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ZEB4ZEN

TRANSNATIONAL HANDBOOK ON ZEB4ZEN PILOTS

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A. Executive summary

The transition towards zero-emission neighbourhoods (ZEN) represents a key priority within European climate and energy policies. However, achieving this objective in historic urban areas presents specific challenges, as it requires preserving cultural heritage while improving energy performance.

Historic city centers are subject to strict preservation laws, architectural constraints, technical limitations, and complex administrative governance. Standard energy-efficiency measures, such as external thermal insulation composite systems (ETICS) or rooftop solar photovoltaic (PV) installations, are often prohibited in heritage zones to protect cultural identity and urban aesthetics.

The Interreg Central Europe project ZEB4ZEN (Zero Energy Buildings for Zero Energy Neighbourhoods) was established to address these precise bottlenecks. ZEB4ZEN tested innovative, heritage-sensitive decarbonization pathways across UNESCO-listed cities.

This Transnational Handbook compiles the real-world operational results from the three pilot investments conducted in Palmanova, Zamość, and Karlovac. It moves beyond theoretical concepts to document the full investment lifecycle: from research, feasibility, and heritage permitting to public procurement, construction, microgrid integration, and verified post-retrofit energy performance.

Originally conceived as an outcome of the "Interactive Exchange of Experience Workshop" (D.2.4.1, 16 September 2025), the handbook was subsequently further developed, incorporating additional inputs collected after the completion of all pilot investments.

This handbook aims to:

- compile the results of the pilot investments as best practices;
- identify common challenges in historic protected urban areas;
- present innovative processes, methods, and technical solutions;
- provide recommendations for transferability and policy support.

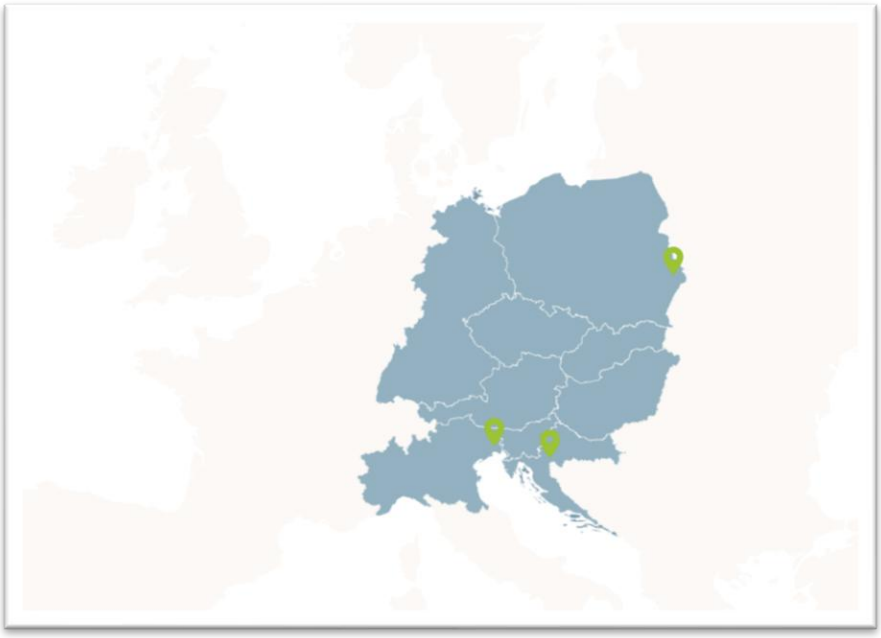


Fig. 1 Map of Central Europe with the three pilot cities of ZEB4ZEN project

B. Detailed case studies

1. Palmanova - Solar energy community

1.1. Original challenges and objectives

Heritage constraints: Palmanova is a UNESCO World Heritage site (listed in 2017 as part of the Venetian works of defense from the 16th to the 17th centuries). Strict landscape, monumental, and historical protection laws ban rooftop solar installations within the star-shaped fortress walls.

Project objectives: enable clean energy self-consumption for public buildings, residents, and commercial activities within the protected historic center without causing physical or visual alterations to heritage structures.

Core approach: utilize the European Union RED II Directive framework to separate energy generation from consumption. By installing a photovoltaic system on an unused municipal brownfield outside the fortress walls, energy is virtually shared among members residing within the same primary substation grid perimeter ("cabina primaria" in Italian).

1.2. Selected technologies and investment configurations

Location: Ex-Miurina area (Via Miurina No. 1), a remediated former municipal landfill qualified as a multi-functional PV park zone (Zone F3/1) under the Municipal General Land Use Plan (PRGC).

Total installed capacity: 108.40 kWp ground-mounted solar PV system, divided into two functionally independent and catastally distinct lots to optimize grid operation:

- Stella Plant (Impianto STELLA): Nominal capacity of 60.51 kWp, coupled with grid connection point POD IT001E133738029 and CENSIMP code IM 3034521.
- Sole Plant (Impianto SOLE): Nominal capacity of 47.89 kWp, coupled with grid connection point POD IT001E135463485 and CENSIMP code IM 3075340.

Grid infrastructure: low-voltage connection line constructed by e-distribuzione S.p.A.

1.3. Implementation procedures and administrative requirements

Legal entity establishment: a non-profit association named "CER Palmanova" was formally established via public notary deed on January 12, 2026. It gained legal personality under Regional Presidential Decree No. 19/2026 (FVG Regional Register No. 353).

Land tenure and public concession: the Municipality of Palmanova granted a 30-year free-of-charge public lease for 1,300 m^2 of land across two municipal decisions (Municipal Council Resolution No. 54 of Dec 18, 2025; Resolution No. 2 of Jan 8, 2026; formal Use Concession Deed Rep. No. 2.972 and No. 2.975).

Building and permitting procedures:

- Stella Plant (60 kWp): authorized through a Simplified Authorization Procedure (PAS - Procedura Abilitativa Semplificata).
- Sole Plant (48 kWp): authorized under Free Building Activity regulations (Edilizia Libera) pursuant to Legislative Decree D.Lgs. 190/2024.

Public procurement and contracting:

- Implementation Agreement (Convenzione Rep. No. 1.723 of March 6, 2026) transferred €105,000 from the Municipality to the CER entity as the project implementer.
- A public market tender (Market Survey Notice Prot. No. 1/2026) was issued in March 2026. The contract was awarded to Daimel S.r.l. at a turnkey benchmark cost of €1,000 / kWp.

1.4. Actual pilot results

Financial breakdown:

- Stella Plant (60.51 kWp): Total investment €76.166,30 (€27,500 Interreg ZEB4ZEN budget + €48.666,30 raised through a civic local crowdfunding campaign).
- Sole Plant (47.89 kWp): Total investment €59.873,70 (51.672,59 through ZEB4ZEN + €8.201,11 raised through a civic local crowdfunding campaign).

Total investment: €136,207 for 108.40 kWp total generation capacity.

Community engagement: 27 initial founding members (Municipal offices, families, SMEs) connected at project closure, with open ongoing enrollment.

Social impact: The REC bylaws include mechanisms to allocate the benefits of shared energy, managed by the Energy Services Manager (GSE), to residents of historic centres who are legally unable to install solar panels on their properties, thereby helping to address energy poverty at the local level.

1.5. Implementation problems and solutions adopted

Problem 1: Complex grid permitting and portals. Bureaucratic bottlenecks within e-distribuzione's digital portal caused delays in processing connection offers.

Solution: Direct technical assistance provided by energy agency APE FVG; splitting the infrastructure into two separate PODs prevented grid overload rejection.

Problem 2: Evolving national REC framework. The regulatory framework governing CACER (Configurations for self-consumption and sharing of Renewable Energy) and the role of the GSE (Energy Services Manager – the Italian public entity responsible for overseeing and supporting the energy sector) created a degree of regulatory uncertainty during the drafting of the charter.

Solution: Engagement of specialized legal counsel (Studio Legale Mainardis) to draft flexible, future-proof association bylaws.

Problem 3: Permitting status modification. Updating grid connection documentation when changing statutory building permits from Free Building to PAS.

Solution: Prompt submission of revised technical parameters to e-distribuzione without cancelling the underlying grid connection request.

1.6. Lessons learned and practical recommendations for replication

Off-site virtual sharing is the key for heritage zones: RECs eliminate the conflict between renewable energy targets and architectural preservation by decoupling generation location from consumption site.

Civic crowdfunding boosts social acceptance: combining EU funds with local crowdfunding (€56.9k raised) fosters strong citizen ownership, high public trust, and active community participation.

Involve regional Energy Agencies early: expert technical support (in this case, APE FVG) is vital to guide municipalities through complex notary, GSE, and utility grid procedures.



Fig. 2 Palmanova from above: the site outside the walls where the solar panels have been installed is highlighted in red

2. Zamość - Optimization of the thermal insulation system of historical tenement houses

2.1. Original challenges and objectives

Heritage Constraints: the pilot building located at Ormiańska Street 11 and the preliminary research benchmark at the Zamoyski Palace outbuilding are registered historical monuments located in the UNESCO World Heritage Old Town of Zamość. External wall insulation (ETICS), alteration of facade profiles, and modern window replacements were strictly prohibited by the Voivodeship Office for the Protection of Monuments.

Project Objectives: reduce heating demand and improve thermal performance while preserving the historic masonry and managing moisture risks through building-specific assessment.

2.2. Selected technologies and investment configurations

Vapor-permeable internal insulation: the implemented attic retrofit used mineral insulation boards on internal external-wall and roof-slope surfaces (typically 10 cm, reduced to 5 cm in selected areas), with 15 cm sheep's wool on the ceiling and roof slopes from the unused loft side. Material selection and vapour-control details must be assessed for each historic building.

Heritage window joinery restoration and replacement: custom-designed double/triple-glazed timber window joinery matching original historical mullion/transom profiles, achieving a better heat transfer coefficient (U-value).

Mechanical ventilation: heating radiators were replaced and mechanical supply/extract ventilation and multi-split air conditioning installed. Heat recovery should only be claimed if confirmed in the final technical documentation.

2.3. Implementation procedures and administrative requirements

Preparatory Research Phase (Sept 2023 – July 2024):

- Architectural and stratigraphic micro-probe testing at Zamoyski Palace outbuilding to verify the absence of 17th-century polychrome layers before sensor installation (Permit No. IN.III.5174.34.1.2023 and No. IN.III.5142.128.2.2023).
- Thermographic surveys and continuous in-situ U-value logging by Lublin University of Technology.
- 2D/3D thermal bridge simulations near window jambs using THERM software.

Design & Permitting Phase (July 2024 – March 2025):

- Drafting of full execution design documentation by Kwadra Studio.
- Conservation Permit No. Z-III.5174.1.1.2025.EB1 for technical installation on a listed monument (Feb 3, 2025).
- Building Permit Decision No. 20/2025 for usable attic wall renovation (March 4, 2025).

Construction Works Phase (March 2025 – Oct 2025): works execution, interim supervision, and formal acceptance.

2.4. Actual pilot results

Verified thermal performance:

- Baseline pre-retrofit wall measurements conducted in Feb 2025 provided real-world U-value benchmarks.
- Post-retrofit verification (13–16 January 2026) included thermography and in-situ U-value measurements. The February 2026 evaluation (D.2.2.3) estimates annual useful heating and ventilation demand decreasing from 131,342 to 74,228 kWh/year: 57,114 kWh/year (43.5%). This is a modelled annual reduction, not a metered annual saving. The measurements provide separate evidence of improved thermal performance; long-term moisture performance requires continued monitoring.

Procurement timelines and execution:

- Initial public procurement (April 2025) cancelled due to over-budget bids.
- Re-issued tender (May 2025) successfully awarded contract on June 7, 2025.
- Physical construction completed on October 2, 2025, followed by final acceptance on October 7, 2025.

2.5. Implementation problems and solutions adopted

Problem 1: Heritage stratigraphy constraints. Micro-probes revealed 17th-century historic plaster layers in the initial test room, blocking sensor attachment.

Solution: Relocated research equipment to neutral masonry sections per guidelines from the Voivodeship Conservation Office.

Problem 2: Market cost overruns in tender. First tender (April 2025) failed because contractor bids exceeded municipal allocations due to specialized heritage restoration requirements.

Solution: Scope adjustment and tender re-issuance within two weeks, securing a bidder compliant with financial caps.

Problem 3: Unforeseen structural defects during construction. Uncovering hidden timber roof rot required immediate scope additions.

Solution: Execution of Contract Amendment No. 1 (Sept 10, 2025) to incorporate necessary structural repairs without violating heritage guidelines.

2.6. Lessons learned and practical recommendations for replication

Never assume standard U-values: design decisions in historic masonry must be based on long-term in-situ monitoring rather than theoretical database tables.

Capillary-active systems are mandatory: Select internal insulation based on hygrothermal assessment, heritage approvals, moisture exposure, and ventilation needs. Capillary-active systems may be appropriate, but no universal material or ventilation specification is suitable for every historic building.

Plan budget for unforeseen heritage works: retrofitting centuries-old buildings inevitably reveals hidden structural issues; public budgets must include dedicated contingency margins (10–15%).

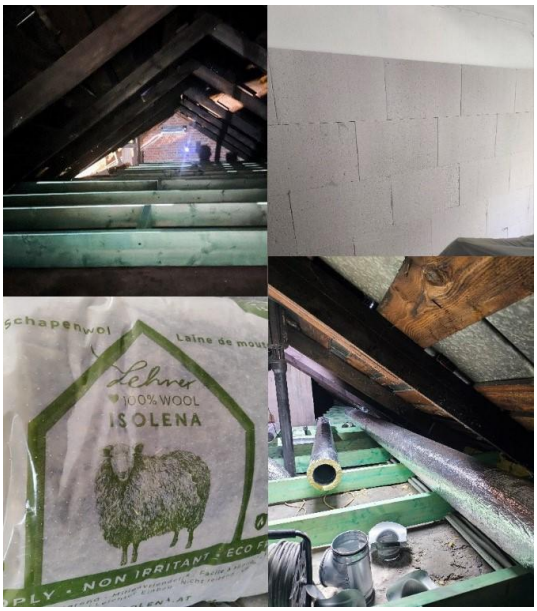


Fig.3 Internal insulation solutions in Zamość

3. Karlovac - Green and digital neighbourhood transformation

3.1. Original challenges and objectives

Heritage constraints: the City Hall building (Banjavčićeva 9) is located in "Zvijezda," Karlovac's protected Renaissance star-shaped core. Heritage rules restrict external alterations and visible solar PV panels.

Project objectives: demonstrate an integrated "green and digital" energy system that links building retrofits with urban electric mobility and smart storage.

Core approach: combine rooftop solar PV, energy storage, bidirectional EV charging, and intelligent software to manage energy flows within a public heritage building.

3.2. Selected technologies and investment configurations

Rooftop solar PV plant: 10 kWp rooftop solar plant installed on the City Hall. Equipped with special red-coloured solar panels to blend visually with the historic red tile roofs of the star-shaped downtown.

Bidirectional EV charging station: multi-standard charger installed in the municipal courtyard (supplied by Neos d.o.o., contract value €20,675.00).

Mobile energy storage via Vehicle-to-Load (V2L): BYD SEAL U COMFORT electric vehicle equipped with V2L technology (supplied by Auto Hrvatska Automobili d.o.o., delivered Feb 2026). The vehicle acts as a mobile battery storage unit, discharging 2–3 kW to supply critical municipal loads (IT servers, backup emergency lighting).

Digital platform: customized Energy Management System (EMS) software (supplied by Neos d.o.o., €19,862.50) linked to a live public dashboard display in the City Hall lobby (senzorika.karlovac.hr).

3.3. Implementation procedures and administrative requirements

Feasibility and concept redesign (Nov 2023 – March 2024): fire safety regulations barred large stationary indoor battery banks inside the historic City Hall. A feasibility study recommended replacing fixed batteries with a mobile EV battery. Interreg Programme approved this activity modification in March 2024.

Public procurement cycle 1 (March 2025 – Nov 2025):

- Contracts awarded for PV (€9,688.00), Charger (€20,675.00), and Software (€19,862.50).
- Tenders for a Vehicle-to-Grid (V2G) electric car failed twice because no vehicle distributor in Central Europe offered active, software-unlocked V2G cars.

Pivot to Vehicle-to-Load (V2L) and Programme approval (Oct 2025): official approval granted by Interreg Program Manager on Oct 31, 2025, to modify the technical scenario from V2G to V2L mobile backup storage.

Public procurement cycle 2 (Nov 2025 – June 2026): Re-tender awarded V2L vehicle in Feb 2026 and solar PV contractor (Đuro Đaković Elektromontaža, €12,409.16) in Jan 2026.

Final permitting and grid connection: Final approval from HEP (DSO) and heritage/fire authorities secured in May 2026; site registered May 20, 2026; project commissioned June 3, 2026.

3.4. Actual pilot results

Financial Breakdown:

- Rooftop PV (10 kWp red panels): €12,409.16
- Charging Station: €20,675.00
- Custom EMS Software & Dashboard: €19,862.50
- Main Project Redesign & Fire Safety Adjustments: €900.00
- Electric Vehicle (V2L): Procured under project mobility allocation.
- Total Pilot Capex: ~€53,846.66 (excluding vehicle base cost).

Technical Metrics: the report records handover on 3 June 2026 and identifies the public dashboard at senzorika.karlovac.hr. Installed equipment and commissioned functions should be distinguished from modelled annual generation, savings and V2L capabilities. No measured annual generation, self-consumption, V2L energy or emissions savings are claimed here without a verified monitoring period.

3.5. Implementation problems and solutions adopted

Problem 1: Market unavailability of V2G technology. Vehicle manufacturers had not software-unlocked V2G functionality in Central Europe, and local distribution grid codes lacked V2G feed-in rules.

Solution: Redesigned the technical solution to Vehicle-to-Load (V2L), allowing the EV to directly power local building critical loads (2–3 kW) as a flexible mobile storage unit.

Problem 2: Sudden change in heritage aesthetics policy. In Nov 2025, heritage authorities unexpectedly withdrew permission for standard black panels, demanding red PV panels matching historic roof tiles.

Solution: Mutual termination of the original PV supply contract, main project redesign, and re-tendering for red PV panels.

Problem 3: Conflicting regulatory approval requirements. Fire safety authorities introduced strict requirements that conflicted with heritage conservation guidelines.

Solution: Organized multi-agency coordination workshops to establish a joint compromise, amending the main engineering project in Feb 2026.

3.6. Lessons learned and practical recommendations for replication

Prepare for immature green tech supply chains: cutting-edge technologies (like V2G) can face severe market availability and regulatory grid hurdles. Pilot designs must include alternative fallbacks (in this case, V2L).

Align heritage and fire safety early: never treat heritage and fire approvals as isolated steps. Joint preliminary consultations are required to prevent late-stage design overhauls.

Use specialized aesthetics in sensitive cores: red-colored solar PV panels provide an effective compromise for historic urban roofs visible from higher vantage points.



Fig. 4 Karlovac City Hall

C. A comparison of experiences

4. Cross pilot comparative analisys

4.1. Matrix of pilot interventions

Assessment parameter	Palmanova (Italy)	Zamość (Poland)	Karlovac (Croatia)
Primary intervention focus	Off-site renewable energy community (REC)	Internal thermal insulation and heritage building envelope	Smart microgrid, rooftop PV and e-mobility (V2L)
Target building / Area typology	Entire historic center (UNESCO buffer zone)	UNESCO listed tenement (Ormiańska 11)	Municipal City Hall (Banjavčićeva 9)
Key technologies applied	108.4 kWp ground PV, low-voltage grid line, virtual REC platform	Calcium silicate insulation, heritage timber windows (Uw0.90), MVHR	10 kWp Red Solar PV, V2L EV, bidirectional charger, EMS software
Primary regulatory barrier	Ban on solar panels inside fortress walls; complex REC national laws	Ban on external facades modifications; strict plaster preservation	Sudden requirement for red PV panels; immature national V2G grid rules
Total pilot capital cost	**€136,040.00** (€79,172.59 EU funds + €56,867.41 crowdfunding)	**~€120,000** (full design, research station & construction)	**€53,846.66** (PV, charger, software, redesign) + EV procurement
Key stakeholders involved	Municipality, citizens, APE FVG, notary, e-distribuzione, GSE	Municipality, Lublin Univ. of Tech., Conservator, Kwadra Studio	Municipality, regional energy agency, Conservator, Fire Dept., HEP (DSO)
Final date of implementation	September 2026	October 2025	June 2026

4.2. Common challenges and context-specific differences

The partnership to compared pilot investments to learn lessons from comparing experiences. As a result, cross-cutting challenges have emerged:

- **Uncoordinated multi-agency governance:** All three pilots suffered delays caused by uncoordinated demands between heritage conservation offices, utility distribution grid operators (DSOs), and fire safety departments.
- **Market immaturity for specialized heritage solutions:** Public procurement procedures failed or were delayed across all cities due to over-budget bids (Zamość), unavailability of commercial V2G software (Karlovac), or supply chain bottlenecks for specialized equipment.
- **Underestimated administrative lead times:** Formal permissions, public tenders, notary deeds, and utility grid interconnections required significantly more time than physical installation works.

The three different pilots faced context-specific differences:

- Spatial strategy: Palmanova bypassed building spatial limitations entirely by moving generation off-site. Zamość and Karlovac implemented on-site interventions, directly dealing with physical building constraints.
- Financing Models: Palmanova introduced an innovative public-private-civic business model by raising €56,867.41 directly through crowdfunding. Zamość and Karlovac relied on public municipal budgets and Interreg funding.
- Decarbonization vector: Zamość focused on thermal energy efficiency and heat loss reduction, whereas Palmanova and Karlovac focused on electrical decarbonization, digital energy management, and sector-coupling (mobility).

4.3. Comparative technical, administrative, and financial insights

Cost efficiency of generation: Palmanova achieved a highly competitive unit cost of € 1,000 / kWp for ground PV through public market tender, whereas Karlovac paid ~ €1,240 / kWp for rooftop PV due to specialized red-colored panel requirements.

Research-driven retrofitting vs. Rapid execution: Zamość demonstrated that internal thermal retrofits in UNESCO sites require an initial 12-month research phase (in-situ measurement, moisture analysis) before drafting technical designs. Attempting physical work without prior hygrothermal research risks building decay.

Digital management integration: Karlovac showed that digital platforms (senzorika.karlovac.hr) and live public dashboards are vital to make invisible energy flows visible to citizens, increasing community support for municipal investments.

5. Recommendations for local authorities and policy makers

Based on the empirical evidence gathered across Palmanova, Zamość, and Karlovac, this Handbook provides six actionable recommendations for municipal leaders, urban planners, energy agencies, and heritage policy makers across Europe:

1. Mandate one-stop shop inter-agency taskforces

Municipalities must establish joint review committees combining heritage authorities, fire departments, building control, and local DSOs before launching technical design phases. Pre-aligning requirements eliminates late-stage design modifications (as experienced in Karlovac) and prevents project delays.

2. Standardize off-site renewable energy community (REC) frameworks

Policymakers should encourage off-site RECs as a primary decarbonization tool for protected urban areas. Where rooftop solar panels are prohibited, national regulations must facilitate clean energy generation on peripheral municipal brownfield land, allowing virtual energy sharing with historic centre inhabitants.

3. Enforce hygrothermal in-situ testing for internal insulation

Local authorities must prohibit standard external insulation (ETICS) on protected facades, while requiring detailed in-situ testing and numerical moisture modelling (e.g., THERM/WUFI) before approving internal wall insulation. Capillary-active materials (calcium silicate) combined with heat recovery ventilation (MVHR) should be established as the standard specification.

4. Allow flexibility

Flexibility is necessary when testing emerging technologies (e.g., V2G, V2L, dynamic tariffs). Public procurement guidelines must allow technical scenario adjustments (e.g., pivoting from V2G to V2L) without forcing full project cancellation when commercial markets fail to deliver.

5. Combine public capital with crowdfunding

Local authorities should replicate the Palmanova financing model by pairing public grant funds with civic crowdfunding. Allowing residents to co-invest in local renewable projects builds public trust, addresses energy poverty, and unlocks local private capital for green infrastructure.

6. Establish pre-approved heritage technology catalogues

Regional heritage authorities and energy agencies should publish pre-approved technical specifications (e.g., solar roof tiles, custom red PV modules, heritage-compliant window profiles, vapor-permeable insulation). Pre-approved options give municipal planners clear parameters, reducing permitting evaluation times.

6. Links to the underlying implementation and evaluation reports

This document is based on the Interactive exchange of experience workshop (D.2.4.1), on further discussions within the partnership and on the deliverables specifically developed for each pilot investment under WP 2, specifically:

- Solar energy community: D.2.1.2 - Report on pilot action 1 implementation phase and D.2.1.3 - Report on pilot action 1 evaluation phase
- Optimization of the thermal insulation system of historical tenement houses: D.2.2.2 - Report on pilot action 1 implementation phase and D.2.2.3 - Report on pilot action 1 evaluation phase
- Green and digital neighbourhood transformation: D.2.3.2 - Report on pilot action 1 implementation phase and D.2.3.3 - Report on pilot action 1 evaluation phase

D. Conclusions

The pilot actions implemented within ZEB4ZEN project in Zamość, Palmanova, and Karlovac demonstrate that the transition to zero-emission neighbourhoods in historic urban areas is feasible, although complex.

Key success factors include:

- Interdisciplinary governance and multi-agency alignment: early and structured collaboration between municipal departments, heritage protection authorities, energy agencies, and fire safety services is vital to resolve conflicting regulatory and aesthetic requirements before entering the procurement phase.
- Context-sensitive technological flexibility: a willingness to adapt innovative concepts—such as transitioning from Vehicle-to-Grid (V2G) to Vehicle-to-Load (V2L) technology in Karlovac or establishing off-site ground-mounted photovoltaic systems in Palmanova—ensures project viability without compromising strict heritage conservation mandates.
- Evidence-based technical and hygrothermal validation: rigorous on-site testing, numerical thermal bridge modeling (THERM), continuous U-value monitoring, and thermographic analysis ensure that energy retrofits perform as intended while preventing moisture-induced damage in historic masonry.
- Proactive citizen engagement and social inclusion: building public trust through transparent communication, civic crowdfunding, and inclusive Renewable Energy Community (REC) bylaws allows historic center residents restricted by monumental constraints to participate directly in the economic and environmental benefits of the energy transition.
- Phased administrative and procurement planning: incorporating realistic buffers into project timelines accounts for complex permitting procedures (PAS, conservation approvals), tender iterations, and unforeseen structural discoveries in historic building stock.

Historic areas, while constrained, can act as innovation laboratories for developing and testing solutions that balance sustainability and heritage preservation.

This Handbook provides a structured knowledge base to support policymakers, planners, and stakeholders in replicating and scaling up these approaches across Europe.