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ZEB4ZEN

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Zero energy buildings for zero Energy neighborhoods

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JOINTLY DEVELOPED SOLUTIONS REPORT

A. INTRODUCTION

Historic urban neighbourhoods represent a significant share of Europe's built environment and are central to cultural identity, urban vitality and tourism. At the same time, they are often characterised by high energy demand, outdated energy systems and limited renovation potential due to heritage protection constraints. This creates a complex challenge: achieving climate neutrality and energy efficiency targets while preserving architectural and cultural values.

Within this context, the ZEB4ZEN project addresses the transition towards zero-emission neighbourhoods (ZEN) by developing and testing integrated approaches that combine energy efficiency (EE), renewable energy sources (RES), digital tools and heritage-sensitive planning methodologies. The project recognises that interventions at the individual building level are insufficient, and instead promotes a neighbourhood-scale perspective, where buildings, infrastructure, public lighting and mobility are treated as interconnected elements of a single urban energy system.

Previous project deliverables have established the key components of this approach:

- a harmonised methodology for data collection and energy flow analysis at building and neighbourhood scale,
- a digitalisation framework integrating spatial, technical and energy-related data through GIS and digital twin environments,
- a set of EE/RES measures and scenarios applicable to heritage contexts, and
- pilot actions and investments demonstrating feasible solutions in real urban settings.

These components together provide a robust analytical and practical basis for assessing energy performance and identifying decarbonisation pathways in historic districts.

The added value of this report lies in its ability to bridge detailed technical analyses with strategic, transferable knowledge. This report:

- offers a holistic perspective on neighbourhood-scale energy transition,
- ensures comparability across pilot cities, despite differences in data availability and local conditions, and
- translates project results into a replicable framework applicable to other historic urban areas in Europe.

By synthesising results across multiple domains, the deliverable supports evidence-based decision-making for municipalities, planners, energy experts and heritage authorities working towards climate-neutral and resilient historic neighbourhoods.

B. METHODOLOGICAL FRAMEWORK

The analysis is based on an integrated, bottom-up approach that combines data collection, spatial integration and energy modelling at neighbourhood scale. The methodology ensures consistent assessment across different pilot areas while remaining adaptable to local conditions and data availability. The approach consists of three main steps: data collection ad structuring, spatial integration and digitalisation, energy modelling and scenario analysis.

2.1 Data collection and structuring

A comprehensive dataset was developed for each neighbourhood.

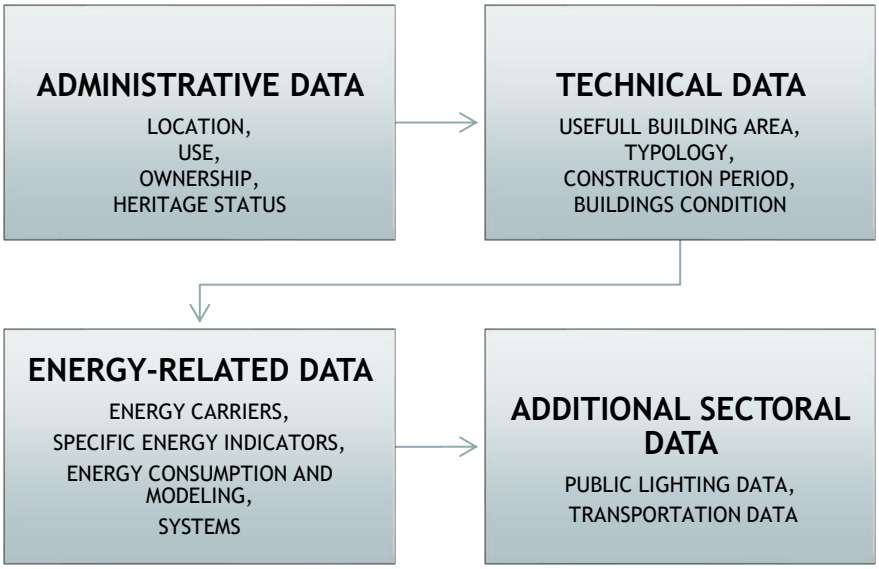


Figure 1: Data collection and structuring

Data were collected from multiple sources, including public databases, GIS systems, field surveys and stakeholder inputs. Where data were missing, values were estimated using typologies and reference indicators. All data were structured into a unified database, with unique identifiers assigned to each building or element, enabling consistent tracking, aggregation and analysis.

2.2 Spatial integration and digitalisation

The structured data were linked to spatial representations of the neighbourhood using GIS-based tools and digital environments. Buildings and other elements were connected to their geographic location allowing the integration of attribute data with spatial layers. The digitalisation approach supports consistent data management, validation and scenario analysis, and provides a basis for future expansion and replication.



Figure 2: Spatial integration and digitalization

2.3 Energy modelling and scenario analysis

Energy performance was assessed using a bottom-up modelling approach, starting from individual buildings and aggregating results to block and neighbourhood level.

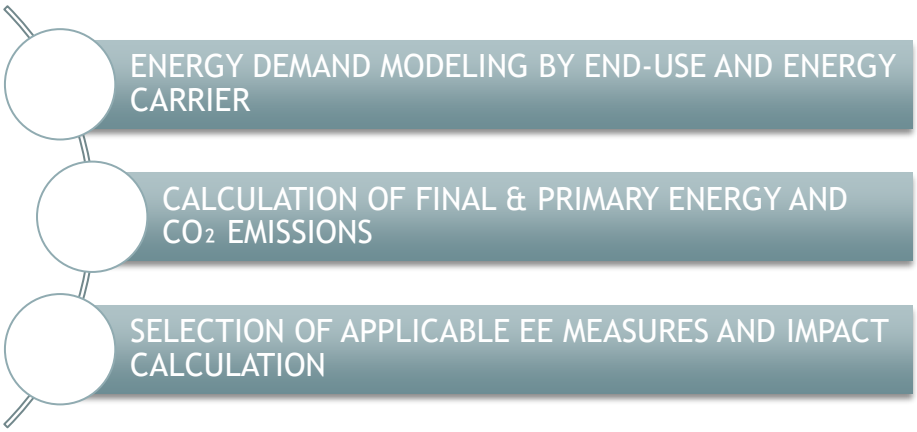


Figure 3: Energy modelling and calculations

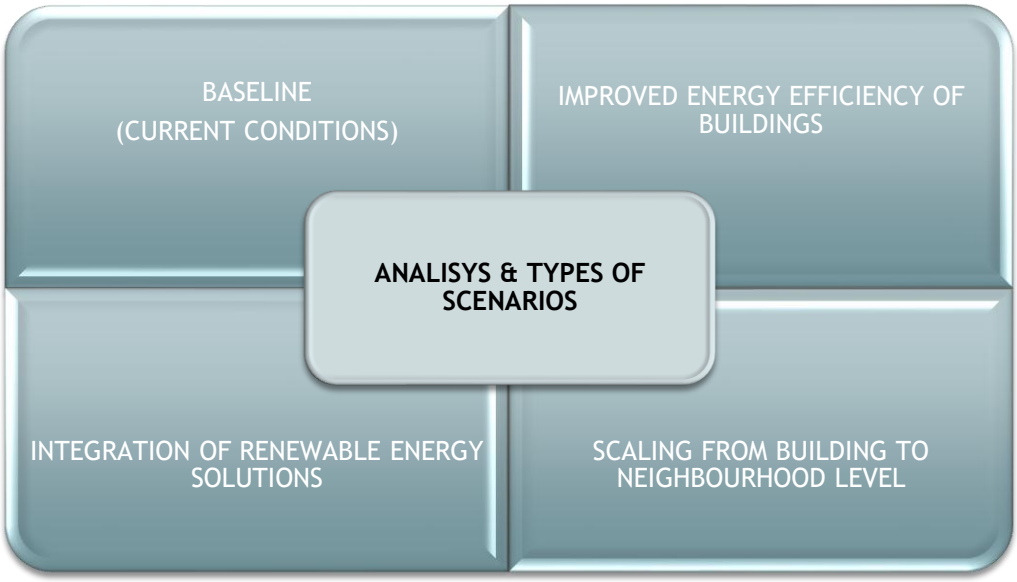


Figure 4: Energy modelling and scenario analysis

Results were expressed through key performance indicators, enabling comparison between scenarios and identification of the most effective decarbonisation pathways.

C. AGGREGATED BASELINE RESULTS

3.1 Overview of baseline energy performance

Baseline analysis provides an overview of current energy needs and emissions across the pilot neighbourhoods, considering buildings, public lighting and transportation as integrated components of the urban system. Results show that buildings are the dominant energy consumer, accounting for the majority of total energy demand and emissions. Public lighting and transportation represent smaller shares of total energy consumption but still contribute significantly to overall emissions and offer clear opportunities for targeted improvements.

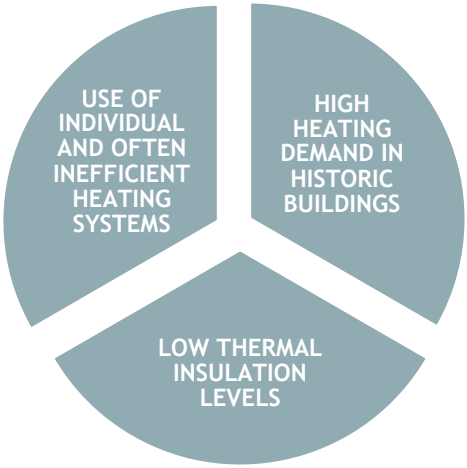


Figure 5: Buildings - the dominant energy consumer

3.2 Buildings

Across all pilot areas, buildings represent the largest share of energy consumption. As a result, buildings are identified as the primary sector for energy savings and emission reduction.

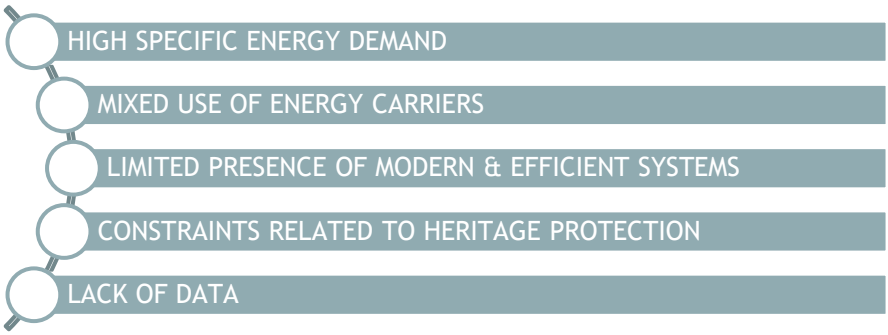


Figure 6: Key characteristics of the building stock

3.3 Public lighting

Public lighting systems are generally based on outdated technologies with relatively high energy consumption per lighting point. Although total energy consumption is significantly lower than in buildings, the sector offers high efficiency potential particularly through LED upgrades and control systems.

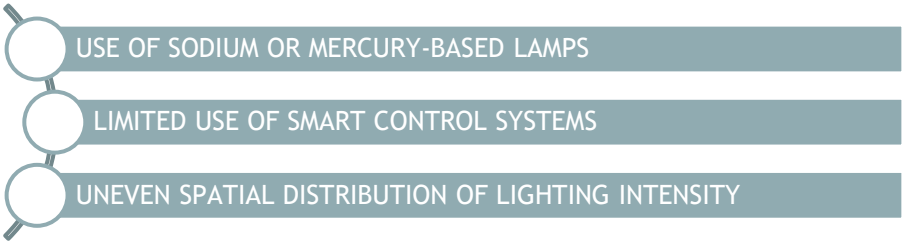


Figure 7: Typical pilots public lightning characteristics

3.4 Transportation

Transportation energy consumption is influenced by local mobility patterns and infrastructure characteristics. While representing a smaller share of total energy demand compared to buildings, transportation contributes noticeably to overall emissions, especially in areas with higher traffic intensity.

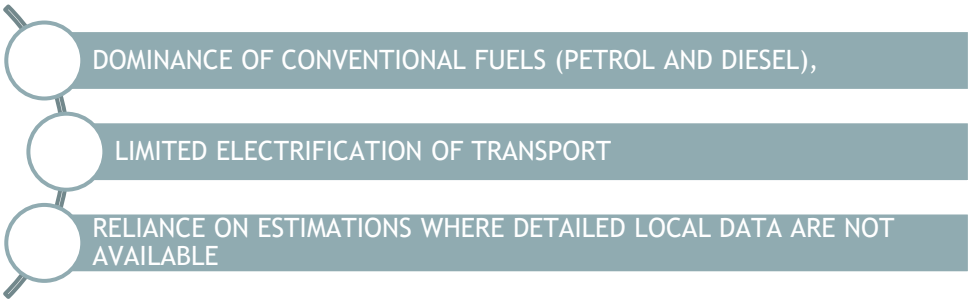


Figure 8: Key observations of pilot's transportation

D. SCENARIO RESULTS AND DECARBONISATION POTENTIAL

4.1 Overview of scenario approach

Scenario analysis evaluates the impact of selected energy efficiency (EE) and renewable energy (RES) measures on energy demand, emissions and system performance at neighbourhood level.

Three main scenario types were considered:

- Baseline – current conditions
- Efficiency scenario – building envelope improvements
- Renewable scenario – integration of RES solutions (e.g. PV, heat pumps, district heating)

All scenarios are assessed using the same key performance indicators, enabling direct comparison and identification of optimal pathways.

4.2 Impact on energy demand and emissions

The results show that significant reductions in both energy demand and CO_2 emissions are achievable across all pilot areas.

Main effects include:

- reduction of heating demand through insulation and system improvements,
- shift from fossil fuels to electricity and renewable heat sources,
- partial coverage of electricity demand through local renewable generation.

Overall, the combination of EE and RES measures enables a transition from fragmented, inefficient systems to integrated low-carbon energy systems at neighbourhood scale.

4.3 Aggregated results – pilot comparison

Table 1 Baseline energy performance for selected pilots

PILOT AREA	Final energy [GWh/year]	Primary energy [GWh/year]	CO_2 emissions [t/year]
Karlovac	31.02	36.26	6,534
Quedlinburg	5.67	6.55	1,367
Zamość	3.04	4.42	1,169
Palmanova	1.17	1.63	384.58

4.4 Scenario impact – indicative reduction ranges

Table 2 Savings and reduction potential of EE/RES scenarios

INDICATOR	Baseline	Scenario (EE + RES)	Reduction
Final energy demand	100%	60-75%	25-40%
Primary energy	100%	50-70%	30-50%
CO_2 emissions	100%	30-60%	40-70%

4.5 Sectoral contributions to decarbonisation

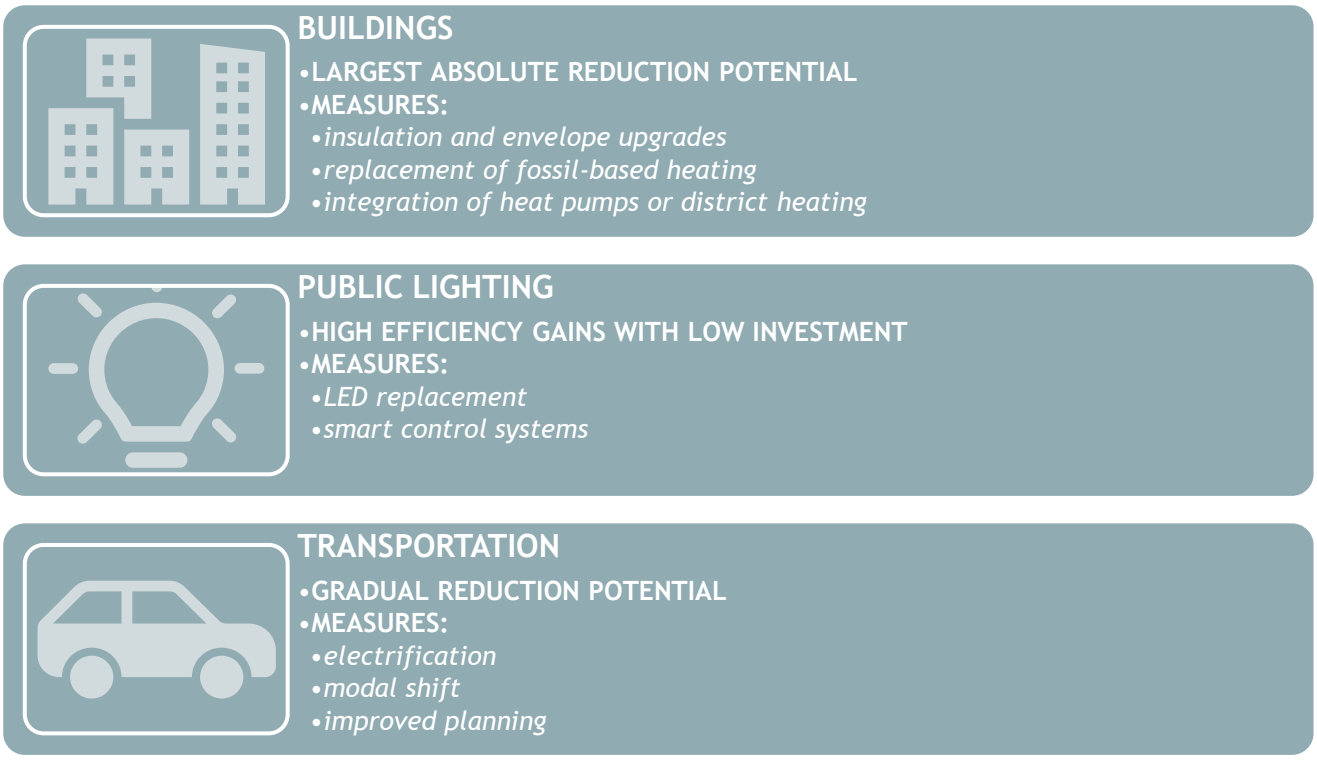


Figure 9: Sectoral contributions to decarbonization

4.6 Energy system transformation

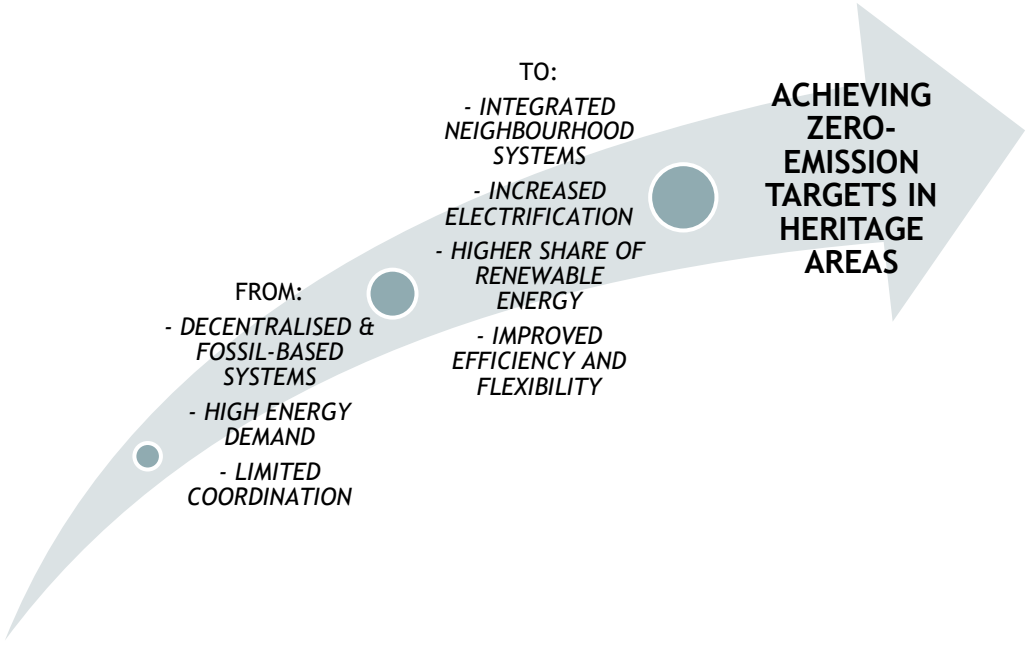


Figure 10: Achieving zero-emission targets in heritage areas

E. PILOT INVESTMENTS AND DEMONSTRATED SOLUTIONS

Pilot actions demonstrate the practical feasibility of implementing low-carbon solutions in heritage-sensitive neighbourhoods. They complement analytical results by providing real-life validation of selected technologies and approaches under actual technical, regulatory and heritage constraints. The implemented solutions cover different intervention types, including renewable energy integration, building retrofitting and system-level optimisation. Together, they illustrate how theoretical scenarios can be translated into concrete, replicable actions.

Table 3: Pilots investment results - comparative table

CATEGORY	KARLOVAC - CITY HALL PILOT	ZAMOŚĆ - ORMIAŃSKA 11 PILOT	PALMANOVA - CER & PV PILOT
PILOT FOCUS	PV + V2G + EV + Digital EMS	Internal insulation + digital twin	Renewable Energy Community + external PV
MAIN TECHNOLOGIES INSTALLED	- 10 kW AC PV (11.7 kWp DC)	- Internal wall insulation (3 systems tested)	- Planned 60 kWp PV outside city walls
	- Bidirectional V2G charger (11-22 kW)	- Ceiling insulation (4 systems tested)	- Full CER legal/organisational setup
	- BYD SEAL U EV with V2L/V2G	- PUR foam, Multipor, mineral boards	- Founding Act, Statute, rules
	- Končar Digital EMS platform	- Triple-glazed wooden windows	- Engagement with SMEs & citizens
		- Building digital twin (LiDAR + photogrammetry)	
INVESTMENT VALUE	PV: **€9,688**	Construction cost included in pilot budget (various components)	
	V2G charger: **€16,540**	Full digital-twin + lab testing funded by project	PV CAPEX TBD after feasibility
	EMS software: **€15,890**		
MEASURED / EXPECTED IMPACT	- ~14 MWh/y renewable generation	- 30-35% reduction in heat-loss on insulated partitions	- 87 MWh/y PV generation expected
	- Reduced grid imports	- 15-20% heating savings top floor	- 17-23 t CO_2 avoided annually
	- EV battery as flexible storage	- 8-12% whole-building heating reduction	- Reduction in electricity purchases for members
	- Peak shaving, improved resilience		
HERITAGE COMPATIBILITY	Fully reversible; rooftop PV allowed; V2G/EV non-intrusive	100% internal; reversible; conservation-approved	PV placed outside city walls; no impact on UNESCO fabric
DIGITALISATION LEVEL	Very high (real-time energy + V2G optim.)	Very high (complete digital twin)	Medium (CER data platform + GSE systems)
REPLICABILITY	High – compact PV+V2G package	Very high – validated internal insulation systems	Very high – CER model ideal for

F. CROSS-PILOT INSIGHTS AND KEY FINDINGS

The cross-pilot analysis shows that meaningful decarbonisation of historic neighbourhoods is achievable only through integrated, multi-level strategies that combine building envelope upgrades, modernised energy systems, renewable energy integration and digital optimisation tools. Digitalisation proves essential for ensuring consistent data, comparing results across buildings, identifying priority intervention zones and supporting scenario development. While common challenges include data gaps, regulatory and heritage constraints, technical complexity and the need for strong stakeholder coordination, pilots that adopt neighbourhood-scale planning, combine energy efficiency and renewable measures, use digital platforms and engage stakeholders early achieve the most robust results and highest impact.

G. REPLICABILITY AND UPSCALING POTENTIAL

The methodology tested across the pilot neighbourhoods proves highly replicable and scalable, offering a flexible framework that can be adapted to diverse historic urban contexts despite differences in data quality, building typologies, climate conditions, regulatory environments and heritage constraints. Its structured approach and digital tools allow cities to begin with basic assessments and progressively advance toward more sophisticated analyses. Scaling from pilot to city level is enabled through aggregation of building-level data, replication of scenario modelling across multiple districts and integration into broader urban and energy planning. The demonstrated solutions—heritage-compatible retrofit strategies, on-site and off-site renewable integration, multi-technology system optimisation and energy community models—can be transferred or combined according to local needs, supporting city-wide decarbonisation while maintaining sensitivity to heritage and spatial conditions.

H. KEY FINDINGS AND LESSONS

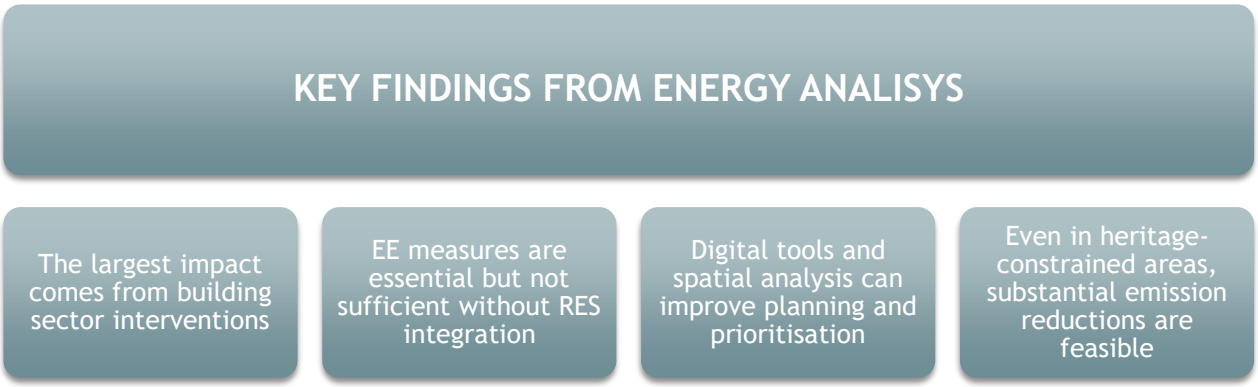


Figure 11: Key findings from energy analysis

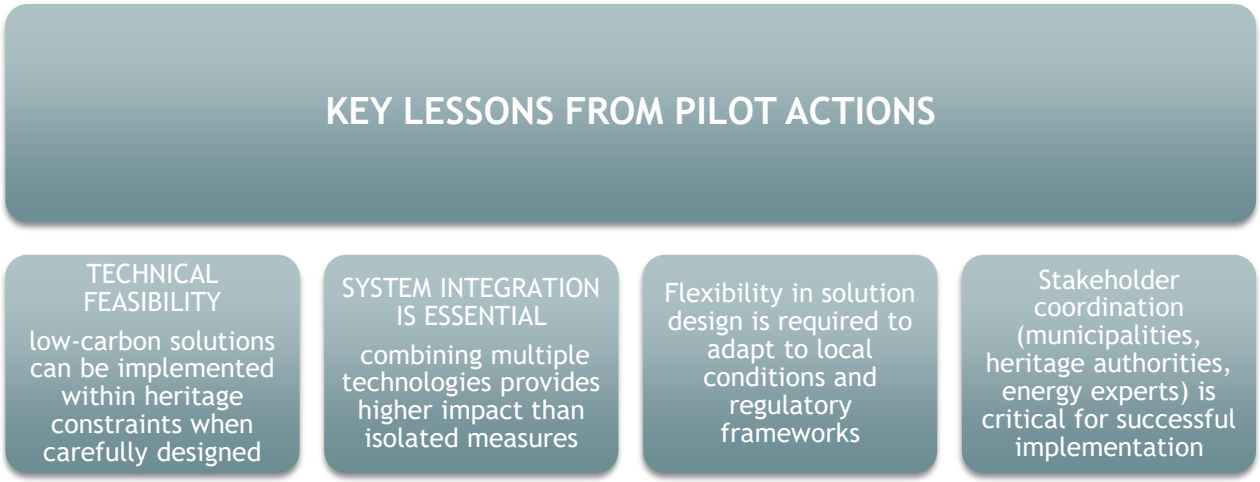


Figure 12: Key lessons from pilot actions

Historic neighbourhoods can achieve substantial emission reductions, but only through integrated, multi-sector approaches that combine technical solutions, spatial planning and stakeholder coordination.

Historic neighbourhoods can become part of Europe's climate-neutral future. Achieving this transition requires integrated planning, adaptable solutions and strong coordination between technical, institutional and heritage perspectives.

I. CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The analysis confirms that historic neighbourhoods face structurally high energy demand, primarily driven by inefficient building stock and fragmented energy systems. At the same time, strong heritage constraints limit the range of applicable interventions, requiring carefully balanced solutions. Despite these challenges, the results demonstrate that substantial reductions in energy consumption and CO_2 emissions are achievable. The most effective outcomes are obtained through integrated approaches that combine:

- building-level energy efficiency improvements,
- transition to renewable and low-carbon energy systems, and
- neighbourhood-scale planning supported by digital tools.

Pilot implementations further confirm that these solutions are not only theoretically viable but also practically feasible in real urban and heritage contexts. The key conclusion is that zero-emission pathways for historic neighbourhoods are achievable, but only through coordinated, multi-sector and data-driven approaches.

9.2 Recommendations

Based on the results, the following recommendations are proposed:

For local authorities and planners

- adopt neighbourhood-scale planning approaches instead of isolated building interventions,

- prioritise buildings as the main source of energy savings,
- integrate energy, spatial planning and heritage considerations from the early stages.

For policy makers

- support flexible regulatory frameworks that enable energy interventions in heritage contexts,
- promote renewable energy communities and shared systems,
- facilitate access to funding for integrated, multi-sector solutions.

For technical experts and project developers

- apply standardised data structures and methodologies to ensure consistency and scalability,
- use digital tools (GIS, digital twins) for analysis, planning and communication,
- combine multiple technologies to maximise system-level impact.

For future projects and replication

- ensure early stakeholder engagement and coordination,
- adopt a step-by-step implementation approach, starting from available data,
- use pilot actions to validate solutions and reduce implementation risks.