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Report on pilot joint requirements, preparation, implementation and evaluation

Pilot action: Analysis of used batteries application to store RES for powering a fast charger as example for strategic orientation towards circularity in Maribor, Slovenia

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1. Executive Summary

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

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

CE4CE jointly develops outputs based on co-creation and peer reviews for uptake by the public transport sector, including pilot actions and solutions such as the CE4CE Circularity Compass for public transport, the CE4CE Circularity Knowledge Platform, a web-based second-hand marketplace, strategies and pilot actions to increase resource efficiency, and practical demonstrations of “use more, reuse and recycle” approaches for the public transport sector.

The CE4CE partnership reflects the entire value chain and system perspective of the transport sector and includes 11 project partners from 6 Central European countries, ranging from public transport authorities and operators to industry, research institutions, and interest groups. To broaden this cooperation, associated partners such as ICLEI, UITP and EIT Urban Mobility/Raw Materials are strategically involved to maximise communication outreach and knowledge transfer of project results.

This document presents the report on the pilot action implemented by the Municipality of Maribor (MOM) under the CE4CE initiative. The report provides an overview of the pilot’s joint requirements, preparation, implementation, and evaluation processes. It explains the objectives, technical and organisational setup, stakeholder involvement, and the contribution of the Maribor pilot to the integration of circular economy principles into public transport operations and planning.

The document is organized as follows:

Chapter 2 addresses relevant regions concerned by the pilot action.

Chapter 3 presents the aim and purpose of the pilot concept and the integration of circular economy principles in the project.

Chapter 4 is about key development phases of the pilot action, starting from the design phase to the reporting and documentation phase.

Chapter 5 focuses on preparation and technical requirements for each phase.

Chapter 6 contains the 4 phases of the pilot action implementation.

Chapter 7 explains the operational launch as part of the evaluation.

Chapter 8 presents the monitoring and evaluation phase as a continuous process following the operational launch.

Chapter 9 offers an overview of best practices among Europe that integrate circular economy principles.

Chapter 10 focuses on risks identification that helps define mitigation measures.

Chapter 11 is about the key impacts of the pilot project.

Chapter 12 addresses the possibility of the pilot project to be implemented in other cities and regions.

Chapter 13 contains the references of the document.

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

The region covered by the pilot action refers to the city of Maribor. Maribor is the second-largest city in Slovenia, with approximately 115,000 inhabitants. It represents the economic, educational, and cultural centre of north-eastern Slovenia and plays a key role in regional mobility and public transport services within the Podravska region.

Maribor is located in the north-east of Slovenia, close to the Austrian border, and serves as an important transport hub connecting local, regional, and cross-border mobility flows. As the administrative centre of the Municipality of Maribor (MOM), the city is responsible for strategic urban development, including sustainable mobility planning and the transition towards circular and resource-efficient public transport solutions.

Country (NUTS 0)	SL
Macroregion (NUTS 1)	SI0 - Slovenia
Region (NUTS 2)	SI03 - Vzhodna Slovenija (Eastern Slovenia)
Sub-region (NUTS 3)	SI032 - Podravska

3. Basic pilot concept

3.1. Aim and Purpose

The pilot project in Maribor aims to improve the sustainability, resilience, and energy efficiency of public transport infrastructure by integrating a Battery Energy Storage System (BESS) composed of second-life batteries with renewable energy sources (RES) to support the fast-charging station for electric buses at the Vzpenjača station.

Following the installation of a fast charger in 2022 and the full electrification of bus line 6 in 2023, the Municipality of Maribor (MOM) seeks to further modernize public transport infrastructure by introducing circular energy solutions. The pilot aims to reduce dependency on the electricity grid, optimize energy flows, and demonstrate the practical application of circular economy principles in energy infrastructure.

The project promotes a shift from a linear energy supply model toward a circular, resource-efficient system where reused batteries are given a second life within public transport operations.

3.2. Integration with Circular Economy Principles

The pilot integrates circular economy principles by extending the lifecycle of battery systems through second-life applications and by enabling the storage and optimized use of renewable energy.

Instead of disposing of batteries after their first lifecycle in electric vehicles, the project reintroduces them into the energy system as part of a BESS. This approach contributes to:

1. Lifecycle extension and cascading use of battery assets

- extension of battery service life through second-life application.
- delayed end-of-life treatment and postponed waste generation.
- cascading use of battery assets prior to final recycling.

2. Energy system optimisation and grid relief

- reduction of peak power demand from the electricity grid (peak shaving).
- smoothing of load curves at the grid connection point.
- increased flexibility and resilience of public transport energy infrastructure.

3. Improved resource and energy efficiency

- partial energy self-sufficiency through the integration of renewable energy sources (RES).
- optimized utilization of grid connection capacity.
- more efficient use of existing infrastructure assets.

3.2.1. Basic Concept of the Pilot Project

As part of the pilot project, a Battery Energy Storage System (BESS) composed of repurposed batteries will be installed at the Vzpenjača fast-charging station. The BESS will function as an intermediary energy buffer between renewable energy generation, the electricity grid, and the fast charger for electric buses. Its technical role is to:

- absorb surplus renewable electricity,
- store energy for later use,
- discharge energy during bus charging events,
- balance instantaneous power demand at the grid connection point,
- manage energy flows between RES production, storage, and consumption.

The system will be integrated into the existing charging infrastructure and operated within current technical and regulatory frameworks.

3.2.2. Main Activities During the Pilot

Preparation Phase

- Technical feasibility study for BESS integration
- Assessment of regulatory and grid connection requirements
- Development of technical documentation
- Preparation and launch of tender procedure
- Application for necessary permits (if required)

Implementation Phase

- Public tender & selection of contractors
- Procurement, installation and integration of BESS
- System commissioning and operational testing

Evaluation Phase

- System validation (configuration & operation)
- Scenario-based testing (peak shaving, hybrid operation)
- Energy flow monitoring
- Battery condition tracking (SOC, SOH)

- Performance assessment (grid impact, RES share)

3.2.3. Alignment with Policies and Strategies

Local Policies and Strategies

The project aligns with key strategic frameworks of the Municipality of Maribor that promote sustainable mobility, circular economy, and energy-efficient urban development.

The **Strategy for the Transition of the City of Maribor to a Circular Economy 2024-2030**[1] provides the overarching strategic context for circular economy implementation in Maribor. This updated strategy embeds circular economy principles into the city's long-term development agenda and highlights the importance of resource efficiency, cascading use of assets, and systemic integration of circular practices across sectors such as mobility, energy, and infrastructure. The strategy specifically supports extending product lifecycles, optimising resource flows, and enhancing synergies between energy, transport, and urban systems — all key elements underpinning this pilot action.

In addition, the Municipality of Maribor's **Sustainable Urban Mobility Plan (SUMP)**[2] — currently under revision with an anticipated update in 2025 — outlines the city's objectives and measures for transitioning toward low-emission, energy-efficient urban mobility. The SUMP supports electrification of public transport, infrastructural modernisation, and the integration of innovative energy and transport solutions, providing a crucial policy framework that aligns with the pilot's focus on electric bus charging and circular energy use.

Other related local strategic frameworks, such as the **Smart City Maribor Strategy 2030**[3], further reinforce long-term goals for sustainability, digitalisation, and resilient infrastructure, creating a conducive policy environment for advanced energy storage, renewable integration, and circular economy initiatives.

Challenges:

- Managing energy transition under constrained urban and financial conditions.
- Ensuring grid stability while scaling up e-mobility infrastructure.
- Operationalising circular economy principles beyond material recycling into energy systems.

Regional Policies and Strategies

At the regional level, the pilot aligns with strategic objectives set out in the Regional Development Programme of the Podravska Development Region 2021–2027[4]. This programme guides integrated territorial development across socio-economic, environmental, and infrastructure domains in the Podravska region, including sustainable mobility and energy transition. The programme also incorporates the Regional SUMP for the Podravska region, which will represent a strategic development document that defines the direction and management of transport development within the region. Through the RCPS, the national government

[1] *Strategy for the Transition of the City of Maribor to a Circular Economy 2024-2030* — available online (in Slovenian): https://rra-podravje.si/assets/docs/SKG-MOM-2024-2030.pdf

[2] *Sustainable Urban Mobility Plan 2025*— available online (in Slovenian): https://maribor.si/mestni-servis/promet-in-javne-povrsine/obcinska-celostna-prometna-strategija-2025/

[3] *Smart City Maribor Strategy 2030* — available online (in Slovenian): https://maribor.si/wp-content/uploads/2022/10/3_Strategija_PMM_Strategija_final_v3_2branje.pdf

[4] *Podravska Development Region 2021-2027: https://www.gov.si/assets/ministrstva/MKRR/DRR/RRP-2021_2027/RRP-Podravske-razvojne-regije.pdf*

and the municipalities within the region jointly agree on and coordinate transport development objectives and priority actions.

Challenges:

- Ensuring coherent and coordinated mobility development across municipalities within the region, while addressing differing local priorities and capacities.
- Supporting the transition toward low-emission and sustainable transport systems in line with broader regional development objectives.
- Integrating transport planning with wider regional goals related to energy efficiency, environmental protection, and long-term territorial development.

National Policies and Strategies

At the national level, the project aligns with Slovenia's strategic framework for sustainable mobility, energy transition, and circular economy development.

It is consistent with the **Transport Development Strategy of the Republic of Slovenia until 2030**[5], and its continuation through the forthcoming **National Comprehensive Transport Strategy (DCPS)**, which strengthen integrated, long-term transport planning.

The project also contributes to objectives of the **National Energy and Climate Plan (NECP 2021-2030)**[6], which outlines national commitments related to greenhouse gas emission reduction, increased use of renewable energy sources, and enhanced energy efficiency as well as to Slovenia's **Roadmap towards the Circular Economy**[7], which promotes lifecycle extension, resource efficiency, and systemic circular transformation.

European Policies and Strategies

At the European level, the project is aligned with key regulatory frameworks supporting circular economy principles, sustainable battery management, renewable energy integration, and energy system flexibility:

- **Circular Economy Action Plan (2020)**[8] – sets the framework for circular design, lifecycle extension, and resource efficiency in priority value chains (including *batteries and vehicles*).
- **Battery Regulation (EU) 2023/1542**[9] – comprehensive regulation governing sustainability, traceability, reuse and second-life applications of batteries in the EU.
- **Renewable Energy Directive (RED III) - Directive (EU) 2018/2001**[10] – promotes increased shares of renewable energy and supports energy storage integration.

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[5] *Transport Development Strategy of the Republic of Slovenia until 2030* - available online: https://www.dlib.si/stream/URN:NBN:SI:DOC-7GJV5ARZ/c14a649c-7c2c-417a-bdb5-798ad89cacb1/PDF

[6] *National Energy and Climate Plan (NECP 2021-2030) — available online: https://commission.europa.eu/publications/slovenia-final-updated-necp-2021-2030-submitted-2025_en*

[7] *Roadmap towards the Circular Economy in Slovenia — available online:* https://circulareconomy.europa.eu/platform/sites/default/files/roadmap_towards_the_circular_economy_in_slovenia.pdf

[8] *Circular Economy Action Plan (2020):* https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

[9] *Battery Regulation (EU) 2023/1542:* https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023R1542

[10] *Renewable Energy Directive (RED III) - Directive (EU) 2018/2001:* https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32018L2001

Under Regulation (EU) 2023/1542, particular relevance is given to:

- the explicit prioritisation of **reuse and repurposing before recycling**,
- mandatory recycling efficiency targets for lithium-ion batteries (65% by 2025; 70% by 2030),
- material recovery targets for critical raw materials (e.g. lithium 50% by 2027 and 80% by 2031; cobalt, nickel and copper 90% by 2027 and 95% by 2031),
- minimum recycled content requirements in new industrial and EV batteries from 2031 onwards,
- the introduction of the **Battery Passport** to ensure lifecycle traceability.

By repurposing batteries in a stationary BESS application, the Maribor pilot **extends battery lifetime and postpones the immediate need for take-back and recycling**. This temporal shift can ease short- and medium-term pressure on stakeholders responsible for establishing large-scale collection and recycling capacities under the new Regulation.

In this sense, BESS systems act not only as technical enablers of renewable integration and grid flexibility, but also as **transition instruments within the circular economy framework**, allowing Member States and industry actors additional time to scale compliant recycling infrastructure while maximising the embedded value of batteries before material recovery.

For a more comprehensive analysis of EU circular economy regulations relevant to public transport, see the **CE4CE Strategy on Circular Economy in public transport (EU Regulatory Framework relevant for Circularity and Sustainability)**.

4. Key pilot development phases

This section gives a short overview over the key phases and timeline of the pilot.

Main milestone	Description	Calendar term	Responsible partner
Pilot Design	Definition of the overall concept of the pilot, including objectives, scope, expected circular economy and operational impacts of the BESS and RES integration.	Apr-23 - Sept-23	MOM (PP07), UM (PP08)
Stakeholder Coordination	Coordination with the PTA (MOM), PTO (Marprom), the energy (electricity) provider, the fast-charger manufacturer, electric bus suppliers, and relevant waste management stakeholders to consolidate technical requirements as well as procedural and regulatory conditions for the implementation of the BESS.	Sept-23 - Mar-24	MOM (PP07), UM (PP08)

Feasibility Study	Comprehensive technical, regulatory, and economic assessment of integrating a Battery Energy Storage System (BESS) composed of second-life batteries. The study evaluated system sizing, grid connection capacity, peak load reduction potential, RES integration scenarios, operational stability, and preliminary cost-benefit considerations.	Mar-24 -Sept-24	UM (PP08)
Preparation of Project Documentation	Preparation of detailed design documentation (PZI) by external experts specialised in small power plant construction, including obtaining the required permits and approvals such as environmental consent, grid connection approval, and fire safety clearance.	Sept-24 -Oct-25	UM (PP08), External experts
Procurement Process	Preparation of tender documentation, definition of technical specifications for the BESS and associated components, evaluation criteria, and contractor selection in accordance with public procurement regulations.	Oct-25 -Feb-26	MOM (PP07)
Implementation	Procurement, installation, integration, and commissioning of the BESS at the Vzpenjača fast-charging station, including system testing and safety verification.	Feb-26- -Mar-26	MOM (PP07), Contractor
Monitoring and Evaluation	Operational monitoring and performance assessment	Feb-26- Mar-26	UM (PP08), MOM (PP07)
Reporting and Documentation	Compiling findings, data, and analyses into comprehensive reports. This includes both interim and final reports to document progress, results, challenges, and lessons learned.	Mar-24 -Mar-26	MOM (PP07), UM (PP08),

5. Preparation and technical requirements

5.1. Pilot Design

This investment represents Maribor's first demonstration project for charging electric buses using a BESS combined with RES. It builds upon previous studies and EU-funded initiatives (e.g., Tramob and EfficienCE), which analysed the technical conditions for full electrification of bus line G6 and confirmed the suitability of opportunity charging at the Vzpenjača terminal.

As part of the electrification of line G6, a 150 kW DC fast charger was installed at the Vzpenjača terminus, supported by an upgraded transformer and a grid connection dimensioned for full-rated charging power. The operational characteristics of the line — short route length (7.7 km one way), modest elevation difference (approx. 55 m), and scheduled layovers of 5–10 minutes — provide favourable conditions for short and intensive opportunity charging cycles. Electric buses operating on the line are equipped with 74 kWh LTO batteries, enabling multiple round trips between charging events.

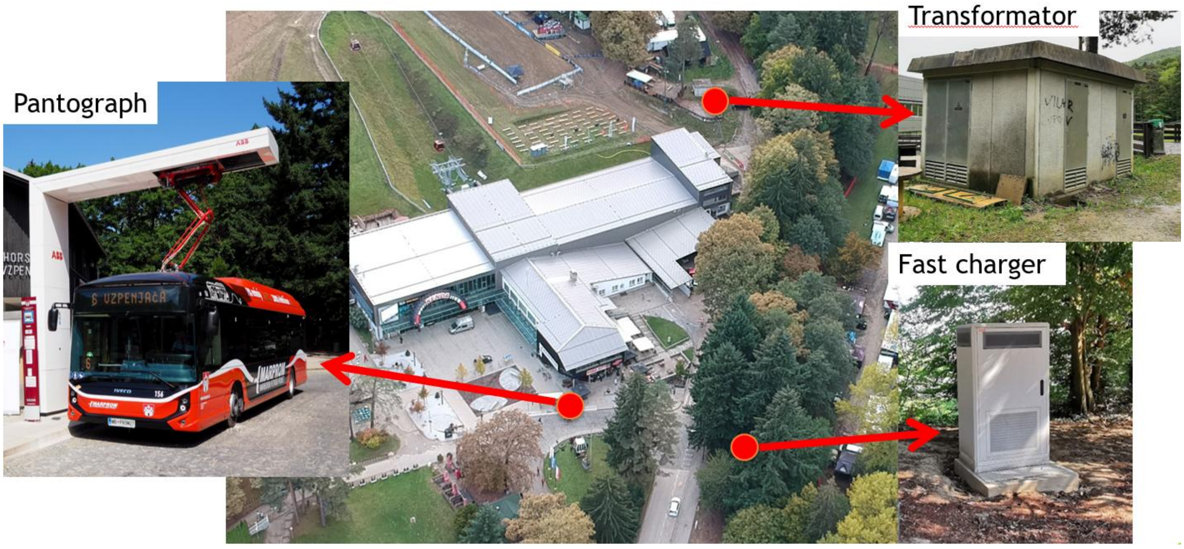

Figure 1: Current charging infrastructure at Vzpenjača station.

Table 1: Technical characteristics of the route driven by line G6.

Parameter	Value / Description
Line length (one-way)	*7.7 km*
Elevation difference	*Approx. 55 m*
Route profile	*Mostly flat with minor inclines*
Turnaround time	*5-10 min (depend on the time of the day)*
Charger location	*Vzpenjača terminal (Pohorje), end of line G6*
Charging regime	*Overhead pathography, opportunity charging*
Grid and Charger power	*150 kW DC fast charger*
Bus battery technology, capacity	*LTO, 74 kWh*

Operational monitoring conducted in 2024 shows an annual charger energy demand of approximately 42 MWh. Average daily consumption was around 400 kWh, with peak values reaching 650 kWh during exceptional operational conditions. Charging sessions lasted approximately five minutes, transferring 8–14 kWh per event, with peak measured power reaching 140 kW. Importantly, although the grid connection is dimensioned for 150 kW continuous availability, full-rated charging power is required only during short charging intervals and primarily during daytime operation, meaning the infrastructure is fully utilised for roughly one quarter of the daily time period.

Table 2: Indicators measured at Vzpenjača terminal station.

Indicator	Measured Value / Range
Annual energy demand	*145000 kWh*
Daily energy consumption (avg. / peak)	*400 kWh / 650 kWh*
Energy consumption per km	*0.89 - 2.47 kWh/km*
Energy use per one-way trip (7.7 km)	*7 - 19 kWh*
Charging session duration (avg.)	*5 minutes*
Energy transferred per session	*8 - 14 kWh*
Peak measured charging power	*140 kW*

The introduction of a BESS is therefore designed to optimise this operational profile through three complementary functional modes:

1. **Reduction of required grid connection capacity (peak shaving):**
   The BESS can buffer charging peaks, potentially reducing the need for a permanently dimensioned 150 kW grid connection despite short-duration charging events.
2. **Tariff optimisation through off-peak charging:**
   The system can store electricity during lower-tariff nighttime periods and discharge it during daytime bus operation, depending on storage capacity.
3. **Partial energy self-sufficiency through RES integration:**
   In combination with photovoltaic generation, the BESS enables local storage and use of renewable electricity for bus charging, with the level of self-sufficiency dependent on installed PV capacity and storage size.

Through this design, the pilot evaluates technical feasibility, economic implications, and grid interaction effects of integrating second-life battery storage into an existing opportunity charging system.

5.2. Stakeholder Engagement and Joint Development

Following the initial definition of the pilot concept, MOM and UM organised a preparatory workshop within the CE4CE framework to assess the current status quo regarding the integration of circular economy principles in the local public transport system. The objective was to identify existing practices, challenges, and potentials for circularity in public transport operations and infrastructure, and to reflect on how these insights could inform the further development of the pilot implementation.

Participating Organizations:

- Municipal level: PTA – MOM, PTO – Marprom, municipal infrastructure and public works company, Local energy and district heating provider, public waste management company
- Regional level: regional development agency, regional energy agency
- Academic and research sector: UM – higher education and research institution
- Technology and private sector stakeholders: fast-charging infrastructure distributor, electric bus distributor

Workshop Outcomes

- Status quo assessment of circular economy integration in public transport (energy, batteries, infrastructure, waste).
- Strong grid dependency and limited renewable energy integration identified as systemic constraints.
- Lack of standardised procedures for end-of-life battery management.
- No structured recycling or second-life pathways for e-bus batteries established.
- Energy storage recognised as a meaningful and feasible solution in the context of increasing grid loads and the potential reuse of batteries.
- Limited knowledge and practical experience regarding the performance, safety, and regulatory conditions of second-life battery applications identified as a key uncertainty.
- Cross-sectoral stakeholder dialogue platform established.

The workshop served as an important catalyst for the later development of the tender documents and helped to formulate the requirements in a practical and targeted manner—without pre-committing to specific providers or technologies.

5.3. Feasibility Study and Preparation

As part of the preparatory coordination, MOM together with project partner UM and internal technical experts assessed the feasibility of integrating a BESS at the Vzpenjača fast-charging station. The objective was to evaluate the technical, operational, and regulatory conditions identified during the stakeholder workshop in terms of their practical implement ability within the existing infrastructure.

The main focus was on assessing the compatibility of second-life battery systems with the existing 150 kW fast charger and grid connection, as well as evaluating potential operational scenarios such as peak load buffering and tariff optimisation. The analysis examined which technical components and configurations correspond to the current state of the art and where additional engineering adaptation would be required.

Experts evaluated:

- The technical characteristics and state-of-health parameters of available second-life batteries
- Compatibility between battery modules, inverters, and the existing charging infrastructure
- Grid connection constraints and peak load profiles
- Safety requirements and regulatory conditions for stationary battery storage

External engineering experts specialised in small power plant and energy storage systems were involved in the assessment to ensure compliance with applicable standards and practical feasibility.

A) Micro-location

The installation site was evaluated within the existing substation area at Vzpenjača. Several technically feasible positions were available between the transformer and the fast charger. The final location was selected adjacent to the transformer, primarily to ensure minimal visual impact and appropriate integration into the surrounding urban environment, while maintaining short cable routes and safe operating distances.

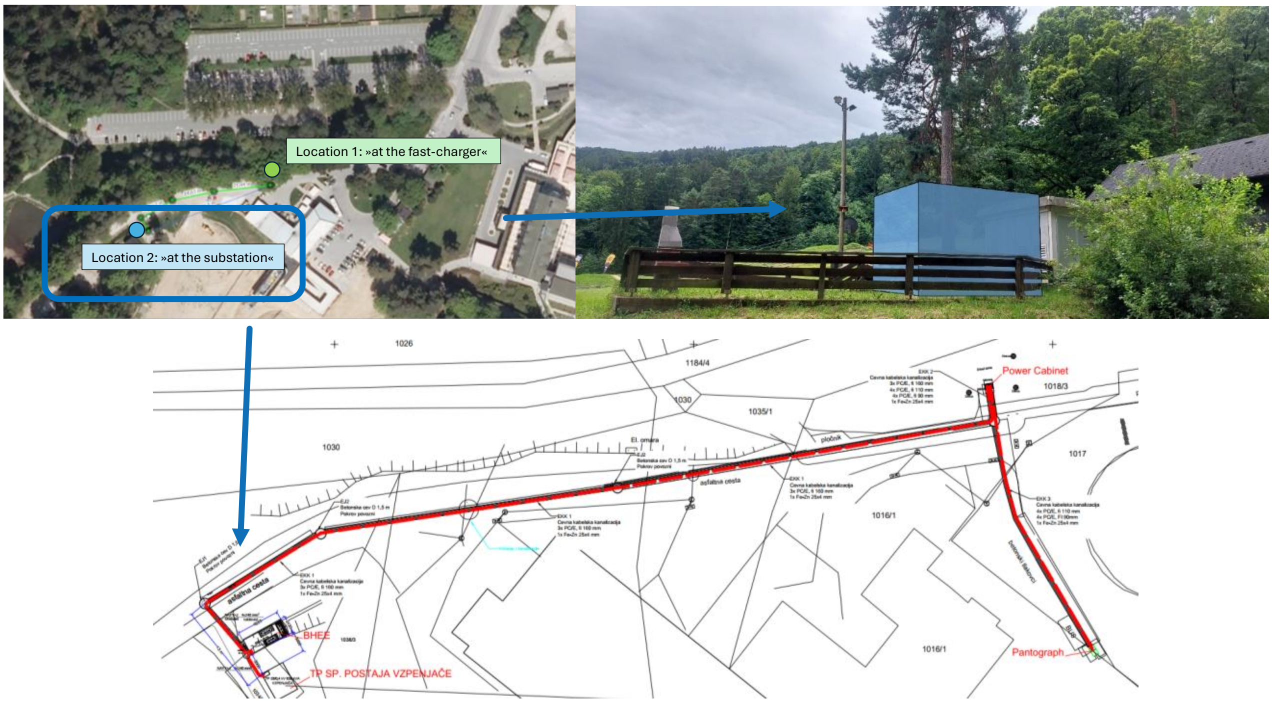

Figure 2: Macro situation at the Vzpenjača station and micro location of the BESS implementation.

B) Battery Type and Acquisition

Different lithium-ion technologies (LFP, NMC, LTO) were assessed regarding suitability for stationary storage, safety, cycle life, and compatibility with fast-charging operation. An audit of the batteries currently installed in Maribor’s municipal e-bus fleet confirmed a state of health above 95%, indicating that they are not yet suitable for second-life repurposing. As a result, externally sourced second-life NMC battery modules (140 kWh total capacity) were obtained from the e-bus manufacturer. Verified SOC/SOH documentation was provided, and ADR-compliant transport procedures were ensured.

C) Connectivity to Grid and Fast Charger

Integration concepts (serial, parallel, and direct hybrid) were analysed with regard to compatibility with the existing charging infrastructure, peak load reduction potential, and system losses. A parallel hybrid configuration was selected, ensuring full compatibility with the existing 150 kW fast charger and enabling simultaneous power supply from both the grid and the BESS, with the storage system operating as a supportive buffer during charging peaks.

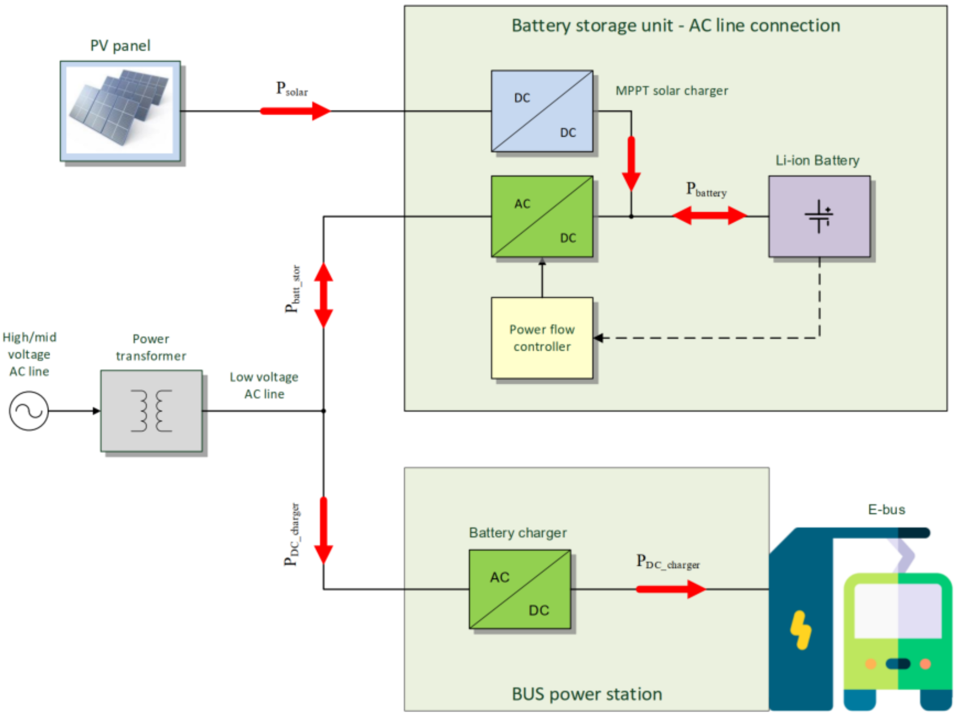

Figure 3: Technical diagram of charging infrastructure. Source: University of Maribor.

D) Required Equipment

The system architecture includes second-life battery modules installed in a purpose-adapted container with defined internal layout, a hybrid bidirectional inverter enabling parallel operation with the grid and future RES integration, active cooling, fire detection and suppression system, and monitoring and control components in compliance with grid and safety requirements.

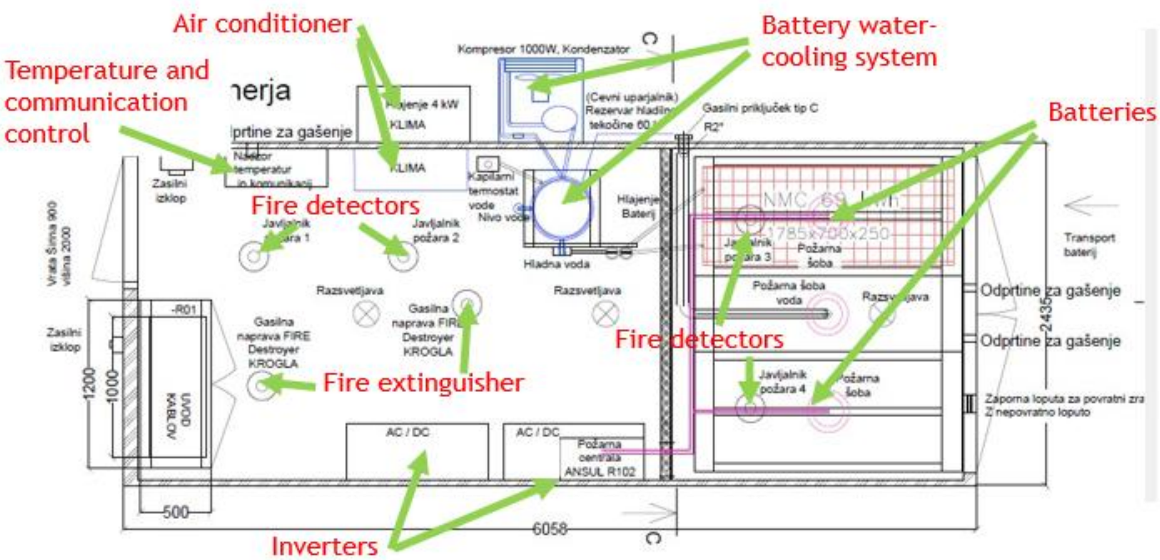

Figure 4:Technical Drawing – Floor Plan of the BESS.

E) Battery and Inverter Integration

The pilot implementation uses second-life battery modules of a single NMC type. Compatibility was therefore verified between the selected battery modules and the hybrid inverter, particularly in terms of voltage range alignment, BMS communication protocol, and safe bidirectional power exchange.

In cases where multiple battery types are combined within one storage system, additional coordination between battery modules is required, including alignment of voltage windows, communication interfaces, and charging behaviour to ensure stable and safe operation.

F) System Operation and Performance Scenarios

Charge and discharge rates (C-rate) were evaluated as part of the operational scenario analysis to ensure stable operation and to understand impacts on battery degradation and thermal stress, considering that higher C-rates increase internal heat generation and accelerate capacity fade in lithium-ion cells[11].

Table 3: Operational Scenarios for Second-Life BESS Deployment in the Maribor Pilot.

Parameter	S.1 - Pilot (25 kW)	Scenario 2 - Contr. 50 kW	Scenario 3 - Min. grid power
Battery capacity	136 kWh (2 × 68 kWh)		
Target power contribution	25 kW	~50 kW	~100 kW
C-rate	0.18 C	0.35 C	0.71 C (max = 1 C)
Energy contribution per charging / bus	~2.1 kWh	~4.2 kWh	~8.4 kWh
Energy daily contribution	100 kWh	200 kWh	400 kWh
Grid load (reduction)	125 (25) kW	100 (50) kW	50 (100) kW
Cooling requirement	Air cooling sufficient	Water cooling (recommended)	Water cooling
Inverter power	50 kW	100 kW	150 kW

[11] Keil, P., & Jossen, A. (2016). Charging protocols for lithium-ion batteries and their impact on cycle life—An experimental study with different 18650 high-power cells. *Journal of Energy Storage*, *6*, 125-141. https://doi.org/10.1016/j.est.2016.02.005

5.3.1. Cost-benefit analysis (CBA)

A cost-benefit analysis (CBA) was conducted for different storage capacity and RES integration scenarios, systematically comparing investment and operational costs with expected benefits such as peak load reduction, tariff optimisation, and energy cost savings. The evaluated scenarios varied in storage size and photovoltaic integration level, balancing technical performance with overall financial feasibility.

For the technical and economic calculations, the BESS contribution was modelled based on 25 kW peak power contribution (Scenario 1), which represents the selected implementation configuration for the Maribor pilot. This conservative sizing ensures operational stability, enables renewable integration, and remains within the financial framework of the CE4CE project.

Basis for Energy Consumption and Cost Modelling

The cost–benefit analysis was based on real operational data recorded at the Vzpenjača fast-charging station. Electricity consumption and load profiles were measured continuously using a permanently installed power quality and energy measurement device (Janitza UMG 800 class system).

The CBA uses full-year operational data (calendar year 2023), ensuring that calculations reflect real charging behaviour, seasonal variations, and actual peak load occurrences. The measured annual electricity consumption in 2023 amounted to **145,000 kWh**, which corresponds to an estimated annual electricity cost of approximately **EUR 35,000** for the charging station. This value was derived under the following assumptions (Slovenian low-voltage connection with measured demand):

- **Connection and operation profile:** contracted capacity 150 kW, charging mainly during daytime operation (05:00–22:00), i.e. predominantly within higher tariff time block(s).
- **Network tariff structure:** cost includes both (1) capacity-based network charge (€/kW/month) and (2) energy-based network charge (€/kWh), applying the officially valid Slovenian time-block tariff system for the relevant user group.
- **Capacity charge exposure:** the annual capacity-based cost was estimated assuming that the relevant monthly peak demand occurs in the highest tariff block (Block 1), i.e. that peak power is driven by fast-charging events during daytime operation.
- **Energy purchase price (supplier component):** electricity supply cost was calculated according to the currently applicable contractual tariff conditions used by the Municipality of Maribor in 2023, reflecting the effective €/kWh rate applied to the charging station (excluding VAT).
- **Excluded elements:** one-off connection costs, grid reinforcement investments, and infrastructure CAPEX are not part of this annual electricity cost estimate; the figure represents operational electricity expenditure (energy purchase + network charges).

The CBA compares four scenarios reflecting different levels of intervention in the energy supply and demand management of the fast-charging station at Vzpenjača. Each scenario represents a distinct optimisation approach:

- **Scenario 0 (S.0) - Existing Condition (Fast Charger Only/No Optimisation)**

Baseline operational state with direct grid supply and full exposure to peak tariffs.

- **Scenario A (S.A) - Pilot Framework (Peak Shaving Demonstration with Second-Life BESS)**

Moderate grid relief through 25 kW peak shaving and limited PV integration.

- **Scenario B (S.B) - Tariff Optimisation Scenario (Load Shifting via Large BESS)**

Night-time charging and daytime discharge to optimise exposure to time-block tariffs.

- **Scenario C (S.C) – RES Integration Scenario (PV-Based Structural Grid Reduction)**

Large-scale PV combined with storage to reduce imported electricity volume and long-term grid dependency.

Table 4: Scenario description and technical parameters

Scenario	Description/Purpose	Technical Parameters
S.0	• Reference case without investment. • Full dependence on grid electricity. • No optimisation of peak demand or energy sourcing.	• Annual consumption: 145,000 kWh • Contracted capacity: 150 kW • Peak demand in highest tariff block
S.A	• Demonstration of second-life BESS integration. • Moderate peak shaving and limited PV contribution. • Focus on technical feasibility and controlled grid relief.	• BESS: 136 kWh (2 × 68 kWh) • Contracted capacity 125 kW • RES (PV): 14 m^2 (roof of container), est. annual production: ~1,800 kWh • Peak demand in highest tariff block
S.B	• Load shifting through night-time charging and daytime discharge. • Reduces exposure to high-tariff blocks but does not reduce total annual energy consumption.	• BESS: 400 kWh (daily contribution coverage) • Contracted capacity: 60 kW • Demand in cheap tariff (night)
S.C	• Structural reduction of grid dependency. • Combines storage with large PV installation to reduce imported energy and price exposure.	• BESS: 400 kWh (daily contribution coverage) • Contracted capacity: 60 kW • Demand in cheap tariff (night), • RES (PV) area: ~750 m^2 (roof of Vzpenjača station), annual production: ~96,000 kWh • Potential self-sufficiency: ~65-70%

PV Electricity Calculation - Input Parameters

The estimation of photovoltaic electricity production is based on site-specific solar potential, assumed system efficiency, and installation cost parameters. The values provided in brackets below refer to the specific assumptions used for the Maribor pilot.

- Annual global solar irradiation (GHI): 1,283 kWh/m^2/year for Maribor
- Assumed PV system efficiency: 10%

- Unit PV installation cost (2023 price level): 120-150 EUR/m^2

Key methodological note (important for interpretation)

PV generation is variable and depends on weather and season. The CBA therefore applies annual-average modelling based on irradiation potential. The grid connection remains fully available; PV is treated as an energy-reduction measure (kWh) rather than a standalone supply source.

Figure 5: Placement of PV – roof of Vzpenjača station in S.3.

Table 5: Scenario-Based Energy and Investment Comparison

Scenario	Annual Grid Energy (kWh)	Contracted Capacity (kW)	Annual Grid Energy Cost (EUR/year)	Total Investment (EUR)
S.0	145,000	150	35,000 €	0 €
S.A	143,200	125	33,080 €	80,000 €
S.B	145,000	60	29,240 €	200,000 €
S.C	48,800	60	12,390 €	302,530 €

CBA Calculation Approach

The cost-benefit analysis was conducted over a 12-year evaluation period, comparing cumulative total costs of each scenario. Investment costs were assumed to occur upfront (Investment), while annual electricity costs were projected for the full operational period.

A 5% annual increase in electricity **costs** was applied to reflect expected long-term energy price growth. This escalation affects only operational energy costs, while investment costs remain fixed.

The analysis includes electricity purchase and network charges but excludes operation and maintenance (O&M) costs, financing costs, component replacement, and residual system value. The results therefore represent a nominal cumulative cost comparison rather than a discounted financial analysis.

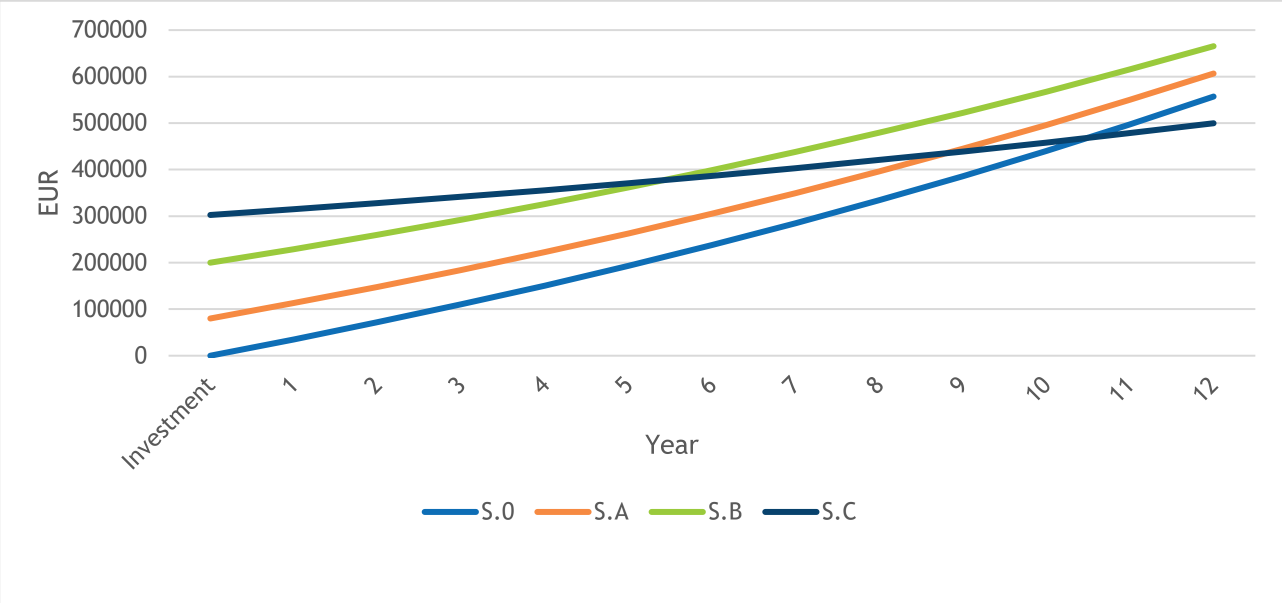

Figure 6: Comparison of cumulative electricity costs across different energy management scenarios.

CBA Result Summary

Within the 12-year evaluation period, assuming a 5% annual increase in electricity prices:

- **S.A** does **not** achieve payback within the analysed timeframe. The reduction in peak demand and limited PV contribution generate savings, but these remain insufficient to offset the initial investment.
- **S.B** also does **not** achieve payback within 12 years. Although it reduces contracted capacity and optimises tariff exposure, the total annual energy consumption remains unchanged, limiting long-term financial impact.
- **S.C does achieve payback** within the evaluation period. The substantial reduction in imported electricity leads to progressively increasing savings as energy prices rise, resulting in cumulative cost parity and subsequent net benefit in the later years.

The analysis therefore indicates that, under the defined assumptions, structural reduction of grid electricity consumption through renewable integration is the only scenario that ensures economic viability within the 12-year horizon.

G) Safety requirements

The project involves the use of second-life lithium-ion battery modules, for which operational and secondary-use frameworks are not yet fully standardised at EU level. In addition, lithium-ion batteries are classified as dangerous goods for transport under ADR, as implemented through Directive 2008/68/EC. Consequently, enhanced safety measures were required in the design phase, including a formal fire safety approval prior to commissioning.

The BESS is installed in a purpose-modified 20 ft container with a dedicated battery compartment constructed from non-combustible materials (fire reaction class A1). The internal layout ensures physical separation between battery racks, inverter, and auxiliary systems to limit thermal propagation.

The safety system includes:

- Integrated fire detection and monitoring (smoke and temperature sensors connected to a fire control panel, continuous BMS temperature supervision).
- Automatic fire suppression system designed for lithium-ion batteries, including inert gas flooding and controlled pressure relief.
- Emergency isolation and intervention interfaces (emergency stop buttons and prepared fire brigade access points).
- Electrical and thermal protection measures, including low-voltage protection devices, surge protection, export limitation control, and active cooling to ensure stable operating temperatures.

Table 6: Description and Technical Specifications of the BESS Pilot System.

Category	Description	Specifications / Implemented in Pilot
Construction works	Civil works required for installation and integration of BESS infrastructure.	Cable routing, excavation works, foundation preparation, cable ducts installation.
Container	Technical housing for stationary battery system with defined internal layout and safety separation.	20 ft modified (regular, used) container; fire-resistant insulation; dedicated battery and inverter compartments.
Battery System	Stationary second-life battery modules including BMS and safety monitoring.	136 kWh installed capacity (second-life NMC modules); integrated BMS.
Hybrid Inverter	Bidirectional inverter enabling grid interaction and RES integration.	80 kW hybrid inverter; voltage range 160–800 V; parallel operation with grid.
Electrical Cabinet (AC LV)	Low-voltage distribution and protection interface between BESS, grid and charger.	400 V LV cabinet; 250 A breaker; surge protection; current transformers; export limitation.
Control System (CNS)	Monitoring, control and power management logic of BESS operation.	Load-based automatic switching; defined interface for data access and monitoring.
Connection Cables	Electrical connection between transformer, BESS and fast charger.	Fire-resistant LV cabling; integration into existing 400 V infrastructure.
Cooling System	Thermal management to maintain battery temperature within safe limits.	Fluid (water-glycol) cooling system; total cooling capacity approx. 7 kW.
Safety System	Fire protection and operational safety monitoring.	Automatic fire detection and extinguishing; smoke sensors; intrusion alarm.
Battery Load (C-rate)	Assessment of battery stress under different charge/discharge rates to balance power contribution and lifetime.	Pilot batteries rated at 1C; pilot target of 25 kW achieved at approx. 0.18C*.

Solar Power Plant (PV)	RES integrated into BESS system.	14 m² (roof of container), est. annual production: ~1,800 kWh

*Behaviour of the batteries under higher C-rate conditions was evaluated during the pilot evaluation phase to assess thermal response, stability, and impact on battery degradation.

5.3.2. Financial Feasibility

In parallel with the technical assessment, the financial feasibility of the pilot preparation was analysed. MOM and UM evaluated the anticipated costs related to the feasibility study, preparation of detailed design documentation, permitting procedures, and external expert involvement, and the implementation phase of the pilot.

The objective was to ensure that the preparatory activities required for the implementation of the BESS pilot could be carried out within the allocated budget of the INTERREG CE4CE project and in accordance with public procurement and reporting requirements.

5.3.3. Securing the Necessary Approvals

Another key aspect of the feasibility assessment was the legal and regulatory safeguarding of the project. For the implementation of the BESS and associated PV system at the Vzpenjača site, the following approvals were required:

- **Grid connection consent**

Approval from the distribution system operator for connection of the BESS and photovoltaic system to the low-voltage grid.

- **Environmental clearance/compliance confirmation**

Verification of compliance with applicable environmental legislation for renewable energy installations and stationary energy storage systems.

- **Fire safety assessment and approval**

Formal fire safety review due to the installation of second-life lithium-ion batteries, including approval of the fire protection concept prior to commissioning.

- **Building permit**

Not required for the rooftop photovoltaic installation, as it qualifies as a small-scale PV system installed on an existing structure in accordance with Slovenian construction regulations.

- **ADR compliance for battery transport**

Application of procedures for handling and transport of lithium-ion batteries classified as dangerous goods.

6. Implementation phase

6.1. Procurement process

Tendering Strategy and Separation of Services

The procurement process was based on detailed project documentation prepared by UM in cooperation with external experts. The documentation included technical specifications, bill of quantities, and defined requirements and recommendations for equipment selection and system design.

In line with public procurement best practices, the preparation of project documentation was commissioned separately from the implementation phase, ensuring clear definition of technical requirements prior to tendering.

The public procurement covered the full scope of implementation, including construction works, equipment supply, installation, and testing and commissioning of the BESS.

The procedure was carried out in accordance with the **Slovenian Decree on Green Public Procurement** which transposes and operationalises key principles of EU public procurement legislation, in particular:

- Directive 2014/24/EU on public procurement,
- Directive 2014/25/EU on procurement by entities operating in the utilities sectors.

A key principle of the decree is that contracting authorities must include **environmental requirements** in technical specifications and award criteria, promoting:

- energy-efficient,
- resource-efficient, and
- low-emission solutions throughout the **(whole) lifecycle** of the procured system.

Outcome of the Procurement Process

The procurement procedure was successfully completed, resulting in the selection of a contractor capable of delivering the BESS system in accordance with the defined technical, safety, and environmental requirements.

6.2. Implementation proces

The pilot implementation is centred around the deployment and operation of the BESS at the ICEM – Institute for Civil Engineering Measurement and Control laboratory, where system assembly, integration, and initial operation are carried out.

The setup enables controlled testing of the complete system, including battery modules, hybrid inverter, control system, and communication interfaces. The focus is on validating the technical concept of using second-life batteries in a stationary BESS to support e-bus charging.

Particular emphasis is placed on system integration, operational functionality, and safe interaction between the BESS, grid, and charging infrastructure.

Figure 7: Key components of the BESS system: PV panels, inverter and second-life battery pack.

7. Testing and evaluation phase

The evaluation focuses on testing system performance under different operating conditions and assessing its contribution to energy management in public transport infrastructure.

Key elements include:

- Verification of system operation in parallel configuration (grid + BESS + charger)
- Testing of different battery load scenarios (C-rate) and their impact on performance and stability
- Analysis of energy flows and simultaneous charging/discharging behaviour
- Monitoring of battery performance (SOC, SOH, degradation trends)
- Assessment of system stability and identification of operational deviations
- Evaluation of peak load reduction and contribution to grid relief
- Analysis of renewable energy integration and hybrid energy supply

To ensure a structured and measurable evaluation, a set of key performance indicators (KPIs) was defined, covering technical, operational, environmental, and economic aspects of the pilot.

Table 7: 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

8. Best practices

As part of the CE4CE pilot in Maribor, a structured review of European good practices in circular public transport energy systems was conducted. The review focused on second-life battery applications, stationary energy storage, renewable energy integration, and grid load optimisation as key enablers of circularity in electrified public transport.

In this field, several advanced practices have already been implemented across Europe. In **Gdynia**, renewable energy integration and energy recuperation at depot level improved system efficiency at infrastructure scale. **Bolzano** demonstrated the combination of renewable hydropower, stationary battery storage, and electric bus fleets to enhance energy self-sufficiency. **Porto** successfully introduced depot-based storage systems to reduce peak grid loads by up to 40% and enable tariff optimisation through off-peak charging. **Hannover** pioneered the reuse of retired electric bus batteries in a 500-kWh stationary storage system, while **Moerdijk** scaled this concept further with a 7.5 MW second-life installation integrating wind and solar energy. **Apeldoorn** demonstrated how local energy storage can capture regenerative braking energy and reduce dependency on the public grid.

From a regulatory and governance perspective, **Malmö** developed responsible battery procurement guidelines that emphasise lifecycle transparency, SOH/SOC verification, extended producer responsibility, and ADR-compliant handling — establishing an institutional framework that supports safe second-life battery applications.

These examples confirm that circularity in public transport energy systems is increasingly shifting from vehicle procurement to infrastructure-level energy management solutions.

The Maribor pilot distinguishes itself in combination of use of second-life batteries, along with use of RES (solar panel) and integration to a e-bus charging infrastructure, i.e. fast-charger.

Table 8: Summary of Applicable Best Practices for the Maribor BESS Pilot.

Location	Main Focus	Scale	Key Contribution	Relevance for Maribor
Gdynia	Energy recuperation & RES at depots	Network level	Infrastructure-level efficiency	Confirms importance of infrastructure modules
Bolzano	RES + storage + e-buses	City scale	Energy self-sufficiency	Supports RES + BESS integration logic
Porto	Peak shaving with depot storage	Depot scale	25–40% grid load reduction	Validates tariff optimisation & grid relief
Hannover	Second-life bus batteries	500 kWh	First operational second-life storage	Demonstrates technical feasibility
Moerdijk	Large-scale second life	7.5 MW	Renewable integration at scale	Confirms scalability potential
Apeldoorn	Local energy reuse	Station level	Energy flow optimisation	Aligns with infrastructure-based storage logic
Malmö	Battery lifecycle governance	Policy level	Transparency & EPR	Confirms need for SOH/SOC & ADR compliance

Transferability and strategic recommendations

The reviewed good practices and the Maribor pilot confirm several key strategic principles:

- Energy storage at infrastructure level is essential for circular electrified public transport.
- Second-life batteries are technically viable when supported by proper SOH/SOC verification and safety measures.
- Grid relief and tariff optimisation are strong economic drivers.
- Fire safety approval and regulatory compliance are critical for implementation.
- Modular and scalable system design enhances transferability.

The CE4CE Maribor pilot demonstrates that circular economy principles in public transport can be operationalised through energy storage, renewable integration, and lifecycle extension of battery assets — not only through material recycling, but through intelligent system design.

9. Risks and contingency approach

As part of the CE4CE pilot project, a structured approach was applied to identify, assess, and manage potential risks. The aim was to detect technical, organizational, and financial challenges at an early stage and to define appropriate mitigation measures.

Technical risks

A key technical risk concerned the integration of second-life lithium-ion battery modules into a stationary BESS due to the non-standardised character of second-life battery integration. The following aspects required careful consideration:

- Compatibility between battery modules and the hybrid inverter, which also enables photovoltaic integration.
- Adequate integration and coordinated operation of the BESS, the grid connection, and the fast charger.
- Thermal behaviour and stability under high discharge loads (up to 150 kW fast-charging support).
- Definition of operational moderate battery load (C-rate) to balance system performance with battery lifetime.
- Compliance with strict safety requirements due to uncertainties in second-life battery behaviour and their classification as dangerous goods.

The discharge contribution of the storage system was therefore deliberately limited (target contribution of 25 kW), ensuring controlled battery stress while still achieving peak shaving objectives. Extensive safety design measures were implemented due to the use of hazardous battery modules and the absence of fully standardised EU-level second-life procedures.

Organizational risks

As the measure represents a non-standardised technical solution, significant discussion and evaluation were required when selecting external experts for the preparation of the detailed design documentation (and others), particularly in the fields of energy storage design, integration, and fire safety.

Additional organisational challenges included:

- Sourcing suitable second-life batteries outside the local bus fleet, as batteries from Maribor's own fleet were not yet suitable for repurposing.
- Coordinating battery audits (SOC/SOH verification) and transport procedures.
- Arranging temporary storage for batteries prior to implementation.

Second-life batteries were ultimately obtained free of charge from the e-bus manufacturer Iveco, which provided a professional SOC/SOH audit and organised transport from Italy to Slovenia. Temporary storage until installation was facilitated by the national distributor.

Close cooperation with technical experts in renewable energy and storage systems was maintained throughout the design process. The system was deliberately designed to allow future upgrades, including the integration of batteries from the local public transport fleet once available.

In addition to limited market maturity, procurement was complicated by the non-standardised and perceived high-risk nature of second-life battery systems. Many contractors were reluctant to provide performance guarantees due to:

- liability concerns related to hazardous goods classification,
- uncertainty regarding long-term behaviour of second-life batteries,
- lack of established reference projects in comparable public transport environments.

This significantly narrowed the pool of eligible bidders and required very precise technical documentation and risk allocation in tender specifications. The lesson learned is that second-life BESS implementation currently demands strong public-sector technical leadership and clearly defined responsibility frameworks.

Financial risks

Financial constraints represented a major challenge. On one hand, the project had to meet clearly defined technical objectives (25 kW grid relief and PV integration); on the other hand, the non-standardised nature of second-life storage resulted in elevated and partially unpredictable costs, particularly related to:

- (Costly) container modification and fire-safe interior design.
- Safety systems and permitting requirements.
- Customised engineering solutions.

A mitigating factor was the fact that the second-life batteries were provided free of charge, significantly reducing overall investment costs. Throughout the design phase, continuous coordination with specialised engineers ensured cost control and alignment with available project funding.

At the current pilot scale, the BESS is not primarily economically driven but serves as a technical and strategic proof of concept. From an economic perspective, the return on investment (ROI) becomes significantly more favourable when second-life battery storage is combined with renewable energy integration and higher storage capacities, enabling stronger peak shaving effects, improved tariff optimisation, and greater overall energy cost savings.

Contingency measures

During implementation, several technical modifications were required. Some adjustments were foreseeable, while others emerged due to practical constraints and regulatory requirements.

Alternative approaches were prepared particularly for:

- Securing second-life batteries from alternative sources.
- Choosing between purchasing a new fire-certified container or modifying a standard used container to meet fire safety requirements.
- Adjusting system configuration based on integration and safety constraints.

Continuous coordination between project partners and external experts enabled flexible problem-solving and ensured that the pilot objectives were achieved despite uncertainties.

10. Pilot impact and sustainability

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

Current impact (implemented pilot):

- Extension of the service life of otherwise decommissioned batteries, thereby postponing their end-of-life treatment and delaying the generation of hazardous waste in a context where recycling pathways are still limited and not fully standardised.
- Reduction of peak power demand and grid load (approx. 25 kW contribution through peak shaving).
- Improved flexibility of the charging setup through digital control and remote energy management.
- Initial integration of photovoltaic generation (5.4 kW) as a technical demonstration of on-site renewable coupling.

These measures provide an alternative to immediate grid capacity upgrades and establish a controlled operational framework for hybrid grid–storage charging.

The pilot therefore functions as:

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

Contribution to the attractiveness and sustainability of public transport

By ensuring reliable and scalable electric charging infrastructure, the project strengthens the long-term sustainability of public transport in Maribor.

Key contributions include:

- Alternative approach to network upgrade to securing sufficient energy supply.
- Increasing resilience of charging infrastructure.
- Supporting the transition toward low-emission mobility.
- Demonstrating visible commitment to circular economy principles (reuse/repurpose, recover)

Through the combination of 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.

11. Transferability of the pilot action

The CE4CE pilot in Maribor demonstrates a modular and technically adaptable approach to integrating second-life battery storage and renewable energy into public transport charging infrastructure. While the system is dimensioned for local conditions, the underlying concept is broadly transferable, subject to site-specific technical and regulatory parameters.

Transferability within Maribor

The pilot establishes a scalable framework for further development within the municipal network.

Concrete expansion potential includes:

- Integration of end-of-life batteries from the local e-bus fleet (primary long-term objective).

- Increasing storage capacity to enhance peak shaving and economic optimisation (night-time tariff utilisation).
- Expansion of photovoltaic installations to increase energy self-sufficiency.
- Replication at additional (fast) charging locations in the city.
- Application at future multimodal hubs enabling energy sharing between bus, rail, or other electrified systems.

The pilot therefore provides a technical and regulatory template for future municipal charging infrastructure projects.

Transferability to Other Cities and Operators

The challenges addressed in Maribor — increasing fleet electrification, grid capacity constraints, rising energy costs, and unclear second-life battery pathways — are common across Europe.

The concept is therefore not location-specific but **parameter-dependent**, meaning that system design and configuration must be adapted to each operational context. Key parameters include:

- The existing vehicle fleet and available battery types.
- State of health and availability of traction batteries.
- Existing charging and grid infrastructure.
- Required energy contribution (peak shaving level, flexibility needs).
- National regulatory and fire safety requirements.

While these boundary conditions vary, the pilot demonstrates that core principles remain transferable — particularly in terms of technical integration, safety architecture, hybrid operation, and second-life battery use. The modular design allows scaling according to local demand and financial capacity, from small peak-support systems to larger hybrid energy hubs. As electrification increases grid pressure, such solutions can deliver both economic and environmental benefits by reducing peak loads, improving flexibility, and extending battery lifecycles.

The CE4CE pilot in Maribor thus provides a scalable model for cities aiming to strengthen energy resilience, optimise infrastructure, and integrate circular economy principles into public transport.

12. Annexes

Annex 1: Pilot CBA calculations (separate annex)