, reducing material and energy demand, and making informed design and planning choices.
- EXTEND aims to preserve value by prolonging the useful life of assets through maintenance, repair, refurbishment, reuse and second-life applications.
- TRANSFORM addresses end-of-life stages by enabling recycling, recovery and responsible disposal, ensuring materials are reintegrated into new value chains.
- ENABLE refers to the cross-cutting conditions that make circularity possible, including governance frameworks, procurement practices, digitalisation, standards, skills and collaboration across value chains.

Applying this framework consistently across energy, infrastructure and rolling stock ensures coherence between strategies and allows cities to identify synergies, avoid trade-offs, and prioritise actions with the highest systemic impact.

Overall goals of the CE4CE strategies

Taken together, the three CE4CE strategies pursue a set of shared overarching goals:

- Reduce embedded and operational environmental impacts across public transport systems.
- Optimise resource use and minimise waste throughout asset life cycles.
- Extend the lifetime and value of public transport assets, reducing the total cost of ownership.
- Strengthen resilience and autonomy by reducing dependency on virgin and critical raw materials.
- Enable innovation and new value chains, including reuse markets, refurbishment services, and digital solutions.
- Support cities and regions in translating circular economy principles into actionable, scalable practices.
- These goals are reflected in each thematic strategy while respecting the specific characteristics and challenges of energy systems, infrastructure assets and rolling stock.

EU regulatory framework supporting circularity and sustainability

The CE4CE strategies are fully aligned with, and reinforced by, the evolving European Union policy and regulatory framework for sustainability and circular economy. Key policy drivers include:

- The European Green Deal, setting the overarching objective of climate neutrality.
- The EU Circular Economy Action Plan, promoting life-cycle thinking, waste prevention and value retention.
- The Clean Vehicles Directive (EU) 2019/1161, encouraging low- and zero-emission public transport vehicles.
- The EU Battery Regulation, strengthening requirements on sustainability, traceability, reuse and recycling of batteries.
- Green public procurement (GPP) rules and guidance supporting circular procurement.

Within this context, CE4CE provides practical guidance to help public transport actors operationalise EU policy objectives, bridge gaps between regulation and implementation, and align local action plans with European sustainability goals.

2.1. Strategy to capture and optimize use of waste energy and renewable energy sources along new life cycle value chains

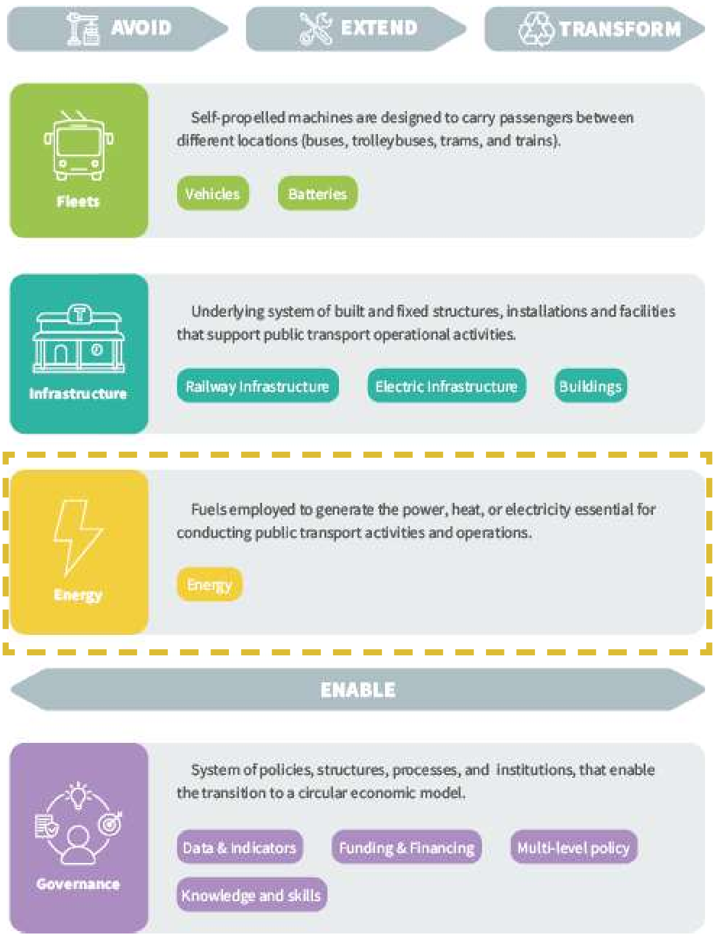

Figure 2. Energy sector in circularity compass structure

Energy use is one of the most critical leverage points for reducing the environmental footprint of public transport systems. While electrification of fleets significantly reduces tailpipe emissions, the overall climate and resource benefits depend strongly on how energy is sourced, managed, reused, and recovered throughout its life cycle. A linear approach to energy based on centralized fossil-based electricity, inefficient charging, and disposal of energy-related assets risks shifting emissions upstream and locking public transport systems into resource-intensive pathways.

A circular economy approach reframes energy as a value stream rather than a consumable input. By prioritising renewable energy sources (RES), capturing waste energy, extending the life of energy assets (especially batteries), and reintegrating energy flows into the system, public transport can significantly reduce operational emissions, embedded emissions, and long-term costs. The CE4CE strategy builds on the Avoid-Extend-Transform-Enable (AETE) life-cycle framework to ensure that circularity is addressed from energy sourcing to end-of-life management.

Specific objectives of the strategy are to:

- Reduce dependency on fossil-based and carbon-intensive electricity.
- Maximise the use of locally generated renewable energy in public transport operations.

- Capture and reuse waste energy (e.g. regenerative braking, surplus renewable generation).
- Extend the lifetime and value of energy-related assets such as batteries and charging infrastructure.
- Enable systemic integration between energy, transport, and urban infrastructure actors.

2.1.1 Approaches

The approaches should translate the energy strategy into practical measures that public transport actors can implement in planning, procurement, operation and end-of-life management. Fleet electrification remains the main entry point, but it should not be treated as a stand-alone solution. Decisions on electric buses should be linked from the outset to charging location, route characteristics, battery type, grid capacity and renewable energy availability. Procurement can play a key role by requiring efficient charging systems, compatibility with open standards, access to battery health data, modular components, and clear arrangements for battery take-back, reuse or recycling.

Charging infrastructure should be planned around actual operational needs rather than applied uniformly across the network. Overnight depot charging can be appropriate where buses have sufficient range and longer parking times, while fast or opportunity charging can support high-frequency routes with short layovers. The choice should consider peak electricity demand, available grid capacity, urban space constraints, charger-bus compatibility and the effect of charging patterns on battery life. Multi-purpose charging hubs can also improve infrastructure efficiency by serving different electric mobility services from the same system, reducing duplication and making better use of limited urban space.

Smart charging and energy storage should be used to reduce pressure on the electricity grid and improve the cost-efficiency of operations. By shifting charging to off-peak periods, controlling charging intensity and using stationary storage during peak demand, operators can lower network fees, avoid power peaks and reduce the need for costly grid upgrades. Storage systems can also support service reliability by acting as a buffer during high-demand periods or grid constraints. Where technically and legally feasible, second-life batteries can be repurposed for stationary storage at depots or charging points, extending their value before recycling.

Renewable energy integration should be prioritised at depots, charging stations and other suitable public transport assets. Solar energy is particularly relevant because it can be installed on existing buildings or transport infrastructure and combined with storage to increase on-site use. This allows surplus renewable electricity to be stored and used later for bus charging, reducing dependence on centralised fossil-based electricity. The design of renewable energy systems should consider available surface area, local irradiation, inverter efficiency, shading, maintenance needs and the match between generation patterns and charging demand. Waste energy recovery should be explored where existing transport systems create usable energy flows. Regenerative braking in rail, tram and metro systems can recover energy that would otherwise be lost and reuse it within the network, store it, or potentially redirect it to other charging needs. Such solutions are most effective where technical infrastructure, storage capacity and regulatory conditions allow recovered energy to be captured and redistributed efficiently.

End-of-life management should be planned before batteries and energy assets reach the end of service. Batteries that no longer meet vehicle performance requirements may still be suitable for less demanding stationary applications, but this depends on reliable state-of-health assessment, safety checks and clear responsibilities between operators, manufacturers, recyclers and waste management companies. When reuse is no longer possible, recycling should recover valuable materials and reduce reliance on virgin critical raw materials. Digital battery passports, transparent ownership arrangements, standardised procedures and cooperation across the value chain are essential to make reuse and recycling feasible at scale.

2.1.2 Key enablers

Successfully implementing circular economy energy strategies in public transport depends not only on technical measures, but also on the presence of enabling conditions that support coordination, learning and long-term transformation. Across energy systems, infrastructure and rolling stock, the CE4CE strategies identify four mutually reinforcing enabler areas: digitalisation, governance, innovation and technology.

Digitalization	Governance	Innovation	Technology	Additional Enablers
Deployment of energy management systems to monitor, optimise and control energy flows across depots, charging infrastructure and vehicles.	Integration of renewable energy and circularity objectives into energy and transport strategies at local and regional level.	Pilot and demonstration projects testing new energy integration models, such as local renewable generation combined with storage.	Deployment of renewable energy technologies, particularly solar PV integrated into depots and charging facilities.	Capacity building for energy management within public transport authorities and operators.
Use of smart charging solutions to align charging profiles with renewable energy availability, off-peak tariffs and grid constraints.	Use of public procurement and energy sourcing policies to prioritise renewable electricity and low-carbon energy carriers.	Experimentation with energy recovery and reuse solutions, including regenerative braking and stationary storage.	Use of energy storage systems, including stationary storage and second-life batteries.	Access to funding and financing instruments supporting renewable energy and storage investments .
Application of real-time monitoring and data analytics to improve energy efficiency and detect losses.	Establishment of long-term energy partnerships with utilities and grid operators.	Collaboration with research institutions, energy providers and technology developers to test innovative solutions.	Implementation of regenerative braking and energy recuperation systems in electric and rail-based transport.	Availability of standards and guidelines for energy efficiency, charging and storage systems.
Use of digital tools to monitor battery performance and degradation, supporting optimal use and lifetime extension.	Alignment with EU and national energy and climate regulations, including renewable energy targets and emissions reduction objectives.	Participation in sector initiatives and knowledge-exchange platforms addressing energy efficiency and electrification in public transport.	Adoption of efficient electric propulsion systems and optimised charging technologies.	Cooperation with energy and grid stakeholders to ensure system integration and flexibility.

Development of digital models and simulations to support planning of charging infrastructure, energy storage and renewable integration.	Clear definition of roles and responsibilities for energy management across public transport organisations.	Use of CE4CE pilot activities as learning environments to reduce risks and support replication.	Use of mature, high-efficiency energy supply solutions, such as trolleybus systems and in-motion charging where relevant.	Monitoring frameworks and indicators to track energy performance and circularity outcomes.
Integration of energy data into broader fleet and operational management systems.			Continuous evaluation of energy technologies using life-cycle and system-level performance criteria.	

Table 1. Key enablers of energy strategies in public transport

2.1.3 Good Practice Examples

Reinforce energy-efficient technology

Good practice 1:

Fast Charging to Maximize Operational Efficiency and Cost Savings

Location: Barcelona, Spain

Focus Area: Reinforce energy efficient technology

Charging infrastructure at bus stop

Objectives: Deploying high-power (400 kW) fast-charging infrastructure at terminal stops to reduce dependence on large onboard batteries, lower energy and operational costs, and demonstrate that fully electric bus lines could operate reliably without diesel backup.

Challenges:

- Maintaining grid stability under high peak loads
- Managing thermal constraints during rapid charging
- Ensuring charger–bus compatibility with manufacturers
- High upfront costs and logistical complexity of high-power infrastructure

Conclusion: The use of high-capacity fast chargers led to energy cost savings of approximately 68%, while maintaining full schedule adherence and operational efficiency. Barcelona's success demonstrates that fast charging can significantly reduce operational costs and enable high-demand electric bus service without major scheduling changes. Cities with dense urban routes and regular terminal stops can benefit from strategically located fast chargers, which reduce the need for oversized batteries and increase vehicle uptime.

Source: TMB Barcelona Public Reports & ELIPTIC Deliverables. https://www.sustainable-bus.com/electric-bus/solaris-delivers-three-articulated-urbino-electric-to-tmb-barcelona/, https://arquivo.pt/wayback/20201230033847/https://eliptic-project.eu/

Recycle energy in storage systems

Good practice 2:

Integrating second-life batteries and solar energy for bus charging

Location: Maribor, Slovenia

Focus Area: Recycle energy in Storage System

The battery bank

Objectives: implement a battery bank utilizing repurposed second-life batteries, powered by renewable energy sources (RES), to support the fast charger at Vzpenjača station.

Challenges:

- High dependence on grid power at the fast-charging station
- Technical, regulatory, and economic constraints for battery integration
- Ensuring stable e-bus charging under different operating conditions

Conclusion: By implementing second-life batteries for e-bus charging, the Maribor pilot showcases how circular economy models can optimize energy use, reduce costs, and improve public transport efficiency. This initiative serves as a blueprint for future investments in sustainable urban transport infrastructure.

Source: https://circularity4publictransport.eu/best_practice/use-of-used-batteries-to-store-energy-for-powering-a-fast-charger/

2.2. Strategy to add and recapture value and optimise delivery of public transport infrastructure along new life cycle value chains

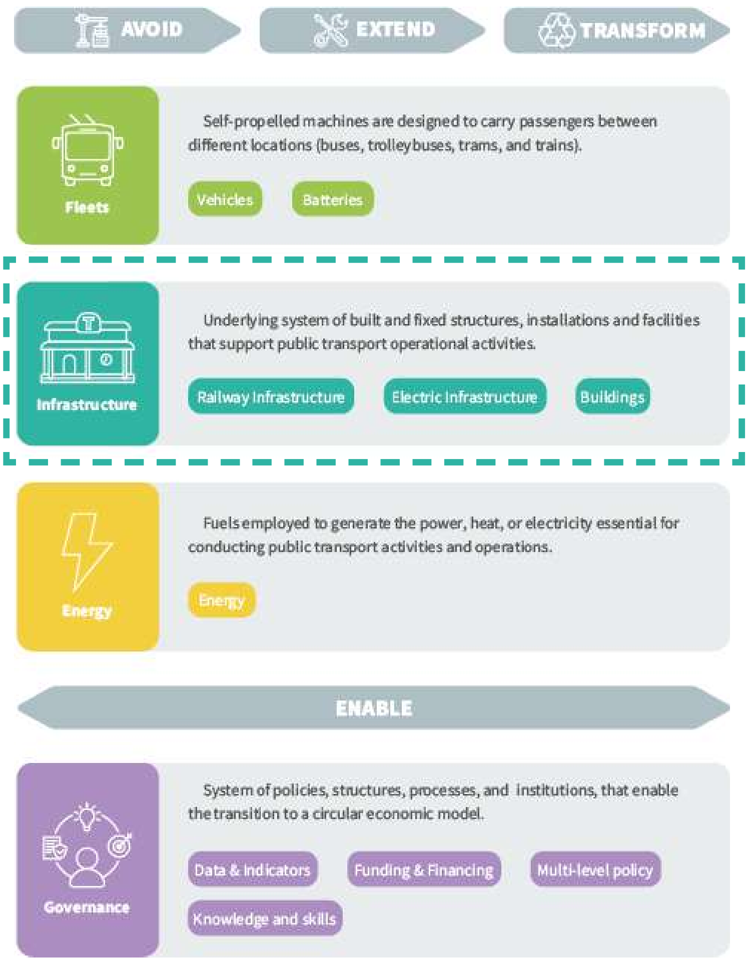

Figure 3. Infrastructure sector in circularity compass structure

Public transport infrastructure such as rail tracks, stations, depots, electric substations and operational buildings represents one of the largest sources of embedded emissions and material consumption in the transport sector. Emissions and environmental impacts are generated not only during operation, but predominantly during planning, construction, maintenance, and end-of-life phases, using carbon-intensive materials like concrete, steel and copper, and through linear construction and demolition practices

A circular economy approach allows public transport authorities and operators to shift from asset replacement to asset stewardship, maximising the value of infrastructure over long lifetimes while minimising waste and resource extraction. By applying circular principles across the full infrastructure life cycle design, construction, operation, maintenance and decommissioning public transport infrastructure can become more resilient, cost-efficient, and environmentally sustainable.

Building on the CE4CE Circularity Compass and the AVOID–EXTEND–TRANSFORM–ENABLE (AETE) framework, this strategy introduces a systemic approach to infrastructure that prioritises early design decisions, life-cycle optimisation, and cross-value-chain collaboration

Specific objectives of the strategy are to:

- Reduce embodied carbon and material use in new infrastructure projects.
- Extend the lifetime and functional value of existing infrastructure assets.
- Enable reuse, repurposing and recycling of infrastructure components.
- Improve transparency and traceability of materials and assets across life cycles.
- Strengthen the role of public procurement and digital tools in driving circular outcomes.

2.2.1 Approaches

The circular strategy for public transport infrastructure shifts the focus from linear construction and replacement cycles toward long-term asset stewardship and life-cycle value optimisation. Infrastructure such as tracks, depots, stations and substations represents a major source of embedded emissions due to carbon-intensive materials like cement and steel. Decisions taken during planning and design therefore determine environmental and financial impacts for decades. Integrating circular principles at this stage allows public transport authorities and operators to avoid unnecessary material use, reduce over-dimensioning and prioritise durable, adaptable and modular solutions. Substituting virgin materials with recycled or lower-carbon alternatives and applying life-cycle assessment (LCA) and life-cycle costing (LCC) methods support informed investment decisions that balance environmental performance and economic viability.

During construction and operation, extending asset lifetime becomes the most effective circular lever. Preventive and predictive maintenance, supported by sensors, data analytics and digital asset management systems, enable operators to detect deterioration early and optimise intervention cycles. This reduces premature replacement, preserves embedded value and increases service reliability. Infrastructure components such as rails, ballast and electrical elements can often be reused within networks or reassigned to less demanding applications. Strengthening these practices requires coordination between operators, infrastructure managers and suppliers, as well as clearer asset inventories and condition monitoring systems.

To further unlock value retention, second-hand markets and digital exchange platforms can facilitate the structured recirculation of components across networks. Transparent quality standards and traceability mechanisms are essential to build trust between actors and scale reuse beyond isolated cases. At the same time, procurement strategies should address supplier dependency and limited spare-part availability by encouraging modular design, repairability and long-term maintenance commitments.

At end-of-life, reuse should be prioritised before recycling. While metals such as steel and copper can be effectively recovered, other materials require improved separation, logistics and collaboration with specialised recyclers. Embedding disassembly considerations already at the design stage enhances future recovery rates. Where reuse is not feasible, infrastructure can be repurposed for alternative functions, avoiding demolition-related emissions and preserving structural value.

Across all life-cycle stages, procurement and governance act as central enabling levers. By embedding circular criteria, life-cycle costing and performance-based requirements into tenders and contracts, public authorities can influence supply chains and promote innovation. Digital tools such as Building Information Modelling (BIM) and material tracking systems strengthen lifecycle transparency, support quantity optimisation and facilitate long-term asset management. Finally, successful implementation depends on internal capacity building and cross-sector collaboration linking transport, construction, waste management and energy stakeholders. Together, these approaches enable infrastructure systems to move from resource-intensive construction models toward resilient, value-retaining circular asset systems.

2.2.2 Key enablers

The circular transformation of public transport infrastructure requires more than technical adjustments; it depends on enabling conditions that support long-term, life-cycle-oriented decision-making. Digital tools, governance frameworks, innovation ecosystems and appropriate technologies create the foundation for reducing embedded emissions, extending asset lifetimes and improving value recovery. The following enablers provide the structural and organisational support needed to implement circular infrastructure strategies effectively and at scale.

Digitalization	Governance	Innovation	Technology	Additional Enablers
Use of BIM for lifecycle planning, material optimisation and design for disassembly.	Integration of circular objectives into infrastructure planning and investment strategies.	Pilot projects for reuse and refurbishment of infrastructure components.	Adoption of low-carbon and recycled construction materials.	Staff training and internal capacity building on circular infrastructure management.
Digital asset management systems to monitor condition, age and performance.	Systematic use of LCC and LCA in procurement and project evaluation.	Development of second-hand markets and exchange platforms.	Modular and standardised infrastructure components.	Access to financing for refurbishment and lifecycle-based investments.
Predictive maintenance tools (sensors, AI, data analytics) to extend infrastructure lifespan.	Circular procurement criteria promoting durability, modularity and recyclability.	Performance-based and service-oriented contracting models.	Advanced inspection and structural monitoring technologies.	Standardised guidelines for reuse and recycling.
Digital material inventories and passports to support reuse and recovery.	Clear responsibilities for maintenance, refurbishment and end-of-life phases.	Collaboration with research and construction sector innovators.	Efficient dismantling and material separation techniques.	Cross-sector cooperation between transport, construction and waste actors.
Development of digital models and simulations to support planning of charging infrastructure, energy storage and renewable integration.	Clear definition of roles and responsibilities for energy management across public transport organisations.	Use of CE4CE pilot activities as learning environments to reduce risks and support replication.	Use of mature, high-efficiency energy supply solutions, such as trolleybus systems and in-motion charging where relevant.	Monitoring frameworks and indicators to track energy performance and circularity outcomes.
Integrated data platforms to track embodied emissions and resource use.	Alignment with EU waste, construction and climate regulations.	Participation in European knowledge-sharing networks.	Upgradeable and adaptable infrastructure designs.	Monitoring frameworks and performance indicators.

Table 2. Key enablers of infrastructure strategies in public transport

2.2.3 Good Practice Examples

Refuse use of carbon-intensive materials

Good practice 1:

Applications of low-carbon materials in public transport facilities

Location: Naples, Italy

Focus Area: Refuse use of carbon intensive materials

Naples Central Station

Objectives: enhances the station's architectural quality and ensures structural stability and durability by utilizing timber as the primary structural element. This material offers structural reliability and cost-effectiveness while significantly reducing the environmental footprint. Furthermore, timber's lightweight nature allows for faster construction, reducing overall energy consumption during assembly.

Challenges:

- Durability and fire safety concerns
- Flexible structural behaviour causes difficulties ensuring reliable alignment and operation in stations with platform screen door.

Conclusion: This project proves that by integrating recycled and circular material such as timbers into public transport infrastructure, cities can achieve lower embodied carbon, increased resource efficiency, and enhanced lifecycle sustainability.

Sources: https://www.arup.com/insights/material-change-can-timber-play-a-role-in-sustainable-rail-infrastructure
https://www.archdaily.com/970506/new-images-reveal-embts-timber-central-station-in-naples

Reuse spare parts and components

Good practice 2:

Reutilizing heavily used trolleybus switches

Location: Szeged, Hungary

Focus Area: Reuse spare parts and components

Trolleybus in Szeged

Sources: https://circularity4publictransport.eu/best_practice/demonstration-on-how-to-prolong-the-lifespan-of-electric-public-transport-infrastructure-reutilizing-heavily-used-trolleybus-switches-in-szeged-hungary/

Objectives: replacing most heavily used trolleybus switches at critical locations with the new units and relocating the worn-out ones to lower-intensity network areas, namely the trolleybus depot at Körtöltés utca for their extended use.

Challenge: trolleybus switches experience varying degrees of wear and tear depending on their location and frequency of use.

Conclusion: the system benefits from both improved reliability at key junctions and prolonged use of valuable materials, aiming to double the typical 15-20-year lifespan of components. The initiative reduces waste and offers a scalable model for sustainable asset management in electric public transport. By aligning assets lifecycle management strategies with the circular economy principles promoted within the CE4CE project framework, Szeged solution will also provide a blueprint for other transport operators searching to adopt similar infrastructure reuse strategies.

2.3. Strategy to add & recapture value and optimise delivery of rolling stock/ vehicles along new life cycle value chains

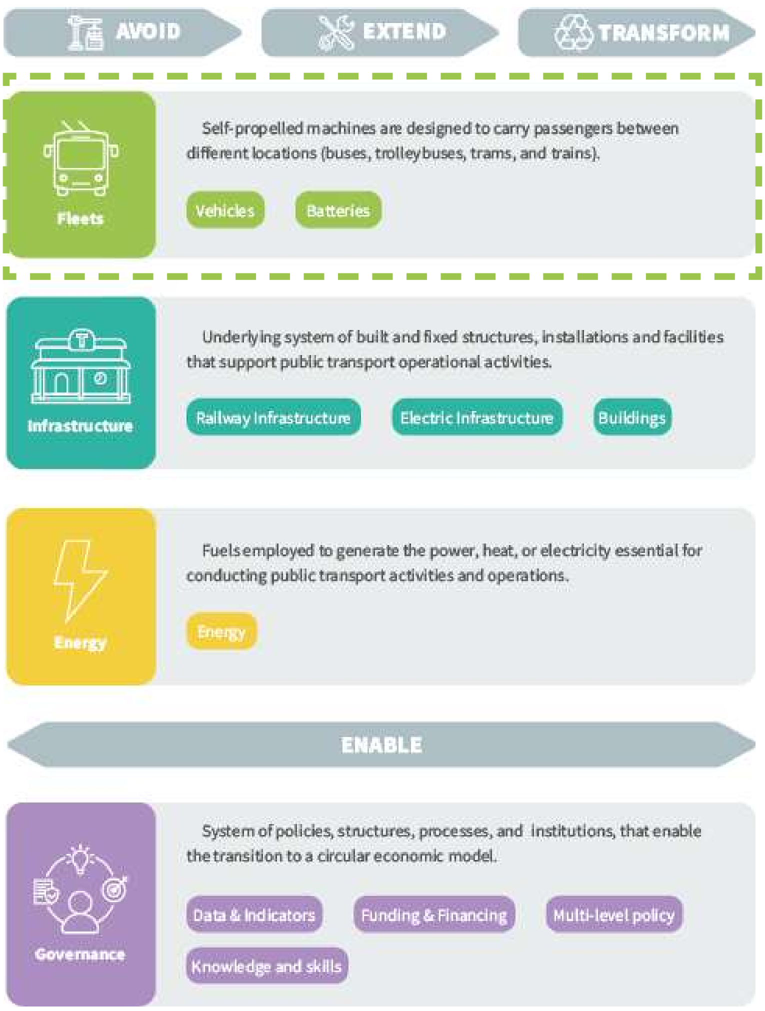

Figure 4. Rolling stock sector in circularity compass structure

Public transport - rolling stock buses, trolleybuses, trams and metro vehicles - plays a central role in the decarbonisation of mobility systems. Electrification is accelerating across Europe, but without a circular economy approach, this transition risks shifting impacts upstream, notably through the intensive use of raw materials, energy-intensive manufacturing processes, and growing waste streams at end-of-life, particularly for batteries and electronic components

A circular economy approach allows PTOs and authorities PTAs to move beyond vehicle replacement cycles and instead manage rolling stock as long-term value assets. By adopting life-cycle thinking in procurement, operation, maintenance, and decommissioning, circular strategies can reduce embedded emissions, extend vehicle lifetimes, optimise resource use, and create new value streams through reuse, refurbishment, and second-life applications.

Building on the CE4CE Circularity Compass and the AVOID-EXTEND-TRANSFORM-ENABLE (AETE) framework, this strategy addresses vehicles, batteries, and maintenance as interconnected sub-systems and identifies procurement as the key leverage point for systemic change

Specific objectives of the strategy are to:

- Minimise material and energy impacts during vehicle design and production.
- Extend the operational life of vehicles and key components.
- Enable reuse, refurbishment and repurposing of rolling stock and batteries.
- Improve traceability and responsibility across the rolling stock life cycle.
- Embed circular economy criteria into procurement and fleet management

2.3.1 Approaches

The circular strategy for rolling stock and vehicles focuses on managing buses, trams, metro vehicles and their components as long-term value assets rather than short replacement-cycle products. Electrification reduces operational emissions, but the production of vehicles and batteries remains resource-intensive and dependent on critical raw materials. A circular approach therefore addresses the full vehicle life cycle from design and procurement to operation, refurbishment and end-of-life management.

The strongest leverage point for circular rolling stock lies at the procurement and vehicle design stage, where decisions taken before a vehicle enters service can determine its environmental performance, maintenance requirements and end-of-life options for decades. Public transport authorities and operators can embed circular economy criteria directly into tender specifications by requiring life-cycle costing (LCC), life-cycle assessment (LCA), modular vehicle architectures, repairability, upgradeability, battery replaceability and high levels of material recoverability. For electric buses and other zero-emission vehicles, procurement specifications can also address battery durability, second-life potential, component standardisation, availability of spare parts and manufacturer responsibilities for take-back or refurbishment schemes. By integrating such requirements from the outset, authorities can avoid premature obsolescence, reduce resource consumption and extend vehicle lifetimes. This shifts procurement decisions away from a focus on upfront purchase costs towards total lifecycle value, operational resilience and long-term environmental performance. Procurement departments, manufacturers and suppliers therefore play a critical role, as contractual requirements directly influence vehicle design, material selection, maintenance models and circular business practices. Performance-based and service-oriented contracts can further incentivise durability, reparability and lifecycle optimisation rather than early replacement.

During vehicle design and fleet planning, circularity is strengthened by avoiding unnecessary material use and over-dimensioning. Optimising battery sizing, selecting efficient propulsion systems and choosing adaptable interior layouts reduce embedded emissions and improve operational efficiency. Digital simulation tools, fleet modelling software and digital twins support scenario analysis and technology comparison, enabling authorities to balance operational needs with resource efficiency.

Extending vehicle and component lifetimes represents another key measure. Preventive and predictive maintenance, supported by onboard diagnostics, sensors and AI-based monitoring systems, allows operators to detect degradation early and intervene before failures occur. Refurbishment programmes such as mid-life overhauls of buses or trams enable structural components to remain in service while updating critical subsystems. Operators, OEMs and maintenance providers must cooperate closely to ensure spare-part availability, technical documentation and long-term support.

Battery management is particularly central to circular rolling stock strategies. Batteries have different degradation profiles than vehicles and can often be repurposed for stationary energy storage once no longer suitable for traction use. Establishing second-life applications requires coordination between operators, energy providers, recyclers and technology integrators. Digital battery passports and performance monitoring tools enhance traceability and facilitate reuse, while compliance with evolving EU battery regulations supports structured recovery and recycling pathways.

At end-of-life, vehicles and components should be designed and managed to facilitate disassembly, material separation and high-quality recycling. Modular construction, reversible connections and clear documentation improve recovery rates and reduce waste. Collaboration between manufacturers, dismantlers and recyclers is essential to close material loops and reintegrate valuable metals and components into new production cycles.

Across all lifecycle stages, governance and internal capacity building are critical. Fleet renewal strategies should align with long-term climate and circular economy objectives, supported by transparent performance indicators and monitoring frameworks. Participation in sector networks and European initiatives enables operators to share lessons learned and accelerate replication of innovative approaches.

Taken together, these measures transform rolling stock management from a linear replacement model into a life-cycle-based value chain approach. By combining procurement leverage, digital tools, predictive maintenance, battery reuse and responsible end-of-life management, public transport authorities and operators can reduce material dependency, optimise lifecycle costs and strengthen resilience in the transition toward climate-neutral mobility systems.

2.3.2 Key enablers

The circular transformation of rolling stock requires more than improvements in vehicle technology; it depends on structural and organisational conditions that enable lifecycle optimisation. Digital tools, forward-looking procurement frameworks, innovation partnerships and appropriate technological choices provide the foundation for extending vehicle lifetimes, enabling battery reuse and ensuring responsible end-of-life management. The following enablers support public transport authorities, operators and suppliers in embedding circularity across the full rolling stock life cycle.

Digitalization	Governance	Innovation	Technology	Additional Enablers
Use of digital twins and fleet simulation tools for lifecycle-based fleet planning and technology comparison.	Embedding circular economy criteria in rolling stock procurement, including durability, repairability and recyclability requirements.	Pilot projects testing battery second-life applications and reuse models.	Adoption of modular vehicle design to enable repair, upgrading and easier disassembly.	Capacity building for procurement and maintenance teams on circular vehicle management.
Deployment of onboard diagnostics and predictive maintenance systems hto extend vehicle and component lifetimes.	Systematic use of life-cycle costing (LCC) and life-cycle assessment (LCA) in fleet renewal decisions.	Development of refurbishment and mid-life upgrade programmes for buses and rail vehicles.	Use of energy-efficient propulsion systems and regenerative technologies.	Access to financing mechanisms supporting refurbishment and lifecycle-based investments.
Implementation of digital asset management systems to monitor vehicle condition and performance.	Clear allocation of responsibilities for maintenance, refurbishment and end-of-life phases.	Service-oriented and performance-based contracting models encouraging durability.	Deployment of advanced battery management systems to optimise performance and lifespan.	Standardised guidelines for repair, reuse and recycling of vehicle components.
Introduction of digital battery passports to improve traceability, reuse and regulatory compliance.	Alignment with EU regulatory frameworks (e.g. Clean Vehicles Directive, EU Battery Regulation).	Collaboration with manufacturers, research institutions and start-ups on circular vehicle design.	Implementation of design-for-disassembly principles to improve recycling and material recovery.	Cross-sector cooperation between transport operators, energy providers and recyclers.
Integration of lifecycle data into fleet management platforms to support refurbishment and replacement decisions.	Long-term fleet strategies aligned with climate neutrality and resource efficiency objectives.	Participation in European and sector networks to exchange best practices and scale solutions.	Integration of adaptable charging and storage technologies to support evolving fleet needs.	Monitoring frameworks and performance indicators to track circular fleet performance.

Table 3. Key enablers of fleets strategies in public transport

2.3.3 Good Practice Example

Good practice 1:

Digital Twin E-corridor simulation tool

Location: Gdynia, Poland

Focus Area: Redesign operations for more energy-efficient solutions

E-Bus in Gdynia

Source: https://circularity4publictransport.eu/best_practice/a-digital-twin-a-circular-economy-business-tool-for-public-transport-planners-and-operators/

Objectives: A digital twin was developed to simulate different electrification and charging scenarios for the city's public transport corridors. The tool supports optimised battery sizing, infrastructure sharing and energy use, enabling resource-efficient fleet planning and extending asset lifetimes through informed decision-making

Challenges:

- Public transport is "low-carbon" but still resource- and waste-intensive
- Data availability + integration across vehicles and infrastructure

Conclusion: All in all, the digital twin can serve as a great starting point for a complex and precise cost-benefit analysis for integrated public transport electrification. In its final phase, based on peer-review and user-feedback, the simulation digital twin is to be transferred to a universal, handy and useful circular business planning tool for electrified public transport fleets and infrastructure.

Good practice 2:

second-hand diesel public buses converted into electric vehicles

Location: Ankara, Turkiye

Focus Area: Retrofit existing vehicle fleet

Retrofitted e-bus in Ankara

Source: : https://academic.oup.com/ijlct/article/doi/10.1093/ijlct/ctae049/7723583

https://aim2flourish.com/innovations/buses-that-come-alive-again-with-electricity-7

Objectives: accelerate the process of transitioning to a more carbon- and environmentally friendly vehicle solution for public transportation that extends the life of buses in a circular manner. In this innovation, the body, chassis, and axles are preserved in their original forms, with old power systems; instead of a diesel engine, transmission, and fuel system; electric motor, battery packs, and battery management systems by placing and it will be transformed into a 100% electric bus.

Challenges:

- Limited range, insufficient charging infrastructure, high initial purchase cost

Conclusion: In conclusion, converting old diesel buses into electric buses is a practical and sustainable way to modernize public transport while reducing waste and costs. The conversion can cost only 35-45% of a new electric bus, pay back in about 24 months, and provide up to 300 km of range after a 3.5-hour charge. Although research shows that converted buses may use more energy than newly built electric buses in some summer conditions, they still offer major environmental benefits, with retrofit studies showing 28–42% lower CO_2 emissions and 57–64% lower energy costs compared with diesel buses.

3. Action Plans for addressing essential challenges in the public transport sector

Building ovn the experiences and results of the CE4CE pilot activities and strategies, the four Action Plans presented in this handbook transform technical testing, stakeholder cooperation, and strategic reflection into implementation-oriented frameworks adapted to specific contexts of the project partners: Leipzig Public Transport Company – LVB (Germany), Gdynia Bus Operator - PKA (Poland), Bergamo Transport Company - ATB Mobility (Italy) and Municipality of Maribor (Slovenia). The CE4CE Action Plans address a wide range of challenges related to public transport infrastructure, rolling stock, energy systems, and operational management. Key topics include predictive maintenance, energy efficiency, circular procurement, infrastructure sharing, renewable energy integration, second-life use of batteries, and lifecycle-oriented asset management.

While each Action Plan reflects the specific needs and priorities of the participating institutions, all of them contribute to the common objective of reducing waste, preserving value, improving resource efficiency, and strengthening the long-term sustainability and resilience of public transport systems. The Action Plans developed for Maribor, Leipzig, Gdynia, and Bergamo demonstrate how circular economy principles can be integrated into mobility planning, infrastructure management, procurement processes, and operational practices through stakeholder cooperation, digitalisation, governance measures, and phased implementation approaches. At the same time, they provide transferable experiences and practical guidance for public transport authorities, operators, municipalities, and other stakeholders interested in applying similar approaches in their own urban and regional contexts.

3.1. Action plan to capture and use waste energy from trains, charge used batteries with renewable energy sources in Maribor, Slovenia

3.1.1 Strategic background and context for the action plan development

Figure 5. Strategic framework supporting the vision for public transport in Maribor (SUMP).

The Maribor Action Plan was developed within the CE4CE project as an update of the 2022 "Strategy for environmentally efficient multifunctional charging infrastructure" and it is strongly embedded in the municipal Sustainable Urban Mobility Plan (SUMP) process. It responds to the need to reduce energy consumption, emissions and inefficiencies in Maribor's public transport system by introducing circular and energy-efficient solutions. The plan is aligned with the Sustainable Urban Mobility Plan of Maribor – SUMP Maribor (updated in 2026), the Circular Economy Transition Strategy of the Municipality of Maribor 2024–2030, and wider EU frameworks such as the European Green Deal and Circular Economy Action Plan supporting the transition towards a decarbonised, energy-efficient and circular transport sector.

The main challenge addressed by the Action Plan is the growing electricity demand linked to the electrification of public transport. Maribor is moving from a fossil-based transport energy system towards a more concentrated electricity-based system, which requires stronger charging infrastructure, better energy management and reduced pressure on the electricity grid. Stakeholder analysis identified several concrete barriers: insufficient integration of renewable energy sources, lack of systematic battery energy storage systems, limited smart charging, underdeveloped reuse of batteries and components, and weak integration between transport, spatial and energy planning. Regulatory constraints between producers, distributors and consumers were scored as one of the most significant barriers, together with dependence on EU and municipal funding.

The Action Plan is not legally binding, but its measures are integrated into the Maribor SUMP, which gives them a stronger implementation basis. The plan therefore acts as an implementation-oriented framework linking mobility, energy and circular economy objectives.

3.1.2 Vision, targets and objectives

The vision of the Maribor Action Plan is to develop competitive, energy-efficient and sustainable public transport services using low-carbon technologies and alternative energy sources. The aim is to reduce emissions, improve air quality, lower noise levels in urban areas, decrease energy consumption for mobility, and establish a user-friendly, digital and socially accepted transport system. The Action Plan defines a phased transition towards a low-emission, energy-efficient and user-oriented public transport system through strategic dimensions and a set of medium- and long-term implementation milestones.

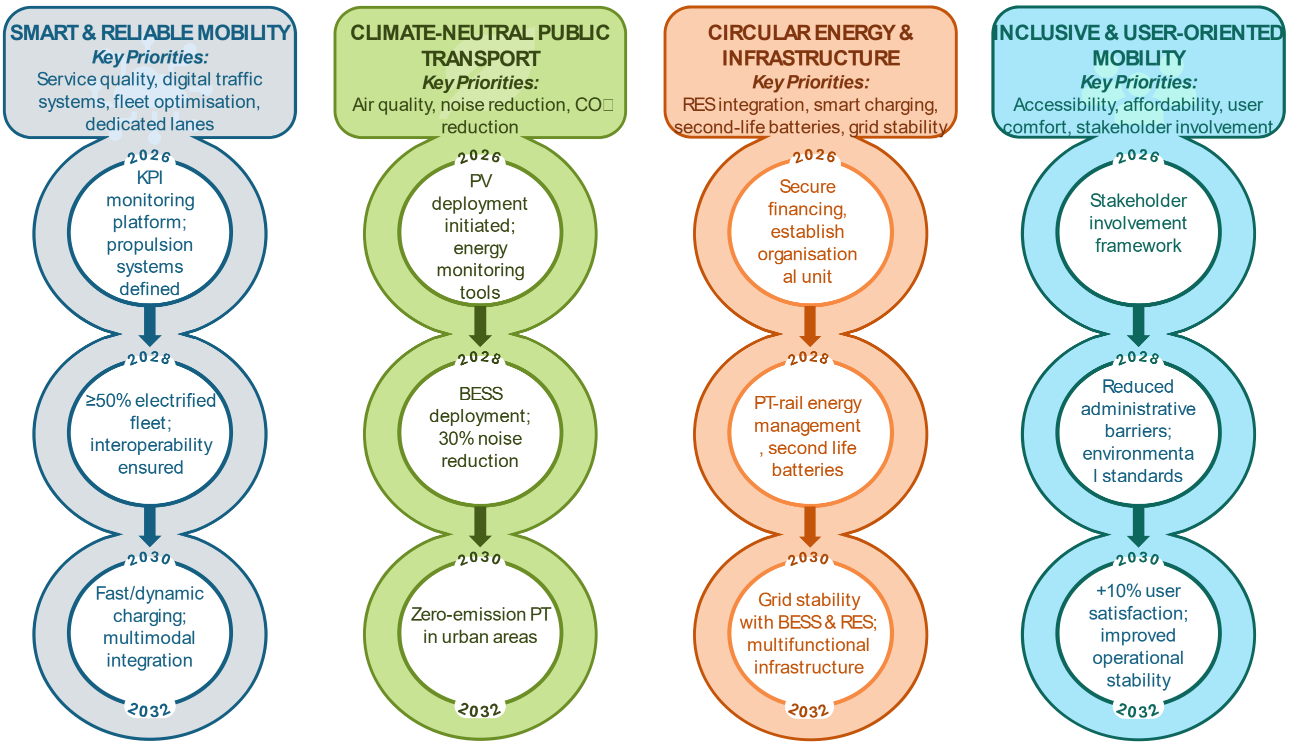

Figure 6. Maribor Action Plan vision and strategic objectives

3.1.3 Key Measures

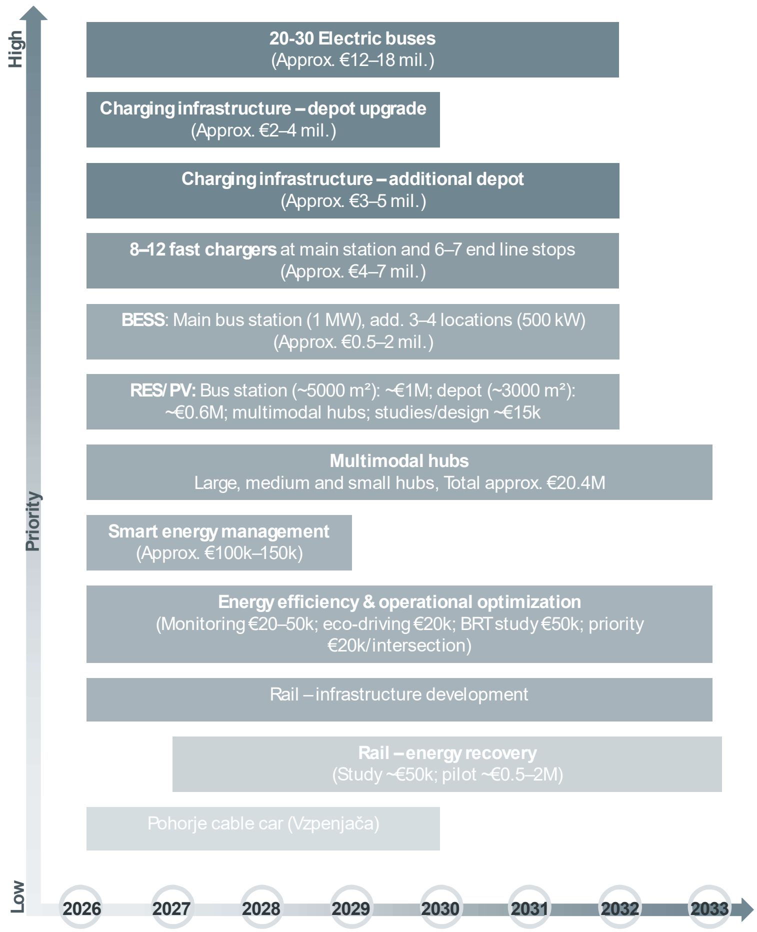

Figure 7. Maribor key measures and implementation timeline

The Action Plan proposes a package of infrastructure, energy, operational and governance measures. The proposed measures include electric bus deployment, charging infrastructure expansion, battery energy storage systems (BESS), and renewable energy integration through photovoltaic (PV) installations. Together, these actions aim to enhance operational performance, reduce emissions, and strengthen long-term energy resilience.

Estimated investments vary significantly depending on the measure, ranging from approximately €15,000 for preparatory studies to around €12-18 million for large-scale electric bus procurement. Most infrastructure-related actions are estimated within a medium investment range of approximately €0.5-7 million.

The implementation relies on a combination of funding mechanisms, with the most frequently referenced sources including local funds, EU funding programmes, the Slovenian Eco Fund, and contributions from the private sector, particularly for renewable energy investments.

Implementation is planned in phases between 2026 and 2032, involving cooperation between municipal authorities, public transport operators, technical partners, and other local stakeholders. The implementation timeline is defined in broader period ranges rather than specific years. A more detailed and operational timeline is provided within the Maribor SUMP, which serves as the main implementation framework for transport development in the city.

3.1.4 Monitoring and evaluation aspects

Monitoring of the Maribor Action Plan will be aligned with the annual monitoring and reporting framework of the Maribor SUMP but extended to include energy and circularity indicators. The Municipality of Maribor will coordinate data collection and processing together with the main stakeholders Marprom, Public Holdings Maribor, the Energy Agency, Elektro Maribor and the University of Maribor.

The monitoring system will use KPIs covering mobility, environment, energy, infrastructure, operations and user-related aspects. Mobility indicators include public transport travel time ratio, punctuality and reliability, passenger numbers and vehicle occupancy. Environmental indicators include CO_2 emissions, air pollutants such as NOx and PM where available, and urban noise levels. Energy indicators include energy consumption per vehicle or passenger, renewable energy share in the public transport energy mix, and peak load reduction from BESS. Infrastructure indicators include installed charging capacity, BESS capacity and PV capacity.

Data will come from fleet management systems, energy monitoring tools, charging infrastructure data, transport analytics, surveys, infrastructure monitoring and external datasets from energy providers. Evaluation will be carried out every 2–3 years and will compare achieved results with planned targets, assess cost-effectiveness, identify implementation barriers and success factors, analyse system-level impacts, and include stakeholder and user feedback. Results will be used to revise measures, refine investment priorities and maintain alignment with the SUMP.

3.1.5 Stakeholder engagement in the preparation and implementation process

Stakeholder engagement was organised through local workshops, expert consultations and within the framework for collaboration and joint development offered by the CE4CE project. The process involved municipal, regional, academic, energy, transport and private-sector actors, as well as the project partners. At municipal level, the main participants included the Municipality of Maribor, Marprom as the public transport operator, municipal infrastructure and public works actors, the local energy and district heating provider, and the public waste management company. Regional actors included the Regional Development Agency for Podravje–Maribor and the regional energy agency. The University of Maribor contributed as the main academic and research partner. Technology and private-sector input came from fast-charging infrastructure and electric bus distributors.

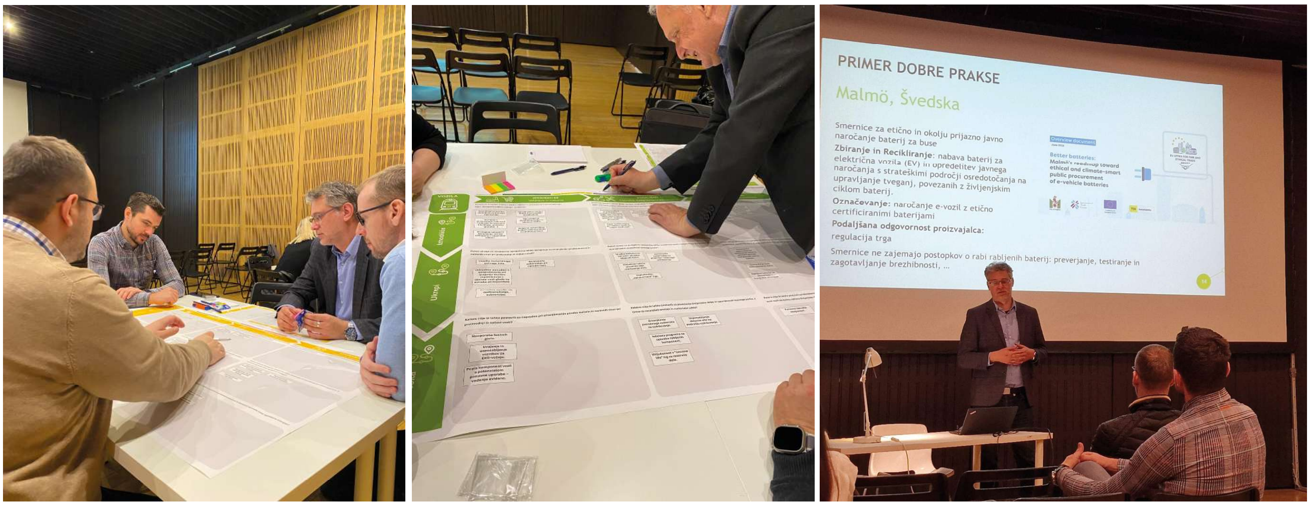

Figure 8. Stakeholder workshop on circular economy and energy in public transport. Credits: Municipality of Maribor, the CE4CE project.

The engagement process focused on identifying challenges and needs for applying circular economy principles in public transport, especially in relation to energy consumption, renewable energy, energy storage and reuse. Stakeholders assessed barriers such as weak integration of renewable energy, lack of smart charging, insufficient monitoring, regulatory constraints, complex permitting procedures, weak coordination between spatial, transport and energy planning, and underdeveloped systems for reusing components and batteries.

The process helped define the Action Plan's priorities, including BESS deployment, smart charging, PV integration, regenerative rail energy use, multimodal energy hubs and improved governance. It also strengthened cooperation between transport and energy stakeholders, which was identified as essential for implementation.

3.1.6 Main takeaways from the action plan development process

The development of the Maribor Action Plan provided important strategic and organisational insights for the transition towards a more sustainable, energy-efficient and circular public transport system. The process highlighted several important aspects relevant for future implementation and long-term urban mobility planning:

MAIN TAKEAWAYS

Strong integration with the SUMP process: The close alignment with the Sustainable Urban Mobility Plan (SUMP) ensures that the proposed measures are embedded within Maribor's long-term mobility, investment and monitoring framework.

Phased and flexible implementation: Due to evolving technologies, regulatory conditions and financial uncertainties, continuous monitoring, evaluation and adaptive management will be essential for ensuring long-term effectiveness and resilience of the proposed measures.

Integrated system approach: Electrification needs to combine transport, energy and spatial planning perspectives. The process confirmed that fleet electrification must be supported by coordinated planning of charging infrastructure, renewable energy integration, storage systems and energy management solutions.

Cross-sectoral cooperation: Stronger collaboration between transport operators, municipal departments, energy providers, infrastructure actors and research institutions emerged as a key enabling factor during the development process.

Digitalisation and data-driven management: Long/ term planning needs monitoring systems, KPI frameworks and optimisation tools. These elements are essential for making adaptive, efficient and evidence-based decision-making energy management solutions.

The importance of pilot and demonstration activities: Experiences from CE4CE demonstrated the importance of testing technologies and organisational approaches before scaling-up or wider deployment.

Institutional capacity and governance structures: The process highlighted the need for clear responsibilities, long-term stakeholder engagement and organisational readiness alongside technical solutions.

Figure 9. Maribor main takeaways

3.2. Action plan to optimise delivery of infrastructure through minimal invasive maintenance work in Leipzig, Germany

3.2.1 Strategic background and context for the action plan development

The Leipzig Action Plan was developed by the Leipzig Transport Company (LVB) within the CE4CE project to explore opportunities for improving infrastructure maintenance through minimally invasive, predictive, and data-driven approaches. The initiative responds to the limitations of traditional maintenance practices, which continue to rely heavily on visual inspections, fixed renewal cycles, and reactive interventions.

The need for more advanced maintenance approaches is particularly relevant for LVB, which operates one of Germany's largest tram networks with more than 300 km of track and high service frequencies. Increasing passenger demand, population growth, mobility transition policies, and expanded night services place growing pressure on infrastructure availability and maintenance efficiency. At the same time, maintenance activities are influenced by challenges such as skilled labour shortages, demographic change, reduced availability of concrete and deep expertise, limited maintenance windows, and incomplete condition data.

Against this background, the Action Plan aims to support a gradual transition from reactive towards predictive asset management and maintenance practices. The approach builds on experiences from the Leipzig CE4CE pilot tests, in which three tram vehicles were equipped with vibration sensors, cameras, laser scanners, energy-flow measurement systems, edge-computing devices, and AI-supported analytics platforms. The pilot activities demonstrated the potential of using these technologies to support the early detection and visualisation of track flaws, overhead-line irregularities, and energy-consumption patterns under real operating conditions.

The proposed approach is also intended to complement LVB's existing Life Cycle Costing (LCC) models. While LCC methods primarily support long-term financial planning, predictive maintenance approaches may provide an additional operational and tactical perspective through the use of current measurement data, condition trends, and infrastructure performance forecasts.

3.2.2 Vision, targets and objectives

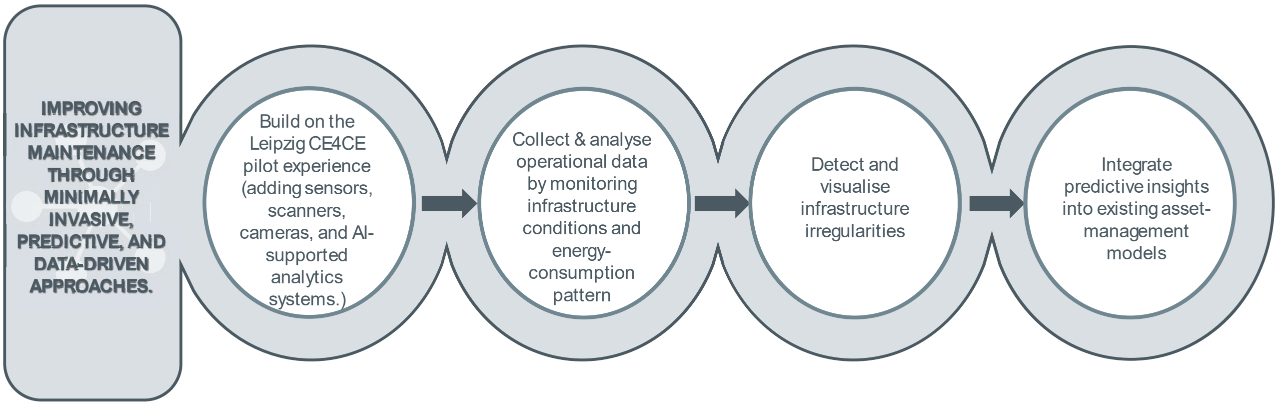

Figure 10. LVB Action Plan vision and strategic objectives

The vision of the Leipzig Action Plan is to establish a scalable predictive maintenance approach that supports infrastructure availability, more efficient resource use, and the gradual alignment of asset management practices with the company's ISO 55001 principles. The Action Plan seeks to enable earlier, more targeted, and less invasive maintenance interventions while strengthening the connection between operational maintenance activities and strategic investment planning.

A central objective is to support the transition from interval-based and reactive maintenance towards a more data-informed system using sensors, AI-supported analytics, dashboards, and parameter models. This approach is intended to improve the identification of potential damage patterns, support risk-based prioritisation of interventions, and contribute to reducing unnecessary renewal works.

The Action Plan further aims to establish a digital damage catalogue, develop a parameter model for scenario and investment control, integrate monitoring data into systems such as MR.pro®, GIS, and ZEDAS, and support the use of dashboards in operational decision-making. In addition, the plan explores opportunities to improve energy efficiency through the analysis of energy consumption per vehicle-kilometre and driving behaviour patterns.

Another important objective concerns organisational cooperation. The Action Plan promotes closer collaboration between maintenance, asset management, digitalisation, operations, controlling, and external partners through shared data structures and clearer decision-making pathways. It also seeks to develop approaches that may be transferable to additional tram lines, other asset classes, bus infrastructure in Leipzig. The knowledge and experience exchange, as well as the joint development of assessment and forecasting methodologies can be transferred to other public transport operators.

3.2.3 Key Measures

The Leipzig Action Plan proposes a structured set of measures to support the integration of predictive maintenance into asset management processes while improving the strategic steering of infrastructure development.

MEASURES

- **Digital damage catalogue:** Records and classifies recurring defects such as rail corrugation, rail breaks, and contact wire defects.
- **Automated fault detection:** Uses sensor data, video inspections, and conventional inspections to identify infrastructure problems.
- **Risk-based prioritisation:** Supports more systematic assessment and ranking of defects based on urgency and impact.
- **Parameter model for scenario analysis:** Combines condition data, lifecycle forecasts, operational impacts, and cost indicators to compare maintenance strategies.
- **Integration of monitoring data:** Connects monitoring outputs with systems such as GIS, MR.pro®, and ZEDAS through interoperable interfaces.
- **Central data platform and dashboards:** Brings together measurement data, images, and fault classifications in map-based visualisations.
- **Organisational development and change management:** Promotes user participation, competence development, interdisciplinary cooperation, and continuous learning.
- **Workshops and stakeholder exchanges:** Gathers user requirements and supports acceptance of new systems and workflows.

Figure 11. Leipzig key measures

One of the key measures is the development of a digital damage catalogue that systematically records and classifies recurring infrastructure defects such as rail corrugation, rail breaks, and contact wire defects. By combining sensor measurements, video inspections, and conventional inspection methods, the catalogue is intended to support automated fault detection, risk-based prioritisation, and more standardised assessment procedures. Experiences from the CE4CE pilot, where AI-supported analyses of typical damage patterns were tested, contribute to the development of this approach.

Another important measure is the development of a parameter model for scenario analysis and investment control. The model combines condition data, lifecycle forecasts, operational impacts, and cost indicators to support the evaluation of different maintenance strategies and long-term investment options. The methodology is based on three complementary information sources: precise individual measurements, structured visual inspections, and continuous monitoring data streams. Together, these elements are expected to provide a more robust basis for forecasting infrastructure conditions and analysing potential maintenance scenarios.

The Action Plan also foresees the integration of monitoring data into existing systems such as GIS, MR.pro®, and ZEDAS through interoperable interfaces and a central data platform. This integration aims to support a more holistic overview of infrastructure conditions by combining measurement data, images, and fault classifications within dashboards and map-based visualisations. Open and standardised interfaces are considered important for enabling future system expansion and transferability to other public transport operators.

In addition to technical measures, the Action Plan highlights the importance of organisational development and change management. The proposed approach emphasises user participation, competence development, interdisciplinary cooperation, and continuous learning processes. Workshops and stakeholder exchanges conducted during the CE4CE pilot contributed to gathering user requirements and supporting the acceptance of new systems and workflows.

Building on the experiences gained during the CE4CE pilot in Leipzig, the Action Plan proposes a phased implementation strategy. This includes identifying critical assets, developing and testing prediction models, and gradually integrating validated tools and processes into operational workflows and strategic planning activities. The iterative implementation approach is intended to reduce risks, support organisational learning, and facilitate the gradual embedding of predictive maintenance practices within long-term asset management structures.

3.2.4 Monitoring and evaluation aspects

Monitoring activities within the Leipzig Action Plan focus on assessing whether predictive maintenance approaches contribute to improvements in technical reliability, operational processes, and strategic asset management decisions. The proposed monitoring framework includes several key performance indicators (KPIs) that are also relevant in the context of ISO 55001 performance evaluation.

The proposed indicators include the early detection of defects before they become critical, the reduction of unplanned maintenance measures, infrastructure availability, energy efficiency, and data quality indicators such as sensor uptime and data transmission reliability. Additional indicators may include response times between fault detection and corrective actions, as well as potential cost savings resulting from avoided repairs and extended asset lifetimes.

Data collection is expected to rely on automated sensor systems and data platforms, complemented by comparisons with MR.pro® data, on-site inspections, surveys, and existing assessment methods. Evaluation activities are intended to combine automated analysis with expert feedback and regular coordination meetings between asset management, maintenance, and digitalisation teams. The results of pilot activities and rollout phases are expected to contribute to the continuous improvement of algorithms, system adaptations, and maintenance planning processes. In the longer term, monitoring activities are intended to support investment controlling and maintenance planning processes through more data-informed decision-making.

3.2.5 Stakeholder engagement in the preparation and implementation process

The Leipzig Action Plan is based on the close cooperation between internal LVB departments, external technical partners and the other municipal companies that are part of the “L” group led by the Municipality of Leipzig (Stadt Leipzig). Within LVB, asset management plays a leading role in integrating predictive maintenance approaches into strategic infrastructure management. IFTEC (responsible for a large share of the technical maintenance and engineering services related to Leipzig’s public transport system) contributes to technical implementation, calibration activities, and feedback regarding damage patterns and maintenance measures. The digitalisation team supports the development of data platforms, dashboards, and interfaces, while operations staff and drivers contribute operational feedback related to ride comfort and service disturbances. Controlling and investment planning units are involved in the use of parameter models for budgeting and scenario development.

External partners contribute hardware solutions, edge-computing technologies, monitoring systems, AI-supported analytics, and energy-consumption analysis tools. The CE4CE pilot involved cooperation with organisations including IFTEC, Kruch Railways (also a CE4CE partner) , CI4RAIL, CEMIT, and PantoHealth. Universities and research institutions provided technical and methodological support, while municipal stakeholders contributed links to Smart City and urban data-platform initiatives.

Stakeholder engagement activities included workshops for requirement definition and system selection, regular coordination meetings, training sessions, and stakeholder review formats. During the pilot phase, these activities supported the collection of user feedback, especially tram drivers, testing of system acceptance, and co-development of dashboards and interfaces.

3.2.6 Main takeaways from the action plan development process

The Leipzig Action Plan development process suggests that predictive maintenance approaches may offer significant potential when integrated into everyday maintenance activities and strategic asset management processes. Experiences from the CE4CE pilot indicated that technologies such as sensors, monitoring systems, and AI-supported analytics can contribute to the identification of critical track sections, rail defects, overhead-line irregularities, and other infrastructure-related issues under operational conditions.

One important takeaway is the added value of continuous monitoring in complementing existing asset management approaches. Combining current measurement data with visual inspection practices and lifecycle cost models may support more dynamic and informed decision-making compared to fixed renewal cycles alone.

The process also highlighted that digitalisation is not solely a technical challenge but also an organisational one. Training activities, user acceptance, data literacy, revised

MAIN TAKEAWAYS

Predictive maintenance potential: Predictive maintenance can add significant value when embedded in daily maintenance and strategic asset management.

Phased and flexible implementation: Due to evolving technologies, regulatory conditions and financial uncertainties, continuous monitoring, evaluation and adaptive management will be essential for ensuring long-term effectiveness and resilience of the proposed measures.

Value of continuous monitoring: Continuous monitoring complements visual inspections and lifecycle cost models by enabling more dynamic, data-informed decisions.

Beyond fixed renewal cycles: Combining real-time data with existing asset management methods may support better timing of maintenance and renewals.

Organisational change needs: Successful digitalisation requires training, user acceptance, data literacy, revised responsibilities, and long-term change management.

Transfer potential: The modular, rail-certified system could be expanded to other tram lines, infrastructure assets, and bus-related applications.

Long-term institutionalisation: Sustained use will depend on stable financing, system integration, staff capacity, and alignment with LVB's asset management processes.

Figure 12. Leipzig main takeaways

responsibilities, and long-term change management processes appear essential for ensuring that dashboards and AI-supported analyses can be effectively integrated into operational practice.

Finally, the Action Plan demonstrates transfer potential beyond the pilot environment. The pilot relied on rail-certified components compliant with EN 50155 and EN 45545 standards, while the modular system architecture may support future expansion to additional tram lines, other infrastructure assets, and potentially bus-related applications such as charging infrastructure. At the same time, the long-term institutionalisation of predictive maintenance approaches is likely to depend on stable financing, system integration, staff capacities, and their continued integration into LVB's broader asset management processes.

3.3. Action plan to optimise delivery of infrastructure by cooperation and sharing between public providers, as update of municipal strategy for electromobility in Gdynia, Poland

3.3.1 Strategic background and context for the action plan development

The Gdynia Action Plan updates the municipal electromobility approach by focusing on circular electrification, infrastructure sharing and cooperation between public service providers PKA - the municipal bus operator and CE4CE project partner and PKT - the municipal trolleybus operator. The plan builds on Gdynia's existing strengths: its long-running trolleybus system, in-motion charging experience and electric buses introduced in 2022.

Figure 13. PV plant feeding Gdynia trolleybuses at the depot. Source: CE4CE Project

The Action Plan responds to five concrete challenges identified by PKA and their partners: aging assets, rising electricity and lifecycle costs, the need for circular procurement, limited decision-support tools for investment planning, and the need to better align electromobility with city climate and mobility objectives. It also addresses risks identified through the pilot conducted in Gdynia within the CE4CE project, including congestion-related energy demand, oversized batteries and charging infrastructure, fragmented data between institutions, uncertain future funding and the possibility of locking the city into inefficient solutions for 12–30 years.

Strategically, the plan is linked to the Strategy of Development of the City of Gdynia 2030, Gdynia's Sustainable Urban Mobility Plan and the SUMPs for BSR work on monitoring and evaluation. At national level, it follows Poland's Act on Electromobility and Alternative Fuels. At EU level, it is aligned with the current regulatory framework formed by the following framework strategies and directives: European Green Deal, Clean Vehicles Directive, Alternative Fuels Infrastructure Regulation, Energy Efficiency Directive and Renewable Energy Directive and Batteries Regulation.

3.3.2 Vision, targets and objectives

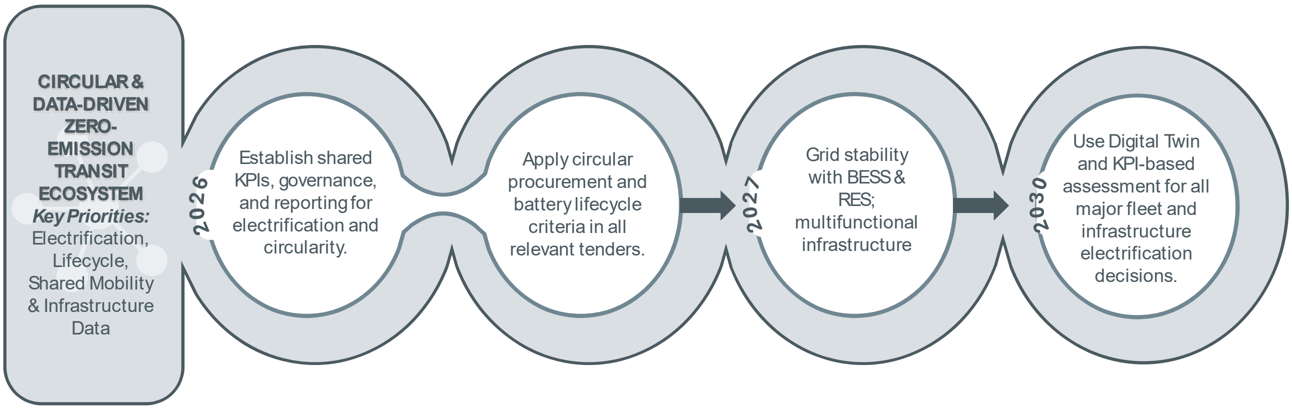

Figure 15. Gdynia key measures and implementation timeline

The vision is that by 2030, PKA Gdynia becomes a more circular, lower-emission and investment-ready public transport provider. The Action Plan aims to scale electromobility through shared data, lifecycle thinking and stronger cooperation between PKA, the city and other public providers, while avoiding unnecessary material and energy use.

The plan sets several concrete targets. By 2026, Gdynia should institutionalise a common KPI set, ownership model and annual reporting routine for circularity and electrification decisions. By 2027, the first implementation package should be prepared and launched, starting with line 194 electrification, depending on funding. Also, by 2027, a depot eco-efficiency and photovoltaic investment package should be completed, including smart charging and storage-ready design. From 2026 onward, circular procurement criteria and battery lifecycle requirements should be used in relevant tenders. By 2030, the Digital Twin and KPI assessment should be applied to all major PKA fleet and infrastructure electrification decisions.

The objectives therefore combine emissions reduction, better service reliability, lower lifecycle cost, reduced battery and material demand, improved funding readiness and clearer governance of circular electromobility.

3.3.3 Key measures

The Action Plan is built around five priority measures:

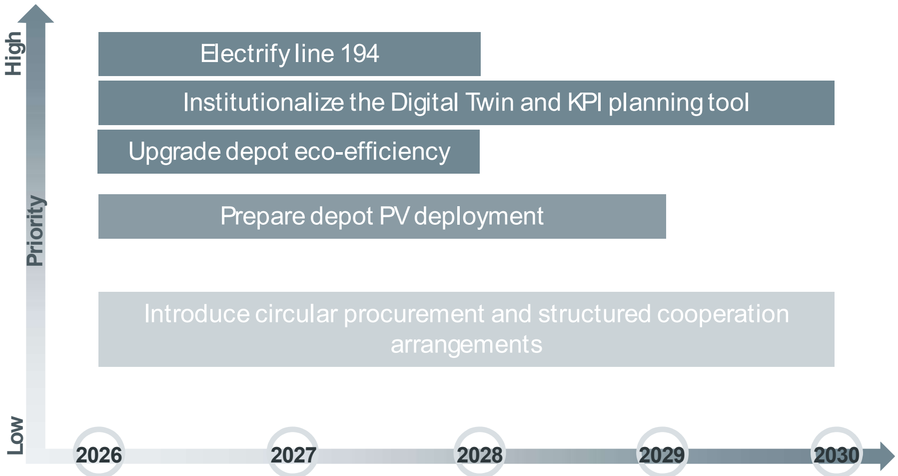

Figure 16. Gdynia main takeaways

The first is the electrification of bus line 194, planned as a high-priority demonstrator for data-backed and circular zero-emission service expansion between 2026 and 2028.

The second is the institutionalisation of the Digital Twin pilot and the Circular business planning tool for electrified public transport fleets and infrastructure, starting in 2026, so that scenario testing and KPI ownership become part of investment and reporting routines.

The third measure is depot eco-efficiency, also high priority for 2026-2028. This includes better metering, smart charging logic, peak-load management and technical retrofits.

The fourth measure is photovoltaic deployment at the depot between 2026 and 2029, with storage-ready design and potential future use of second-life batteries where feasible.

The fifth measure covers circular procurement and structured cooperation arrangements for procurement processes, starting already in 2026 and planned as a continuous measure. This includes lifecycle battery management, reusable technical specifications, circular tender clauses and improved data-sharing with municipal providers and city units.

The measures are designed as a staged package rather than a single large rollout, allowing Gdynia to test, adjust and scale investments. Cost estimates are not yet detailed, however there is a strong commitment by the two municipal public transport operators to implement the measures as planned and secure funding from multiple sources. The plan defines order-of-magnitude needs: high expenditure for line 194 electrification, low to medium expenditure for the Digital Twin and Circular business planning tool for electrified public transport fleets and infrastructure, medium expenditure for depot eco-efficiency, medium to high expenditure for PV and storage-ready infrastructure, and mainly organisational effort for enhancing circular procurement.

3.3.4 Monitoring and evaluation aspects

The monitoring system is based on a compact KPI set linked to the Circular business planning tool for electrified public transport fleets and infrastructure and, where relevant, to SUMP and urban-node reporting as part of the EU requirements based on the revised TEN-T Regulation (adopted in 2025). The proposed indicators include the share of zero-emission vehicle-kilometres, annual electricity consumption per vehicle-kilometre, average battery capacity in procured vehicles, share of internally generated electricity, implementation status of priority measures, and the share of relevant procurements containing circular and lifecycle clauses.

Data is planned to be collected quarterly and consolidated annually. Operational data will come from vehicle telematics, depot chargers, energy meters and timetable systems. Investment and procurement information will come from project files and contract registers, while ESG and governance data will be taken from management reporting. PKA should maintain the central KPI register, with ZKM Gdynia (Public Transport Authority in Gdynia) and municipal departments providing additional input where indicators overlap with city-level reporting.

Evaluation should combine process and outcome assessment. Process evaluation checks whether measures are launched, funded, assigned to owners and embedded in procurement and operations. Outcome evaluation compares results against the 2025/2026 baseline and Digital Twin scenarios, especially for energy use, battery demand, infrastructure efficiency, service robustness, funding leverage and circularity effects. A mid-term review is recommended in 2028 and a fuller review in 2030.

3.3.5 Stakeholder engagement in the preparation and implementation process

The stakeholder process was organised around a core development team and a broader institutional map. The core team included PKA Gdynia, the University of Gdansk and KRUCH Railways, who worked on the technical evidence base, local applicability and measure design. The broader stakeholder map included the Municipality of Gdynia, ZKM Gdynia, PKT Gdynia and other public providers and city units responsible for mobility, energy, procurement and strategy.

The discussions focused on practical implementation questions: corridor selection, infrastructure options, KPI ownership, funding logic and operational constraints. From September 2023 onward, the process moved through joint problem definition, scenario testing and internal review. By March 2026, the draft Action Plan, stakeholder mapping and KPI framework had been completed.

Stakeholder engagement helped shift the Action Plan from a technical electrification exercise towards a governance and cooperation framework. It clarified that circular electromobility depends not only on vehicles and chargers, but also on shared standards, data exchange, procurement rules, funding preparation and coordination between PKA, the municipality and other public providers.

3.3.6 Main takeaways from the action plan development process

MAIN TAKEAWAYS

Electrification must consider infrastructure and lifecycle impacts: The Gdynia process showed that electrification should not simply replace diesel buses one-for-one. Instead, planning should account for charging infrastructure, operational needs, and long-term vehicle performance.

In-motion and opportunity charging reduce battery size requirements: The CE4CE pilot demonstrated that combining in-motion charging (IMC) with opportunity charging can drastically reduce battery capacity needs. On Route 141, the required battery size dropped from around 700 kWh with overnight charging to about 60 kWh

Digital tools are only effective when integrated into decision-making: The Digital Twin and KPI systems only create value if they are actively used in management processes, procurement, annual reporting, and funding applications. Reliable and high-quality data is therefore critical.

Circularity requires cross-department collaboration: The process confirmed that circularity cannot be managed by a single department. Operations, technical teams, procurement, finance, strategy units, and municipal partners all need shared responsibilities and strong internal

Management support is essential for long-term progress: Even technically strong measures can lose momentum without clear ownership and visible support from leadership. Internal buy-in is necessary to maintain implementation efforts.

Phased implementation reduces risk and supports learning: Starting with smaller actions such as Line 194, depot eco-efficiency measures, and KPI governance allows Gdynia to test approaches, learn from experience, and scale up gradually.

Figure 17. ATB Mobility Bergamo

The Gdynia process demonstrated that successful public transport electrification requires more than simply replacing diesel buses with electric ones. The CE4CE pilot, which stays at the basis for their Action Plan, highlighted the importance of integrating infrastructure planning, lifecycle thinking, digital decision-support tools, and cross-departmental cooperation into a long-term transition strategy. The experience also showed that phased implementation and clear governance structures are essential for scaling electromobility efficiently while avoiding unnecessary material and energy use.

The Gdynia process showed that future electrification should be infrastructure-aware and lifecycle-aware, not simply based on replacing vehicles line by line. The CE4CE pilot demonstrated that in-motion charging and opportunity charging can significantly reduce battery needs compared with pure overnight-charging concepts. For example, on route bus line 141, the battery requirement falls from about 700 kWh in an overnight-charging option to about 60 kWh with IMC plus opportunity charging.

A second takeaway is that digital tools only create value if they are embedded in decision-making. The Digital Twin and KPI workflow need clear ownership, annual reporting and use in procurement and funding applications. Data quality and management is therefore as important as the technology itself.

The process also confirmed that circularity cannot sit in one department only. Operations, technical teams, procurement, finance, strategy and municipal partners, all need shared responsibilities. Internal management buy-in is essential, because even technically strong measures can lose momentum without visible ownership.

Finally, the plan highlights the value of phased implementation. Starting with line 194, depot eco-efficiency and KPI governance, the measures' evaluation allows Gdynia to learn before scaling up. A current limitation is that the plan still requires final approval, financing confirmation and formal allocation of responsibilities before implementation can fully begin.

3.4. Action plan to add value on the supply chain and optimise delivery of vehicles by circular procurement in Bergamo, Italy

3.4.1 Strategic background and context for the action plan development

The ATB Mobility Bergamo Action Plan was developed within a multi-level strategic framework linking local, national and European mobility, climate and circular economy policies. At local level, the Action Plan is aligned with Bergamo's Sustainable Energy and Climate Contract (CCC) and the city's Sustainable Urban Mobility Plan (SUMP), ensuring that circular economy principles become an integrated component of long-term transport planning rather than a stand-alone initiative.

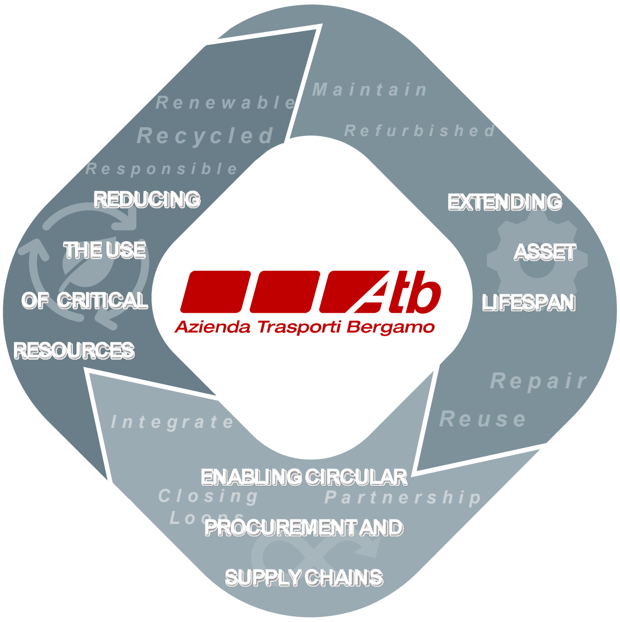

Figure 18. Bergamo Action Plan vision and strategic objectives

At national level, the Action Plan is supported by investment opportunities linked to the Italian Recovery and Resilience Plan (PNRR), particularly for infrastructure modernisation, electrification and innovative transport systems such as eBRT. At European level, the Action Plan builds on the Interreg CE4CE project and synergies with other projects such as Interreg Euro-MED E-MED and Interreg Alpine Space Degree4Alps, supporting the testing and scaling of circular solutions in public transport.

The Action Plan responds to several key challenges identified by ATB Mobility:

- high energy and material consumption within public transport operations,
- limited lifecycle management of rolling stock and infrastructure,
- rising operational costs and increasing regulatory requirements,
- the need to integrate renewable energy and storage solutions,
- insufficient integration of circularity principles in procurement and maintenance practices.

The overall objective is to support ATB's transition towards a more sustainable, resource-efficient and circular public transport system capable of generating environmental and economic benefits for the Bergamo metropolitan area.

3.4.2 Vision, targets and objectives

The vision of the Action Plan is to transform ATB into a circular Public Transport Operator by embedding circular economy principles across operational, infrastructural and strategic activities.

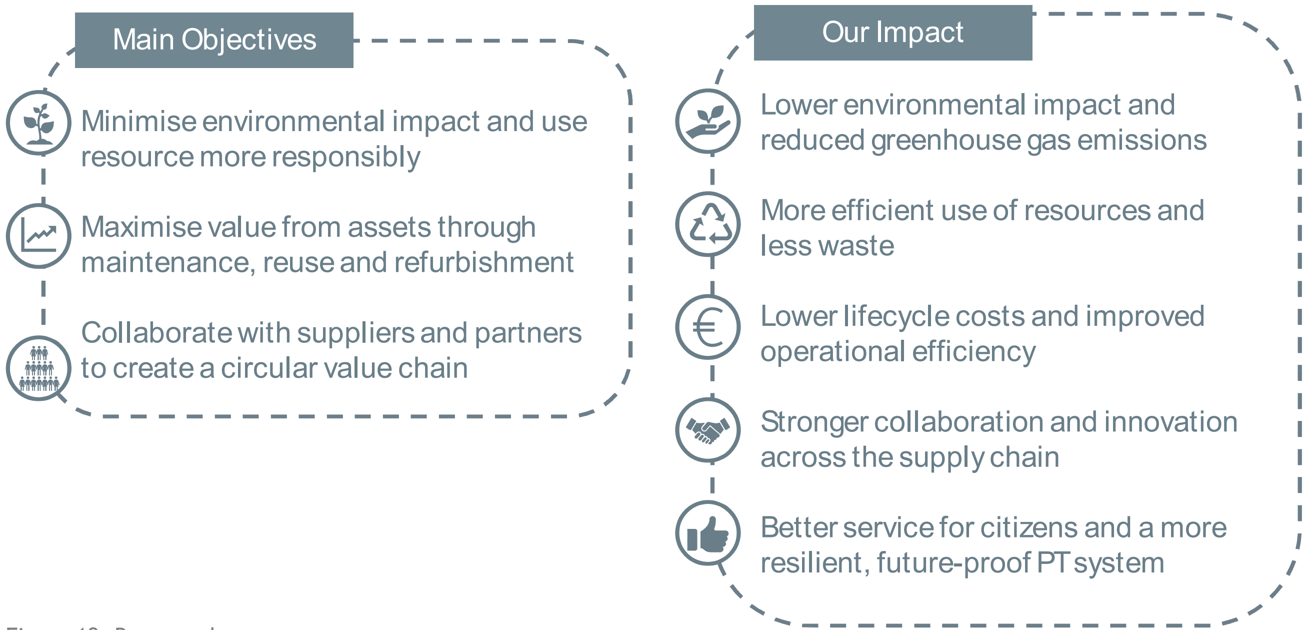

Figure 19. Bergamo key measures

3.4.3 Key measures

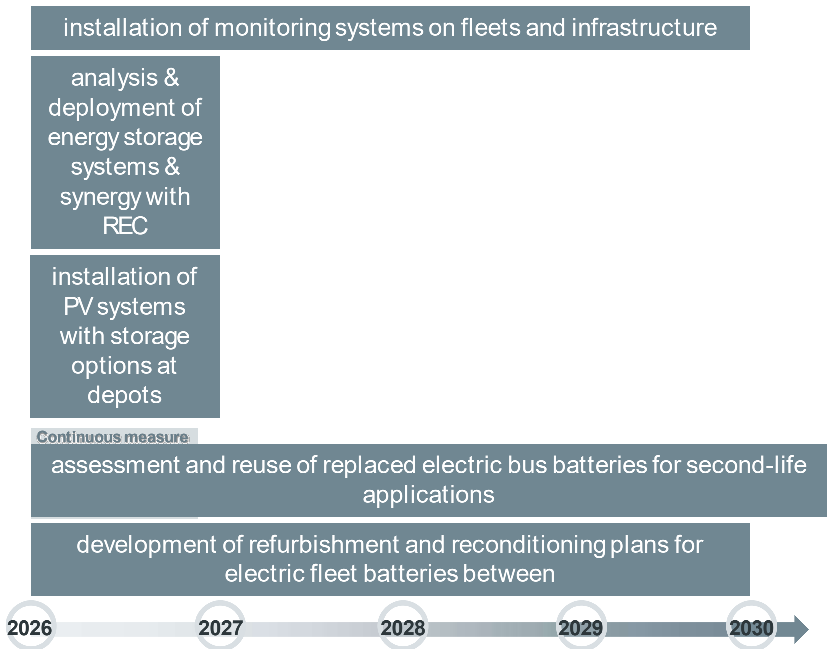

Figure 20. Bergamo Main Takeaways

The Action Plan defines a package of operational, energy, maintenance and procurement measures to support the transition towards circular public transport operations:

Key measures include:

- installation of monitoring systems on fleets and infrastructure to optimise energy use and predictive maintenance by 2030,
- analysis and deployment of energy storage systems and synergies with Renewable Energy Communities (REC) by 2027,
- installation of photovoltaic systems with storage options at depots by 2027,
- assessment and reuse of replaced electric bus batteries for second-life applications from 2026 onward,

- development of refurbishment and reconditioning plans for electric fleet batteries between 2026-2030,
- preparation of a corporate circularity strategy covering operational activities and governance processes,
- integration of circular procurement principles into rolling stock and supply-chain purchasing procedures.

The Action Plan also promotes:

- predictive maintenance approaches,
- energy-efficiency optimisation,
- lifecycle-oriented asset management,
- integration of renewable energy generation and storage within transport infrastructure

3.4.4 Monitoring and evaluation aspects

The Action Plan establishes a structured monitoring and evaluation framework designed to track both the implementation progress and the long-term impacts of circular economy measures within ATB Mobility. The monitoring system is organised around three complementary dimensions: the implementation of physical measures, the development of strategic and organisational outputs, and the integration of circular procurement practices.

The monitoring of physical measures focuses on operational aspects such as the share of monitored fleet and infrastructure, installed renewable energy capacity, deployment of energy storage systems, and the number of assets managed through predictive maintenance approaches. In parallel, strategic indicators are used to assess the development and implementation of circularity-related plans, strategies and pilot actions, as well as the level of integration of circular principles into company processes and governance structures. Procurement-related monitoring evaluates the gradual incorporation of circularity criteria into purchasing procedures, including the share and value of procurement processes applying lifecycle and sustainability requirements.

The Action Plan also foresees broader impact monitoring linked to renewable energy generation and self-consumption, asset lifespan extension, maintenance savings, lifecycle cost reductions and deferred capital investments.

The evaluation methodology combines automated operational data collection with structured internal reporting processes. Data sources include fleet management systems, maintenance databases, energy management systems, procurement records and project documentation. Operational indicators are expected to be reviewed quarterly, while strategic and financial indicators are assessed at longer intervals to support medium- and long-term decision-making.

3.4.5 Stakeholder engagement in the preparation and implementation process

Stakeholder engagement played a central role throughout the development of the Action Plan and was integrated as a continuous process rather than a one-off consultation exercise. Early activities focused on engaging suppliers and technical stakeholders through workshops, surveys and discussions on circular procurement approaches and green procurement criteria at both EU and national level. These exchanges helped identify practical opportunities and barriers related to circular supply chains and procurement practices. The preparation process involved extensive internal coordination across ATB Mobility and its subsidiaries, including TEB and ATB Servizi, ensuring that operational, technical and strategic perspectives were incorporated into the definition of measures. Externally, the Municipality of Bergamo played a key role as both shareholder and institutional partner, supporting the alignment of the Action Plan with broader urban mobility, climate and sustainability objectives. The stakeholder process also benefited from knowledge exchange within European cooperation projects and international expert networks. In particular, the collaboration within projects such as Interreg Alpine Space Degree4Alps and Interreg Euro-MED E-MED supported the assessment of scalability, transferability and innovation potential of the proposed measures. For implementation, ATB Mobility is expected to coordinate the overall delivery and monitoring process, while subsidiaries, technical partners and external stakeholders contribute to operational implementation, data provision, technical expertise and evaluation activities.

3.4.6 Main takeaways from the action plan development process

The development process demonstrated that circular economy principles can be systematically integrated into public transport planning and operations through a combination of technical, organisational and governance measures.

The process also reinforced the importance of integrating circular procurement, predictive maintenance, renewable energy systems and lifecycle management into long-term public transport planning. Overall, the Action Plan provides a practical framework for supporting ATB's transition towards a more sustainable, resilient and circular public transport system.

MAIN TAKEAWAYS

Holistic and strategically aligned approach: Integrating circularity into public transport systems works best when it is addressed across departments and aligned with broader mobility and climate strategies, especially the Sustainable Urban Mobility Plan (SUMP).

Internal coordination: Early and continuous collaboration within the organisation helps ensure that proposed measures are feasible, practical, and supported by the teams responsible for implementation.

External engagement: Working with external stakeholders helps connect circularity measures with wider policy objectives, funding priorities, and regulatory expectations.

Pilot actions support informed decision-making: Pilot projects are valuable for testing innovative solutions, identifying challenges, and generating lessons before scaling.

Flexibility to manage uncertainty: Circularity planning must remain adaptable to changing conditions around funding, technology, and regulation.

Data and monitoring for evidence-based planning: Reliable data and monitoring systems are necessary to track progress, evaluate results, and support better **strategic decisions.**

4. Lessons learned and recommendations

The development of the CE4CE Strategies and Action Plans demonstrated that circular economy principles can support public transport authorities and operators in moving from isolated circular measures towards systemic, life-cycle-based approaches. The strategies highlighted the importance of reducing waste, optimising resources and creating long-term value across energy systems, infrastructure and rolling stock.

4.1. Lessons learned from the strategies and action plans development process

One of the main lessons learned is that circularity requires a life-cycle perspective across planning, operation, maintenance and end-of-life management. The document emphasises that recycling alone is insufficient if applied only at the end of the life cycle, and that value must instead be preserved and regenerated throughout the entire life of assets through reducing material demand, extending asset lifetimes, reuse, refurbishment and recycling.

Another important lesson concerns the role of digitalisation and data management. The strategies identify digitalisation as a key enabling condition for circularity, including the use of energy management systems, real-time monitoring, data analytics, digital models and simulations to support planning, maintenance and operational optimisation.

The CE4CE Action Plans and Strategies also demonstrated the importance of cooperation between stakeholders. Circular economy implementation depends on collaboration between public transport authorities, public transport operators, municipalities, suppliers, research institutions, energy providers and other actors across the value chain. The strategies repeatedly emphasise coordination, knowledge exchange and stakeholder involvement as important enabling conditions for implementation.

Another lesson learned is that extending the lifetime of assets represents an important opportunity for reducing resource consumption and preserving embedded value. The strategies highlight preventive and predictive maintenance, refurbishment, second-life applications and reuse of infrastructure components and materials as important approaches for achieving circularity objectives.

The strategies also underline the importance of integrating circular economy principles into procurement and governance processes. They highlight that procurement procedures, contracts and performance requirements can influence supplier behaviour and support innovation along the value chain.

Finally, the Strategies and Action Plans showed that pilot activities and practical experimentation are important for reducing implementation risks, testing innovative solutions and supporting replication in other public transport contexts.

4.2. Recommendations for measure implementation

The following key aspects were identified in the CE4CE Strategies and Action Plans as important recommendations and conditions supporting the implementation of circular economy approaches in public transport systems.

Strategic and planning aspects

- Apply life-cycle thinking across planning, operation, maintenance and end-of-life management.

- Integrate circular economy objectives into transport, energy and sustainability strategies.
- Align local implementation with European and national circular economy and climate objectives.
- Use tools such as life cycle assessment (LCA), life cycle costing (LCC) and digital models To support decision-making.

Digitalisation and monitoring

- Deploy energy management systems to monitor and optimise energy flows.
- Apply real-time monitoring and data analytics to improve energy efficiency and detect losses.
- Use digital tools to monitor battery performance and degradation.
- Develop digital models and simulations to support planning of charging infrastructure, energy storage and renewable integration.
- Integrate energy data into broader fleet and operational management systems.

Governance and stakeholder cooperation

- Establish long-term partnerships with utilities, grid operators and other stakeholders.
- Define clear roles and responsibilities for energy and asset management.
- Promote cooperation between public transport authorities, operators, suppliers and research institutions.
- Support participation in sector initiatives and knowledge-exchange platforms.
- Ensure stakeholder engagement during preparation and implementation processes.

Technical and operational aspects

- Prioritise preventive and predictive maintenance approaches.
- Support reuse, refurbishment and second-life applications for infrastructure and rolling stock.
- Implement regenerative braking and energy recuperation systems where relevant.
- Deploy renewable energy technologies and energy storage systems.
- Use mature and efficient energy supply solutions where appropriate.

Financial and organisational aspects

- Support access to funding and financing instruments for renewable energy and storage investments.
- Promote capacity building within public transport authorities and operators.
- Use pilot activities as learning environments supporting replication and implementation.
- Monitor energy performance and circularity outcomes using defined indicators and frameworks.

5. Conclusions

The CE4CE Strategies and Action Plans demonstrate how circular economy principles can support more resource-efficient and sustainable public transport systems. By applying the AVOID–EXTEND–TRANSFORM–ENABLE (AETE) framework across energy systems, infrastructure and rolling stock, these strategic documents promote a life-cycle-based approach focused on reducing waste, preserving value and optimising resource use.

The strategies show that circularity in public transport depends on combining technical, organisational and governance approaches. Digitalisation, stakeholder cooperation, innovation, procurement practices and long-term planning are presented as important enabling conditions supporting implementation and scalability of circular solutions.

The CE4CE Action Plans also highlight the importance of pilot projects, experimentation and knowledge exchange for supporting implementation, upscale and transferability. Through practical testing and cooperation between stakeholders, as well as based on a solid strategic base evidence, the project partners prepared Action Plans that contribute to reducing barriers and supporting the transition towards circular public transport systems in their local and regional context.

Looking forward, the strategies provide a basis for further development of circular economy practices in public transport. Continued cooperation, capacity building, digitalisation and integration of circular principles into planning and procurement processes will remain important for supporting long-term implementation and alignment with European sustainability objectives.

For more details on the strategies and action plans, as well as on the pilots and solutions developed within CE4CE, we invite you to visit the project website: https://www.interreg-central.eu/projects/ce4ce/

6. References

- CE4CE project deliverables published on the project website
- Deliverable D.2.1.1 Report on joint circular strategy development for better use of waste energy and renewable energy sources in public transport operations
- Deliverable D.2.2.1 Report on joint circular strategy development to preserve value and reduce waste infrastructure
- Deliverable D.2.3.1 Report on joint circular strategy development to preserve value and reduce waste of public transport vehicles/rolling stock
- Deliverable D.2.1.2 Action Plan Maribor, Slovenia
- Deliverable D.2.2.2 – part 1 Action Plan Leipzig Transport Company, Germany
- Deliverable D.2.2.2 – part 2 Action Plan Gdynia, Poland
- Deliverable D.2.3.2 Action Plan ATB Mobility, Bergamo, Italy

Strategic and regulatory framework

- Alternative Fuels Infrastructure Regulation (AFIR): https://transport.ec.europa.eu/transport-themes/clean-transport/alternative-fuels-sustainable-mobility-europe/alternative-fuels-infrastructure_en
- Batteries Regulation: https://eur-lex.europa.eu/eli/reg/2023/1542/oj/eng
- Bergamo's Sustainable Energy and Climate Action Plan: https://www.terraria.com/en/case-studies/secap-of-the-municipality-of-bergamo/
- Circular Economy Action Plan: https://environment.ec.europa.eu/strategy/circular-economy_en?prefLang=de
- Clean vehicles directive: https://eur-lex.europa.eu/eli/dir/2019/1161/oj/eng
- Energy Efficiency Directive: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en
- European Green Deal: https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF
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- Poland's Act on Electromobility and Alternative Fuels: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20180000317
- Renewable Energy Directive: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en
- Revised TENT Regulation: https://urban-mobility-observatory.transport.ec.europa.eu/news-events/news/revised-ten-t-regulation-adopted-sustainable-and-resilient-transport-network-bringing-europe-closer-2024-06-25_en
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- SUMP Gdynia: https://www.climatehub.si/en/sustainable-mobility-good-practice-1/
- SUMP Maribor: OCPS-MOM-brosura-05.pdf
- SUMPs for BSR: https://interreg-baltic.eu/project/sumpsforbsr/
- The Circular Economy Transition Strategy of the Municipality of Maribor 2024–2030: https://circularcitiesdeclaration.eu/fileadmin/user_upload/Materials/SKG_MOM_2024%E2%80%932030__1_.pdf
- The Climate City Contract Bergamo: https://netzerocities.app/resource-4432
- Urban data platform: Welcome - Connected Urban Twins

Support actors and experts

- CEMIT - Centre for Monitoring, Information Technologies and Transport Systems: https://cemit.com/
- CI4RAIL - Condition Intelligence for Rail: https://www.ci4rail.com/
- IFTEC GmbH & Co. KG: https://www.iftec.de/index.html
- ZENIT GmbH – Zentrum für Innovation und Technik in Nordrhein-Westfalen: https://www.zenit.de/english/
- PKT Gdynia – Trolleybus Operator Gdynia: https://pktgdynia.pl/en/firm/
- ZKM Gdynia - Gdynia Public Transport Authority: https://zkmgdynia.pl/
- ICLEI Europe - Local Governments for Sustainability: https://iclei-europe.org/
- UITP - International Association of Public Transport: https://www.uitp.org/
- EIT Urban Mobility – Hub East: https://www.eiturbanmobility.eu/
- PantoHealth - PANTOhealth: https://pantohealth.com/
- Marprom - Marprom Public Transport Enterprise Maribor: https://www.marprom.si/
- Public Holdings Maribor - Javni holding Maribor: https://www.jhmb.si/
- Energy Agency / ENERGAP - Energy and Climate Agency of Podravje / Energetsko podnebna agencija za Podravje: https://www.energap.si/homepage
- Elektro Maribor d.d.: https://elektro-maribor.si/
- RRA Podravje–Maribor - Regional Development Agency for Podravje–Maribor: https://rra-podravje.si/
- Smart City Lab Leipzig - City of Leipzig: https://www.leipzig.de/leipzig-strategie/digitale-stadt/smart-city-lab-leipzig
- Connected Urban Twins - Connected Urban Twins / urban data-platform initiative: https://www.connectedurbantwins.de/
- MR.pro® - MR.pro® Infra Data Management Software: https://www.mr-pro.de/en/indexEN.php
- ZEDAS - ZEDAS GmbH / zedas®asset: https://www.zedas.com/en/
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- NetZeroCities - Climate City Contract platform: https://netzerocities.app/

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.

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YouTube: https://www.youtube.com/@InterregCE4CE
Project knowledge platform: https://circularity4publictransport.eu/

Leipziger Verkehrsbetriebe | PKA | SZEGEDI KÖZLEKEDÉSI TÁRSASÁG | KRUCH RAILWAY INNOVATIONS | Atb Azienda Trasporti Bergamo
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