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Transferable business models for re-use of batteries to store renewable energy sources (RES) in public transport systems

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1. Executive Summary

Deliverable presents Solution O3.8 – *Transferable business models for re-use of batteries to store renewable energy sources (RES) in public transport systems*, developed and validated within the CE4CE project through the pilot action implemented in Maribor, Slovenia.

The solution addresses one of the key challenges of electrified public transport systems: how to increase resource efficiency and energy resilience while managing growing grid loads and the future end-of-life of traction batteries. By introducing a Battery Energy Storage System (BESS) composed of second-life lithium-ion batteries and integrating it with renewable energy sources and fast-charging infrastructure, the Maribor pilot demonstrates a practical pathway towards circular and energy-efficient public transport infrastructure.

The primary objective of Solution O3.8 is to develop a technically validated and economically assessable framework for reusing electric bus batteries in stationary applications, combined with renewable energy integration, and to translate this framework into transferable business model options for public transport authorities and operators across Central Europe.

The Maribor pilot tested the integration of a 136 kWh second-life battery system with a 150 kW fast charger and a photovoltaic installation at the Vzpenjača terminal. The system was designed to:

- reduce peak grid loads (peak shaving),
- enable tariff optimisation through controlled charging strategies,
- increase local use of renewable electricity,
- extend battery lifecycle through second-life application prior to recycling.

Beyond technical validation, the solution defines business model configurations, stakeholder roles, risk allocation principles, and financial logic that can be replicated in other public transport systems. It provides guidance on procurement structures, ownership models, operational responsibility schemes, and revenue/cost optimisation mechanisms.

The key impacts of the solution include:

- extension of battery service life and delayed waste generation,
- improved grid stability and reduced infrastructure reinforcement needs,
- enhanced energy autonomy of public transport systems,

- creation of new circular value chains between public transport operators, municipalities, battery suppliers, and energy stakeholders.

The developed framework contributes directly to CE4CE objectives by operationalising circular economy principles in energy infrastructure, reducing waste, preserving asset value, and supporting long-term sustainable electrification strategies.

2. Project context

The CE4CE project empowers circular economy system thinking for actors in public transport from Central European countries to reduce waste and create value along new life cycles of infrastructure and rolling stock. To achieve this, CE4CE jointly develops solutions that enhance knowledge and capacities for the sector, reduce barriers and costs, and initiate the development of new services and skilled jobs. Additionally, the project focuses on strategies and action plans that support policy development, learning, and exchange at both regional and transnational levels.

One of key aspects of CE4CE's initiatives is the implementation of pilot actions that demonstrate and validate circular economy principles in public transport. By applying these principles in real-world settings, CE4CE aims to create new value chains, optimize resource efficiency, reduce costs, and foster innovation within the sector. These pilot initiatives serve as practical examples of how circular economy strategies can be integrated into public transport operations, ultimately contributing to a more sustainable and resource-efficient mobility system.

To achieve this, CE4CE pilots will test solutions that enhance knowledge and capacities for public transport stakeholders, address regulatory and financial barriers, and support the development of new services and job opportunities. The results of these pilots will contribute to shaping policies, guiding investments, and facilitating knowledge exchange at both regional and transnational levels.

Furthermore, CE4CE pilot actions will enable cooperation among key transport actors to co-develop and refine processes that integrate circular economy principles. This includes innovative procurement strategies, circular business models, extended life-cycle assessments, and cost-benefit methodologies.

3. The objectives and scope of the solution

3.1 Objective

3.1.1. Main objective

The primary objective of the Maribor pilot solution is to design, implement and test a second-life Battery Energy Storage System (BESS) integrated with renewable energy sources (RES) to support electric bus fast-charging infrastructure, and to evaluate its technical feasibility, operational performance, and economic potential within a real public transport environment.

The core challenge addressed by the pilot is practical implementation:

- **Can second-life batteries be safely, reliably and effectively integrated into an existing electric bus charging system?**
- **Can such a system operate under real grid conditions and deliver measurable benefits in terms of peak load reduction, energy optimisation, and infrastructure resilience?**

By deploying a 136 kWh second-life NMC battery system connected in parallel to a 150 kW fast charger and a photovoltaic installation at the Vzpenjača terminal, the pilot moves from theoretical feasibility to real-world validation. The solution therefore transforms the concept of battery reuse from a theoretical circular economy principle into an operationally tested infrastructure component within public transport systems.

Electrification of bus fleets increases peak power demand and grid dependency. By integrating second-life BESS with RES, the solution supports:

- peak load reduction,
- optimisation of grid connection capacity,
- increased flexibility of energy management,
- partial energy self-sufficiency at charging sites.

3.1.2. Circular economy objective

The circular economy objective of the solution is to extend the lifecycle of traction batteries through cascading use and thereby reduce resource consumption, environmental burden, and hazardous waste generation.

Electric bus batteries contain valuable critical raw materials and are classified as hazardous goods. While recycling technologies are developing and the EU Battery Regulation (EU) 2023/1542 establishes mandatory recovery targets and sustainability requirements, industrially mature and fully closed-loop recycling systems are not yet comprehensively implemented across Europe.

From a circular economy hierarchy perspective, reuse and cascading applications are prioritised over recycling. A second-life application in stationary storage therefore represents a value-preserving intermediate stage before final material recovery.

The second-life use enables:

- extension of battery service life beyond first vehicle application,
- postponement of end-of-life treatment and hazardous waste handling,
- more efficient utilisation of battery systems prior to final recycling,
- facilitation of efficient use of renewable energy sources through local storage and peak load management.

By supporting renewable energy integration and reducing peak demand stress on the electricity grid, the system contributes to cleaner and more efficient energy use in public transport operations.

The solution therefore complements existing recycling obligations and supports the broader objectives of the EU regulatory framework by introducing a practical intermediate step in the battery lifecycle.

Strategic Objective

Strategically, the Maribor pilot represents a starting point for evaluating the long-term role of second-life battery storage within the electrification pathway of the municipal bus fleet.

The pilot provides:

- empirical data on technical performance and system behaviour,
- insights into regulatory, safety and permitting requirements,
- initial cost-benefit assessment logic,
- understanding of operational integration with charging infrastructure.

This knowledge forms the foundation for future decision-making regarding:

- structured second-life use of batteries from Maribor's own e-bus fleet once their state-of-health declines below traction thresholds,
- integration of larger storage capacities at charging/depot level, including mobility hubs,
- limitation of the need for grid reinforcement and capacity upgrades in future,

thereby enabling the systematic incorporation of energy storage solutions into long-term mobility and energy strategies.

3.1.3. Scalability and replicability objective

The solution is relevant for public transport systems that rely on electric energy and are undergoing fleet electrification or infrastructure modernisation. Across different cities and regions, such systems face comparable structural challenges, particularly in relation to:

- end-of-life management of batteries,
- increasing energy and infrastructure requirements linked to emerging electrification.

While the technical characteristics of each system differ — depending on fleet size, charging concept, grid conditions, and renewable energy availability — the underlying challenges remain similar.

The Maribor pilot demonstrates a feasible approach to addressing these issues through the integration of second-life battery storage into charging infrastructure. The specific technical configuration must always be adapted to local system characteristics, but the core concept is transferable.

The objective of scalability and replicability is therefore to provide a practical reference model that can be adjusted and applied in different public transport contexts facing similar transition challenges.

3.2 Target groups

The solution addresses multiple target groups at local, regional, national, and transnational levels. These groups are structured according to their role in implementation, decision-making, financing, or replication.

3.2.1. Primary target groups (direct users and implementers)

1. **Public transport authorities (PTAs)**

Municipal or regional authorities responsible for infrastructure planning, investment decisions, and mobility strategies. As in most urban public transport systems, this role in Maribor is performed by the Municipality of Maribor. PTAs play a central role in shaping the city's strategic development of public transport, including decisions related to rolling stock, charging infrastructure, and long-term investment priorities. As such, they represent the key decision-making level for the integration of BESS into charging infrastructure and for ensuring its alignment with sustainable mobility and circular economy strategies.

2. **Public transport operators (PTOs)**

Operators responsible for the operational delivery of public transport services, including the management of electric bus fleets and charging infrastructure. For PTOs, BESS represent an operational support mechanism. They can contribute to:

i. ensuring stable and reliable charging conditions for electric buses,
ii. optimised use of electrical energy within daily operations,
iii. reduced exposure to peak-related electricity costs,
iv. improved operational continuity and service reliability.

From the operator's perspective, BESS solutions are relevant primarily in the context of maintaining uninterrupted public transport services and managing operational energy costs. Economic implications related to the execution and financial balance of public transport services fall within the domain of the PTO, whereas broader grid management impacts remain under the responsibility of the electricity distribution system operator.

3. **Electricity distribution system operators (DSOs)**

Distribution system operators are responsible for:

- management of grid connections,
- assessment and allocation of connection capacity,
- approval of infrastructure upgrades,
- planning and dimensioning of network expansion in line with increasing electrification demand.

With growing electrification of public transport fleets, grid operators face increasing load requirements and potential transformer capacity limits. Infrastructure upgrades are possible but constrained by technical thresholds and associated investment costs.

In this context, BESS can serve as a complementary solution that, within defined operational limits, reduces peak demand at the connection point and may postpone or limit the need for grid reinforcement investments. From the DSO perspective, the key relevance of BESS lies in improved load management and increased system flexibility within existing infrastructure capacities.

3.2.2. Secondary Target Groups

Secondary target groups include stakeholders that are not primary decision-makers in public transport operations but play an important technical, industrial, or lifecycle-related role in the implementation and scaling of second-life BESS solutions.

1. BESS manufacturers and system integrators

Manufacturers and integrators of Battery Energy Storage Systems are directly involved in the technical design, configuration, and safe integration of second-life battery modules into stationary storage applications. Their role includes:

- system design and technical specification,
- integration of battery modules and inverters,
- ensuring compliance with safety and communication standards,
- support in defining operational parameters and protection mechanisms.

They are essential for translating second-life battery concepts into functional and certifiable infrastructure systems.

2. Charging infrastructure providers and maintenance

SMEs or specialised companies responsible for the installation, operation, and maintenance of public transport charging infrastructure. In the Maribor pilot, this refers to the superfast-charging unit at the Vzpenjača terminal. Their core activity is ensuring reliable, safe, and technically compliant operation of charging systems. In relation to BESS, their key relevance lies in:

- ensuring technical compatibility between charging units and hybrid grid-storage configurations,
- adapting and maintaining charging systems within integrated energy setups that include stationary storage.

3. RES providers and energy distributors

Entities responsible for the installation, ownership, operation, or distribution of renewable energy systems (e.g. photovoltaic installations). Depending on contractual arrangements, the investor, system owner, and energy distributor may be different actors. Their main activity concerns renewable electricity generation and its integration into local consumption systems. In relation to BESS, their key relevance lies in:

- enabling local storage (and use) of renewable electricity,
- supporting coordinated operation between renewable generation, storage, and charging infrastructure.

4. Electric vehicle and battery manufacturers

Manufacturers of electric buses and traction batteries represent a key secondary stakeholder group, especially when batteries are repurposed for second-life use. In context of BESS their role includes:

- provision of technical specifications and performance data,
- support in battery health assessment (State of Health – SOH, State of Charge – SOC),
- guidance regarding safe handling, communication protocols, and compatibility requirements,
- technical cooperation in battery auditing and evaluation prior to second-life deployment.

Access to reliable battery data and cooperation with manufacturers is crucial for safe and effective second-life integration.

5. Waste management and recycling stakeholders

Waste management companies and certified recycling operators are responsible for the proper handling and final treatment of batteries at the end of their operational lifecycle. Second-life BESS applications extend battery service life and therefore postpone the moment of final recycling. This has two implications:

- it delays the generation of battery waste streams,
- it provides additional time for the development and scaling of recycling technologies and regulatory implementation under the EU Battery Regulation.

The topic of battery end-of-life management is increasingly relevant, as first-generation electric bus batteries in several European cities are approaching replacement age. Second-life applications therefore represent a complementary approach within the broader lifecycle management framework.

6. Permitting authorities and safety institutions

This group includes public authorities and certified bodies responsible for issuing mandatory approvals and ensuring compliance with construction, environmental, grid connection, and fire safety regulations. It also includes emergency response stakeholders involved in operational safety procedures.

Their role relates to the legal, environmental, and safety validation of BESS implementation.

In relation to BESS, their key relevance lies in:

- granting required approvals (e.g. building permits, environmental compliance, grid connection consent, fire safety assessment) necessary for the installation and commissioning of storage systems,
- defining and overseeing safety protocols, emergency response procedures, and coordination mechanisms (e.g. alarm systems, control platforms, fire brigade access and intervention planning).

The involvement of these stakeholders is particularly critical due to the use of second-life lithium-ion batteries, which are classified as hazardous goods and require enhanced safety and compliance measures.

3.3 Transfer and replication target groups

The solution is designed for uptake beyond the pilot area and is transferable to public transport systems facing similar electrification and energy infrastructure challenges.

Public transport operators, infrastructure owners and transport authorities in Europe can adopt the second-life BESS integration concept within electrified public transport systems, benefit from a tested implementation framework addressing end-of-life battery management and increasing energy infrastructure requirements, and can adapt the model according to local fleet size, charging concepts, grid constraints, and renewable energy integration levels.

Moreover, technology providers and system integrators can integrate second-life battery solutions into charging infrastructure and energy management systems, can develop modular and adaptable system configurations tailored to local technical and regulatory conditions, and benefit from a validated reference case demonstrating feasibility and compliance.

4. The solution conceptualisation and design

4.1. Summary description of the pilot action leading to the solution

The Maribor pilot was designed as a real-world demonstrator of second-life battery integration into electric bus charging infrastructure. The objective was not only to test technical feasibility, but to evaluate operational behaviour, regulatory requirements, safety constraints, and economic implications under real grid and service conditions. The pilot was implemented in structured phases:

1. **Concept definition and stakeholder coordination** – identification of technical requirements, regulatory constraints, and grid conditions at the Vzpenjača fast-charging location.
2. **Feasibility assessment -** technical evaluation of battery compatibility, inverter configuration, grid connection constraints, safety requirements, and operational charging patterns; in parallel, a scenario-based cost-benefit analysis (CBA) was conducted to assess different storage sizing options, peak load contribution levels, and renewable integration scenarios.
3. **System design and permitting** – preparation of technical documentation, definition of containerised BESS layout, fire safety concept, and acquisition of required approvals (grid connection consent, fire safety assessment, environmental compliance).
4. **Procurement and implementation** – preparation of technical specifications and tender documentation, execution of a public procurement procedure in accordance with applicable regulations, selection of the contractor, acquisition of second-life NMC battery modules, integration with a hybrid inverter, installation of the photovoltaic system, and connection to the existing 150 kW fast charger.
5. **Operational testing and monitoring** – validation of peak load contribution, charging stability, thermal behaviour, and interaction between grid, storage, and renewable generation.

The pilot therefore served as a validation platform from which key technical, organisational, safety, and financial parameters were extracted and translated into a structured solution framework.

4.2. Summary description of the solution

The solution builds upon the validated pilot experience and transforms it into a transferable integration model for second-life Battery Energy Storage Systems in public transport infrastructure. Rather than prescribing a fixed technical configuration, the solution defines:

- operational behaviour and interaction of core components (storage sizing logic, battery C-rate behaviour, grid-BESS-charger interface, and integrated safety and control mechanisms)
- regulatory and permitting pathways,
- stakeholder roles and coordination mechanisms,
- economic assessment logic for evaluating storage feasibility in electrified PT systems.

The core of the solution is therefore not the specific 136 kWh installation in Maribor, but the structured methodology for assessing when and how second-life battery storage is feasible and beneficial within different public transport contexts.

4.3. Rationale for re-using batteries from electric buses or other PT applications

The rationale for second-life use is based on three complementary considerations:

1. **Technical feasibility**

Traction batteries removed from electric buses typically retain substantial residual capacity (depending on SOH thresholds). While no longer optimal for traction use, they remain technically suitable for stationary storage applications with lower dynamic stress requirements.

2. **Economic evaluation**

The pilot assessed not only technical viability but also economic parameters, including:

- avoided or postponed grid reinforcement costs,
- peak demand charge reduction potential,
- utilisation of lower-tariff electricity periods,
- integration of locally generated solar energy and its impact on self-consumption rates,
- investment cost of storage integration versus infrastructure upgrade scenarios.

3. **Lifecycle optimisation**

From a lifecycle perspective, second-life deployment enables continued functional use prior to final recycling, improving overall resource efficiency and reducing premature waste generation.

4.4. Circular economy principles addressed

Building on the objectives outlined earlier, the solution operationalises circular economy principles through practical infrastructure integration. In alignment with CE4CEs' circular economy hierarchy approaches (e.g. AETE classification of circular strategies), the solution primarily addresses:

- **Lifetime extension (Reuse / Repurpose)** – second-life deployment of traction batteries in stationary applications,
- **Cascading use of assets** – transitioning batteries from high-performance traction use to lower-intensity stationary storage,
- **Resource efficiency and system optimisation** – improving utilisation of existing energy and battery assets,
- **Integration of renewable energy systems** – enabling local storage and effective use of renewable electricity.

Unlike recycling-focused strategies, the solution operates at a higher level of the circular hierarchy by maintaining product functionality prior to material recovery.

4.5. Identification of circularity gaps the solution addresses

The pilot identified several circularity gaps within electrified public transport systems:

1. **Absence of structured second-life pathways for traction batteries**

Many systems lack defined procedures for repurposing batteries once they are no longer suitable for vehicle use.

2. **Disconnection between electrification strategies and battery lifecycle planning**

Fleet electrification often progresses without parallel planning for battery end-of-life management.

3. **Infrastructure-focused electrification without integrated energy storage planning**

Charging infrastructure is typically dimensioned for peak demand without considering storage as a flexibility mechanism.

4. **Regulatory and safety uncertainty regarding second-life applications**

Permitting procedures for reused lithium-ion batteries are not yet standardised across jurisdictions.

4. The solution development

5.1 Technical and functional requirements

A transferable second-life BESS solution for public transport infrastructure must be structured across five core design domains:

1. Operational requirements of the storage system
2. Grid and charging infrastructure integration model
3. Battery subsystem characteristics and qualification
4. Physical storage design and spatial integration
5. Control, monitoring and energy management logic

Each domain defines a specific layer of system design and together they determine technical feasibility, safety and performance.

5.1.1. Operational requirements of the BESS

Before technical design, the functional objectives of the storage system must be clearly defined.

In electrified public transport systems, a second-life BESS may be required to:

- **balance short-term power demand during high-power charging events**

In opportunity charging systems, charging occurs only during limited time windows. The BESS can smooth short-term power spikes by supplementing the grid supply during these intervals, aligning instantaneous demand with available connection capacity.

- **Limitation of maximum power draw at the grid connection point**

Where grid capacity is constrained (e.g. depot charging or heavily loaded substations), the BESS can cap peak demand at a predefined level, thereby reducing stress on the grid and potentially avoiding connection upgrades.

- **Optimisation of energy consumption (lower tariff periods)**

Where tariff systems differentiate between day and night electricity prices, the BESS can be charged during lower-cost periods (e.g. night tariff) and discharged during higher-demand intervals. The economic viability of this function depends primarily on sufficient storage capacity and the price differential between tariff periods.

- **Integration of locally generated renewable electricity**

The BESS enables storage of locally produced renewable energy (e.g. photovoltaic generation) and its subsequent use for vehicle charging. This increases the share of clean energy in transport operations and can partially reduce dependence on grid-supplied electricity.

- **Operational resilience in case of short-term grid disturbances.**

Depending on its installed capacity and state of charge, the BESS can provide temporary charging support during short-term grid outages or voltage disturbances. While it cannot replace grid supply over extended periods, it can increase operational resilience by enabling limited charging continuity or controlled load management during disruptions. The level of resilience provided is directly dependent on storage capacity and predefined emergency operating strategies.

5.1.2. Grid and charging infrastructure integration

The integration model defines how the BESS is connected to and interacts with existing electrical infrastructure and, where applicable, renewable energy systems.

- **Existing electrical infrastructure (grid and charging systems)**

The BESS must be electrically compatible with the existing grid connection and charging infrastructure, including voltage level, protection schemes and connection capacity. Depending on the initial system configuration, implementation may require either adaptation to existing infrastructure or targeted upgrades to ensure safe and stable operation. Compatibility between grid, charger and storage system is a fundamental precondition.

a) **Serial configuration (storage-dominant supply)**

The charging system is supplied primarily through the BESS. The grid charges the storage, and the charger draws power from the storage system. All charging power therefore flows through the inverter and battery system. This configuration allows full control over charging power but requires the inverter and storage to be dimensioned for the full charger capacity.

b) **Parallel configuration (partial support mode)**

The grid supplies the base load, while the BESS contributes additional power during peak demand. The charger is supplied simultaneously by the grid and the storage system. This allows partial peak shaving without requiring the storage system to match the full charger power.

c) **Direct (DC-coupled) configuration**

The storage system is connected directly on the DC side of the charging infrastructure. In this case, energy from the battery can be supplied to the charger without double AC-DC-AC conversion, improving conversion efficiency. This configuration requires technical compatibility at the DC level and is typically feasible only when system architecture allows direct integration.

5.1.3. Optional renewable energy systems

Where photovoltaic or other renewable energy installations are present or planned, the BESS design must enable coordinated energy flow between generation, storage and charging demand. Integration of RES should be considered at the design stage, even if implemented in a later phase.

Possible integration topologies include serial, parallel and direct (DC-coupled) configurations. The selection depends on the intended operational behaviour and on the technical characteristics of the existing charging infrastructure.

1. **Battery Subsystem Design**

The battery subsystem represents the core of a second-life BESS and requires a dedicated qualification and compatibility framework. Key design considerations include:

- **battery chemistry (e.g. NMC, LFP, LTO) and suitability for stationary use**

Various lithium-ion chemistries exist, each with distinct characteristics regarding energy density, thermal behaviour, cycle life and safety. The most common chemistries in electric bus applications include NMC, LFP and LTO, but other variants may also be encountered. Selection for second-life stationary use must consider the intended operational profile, required power capability and thermal stability under expected duty cycles.

- **residual State of Health (SOH) threshold definition and battery condition assessment**

A minimum SOH level must be defined to ensure predictable performance and remaining useful life. For second-life applications, professional technical assessment (audit) is essential to verify the actual condition of the battery system, including SOH, State of Charge (SOC), cell balance, and operational integrity. SOH alone does not determine suitability; it must be evaluated in relation to the intended operating stress and system requirements.

- **compatibility between battery voltage range and inverter operating window,**

The nominal and operational voltage range of the battery system must be compatible not only with the inverter’s DC input range, but also internally consistent when multiple battery modules are combined. If different module types, capacities or ageing levels are used, voltage windows and communication interfaces (BMS) must be aligned to ensure stable operation. The inverter remains the key interface component, as it defines the permissible DC operating range and governs bidirectional power exchange with the grid.

- **operational management of battery stress**

The storage system must be dimensioned and operated to provide sufficient power and energy for the intended operational objectives. At the same time, charge and discharge rates should be defined in a manner that avoids unnecessary stress on second-life batteries. Controlled operating limits, appropriate thermal management and continuous monitoring support stable performance and help preserve the remaining useful life of the battery system.

5.1.4. Physical storage design and spatial integration

Beyond electrical integration, the physical design of the storage system must ensure structural safety, fire protection compliance and functional accessibility. Design considerations include:

- **fire-resistant structural design (external and internal layout)**

The BESS enclosure (e.g. containerised or building-integrated solution) must be constructed from non-combustible materials (e.g. fire reaction class A1 or equivalent). Internal compartmentalisation should limit thermal propagation between battery modules, inverter and auxiliary systems.

- **functional spatial organisation and safety clearances**

The internal and external layout must ensure adequate cable routing, defined safety distances, ventilation and thermal management pathways. The design must comply with applicable fire safety and electrical installation regulations.

- **accessibility for maintenance and emergency intervention**

The installation must allow safe access for inspection, servicing and emergency response. Clear intervention points, isolation switches and coordination with local fire services form part of the spatial safety concept.

Due to the fire risk profile of lithium-ion batteries and their classification as hazardous goods for transport, safety-driven spatial design is a core architectural requirement rather than a secondary consideration.

5.1.5. Control, monitoring and energy management logic

A second-life BESS requires an integrated control and monitoring architecture to ensure safe and coordinated system operation. Continuous monitoring of electrical and thermal parameters is essential to ensure long-term operational stability and to track degradation behaviour. The control system must enable:

- **management and monitoring of energy flows and system loads**

The system must dynamically regulate charging and discharging of the battery in coordination with grid supply, charging demand and, where applicable, renewable generation. Continuous supervision of power levels and operating limits is required to prevent overloading and to maintain defined operational parameters.

- **safety monitoring and emergency signalling**

Integrated safety sensors (e.g. temperature, smoke, fault detection) and alarm mechanisms must enable automatic protective actions and structured emergency response procedures.

5.2 Solution development and implementation

Table 1: BESS Implementation Framework Based on the Maribor Pilot.

Phase	Key Considerations	Main Activities
1. Baseline assessment	**Define** the primary purpose of the BESS before technical design; early alignment reduces later redesign	• clarification of operational objectives (e.g. peak limitation, RES integration, resilience), • analysis of existing load profiles and grid constraints • roader stakeholder engagement and knowledge take-up activities
2A. Feasibility study	**Combine** technical feasibility assessment with market availability analysis and	• market research and review of existing practices • definition of intended system design and operational concept

	economic evaluation to ensure realistic and implementable system design.	- scenario modelling (technical and economic performance simulation) - contingency approaches
2B. Technical Documentation	**Prepare** detailed technical documentation to support investment approval, permitting procedures and procurement processes.	- preparation of documentation for investment approval and tendering - detailed technical specifications and bill of quantities (location, grid integration, BESS design and component specification, operational concept, safety concept)
2C. Stakeholder coordination	**Engage** specialized technical expertise and ensure continuous coordination among key stakeholders during investment planning.	- primary: BESS engineering specialists, - secondary: DSO, PTO, battery manufacturer, BESS equipment suppliers
3. Procurement and contracting	**Define** performance, safety and integration requirements	- preparation of technical specifications based on approved documentation - public procurement procedure - contractor selection
4. Implementation	**Ensure** continued coordination among technical experts, contractors and relevant authorities during implementation.	- implementation (Civil works, container placement, electrical and control system integration) - commissioning and handover of the system for operational deployment
5. Testing and evaluation	**Evaluate** system performance based on predefined KPIs (case of Maribors‘ pilot)	- evaluation of implementation success - operational and economic performance assessment - testing of different operational scenarios under real conditions

Roles of involved stakeholders

- **Municipality of Maribor (PTA)** – strategic oversight, investment responsibility, coordination of permitting procedures and alignment with sustainable mobility and energy strategies.
- **Public Transport Operator (PTO)** – operational charging management, fleet coordination and direct definition of operational requirements based on real service conditions, provision of necessary operational data.

- **BESS engineering specialists** - preparation of technical and project documentation (in the Maribor pilot: in coordination with University of Maribor), including system architecture design, integration planning and technical specification development.
- **Battery manufacturer (second-life battery source)** - provision of battery documentation, SOH/SOC verification data and technical compatibility support.
- **Technology providers/BESS equipment suppliers** - delivery and integration of battery modules, inverter configuration, control systems and safety equipment.
- **Distribution System Operator (DSO)** - grid connection approval, verification of technical compliance, definition of connection conditions and export limitations.
- **Regulatory and permitting authorities** - approval of environmental compliance and confirmation of regulatory conformity where applicable.
- **Fire safety authority/emergency services** - review and approval of fire safety concept, intervention planning and emergency access coordination.
- **Civil works, RES and electrical contractors** - execution of construction works, installation, electrical integration and commissioning activities.

5.3 Operational use, performance and maintenance

Operational modes

Depending on system design, storage size and integration strategy, a second-life BESS can fulfil different operational roles within electrified public transport infrastructure. The realised function depends on technical configuration, available grid capacity, tariff structure and renewable generation potential.

Table 2: Operational stages of second-life battery storage integration in public transport charging infrastructure.

Stage/Operational Area	Key aspects
Stage 1: Grid capacity optimisation	• Peak shaving through buffering of short-duration charging peaks • Reduction of required grid connection power • Small-scale capacity providing real-time support • Increased resilience during short-term (hour-level) grid disturbances
Stage2: Tariff optimisation	• Storage and use of electricity during lower-tariff periods • Discharge during operational demand periods • Economic effectiveness dependent on installed BESS capacity • Potential resilience support during extended grid disturbances (capacity-dependent)
Stage 3: Renewable energy integration	• Local storage and use of renewable energy sources • Alternative energy supply for charging operations • Balancing between RES production and storage capacity

	• Potential export of surplus energy to the grid (where permitted) • Resilience dependent on sufficient renewable generation and storage availability

Lifecycle extension and cascading use (cross-cutting effect)

Independent of the operational stage (grid optimisation, tariff optimisation or RES integration), second-life deployment of batteries inherently enables:

- extension of battery service life beyond first vehicle application
- postponement of end-of-life treatment and waste generation
- cascading functional use prior to final recycling

Energy management strategies and performance indicators (KPIs)

Energy management strategies depend on the selected operational stage and system configuration. Performance evaluation should therefore rely on a structured, yet adaptable set of indicators aligned with circular, operational and economic objectives.

Table 3: Key Performance Indicators (KPIs) for Pilot Monitoring and Evaluation.

Category	Indicator	Unit	What It Measures
Grid Optimisation	Peak power reduction at connection point	kW/%	Reduction of maximum grid demand due to BESS support
	Grid capacity utilisation rate	%	Extent to which installed grid connection is optimally used
Tariff Optimisation	Off-peak energy share	%	Share of energy charged during lower-tariff periods
Renewable Integration	Renewable energy share in charging	%	Portion of charging energy sourced from RES
	Energy self-sufficiency level	%	Share of total energy demand covered by local generation and storage
Lifecycle Extension	Share of batteries repurposed before recycling	%	Portion of decommissioned traction batteries entering second life use instead of direct recycling
	Avoided or postponed battery waste treatment	Years/%	Delay in transfer of batteries to end-of-life processing due to second-life deployment
System Performance	Status of SOH and SOC	%	Health and performance of battery modules
	Charging stability	Qual./%	Reliability of charging operations under BESS integration

	Thermal compliance	%	Operation within predefined temperature limits/thresholds
Economic Performance	Return on investment (ROI)	€/%/Years	Financial performance of the BESS investment
	Energy cost savings from storage	€/%	Financial benefit achieved through load shifting

Monitoring and data management architecture

Effective operation of a second-life BESS requires an integrated monitoring architecture combining battery, inverter, grid and safety subsystems. The system may include:

- **Battery Management System (BMS)** for monitoring battery health, performance,
- **Inverter** managing and monitoring for power flows and conversion control,
- **Energy Management System (EMS)** controlling charge-discharge logic,
- **External energy meters** at the grid connection and charger output,
- **Sensor system** for monitoring temperature, smoke, gas detection, humidity, current/voltage sensors,
- **RES interface** for monitoring renewable energy production,
- **Central data logger** and **remote monitoring platform** - collection, storage and remote visualisation of operational and safety data.

Devices should enable automated data collection and centralised storage in a time-synchronised format where technically feasible. Depending on system architecture, monitoring and control functions may be integrated within single platforms (e.g. inverter-EMS integration or BMS-inverter-EMS combined control units).

Performance, maintenance and safety management

Operation of a second-life BESS must follow defined technical, safety and maintenance protocols. Monitoring, inspection and safety management must be continuous and aligned with manufacturer specifications and applicable regulatory standards.

Operational management includes:

- continuous monitoring of BESS operational performance,
- regular inspection of electrical, control and cooling components,
- periodic validation of measurement data and grid compliance.

In addition, long-term performance tracking include:

- monitoring long-term BESS performance and battery health trends,
- estimating longevity of BESS (batteries).

5.4 Integration and transferability

Table 4: Key Criteria for Assessing BESS Feasibility and Transferability.

Area	Key Aspects
Transferability criteria	- ongoing or planned fleet electrification - emerging volumes of traction batteries reaching end-of-(first)life - need/desire for peak shaving or tariff optimisation (i.e. grid upgrade) - regulatory environment permitting stationary second-life battery use - strategic commitment to circular economy objectives in public transport
Technical System Conditions	- presence of peak-load constraints or grid capacity limitations - compatibility of existing charging infrastructure with storage integration - defined integration topology (serial, parallel or hybrid) - availability of technically verified second-life battery modules - spatial availability for compliant BESS installation
Economic Feasibility Conditions	- grid reinforcement represents a relevant cost alternative - tariff structures enable optimisation potential - defined cost-benefit evaluation framework (BESS vs. infrastructure upgrade scenarios)
Organisational Readiness	- clear allocation of responsibilities between PTA, PTO, DSO and technical experts - access to operational data (energy flow, charging, fleet, etc.) - capacity to manage permitting and safety procedures
Regulatory Feasibility	- defined list and pathway for required permits - fire safety compliance framework for lithium-ion systems, - EU status of handling/integrating second-life batteries
Safety and Risk Management	- compliant fire protection systems, - defined emergency response protocols, - continuous monitoring and technical supervision

Linkage with CE4CE Circularity Knowledge Platform

The technical findings, regulatory pathways, and stakeholder coordination model can be documented and shared through the CE4CE Circularity Knowledge Platform to support replication in other regions.

5. Challenges and lessons learned

The Maribor pilot provided practical insight into the technical, organizational, economic and regulatory dimensions of integrating second-life battery storage into public transport infrastructure. Beyond validating technical feasibility, the pilot highlighted critical enabling conditions and potential constraints relevant for replication in other contexts. The lessons learned are structured across technical, economic, organizational and circular economy dimensions, and summarized in a consolidated table at the end of the chapter.

5.2. Technical lessons learned

1. **Connection of the BESS to the existing grid and charging infrastructure**

The first level concerns external integration — the connection of the BESS to the existing grid and charging infrastructure. This includes defining the integration topology (serial, parallel or hybrid), ensuring compatibility with grid voltage levels and protection schemes, and aligning the storage system with charging behaviour.

2. **Internal BESS system configuration**

The second level concerns internal system configuration — the organisation of the battery subsystem itself. When combining multiple battery modules (potentially with different operational histories), careful alignment of voltage ranges, communication protocols and operational limits with the inverter is essential. Voltage compatibility and stable communication between battery modules and inverter proved to be critical success factors for reliable operation.

3. **Safety requirements**

The pilot further confirmed that safety requirements must not be treated as auxiliary components but as core structural elements of system design. Fire protection systems, thermal management, monitoring architecture and emergency shutdown mechanisms must be integrated from the initial design phase.

4. **Scalability-Enabled Design**

An additional lesson concerns scalability. BESS design should anticipate potential future expansion depending on operational needs, electrification growth and strategic objectives. Modular architecture enables the addition of battery modules or capacity increase without requiring fundamental redesign of the system. Designing with scalability in mind reduces long-term investment risk and supports phased implementation strategies.

5.3. Economic lessons learned

1. **System functionality and operational resilience**

The first prerequisite is that the system reliably performs its intended function. Technical functionality and operational resilience are foundational conditions before any financial return can be considered. A BESS that stabilises charging operations and increases infrastructure resilience already generates operational value, even if direct financial return is limited.

2. **Avoided or postponed grid reinforcement**

A major economic driver is the potential to replace or postpone grid infrastructure upgrades. In the Interreg CE project EfficienCE (2019-2022), solely grid reinforcement amounted to approximately 180,000 EUR.

Where grid upgrade is technically complex, spatially constrained or financially significant, BESS integration may represent a viable alternative or complementary solution.

However, economic performance depends on storage capacity and operational role. If the BESS is dimensioned only for partial peak support, it may reduce stress but not fully eliminate the need for reinforcement. Full substitution requires sufficient storage capacity aligned with peak demand duration.

3. **Energy cost optimisation and return on investment**

Based on the calculations performed for the Maribor pilot, a BESS deployed at pilot scale (limited peak shaving) does not achieve return on investment within the 12-year evaluation period. Likewise, a larger BESS dimensioned primarily for tariff optimisation through night-time charging does not reach ROI under the current tariff structure and assumed energy price escalation.

Return on investment within the analysed 12-year horizon is achieved only in the scenario where storage is combined with renewable energy integration (year 11).

Economic performance is highly dependent on:

- the necessity and cost of grid or charging infrastructure upgrade (not the case of the pilot and CBA),
- local tariff structures,
- daily energy consumption profile,
- BESS capacity,
- amount of renewable generation.

Notably, the financial calculations for renewable integration and tariff optimisation were based on full daily storage utilisation, whereas peak-load support scenarios depend on sufficient instantaneous capacity for short-duration contribution.

5.4. Organisational and regulatory lessons learned

Early involvement of specialised BESS engineering expertise significantly reduced redesign risks and supported compliance with safety and permitting requirements. Continuous coordination between the municipality, PTO and DSO proved essential for maintaining implementation timelines.

1. **Battery sourcing and qualification challenges**

A key lesson concerns the acquisition and qualification of second-life batteries. In the case of the Maribor pilot, batteries could not be sourced directly from the local public transport fleet, as the existing batteries were not yet at an appropriate stage for second-life deployment. This required sourcing batteries externally.

However, structured and standardised practices for transferring used traction batteries between PTOs are not yet established. While operators may be willing to release used batteries, significant challenges arise regarding:

- verification of battery condition and operational history,
- lack of guaranteed documentation on storage and handling conditions,
- absence of clear warranty frameworks,
- need for professional technical audit (SOH, SOC, degradation profile).

Acquiring batteries without verified technical audit represents a significant investment and safety risk. The investor must be confident that the batteries are technically suitable and have not been improperly stored or damaged. In the Maribor pilot, this risk was mitigated because the batteries were sourced directly from the e-bus manufacturer. The manufacturer had used them as laboratory test units and was able to provide:

- verified technical documentation,
- professional battery audit,
- technical support during integration,
- assistance with ADR-compliant transport procedures.

This significantly reduced uncertainty and implementation risk.

2. Implementation and Contractor Constraints

Another major challenge was the limited market readiness for second-life BESS integration. Such systems are currently not standardised products but custom-built solutions. As a result:

- identifying a contractor with relevant technical expertise proved difficult
- many potential contractors were reluctant to assume liability
- concerns regarding hazardous goods classification and fire risk limited willingness to provide performance guarantees

The perception of risk — particularly related to lithium-ion battery safety — influenced procurement and contractor engagement. This confirms that market maturity for second-life battery integration remains limited, and implementation requires strong technical specification, risk clarification and clear allocation of responsibility.

5.5. Circular economy lessons learned

Second-life deployment represents a practical intermediate stage in the battery lifecycle, aligned with circular economy hierarchy principles prioritising reuse before disposal (recycling).

The pilot highlighted the importance of integrating battery reuse planning into long-term fleet renewal strategies rather than treating storage as a standalone technical add-on.

Long-term degradation monitoring is essential to determine the optimal transition point to final recycling in accordance with EU Battery Regulation requirements.

5.6. Summary of key lessons learned

Table 5: Lessons learned for implementing second-life BESS in public transport systems.

Area	Key Lessons
Technical	• BESS integration must address both external (grid and charging infrastructure) and internal (e.g. battery-inverter configuration) compatibility • Integration topology (serial, parallel, hybrid) must be defined early • Voltage alignment and stable communication between battery modules and inverter are critical success factors • Safety architecture (fire protection, thermal management, monitoring, emergency shutdown) must be integrated from the design phase

	• System design should enable modular scalability and future battery addition
Economic	• Operational functionality and resilience are prerequisites before financial return can be considered • Avoided or postponed grid reinforcement can represent a major economic driver • Full substitution of grid upgrade requires sufficient storage capacity aligned with peak duration • Economic performance depends on grid upgrade necessity, BESS capacity, renewable generation, tariff structure and daily load profile • ROI (12-year time) is only achieved with renewable integration + large capacity BESS • Tariff optimisation alone yields longer payback, while pure reduction of contracted power does not ensure investment recovery
Organisational & Regulatory	• Early involvement of specialised BESS engineering expertise reduces redesign and permitting risks • Continuous coordination between municipality, PTO and DSO is essential • Structured and verified battery sourcing is critical; professional SOH/SOC audit is mandatory • Lack of standardised second-life battery transfer practices increases investment risk • Implementation requires strong technical specification due to limited contractor experience • Fire safety approval and ADR compliance are critical regulatory milestones
Circular Economy	• Second-life deployment represents an intermediate lifecycle stage prioritising reuse before recycling • Battery reuse planning should be integrated into long-term fleet renewal strategies • Long-term degradation monitoring supports optimal timing for final recycling in line with EU Battery Regulation • Circular value creation depends on alignment between fleet management and energy infrastructure planning

6. Expected change

6.1. Immediate results of the pilot

With increasing electrification of bus fleets, local grid capacity constraints are expected to intensify. The Maribor pilot demonstrates that second-life battery storage application can already generate measurable technical and systemic benefits at the current implementation scale.

Implemented Results

- Extension of the service life of otherwise decommissioned batteries, postponing end-of-life treatment and delaying hazardous waste generation in a context where recycling pathways are still evolving.
- Reduction of peak power demand and grid load (approx. 25 kW peak shaving contribution).
- Improved operational flexibility of the charging infrastructure through digital control and remote energy management.
- Initial integration of photovoltaic generation (5.4 kW) demonstrating technical feasibility of on-site renewable coupling.

These measures provide a structured alternative to immediate grid capacity upgrades and establish a controlled operational framework for hybrid grid-storage charging. However, the pilot also confirms that storage integration does not universally replace infrastructure reinforcement and must be dimensioned according to actual load profiles, grid constraints and economic conditions. The pilot therefore functions as:

- A technical proof of concept for second-life battery integration.
- A financial and operational learning case.
- A strategic reference model for long-term energy infrastructure planning in electrified public transport systems.

Expected Territorial and Systemic Change

The expected change extends beyond the individual installation and contributes to structural development of sustainable public transport energy systems.

Energy and Infrastructure Impact

- Reduced pressure on local grid infrastructure in the context of increasing fleet electrification.
- Alternative pathway to costly and spatially constrained grid upgrades.
- Increased resilience of charging infrastructure against short-term disturbances.
- Gradual development toward hybrid grid–storage–RES energy hubs.

6.2. Long-term and lasting effects

In the longer term, the pilot is expected to contribute to:

- Increased confidence in second-life battery deployment within public transport systems.
- More structured end-of-life battery planning at fleet level.

- Progressive scaling of modular BESS installations aligned with electrification growth.
- Reduced investment risk for future hybrid charging infrastructure projects.
- Integration of circular economy logic into energy infrastructure planning.

6.3. Uptake potential by relevant organisations

The pilot creates replicable knowledge and operational confidence among key actors:

Public transport authority (PTA) – gains a validated reference for strategic infrastructure planning and circular investment decisions.

Public transport operator (PTO) – gains operational experience in hybrid energy management and storage integration.

Distribution System Operator (DSO) – gains insight into storage-supported grid interaction models.

Technology providers and engineering experts – gain reference case experience in second-life BESS integration.

Waste management and recycling stakeholders – experience delayed battery inflow due to extended second-life application, while gaining clearer visibility on future recycling volumes and improved lifecycle planning in line with EU Battery Regulation requirements.

Other cities and PT authorities – gain a transferable framework for assessing technical and economic feasibility.

The structured documentation within CE4CE supports knowledge transfer and cross-regional replication.

7. Sustainability, transferability and replicability

7.1. Environmental and economic sustainability

The Maribor pilot demonstrates that second-life battery integration can contribute simultaneously to environmental and economic sustainability when aligned with local infrastructure needs and operational objectives.

Circular Economy Impact

- Operationalisation of cascading battery use prior to recycling.
- Integration of battery reuse planning into long-term fleet management strategies.
- Practical demonstration of circular economy principles in an energy-intensive public service.

Climate and Sustainability Impact

- Increased share of renewable electricity in public transport operations.
- Reduced reliance on fossil-based energy supply.
- Strengthening the systemic sustainability of electrified public transport beyond vehicle replacement alone.

By combining second-life battery use, renewable energy integration and grid-support functionality, the pilot moves beyond simple fleet electrification and addresses the systemic sustainability of public transport energy supply.

7.2. Transferability and replicability

The solution is transferable to other cities and public transport systems under clearly defined boundary conditions.

Transferability is strongest in systems where:

- fleet electrification increases peak-load demand at charging locations,
- battery end-of-life volumes are emerging due to fleet renewal cycles,
- grid capacity constraints create technical or financial pressure for alternative solutions,
- renewable energy integration forms part of local mobility or energy strategies.

The concept is not location-specific but parameter-dependent. Key contextual variables include:

- fleet structure and battery availability,
- existing charging and grid infrastructure configuration,
- regulatory and fire safety frameworks,
- operational load profiles and energy demand patterns.

The modular and scalable design approach enables adaptation to different system sizes — from small peak-support installations to larger hybrid energy hubs integrated with renewable generation.

Replication does not require identical technical configurations, but application of the structured feasibility, integration and governance framework validated in the pilot.

7.3. Future development and upscaling potential

Future development pathways include:

- scaling storage capacity in line with fleet electrification growth,
- expanding renewable generation integration,
- integration of additional second-life battery streams,
- development of multi-site storage strategies across depots and mobility hubs.

As electrification intensifies, hybrid grid-storage-RES configurations may become standard components of public transport energy infrastructure.

7.4. Actions to encourage uptake by decision makers

To support adoption by policymakers, transport authorities and operators, the following actions are planned or ongoing:

- dissemination of pilot results through CE4CE Circularity Knowledge Platform,

- presentation of technical and economic findings to municipal and national stakeholders, structured documentation of feasibility methodology and regulatory pathways,
- integration of lessons learned into strategic mobility and energy planning documents,
- development of decision-support materials comparing BESS integration with grid reinforcement alternatives.

By providing a validated reference case, quantified economic scenarios and documented regulatory procedures, the project reduces uncertainty and perceived risk for future adopters.

8. Conclusions

8.1. Summary of achievements

The project validated:

- safe and compliant integration of second-life battery modules into a hybrid grid-storage configuration,
- measurable peak load contribution under defined operating limits,
- initial coupling of renewable generation with storage-supported charging,
- a structured methodology for feasibility, regulatory approval and economic assessment.

At the same time, the pilot revealed important boundary conditions and limitations:

- second-life battery sourcing lacks standardised transfer practices and requires professional audit procedures,
- contractor market maturity for custom second-life BESS installations remains limited,
- economic viability is strongly dependent on local tariff structures and grid upgrade alternatives,
- scalability must be planned from the outset to avoid future redesign.

These findings confirm that second-life BESS integration is feasible, but context-dependent and requiring structured planning.

8.2. Contribution to CE4CE project objectives

The solution directly contributes to the core objectives of the CE4CE project by operationalising circular economy principles in public transport energy systems.

Specifically, the pilot:

- Extends the lifecycle of traction batteries through cascading second-life application prior to recycling.
- Demonstrates practical implementation of reuse-based circular strategies within an energy-intensive public service.
- Provides a validated, transferable framework for integrating second-life BESS into charging infrastructure.
- Supports resource efficiency and reduction of hazardous waste generation.

- Strengthens the systemic sustainability of electrified public transport beyond vehicle replacement alone.

By transforming a pilot implementation into a structured and replicable business model, the project advances CE4CE's objective of accelerating circular economy adoption across Central European public transport systems.

The Maribor case confirms that second-life battery integration is not merely a technical experiment but a scalable and strategically relevant component of future-proof public transport infrastructure.

9. Annexes

Annex 1: CE4CE Maribor Pilot Report (separate annex)

Annex 2: CE4CE Strategy on energy use (separate annex)