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D.4.1.2. Development of Green and Digital Energy Action Plan

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The City of Quedlinburg, as an Associated Partner of the ZEB4ZEN project, will play a key role in supporting the implementation of the Green and Digital Energy Action Plan at the local level. The Municipality is expected to facilitate coordination among relevant stakeholders, including heritage conservation authorities, building owners, energy utilities, technology providers and regional institutions. Particular attention should be given to ensuring that energy efficiency measures, electrification of the heating sector and building-integrated photovoltaic systems comply with the specific requirements for the protection of Quedlinburg's UNESCO World Heritage status. Cooperation with the Magdeburg-Stendal University of Applied Sciences, as a ZEB4ZEN project partner, can support the transfer of technical knowledge, the evaluation of decarbonisation scenarios and the identification of suitable funding opportunities. Stakeholder engagement, particularly involving private building owners and local energy suppliers, will be essential to encourage the adoption of proposed measures. Furthermore, the Municipality will promote the integration of energy-related data and monitoring activities into existing urban planning and heritage management processes, supporting the long-term implementation and periodic updating of the Energy Action Plan. During the implementation phase, particular attention should be given to the involvement of building owners, landlords and tenants, as well as to the provision of information on financial support mechanisms and heritage-compatible renovation solutions. These activities should be coordinated with the responsible municipal and heritage conservation authorities..... 39

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DEVELOPMENT OF GREEN AND DIGITAL ENERGY ACTION PLAN

A. INTRODUCTION

The transition to a sustainable, resilient, and climate-neutral society requires cities and communities to fundamentally rethink the way they plan, produce, distribute, and consume energy. The development of Green and Digital Energy Action Plans represents a cornerstone of this transformation. These strategic documents are designed to provide a long-term framework for reducing greenhouse gas emissions, increasing energy efficiency, and integrating renewable energy, while simultaneously leveraging digital technologies to enable transparency, optimization, and citizen engagement.
The Energy Action Plan combines the data collected in working package one (neighborhood energy flows), working package two (small-scale demonstration pilot investments) and working package three (cultural heritage and historic neighborhood preservation) and creates a tangible output which envisions the use of energy efficient and renewable energy system measures in the timeframe until 2050. The EE/RES measures include measures of TRL 9 such as heat pumps, photovoltaic systems and electric vehicles as well as new, disruptive technology such as perovskite pv systems for building integration. The measures were included in the ZEN (Zero Emissions Neighborhood) scenarios as opposed to the BAU (business as usual) scenarios to show the impact of the scenarios.

The “green” dimension of the Action Plan focuses on:

- Decarbonising the built environment by improving the energy performance of buildings through deep renovation.
- Promoting clean heating and cooling solutions, such as heat pumps, district heating from renewable sources (e.g. geothermal).
- Expanding local renewable energy production, including photovoltaic installations on rooftops and the development of photovoltaic energy communities.
- Modernising infrastructure—such as public lighting, transport systems, and energy networks—to become more efficient and climate-friendly.
- Ensuring the alignment of urban energy strategies with broader frameworks like the EU Green Deal, Fit for 55, and REPowerEU.

These goals are achieved through scenario-based planning, cost-benefit analysis, and alignment with environmental protection and architectural conservation.

The “digital” dimension of the Action Plan focuses on:

- Digital mapping and GIS-based building stock models that provide granular data on energy consumption, emissions, building types, and renovation potential.
- Simulation and modelling tools to test decarbonisation scenarios under different economic, technical, and policy assumptions.
- Data-driven solutions, ensuring that public investments deliver measurable energy and emissions savings.

- Digital platforms for participation, allowing stakeholders to visualize plans, to upgrade and update dana, co-design measures, and track progress in transparent ways.

The plan provides a clear roadmap for action, identifying:

Detailed analysis and proposal of energy efficiency (EE) and decarbonisation measures, that include building envelope upgrades, transition to renewable-based heating and cooling systems, electrification of end uses, public infrastructure modernization, and integration of local renewable generation.

Decarbonisation roadmap, recomending trajectory for measures implementation grouped into logical timeline phases.

Investment estimation, providing a quantified forecast of total capital needs across the roadmap horizon. Each group of measures (e.g., building renovation, RES installation, lighting retrofit) is costed based on unit benchmarks and scaled across the building stock and infrastructure assets.

Implementation timeline (until 2050), structured into gradually long-term (2050) milestones, aligning with EU climate neutrality objectives.

Savings calculations in primary energy and CO_2 emissions, calculated for each scenario and project graduation period.

Key Performance Indicators (KPIs), clearly defined and measurable. KPIs cover:

- Reduction in final and primary energy use (kWh/m²),
- Decrease in CO_2 emissions (tons/year),
- Share of renewable energy in final consumption (%),
- Renovated floor area (m²),
- Installed RES capacity (kWp),
- Payback period.

Digital visualisation and spatial planning framework, enabling the structured representation of the building stock, current energy performance, and planned interventions in digital and georeferenced form. The plan includes GIS-based layers that map:

- Buildings and blocks spatial presentation,
- Data of buildings,
- Energy and emissions data on buildings block level,
- Potential and simulated effects of measures implementation on buildings block level.

Finalization of Energy Action Plans

Four Green and Digital Energy Action Plans were developed within the ZEB4ZEN project, covering the pilot neighbourhoods of Zvijezda in Karlovac (Croatia), Quedlinburg (Germany), Zamość (Poland), and Palmanova (Italy). All four Energy Action Plans were technically finalised on 15 May 2026 (see Table 1). Their development was supported by building-level energy assessments, scenario modelling, investment estimates, and phased implementation roadmaps, as documented in the corresponding technical calculation files. The finalisation date refers to the completion of the technical planning activities within the ZEB4ZEN project and should be distinguished from any subsequent formal adoption or implementation decisions by the responsible municipal authorities.

Table 1 Finalization of EAPs

Pilont neighbourhood	Technical finalization date
Zvijezda, Karlovac (Croatia)	15 May 2026
Quedlinburg (Germany)	15 May 2026
Zamość (Poland)	15 May 2026
Palmanova (Italy)	15 May 2026

Progress archieved by 31 March 2026 and activities completed during the final reporting period

By 31 March 2026, the energy baselines for all four ZEB4ZEN pilot neighbourhoods had been finalised. These baselines provided the reference conditions for the subsequent assessment of energy efficiency measures and decarbonisation scenarios, including the evaluation of energy consumption and associated CO_2 emissions. During the final reporting period, the remaining scenario calculations and implementation roadmaps were completed and consolidated. This work included the finalisation of the quantitative assessment of proposed measures, their expected energy and environmental impacts, and the corresponding implementation phases. The four Green and Digital Energy Action Plans were technically finalised on 15 May 2026, integrating the completed baseline assessments, decarbonisation scenarios, proposed measures, and implementation roadmaps into the final planning documents.

B. GREEN AND DIGITAL ENERGY ACTION PLAN FOR ZVIJEZDA, CROATIA

1. Existing Conditions and Baseline Assessment

1.1. Urban and Heritage Context

The Zvijezda district, the historic core of the city of Karlovac, is a rare example of Renaissance star-shaped urban planning, originally constructed as a military fortress in the 16th century. It retains its geometric block structure and contains a diverse range of buildings, including residential units, civic and cultural institutions, and administrative premises. The area is under cultural protection, imposing strict conditions for physical interventions.

1.2. Building Stock Characteristics

- Majority of buildings are over 100 years old, with limited or no thermal insulation.
- High heat loss due to poor envelope performance.
- Dominance of outdated heating systems: wood stoves, gas boilers, electric heaters.
- Lack of unified energy infrastructure – fragmented, building-level energy management.

1.3. Energy and Emissions Baseline

- Primary Energy Consumption: kWh/year
- CO_2 Emissions: tons/year
- Heating Energy Demand: accounts for ~50% of total energy use
- Main fuels: biomass (firewood), natural gas, fuel oil, electricity (resistive heating)

1.4. GIS Representation

A geospatial model was developed for the entire district, identifying:

- 29 urban blocks
- 234 buildings (residential and public use)
- Zoning layers, energy infrastructure, cultural status tags

Commented [PL1]: Please complete the missing baseline values for primary energy consumption and CO_2 emissions, and explicitly include final energy consumption. Ensure that the figures and units are consistent with Table 1 and the underlying Excel baseline model. Please also specify the reference year (2020).

Commented [IH2R1]: Baseline - final energy, primary and CO2 are presented in chapter 1.5 1.5. KPIs and Impact Summary - Table 2. Total and specific values for final, primary and CO2 for baseline and OPEX are shown here. The data is aligned with the tables from the Input folder.



Figure 1: Buildings blocks CO_2 emissions [tCO_2/year] – Baseline Scenario

1.5. KPI`s - Baseline Scenario

Table 2 KPI`s (Baseline Scenario) – year 2020

INDICATOR	VALUE
Primary Energy Needs [kWh/y]	44.596.444
Specific Primary Energy Needs [kWh/m²/y]	336,85
Final Energy Needs [kWh/y]	36.878.376
Specific Final Energy Needs [kWh/m²/y]	278,55
CO_2 Emissions [tCO_2/y]	5.247
Specific CO_2 Emissions [$kgCO_2/m^2/y$]	39,63
OPEX [€/y]	3.028.662

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2. Integration of Existing City Strategies into the Zvijezda Green and Digital Energy Action Plan

This chapter outlines the alignment between proposed measures for the Zvijezda district and the broader energy and climate objectives defined in the following official city documents:

- Action Plan for Green Karlovac
- Sustainable Energy and Climate Action Plan (SECAP) of Karlovac
- Development Plan of the City of Karlovac 2021-2030
- Guidelines for Integrating Sustainable Energy and Climate Planning into the City's Urban Plans (EKPP Guidelines)

The following thematic areas have been identified as priorities, and are fully consistent with measures included in the Green and Digital Energy Action Plan for Zvijezda under the ZEB4ZEN framework:

1. **Energy-Climate Zoning**

As part of the "Guidelines for Integrating Sustainable Energy and Climate Planning into the Urban Plan of the City of Karlovac", a spatial framework for energy-climate zoning was proposed. This zoning aims to tailor energy efficiency and climate resilience measures to the specific urban morphology, heritage constraints, and energy infrastructure of each part of the city.

The Zvijezda district — the historic star-shaped core of Karlovac—is explicitly designated as Zone Z1 (Z1-01), a priority area under conservation protection.

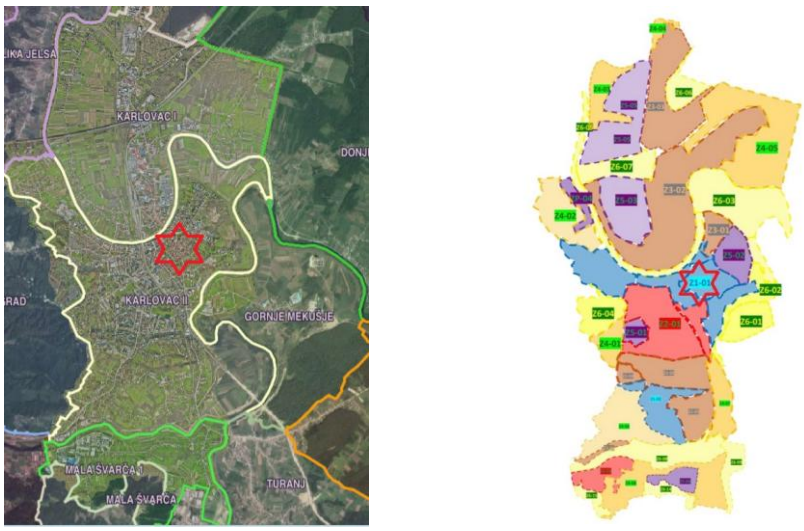


Figure 2: Overview of the recommended areas of energy and climate zones within the scope of the GUP, (Sources: GIS Karlovac, REGEA)

Key characteristics of Zone Z1 (Zvijezda and surroundings):

- Includes the core urban structure of Zvijezda, its green buffer zones, the old town centre, and historically significant areas along the Korana and Kupa rivers.

- Subject to strict heritage protection regulations under the Urban Development Plan (UPU).
- Recognised as a strategic site for energy transition and climate neutrality.

Strategic Recommendations for Zone Z1:

- Mandatory connection to the district heating system or the use of a central renewable-based heating/cooling system (e.g. geothermal).
- Obligation to achieve climate neutrality upon adoption of amendments to the General Urban Plan (GUP).
- Application of integrated planning principles, in accordance with the city's Sustainable Energy and Climate Action Plan (SECAP) and specifically:
    - **Measure 3:** Introduction of integrated energy and climate planning.
    - **Measure 26:** Establishment of energy zoning in the urban planning framework.

By designating Zvijezda as Zone Z1, the City of Karlovac reinforces its intention to preserve architectural heritage while also pursuing an ambitious climate and energy transition agenda. This zoning recommendation directly supports the goals and structure of the Zvijezda Green and Digital Energy Action Plan, ensuring that proposed building renovations and energy system upgrades are consistent with long-term urban and environmental strategies.

2. **Geothermal and District Heating System**

Karlovac Development Plan and SECAP propose the transition to low-carbon district heating, with emphasis on future integration of geothermal sources to reduce dependence on fossil fuels and improve air quality.

Zvijezda is identified as a strategic location for connection to a modernised district heating system, particularly through potential geothermal energy infrastructure already under study.

Linked measure in Zvijezda Green and Energy Action Plan:

Full conversion of heating systems to geothermal-powered district heating, combined with thermal retrofitting of buildings.

3. **Heat Pumps as Decentralised Low-Carbon Technology**

The EKPP Guidelines support the application of heat pumps in buildings that are not suitable for district heating, especially in heritage zones where invasive interventions are limited.

SECAP includes the use of high-efficiency heating and cooling systems, explicitly naming heat pumps as a priority solution for decarbonisation in residential buildings.

Linked measure in Zvijezda Green and Energy Action Plan:

Building-level implementation of air-to-water or ground-source heat pumps, where connection to district heating system is not viable.

4. **Photovoltaics on Buildings**

All three documents encourage the deployment of solar PV systems on rooftops, with SECAP targeting significant increases in the share of renewable energy in the building sector.

The Karlovac Development Plan promotes the creation of energy self-sufficient public buildings through PV installations.

Linked measure in Zvijezda Green and Energy Action Plan:

Installation of building-integrated PV systems on suitable residential and public buildings in Zvijezda.

5. **Energy Communities and Off-Site PV Systems**

The EKPP Guidelines support the formation of renewable energy communities as a model for collective investment in PV systems.

SECAP calls for citizen engagement in clean energy generation and for exploring municipal land as potential locations for PV plants linked to urban districts.

Linked measure in Zvijezda Green and Energy Action Plan:

Establishment of an energy community for Zvijezda, enabling local residents and institutions to benefit from off-site solar production.

6. **Public Lighting Modernisation**

SECAP includes the objective of full LED conversion of the public lighting network, with smart controls to reduce consumption and light pollution.

Ongoing public lighting replacement programmes in Karlovac have already targeted thousands of luminaires.

Linked measure in Zvijezda Green and Energy Action Plan:

Replacement of all public lighting in Zvijezda with heritage-appropriate LED systems and smart dimming technologies.

7. **Sustainable Mobility and Transport Electrification**

The Karlovac Development Plan promotes an integrated urban mobility approach, including public transport electrification, cycling infrastructure, and pedestrian zones.

SECAP supports the development of EV charging infrastructure and low-emission zones in the city centre.

Linked measure in Zvijezda Green and Energy Action Plan:

Installation of EV chargers at district entry points, promotion of e-bikes, and gradual limitation of fossil-fuel vehicles in the historic core.

3. Analasys Limitations and Assumptions

The energy modelling and scenario analysis presented in this Action Plan are based on the best available data at the time of preparation. However, several limitations must be acknowledged, particularly considering the complex historical and cultural nature of the Zvijezda district and the challenges associated with data availability and quality:

- **Incomplete and inconsistent data**

For many buildings, especially those without energy performance certificates, information regarding heating systems, floor area, usage patterns, and renovation status was either unavailable or incomplete. In such cases, reasoned assumptions were made based on typologies, visual inspections, and statistical averages.

- **Use of generalized values**

In the absence of building-specific data, average specific energy demand values (e.g., 350–380 kWh/m²) and heating demand factors were applied. This approach introduces a level of uncertainty at the individual building level, though the methodology is more reliable when assessed at the district scale.

- **Heritage constraints and structural condition**

Many buildings in Zvijezda are protected cultural assets and/or damaged by recent earthquakes. Their structural condition and architectural restrictions significantly affect the feasibility and applicability of certain renovation measures. This affects the energy modelling assumptions and must be considered when interpreting the results.

- **Diversity and overlap of energy sources**

Survey results and historical data indicate that multiple energy sources are often used in parallel (e.g., firewood and electric heaters). The modelling approach distributes heating energy demand among different carriers using proxy data and assumptions, which may not reflect actual usage precisely.

- **Limitations Related to Buildings Use and Resident Behaviour**

Another limitation affecting the reliability of the model is the **lack of complete and up-to-date information on the actual use of residential and non-residential units within buildings**. Due to ongoing infrastructure works in the district (e.g., the Agglomeration project), as well as demographic and economic shifts, the occupancy status of many buildings is uncertain. Some units may be temporarily vacant, under renovation, or partially in use. Furthermore, a notable portion of the building stock is in **poor structural condition**, and a significant share of residents could be affected by energy poverty. This results in a behavioural pattern where living spaces are underheated or not heated at all during winter months, and cooling is entirely absent in summer, leading to significantly lower real energy consumption than expected under normative conditions. These factors are not fully captured in the model, which assumes standardised usage profiles and heating demand, and thus may overestimate actual energy needs in some cases.

- **Calibration challenges**

While the model was calibrated using real energy consumption data where available (especially for public buildings and electricity), no comprehensive consumption datasets exist for natural gas, heating oil, or firewood. This impacts the precision of fuel-specific projections and investment estimates.

- **Temporal evolution of the district**

Ongoing infrastructure works (e.g., Agglomeration project) and potential changes in building usage or ownership mean that the current energy model represents a snapshot in time, and will need to be updated regularly to remain relevant and accurate.

- **Conservation Constraints and Compatibility with Decarbonisation Goals**

An additional limitation specific to the Zvijezda district is its protected cultural heritage status, which imposes strict regulations on any physical interventions. Measures such as thermal insulation of facades, replacement of windows, installation of solar panels, or placement of external heat pump units are often restricted or prohibited under conservation guidelines. These constraints can significantly limit the technical feasibility or cost-effectiveness of standard energy renovation approaches. As a result, certain assumptions made in the modelling (e.g. insulation thickness, PV installation, mechanical system replacement) may not be permitted or only partially implementable without specific waivers or alternative technical solutions. The Action Plan aims to identify viable decarbonisation strategies that are technically flexible, visually unobtrusive, and culturally respectful, but acknowledges that full harmonisation between heritage protection and climate targets remains a complex, case-by-case challenge.

As a result, all projections and scenario-based evaluations in this Plan should be interpreted as indicative and subject to refinement as more precise or updated data become available. The methodology prioritises transparency, replicability, and strategic insight over building-level precision.

4. Decarbonisation Strategy Scenario 1: Block-Level Buildings Renovation with Centralised Heating, Smart Lighting and E-Mobility

4.1. Scenario Overview

This scenario proposes a neighbourhood-scale renovation approach based on the deployment of a modern, low-emission centralised District Heating System (DHS) powered by geothermal energy. It is accompanied by a set of supporting measures aimed at improving building performance and increasing local renewable energy production.

4.2. Technical Measures

1. **Thermal Envelope Refurbishment**
   - Exterior wall insulation using mineral wool (where permitted)
   - Roof/attic insulation
   - Window replacement with heritage-compatible triple-glazed units
   - Floor insulation from basement/cellar side
2. **Heating System Shift**
   - Full replacement of individual heating systems with district heating substations (hydraulic interface units)
   - Geothermal heat source located outside the district and piped in via pre-insulated distribution network
3. **On-Site Renewable Energy**
   - Rooftop photovoltaic (PV) systems on suitable public and private buildings
   - Average size: 3–10 kWp per building (subject to roof orientation, shading, and structural limits)
4. **Off-Site RES via Energy Communities**
   - Participation of Zvijezda residents in solar farms located on municipal land outside the heritage zone
   - Virtual net metering and prosumer rights enabled
5. **Public Lighting Retrofit**
   - Replacing all existing sodium/fluorescent lamps with LED fixtures
   - Adding smart controls (dimming, motion sensors)

Table 3 Key Performance Indicators - public lightning retrofit in Zvijezda neighbourhood (Phase 1- 2025)

Parameter:	Value:
Energy consumption before [kWh/y]:	151.571,88
Installed power before [kW]:	30,58
Unit price of electricity [€/kWh]:	0,105
CO_2 factor for electricity [$kgCO_2$/kWh]:	0,159
OPEX before [€/y]:	15.859,17
CO_2 emissions before [tCO_2/kWh]:	24,10
Energy consumption after [kWh/y]:	25.770,96
Installed power after [kW]:	8,64
OPEX after [€/y]:	2.696,45
CO_2 emissions after [tCO_2/kWh]:	4,10
Final Energy savings [kWh/y]:	**125.800,92**
Primary Energy savings [kWh/y]:	**188.450,78**
Installed power reduction [kW]:	**21,94**
OPEX savings [€/y]:	**13.162,72**
CO_2 emission reduction [tCO_2/kWh]:	**20,00**
Number of public lighting fixtures in Zvijezda:	194
Unit price [€/piece]:	465,65
Investment [€]:	**90.335,27**
Investment quality [€/kW]:	4.118,32
Investment quality [€/kWh]:	0,72
Investment quality [€/tCO_2]:	4.516,23
Simple Payback Period [years]:	**6,86**

Table 4 Key Performance Indicators - public lightning retrofit in Zvijezda neighbourhood (Phase 2 - 2038)

Parameter:	Value:
Energy consumption before [kWh/y]:	25.770,96
Installed power before [kW]:	8,64
Unit price of electricity [€/kWh]:	0,105
CO_2 factor for electricity [$kgCO_2$/kWh]:	0,159
OPEX before [€/y]:	2.705,95
CO_2 emissions before [tCO_2/kWh]:	8,64
Energy consumption after [kWh/y]:	16.285,82
Installed power after [kW]:	6,05
OPEX after [€/y]:	1.704,01
CO_2 emissions after [tCO_2/kWh]:	2,59
Final Energy savings [kWh/y]:	**9.485,14**
Primary Energy savings [kWh/y]:	**14.208,74**
Installed power reduction [kW]:	**2,59**
OPEX savings [€/y]:	**992,44**
CO_2 emission reduction [tCO_2/kWh]:	**1,51**
Number of public lighting fixtures in Zvijezda:	194
Unit price [€/piece]:	100,00
Investment [€]:	**19.400,00**
Investment quality [€/kW]:	7.484,57
Investment quality [€/kWh]:	2,05
Investment quality [€/tCO_2]:	12.863,54
Simple Payback Period [years]:	**19,55**

6. **Traffic shutdown (except for residents) & electrification of transport**
    - Introduction of e-vehicle charging stations on the perimeter of Zvijezda
    - Incentives for e-bike sharing and electric minibuses

Table 5 Indicative energy reduction in transport

Year	Transport Measures in Zvijezda	Traffic Reduction [%]	Energy consumption [kWh/y]	Energy reduction [kWh/y]	CO2 emissions [tCO2/y]	CO2 emission savings [tCO2/y]
2025	No measures	0%	1.090.788	0	305,89	0
2030	Traffic ban for trucks	30%	763.552	327.236	214,12	91,77
2040	**Traffic ban for petrol, diesel and LPG vehicles**	**80%**	**152.710**	**610.841**	**42,82**	**171,30**
2050	Pedestrian-priority zone	100%	0	152.710	0,00	42,82

4.3. KPIs and Impact Summary (Scenario 1)

Table 6 KPIs and Impact Summary (Scenario 1) - year 2050.

INDICATOR	VALUE
Heating Supply Type:	Geothermal District Heating
Primary Energy Needs [kWh/y]:	22.792.434
Final Energy Needs [kWh/y]:	20.519.279
CO_2 Emissions [t CO2/y]:	790
Useful Area [m2]	132.392
Specific Primary Energy Needs [kWh/m2/y]:	172,16
Specific Final Energy Needs [kWh/m2/y]:	154,99
Specific CO_2 Emissions [kg CO2/m2/y]:	5,97
Primary Energy Savings [kWh/y]:	21.804.010
Final Energy Savings[kWh/y]:	16.359.097
CO_2 Emissions Savings [t CO2/y]:	4.457
OPEX Savings [€/year]:	1.095.560
Investment (TI, Geoth) (2024) [€]:	43.839.021
Simple Payback Period [years]:	40,02
Installed PV Capacity [kW]:	2.577
PV Production [kWh/y]:	2.834.783
RES-Share in Final Energy [%]:	13,82
Electricity Primary Energy Factor [-]	1,498
Solar Electricity Primary Energy Factor [-]	1,000
Electricity CO2 Factor [€/kWh]	0,159
Electricity Unit Price [€/kWh]	0,131
PV Primary Energy Savings [kWh/y]:	4.246.505
PV Final Energy Savings [kWh/y]:	2.834.783

PV CO2 Savings [t CO2/y]:	451
PV OPEX Savings [€/year]:	371.357
Investment (PV) (2024) [€]:	5.154.146
Simple Payback Period (PV) [years]:	13,88
TOTAL PRIMARY ENERGY SAVINGS [kWh/y]:	26.050.515
TOTAL FINAL ENERGY SAVINGS [kWh/y]:	19.193.880
TOTAL CO2 SAVINGS [t CO2/y]:	4.908
TOTAL OPEX SAVINGS [€/year]:	1.466.917
TOTAL INVESMENT [€]	48.993.167
SIMPLE PAYBACK PERIOD [years]:	33,40

4.4. Action plan (Scenario 1)

Table 7 Action plan for Scenario 1 (2025 – 2050)

SEGMENT	Year	CAPEX [€]	OPEX savings [€/year]	Final energy savings [kWh/year]	Primary energy savings [kWh/year]	Production [kWh/year]	CO2 savings [t/year]	Simple payback period [years]
BLOCK 1	2025	5.054.319	107.729	1.492.853	1.829.434	281.065	370	48,00
BLOCK 2	2025	1.473.815	30.595	375.680	462.198	111.078	86	51,75
BLOCK 3	2025	1.628.499	49.209	385.440	504.523	209.105	119	39,14
BLOCK 4	2025	360.668	8.988	166.290	202.842	39.853	10	40,00
BLOCK 5	2030	2.752.814	45.229	485.815	611.798	73.524	237	56,67
BLOCK 6	2030	1.354.938	27.721	521.566	694.367	46.569	120	51,88
BLOCK 7	2030	1.229.330	34.005	440.018	733.733	63.789	204	42,57
BLOCK 8	2030	1.821.561	57.601	521.887	649.299	166.254	183	38,14
BLOCK 9	2030	1.189.414	41.502	414.656	541.849	99.230	105	38,00
BLOCK 10	2035	1.741.331	61.962	667.058	921.273	120.491	121	61,18
BLOCK 11	2035	1.383.586	29.100	559.904	682.609	68.776	100	56,00
BLOCK 12	2035	782.828	22.155	365.976	468.604	26.528	63	43,70
BLOCK 13	2040	5.766.399	161.954	2.150.737	2.891.452	255.035	409	40,61
BLOCK 14	2040	2.260.939	76.093	633.339	945.915	169.018	223	29,00
BLOCK 15	2040	1.360.243	62.023	510.016	712.761	91.495	165	22,67
BLOCK 16	2040	249.744	1.854	-85.220	-56.416	0	9	135,00
BLOCK 17	2040	1.162.922	34.802	462.369	608.260	75.702	69	43,57
BLOCK 18	2040	1.907.300	82.359	718.768	1.016.030	145.494	174	24,42
BLOCK 19	2045	2.245.548	111.584	857.113	1.193.248	161.955	314	23,67
BLOCK 20	2045	2.115.905	93.526	790.697	1.075.346	167.642	251	23,00
BLOCK 21	2045	1.138.919	33.451	431.823	567.790	57.533	91	34,75
BLOCK 22	2045	550.545	16.548	248.787	333.042	17.508	35	41,67
BLOCK 23	2045	2.980.126	76.447	960.772	1.336.271	85.825	197	44,69
BLOCK 24	2045	135.550	4.595	64.974	89.213	0	12	29,00

BLOCK 25	2045	779.817	27.760	253.907	342.007	37.028	90	37,43
BLOCK 26	2050	1.507.749	33.342	290.076	335.311	130.358	118	45,00
BLOCK 27	2050	2.118.509	54.155	920.404	1.077.852	0	379	39,00
BLOCK 28	2050	811.186	29.804	344.197	476.895	28.660	73	28,38
BLOCK 29	2050	1.128.663	50.825	409.195	556.504	105.268	130	23,50
PUBLIC LIGHTNING 1. phase	2025	90.335	13.163	125.801	188.450	0	20	6,86
PUBLIC LIGHTNING 2. phase	2038	-	-	-	-	-	-	-
TRANSPORT 1. phase	2030	-	116.368	763.552	889.988	0	214	-
TRANSPORT 2. phase	2040	-	23.274	152.710	177.998	0	43	-
TOTAL:		**49.083.502**	**1.619.721**	**17.401.160**	**23.060.446**	**2.834.783**	**4.734**	**41,31**

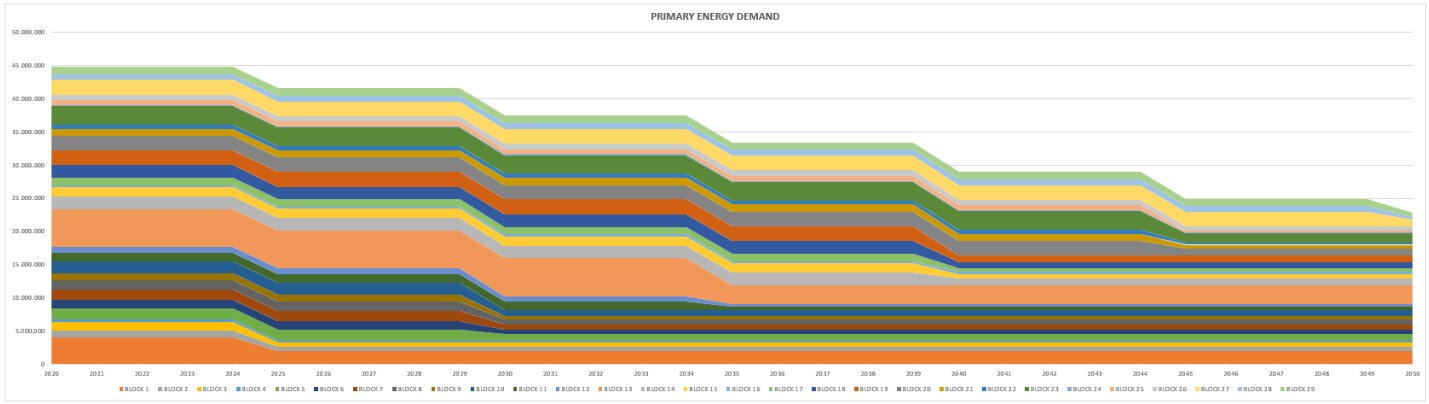


Figure 3: Scenario 1 – Primary energy demand reduction (2025 – 2050)

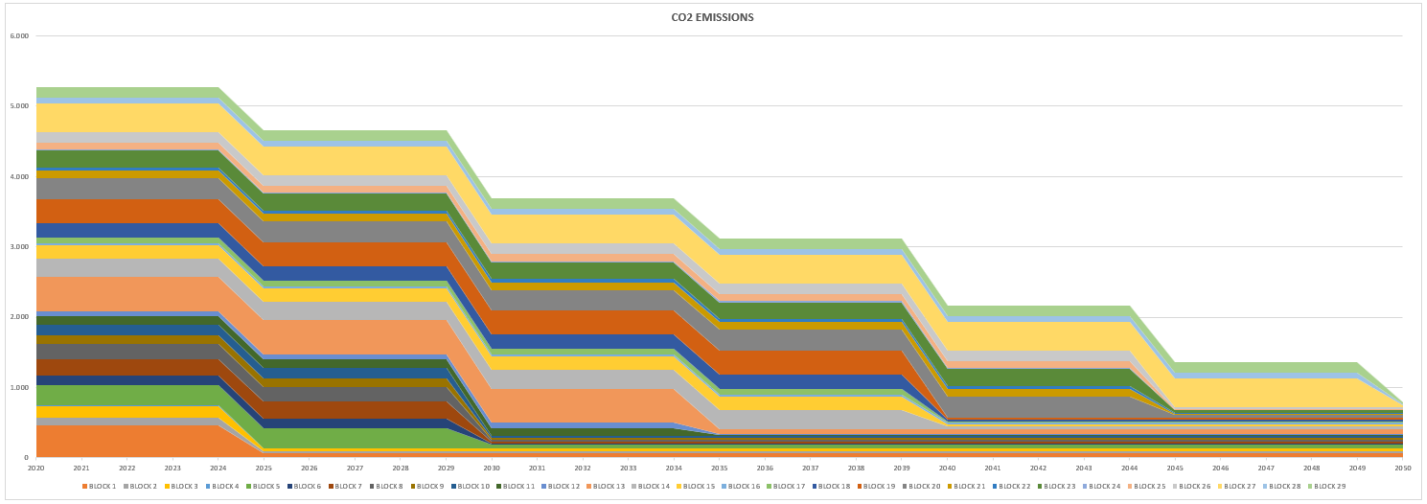


Figure 4: Scenario 1 – CO_2 emissions reduction (2025 – 2050)

5. Decarbonisation Strategy Scenario 2: Block-Level Buildings Renovation with Heat Pumps, Smart Lighting and E-Mobility

5.1. Scenario Overview

This alternative approach focuses on building-level heating solutions, replacing fossil fuel systems with electric air-to-water or ground-source heat pumps, while maintaining all other renovation and energy production measures from Scenario 1.

5.2. Technical Measures

1. **Thermal Insulation and Windows**
    - Identical to Scenario 1 (with special attention to façade-integrated insulation where heritage allows)
2. **Heat Pump Implementation**
    - Individual units sized per building heat demand
    - SCOP assumed: 4.3 (annual performance)
    - Some buildings may require hybrid systems (e.g., HP + auxiliary electric heater for peak loads)
3. **Same RES Measures**
    - On-site PV for electricity production (self-consumption model)
    - Off-site PV through energy community participation
4. **Public Infrastructure Improvements**
    - Same LED street lighting upgrade and smart controls
    - Electrification of transport as in Scenario 1

5.3. KPIs and Impact Summary (Scenario 2)

Table 8 KPIs and Impact Summary (Scenario 2) – year 2050

INDICATOR	VALUE
Heating Supply Type:	Shallow ground-source heat pumps
Primary Energy Needs [kWh/y]:	12.300.519
Final Energy Needs [kWh/y]:	8.310.232
CO_2 Emissions [t CO2/y]:	1.348
Useful Area [m2]	132.392
Specific Primary Energy Needs [kWh/m2/y]:	92,91
Specific Final Energy Needs [kWh/m2/y]:	62,77

Specific CO_2 Emissions [kg CO2/m2/y]:	10,18
Primary Energy Savings [kWh/y]:	32.295.925
Final Energy Savings[kWh/y]:	28.568.144
CO_2 Emissions Savings [t CO2/y]:	3.899
OPEX Savings [€/year]:	1.270.346
Investment (TI, HP) (2024) [€]:	55.889.721
Simple Payback Period [years]:	44,00
Installed PV Capacity [kW]:	2.577
PV Production [kWh/y]:	2.834.783
RES-Share in Final Energy [%]:	34,11%
Electricity Primary Energy Factor [-]	1,498
Solar Electricity Primary Energy Factor [-]	1,000
Electricity CO2 Factor [€/kWh]	0,159
Electricity Unit Price [€/kWh]	0,131
PV Primary Energy Savings [kWh/y]:	4.246.505
PV Final Energy Savings [kWh/y]:	2.834.783
PV CO2 Savings [t CO2/y]:	451
PV OPEX Savings [€/year]:	371.357
Investment (PV) (2024) [€]:	5.154.146
Simple Payback Period (PV) [years]:	13,88
TOTAL PRIMARY ENERGY SAVINGS [kWh/y]:	36.542.430
TOTAL FINAL ENERGY SAVINGS [kWh/y]:	31.402.927
TOTAL CO2 SAVINGS [t CO2/y]:	4.350
TOTAL OPEX SAVINGS [€/year]:	1.641.703
TOTAL INVESMENT [€]	61.043.867
SIMPLE PAYBACK PERIOD [years]:	37,18

5.4. Action plan (Scenario 2)

Table 9 Action plan for Scenario 2 (2025 - 2050

SEGMENT	Year	CAPEX [€]	OPEX savings [€/year]	Final energy savings [kWh/year]	Primary energy savings [kWh/year]	Production [kWh/year]	CO2 savings [t/year]	Simple payback period [years]
BLOCK 1	2025	6.248.392	122.321	2.535.015	2.723.321	281.065	324	50,94
BLOCK 2	2025	1.808.087	34.841	651.407	700.628	111.078	73	50,88
BLOCK 3	2025	2.138.198	53.697	707.729	780.829	209.105	104	43,29
BLOCK 4	2025	436.414	10.301	259.648	282.950	39.853	6	42,00
BLOCK 5	2030	3.441.178	51.569	998.098	1.047.005	73.524	215	62,00
BLOCK 6	2030	1.688.789	33.652	898.621	1.021.071	46.569	102	52,75
BLOCK 7	2030	1.521.941	39.052	781.765	1.028.198	63.789	188	44,29
BLOCK 8	2030	2.220.859	62.898	895.779	970.331	166.254	165	41,00
BLOCK 9	2030	1.454.599	45.653	691.818	780.975	99.230	93	40,33
BLOCK 10	2035	2.160.376	69.004	1.148.374	1.335.639	120.491	100	60,00
BLOCK 11	2035	1.714.357	35.045	931.126	1.004.777	68.776	83	55,50
BLOCK 12	2035	975.897	25.403	597.305	667.077	26.528	52	44,40
BLOCK 13	2040	7.272.403	186.172	3.818.835	4.326.570	255.035	329	42,45
BLOCK 14	2040	2.774.393	82.503	1.082.753	1.332.034	169.018	204	32,86
BLOCK 15	2040	1.674.022	67.177	867.188	1.019.948	91.495	147	26,33
BLOCK 16	2040	531.357	3.401	25.959	38.887	0	4	156,00
BLOCK 17	2040	1.432.387	38.953	759.112	862.763	75.702	54	45,86
BLOCK 18	2040	2.339.053	89.482	1.221.276	1.447.508	145.494	151	27,50
BLOCK 19	2045	2.758.333	120.341	1.475.504	1.724.195	161.955	286	26,50
BLOCK 20	2045	2.591.900	101.344	1.332.516	1.541.343	167.642	227	26,00
BLOCK 21	2045	1.410.757	37.909	746.041	837.625	57.533	76	37,88
BLOCK 22	2045	686.873	18.814	410.355	471.657	17.508	28	43,17
BLOCK 23	2045	3.722.354	88.087	1.783.591	2.042.675	85.825	160	46,69
BLOCK 24	2045	171.175	5.213	108.883	126.889	0	10	33,00
BLOCK 25	2045	967.071	30.658	458.246	517.470	37.028	82	39,86
BLOCK 26	2050	1.841.724	36.321	499.747	515.382	130.358	109	51,00
BLOCK 27	2050	2.675.296	63.807	1.606.649	1.666.698	0	348	42,00
BLOCK 28	2050	1.010.687	33.215	585.210	683.817	28.660	62	31,63
BLOCK 29	2050	1.374.995	54.871	689.594	797.663	105.268	117	27,00
PUBLIC LIGHTNING 1. phase	2025	90.335	13.163	125.801	188.450	0	20	6,86
PUBLIC LIGHTNING 2. phase	2038	-	-	-	-	-	-	-
TRANSPORT 1. phase	2030	-	116.368	763.552	889.988	0	214	-
TRANSPORT 2. phase	2040	-	23.274	152.710	177.998	0	43	-
TOTAL:		**61.134.202**	**1.794.507**	**29.610.207**	**33.552.361**	**2.834.783**	**4.176**	**44,33**

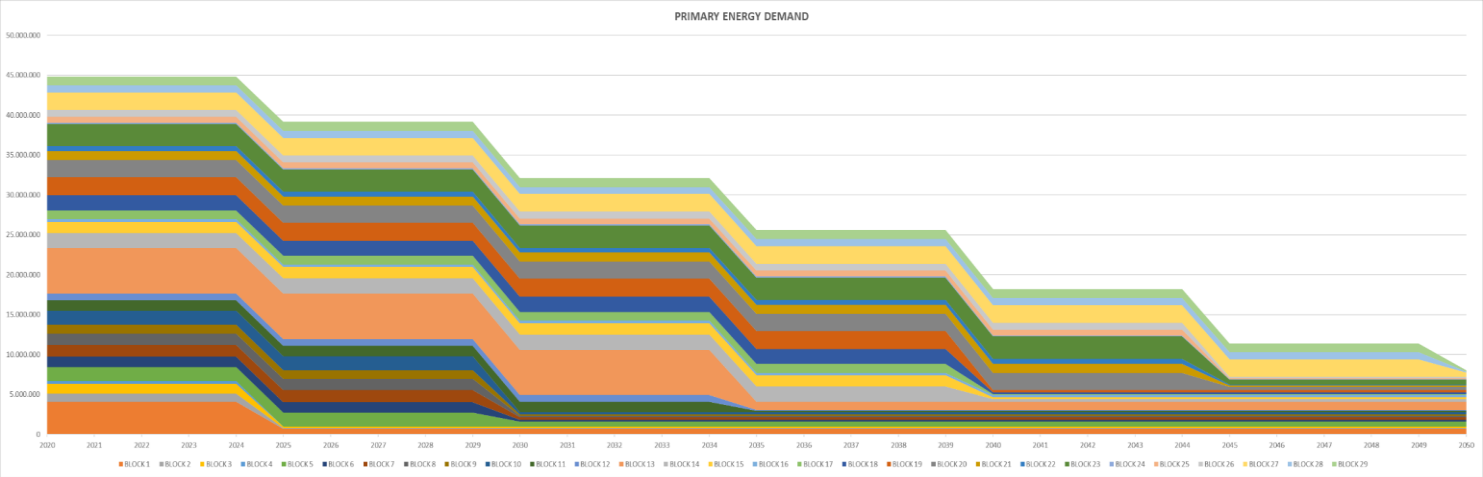


Figure 5: Scenario 2 – Primary energy demand reduction (2025 – 2050)

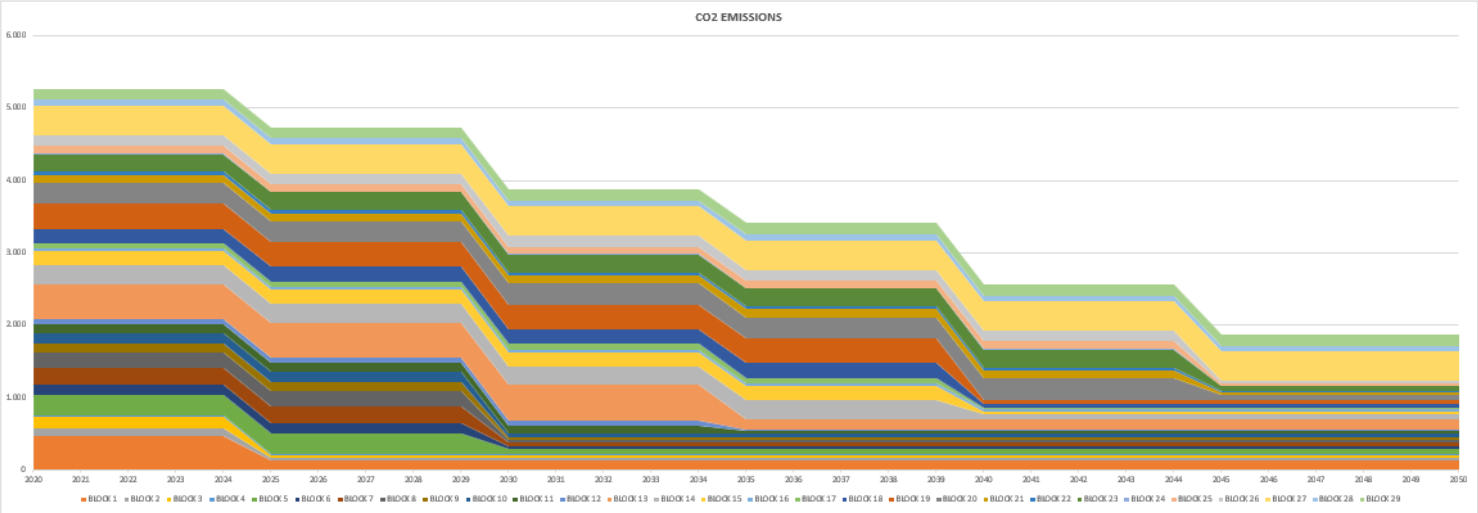


Figure 6: Scenario 2 – CO_2 reduction (2025 – 2050)

6. Implementation Roadmap and Milestones

The Green and Digital Energy Action Plan for Zvijezda was prepared while the district itself was changing quickly. During the project, large infrastructure works were under way, including the Agglomeration project (water supply and sewerage), along with the reconstruction of some public buildings. Some buildings were renovated in the meantime, partly as part of post-earthquake reconstruction, while others were demolished or became vacant. Under these conditions, it was not practically possible to track the state of every building on the ground in real time. Continuously updating the input data would have made it impossible to produce a consistent and comparable set of scenarios. For this reason, the modelling is based on a clearly defined reference state of the district. The baseline (2020, see Table 2) records the building stock, energy carriers, consumption and emissions at one point in time. All decarbonization scenarios are calculated against this baseline. Freezing the reference state is a common methodological choice in strategic energy planning. It keeps the scenario results internally consistent, traceable and comparable, both with each other and with the baseline. It also means that changes in the district after the reference date are not shown measure by measure in the scenario results. This applies, for example, to a building renovated or demolished in the meantime. Similarly, the implementation years in the scenario action plans (Tables 7 and 9) are modelled planning assumptions, not records of completed measures. They phase the investment programme across the 2025–2050 planning horizon in five-year implementation windows. The aim is to show the expected trajectory of energy and CO_2 savings and the order of priority between building blocks. Measures assigned to 2025 in the building renovation scenarios (Blocks 1–4) should be read as the first, priority implementation window, to be prepared and carried out after the technical finalization of the Plan on 15 May 2026. Actual implementation dates will be set by the City of Karlovac and the building owners when they make investment, permitting and financing decisions.

The Action Plan should therefore be understood as a planning model and a methodological framework for the energy transition of the district, not as a fixed, final schedule. All calculations are done in structured Excel models linked to the ZEB4ZEN tool and the GIS platform, building by building and block by block. As a result, the implementation schedule, unit investment costs, energy prices and emission factors can be updated easily and transparently. Measures carried out in practice can also be entered when they happen. The City can update the Plan regularly, for example as part of SECAP monitoring and reporting, without changing the methodology. This keeps the Plan useful as a decision-support tool over the whole planning horizon.

PUBLIC LIGHTING – IMPLEMENTED MEASURE

Phase 1 of the public lighting retrofit has already been implemented. The public lighting in Zvijezda was modernised as part of a city-wide project, which made Karlovac the first city in Croatia to switch fully to a smart, energy-efficient public lighting system. More than 9,000 light fixtures across the city were replaced with remotely controlled LED luminaires, cutting electricity consumption for public lighting. The project was officially completed in March 2025. It was carried out as an ESCO (Energy Service Company) service, so the investment is being repaid directly from the energy cost savings achieved, without upfront capital investment by the City. The year 2025 shown for Phase 1 in Tables 3, 7 and 9 is therefore the actual completion year of the measure, not a modelled assumption. The savings for this measure were calculated using actual data on the installed luminaires, their power before and after the replacement, and their operating hours. This makes the public lighting retrofit the first verified step in the district's decarbonization pathway. Phase 2 (2038) remains a modelled planning assumption. It covers a possible future upgrade of the LED system as technology improves.

Commented [PL5]: Please clarify that the implementation years shown in the scenario roadmaps represent modelled planning assumptions and do not necessarily indicate measures already implemented. This distinction is particularly important for interventions scheduled in 2025, since the Energy Action Plan was technically finalised on 15 May 2026. Please also identify any major dependencies, including financing, technical feasibility and heritage-related authorisations.

Commented [IH6R5]: Clarified. I hope that's okay. If not, we can shift the timeframe by 5 years...

6.1 Interpretation of implementation years

The implementation years shown in the scenario action plans (Tables 7 and 9) and in the public lighting KPI tables (Tables 3 and 4) are modelled planning assumptions. They are not records of measures that have already been carried out. They were set to phase the investment programme across the 2025–2050 planning horizon. Building blocks were grouped into five-year implementation windows (2025, 2030, 2035, 2040, 2045 and 2050), and the public lighting retrofit was split into two phases (2025 and 2038). The same phasing is used in all scenario calculation files, so the scenarios can be compared year by year.

This distinction matters most for the interventions assigned to 2025. In the model, these are Blocks 1–4 (34 buildings) and Phase 1 of the public lighting retrofit (194 luminaires). The Energy Action Plan was technically finalised on 15 May 2026, after the 2025 implementation window. The year 2025 therefore marks the first implementation window of the roadmap and the reference point for the modelled savings trajectory. It does not mean these measures were completed in 2025. In the calculation files, all measures are treated as planned. The energy baseline (2020) and the public lighting inventory (data recorded in October 2019, with existing high-pressure sodium, metal halide and mercury-vapour luminaires) describe the condition before any intervention. Their actual timing depends on the dependencies set out in Section 6.2.

The modelled years are used to show the expected trajectory of energy and CO_2 savings. They should not be read as a binding schedule. Actual implementation dates will be set by the City of Karlovac and the building owners when they make investment, permitting and financing decisions. The roadmap should be updated as measures are carried out.

6.2 Key implementation dependencies

Whether and when the measures in both scenarios are implemented depends on the following conditions:

FINANCING

The total modelled investment is about €49.0 million in Scenario 1 and €61.0 million in Scenario 2 (2024 price level), including rooftop PV. The building measures assigned to the first implementation window (Blocks 1–4) account for about €8.5 million and €10.6 million respectively, around 17% of the total. The simple payback period of the integrated scenarios is about 33 years (Scenario 1) and 37 years (Scenario 2), and for the building renovation and heating measures alone it is 40 and 44 years. Most building measures therefore cannot be financed from energy cost savings alone. They will depend on grant co-financing, for example national energy renovation and post-earthquake reconstruction programmes, EU cohesion funds, the Environmental Protection and Energy Efficiency Fund, and future support for energy-poor households. The citizen survey (D.4.1.1) confirms this. High renovation costs were the most frequently reported barrier (83%), and 47% of respondents said they could personally cover no more than 25% of the costs.

TECHNICAL FEASIBILITY

Scenario 1 depends on a geothermal heat source being confirmed, which is currently under study. It also depends on building a district heating distribution network through the historic core, coordinated with ongoing infrastructure works (Agglomeration project).

Scenario 2 depends on local conditions for heat pumps. These include space for outdoor units or boreholes for shallow ground-source systems in dense urban blocks, and enough capacity in the low-voltage electricity network for the added heating load. Many buildings are damaged by recent earthquakes and are in poor structural condition. In those buildings, structural repair has to come before, or together with, energy renovation. Rooftop PV also depends on the load-bearing capacity of roofs, their orientation and shading. Energy communities and off-site PV depend on the regulatory framework for collective self-consumption and on available municipal land outside the heritage zone. Transport measures depend on traffic regulation decisions by the City of Karlovac.

HERITAGE-RELATED AUTHORISATIONS

Zvijezda is a protected cultural-historical unit, so all physical interventions require prior approval and special conditions from the competent conservation authority (Ministry of Culture and Media, Conservation Department in Karlovac). This applies especially to facade insulation, window replacement, visible rooftop PV, external heat pump units and new public lighting fixtures. The modelled measures may be permitted only partly, or may need alternative, some other specific heritage-compatible solutions. That would affect both costs and achievable savings. Public lighting must use heritage-appropriate luminaires approved by the conservation authority.

GOVERNANCE AND OWNERSHIP

Most residential buildings are multi-apartment buildings with several owners. Implementation requires co-owner consent and organized building management. Implementation should also be aligned with the planned amendments to the General Urban Plan (GUP) and the Urban Development Plan (UPU), including the energy-climate zoning of Zone Z1.

7. Scenario Calculations and GIS Integration Overview

7.1. Energy Modelling and Scenario Tables

Commented [PL7]: Please clarify how the different Excel models are used in the Action Plan. In particular, distinguish the two alternative integrated scenarios (geothermal district heating with PV, and heat pumps with PV) from the separate PV and public lighting assessments. Confirm that the results of individual measures have not been added twice when calculating the overall scenario impacts.

The core of the analytical work for the Zvijezda Green and Digital Energy Action Plan was carried out through a dedicated Excel-based model. This tool was developed to calculate baseline energy demand and simulate the effects of different renovation and decarbonisation scenarios. The quantitative results of the Action Plan come from four Excel calculation models. All of them use the same building register (building ID, block, cadastral parcel, useful floor area: 132,392 m²) and the same energy baseline (2020, Table 2). The results of every model are calculated against this common baseline, building by building, and then aggregated by block and by implementation year.

Model	Measures covered	Role in the Action Plan
003_EEM_TI_GEOTH_final	Thermal envelope refurbishment + geothermal district heating, with rooftop PV as a separately reported component	**Scenario 1** (integrated)
005_EEM_TI_HP_final	Thermal envelope refurbishment + heat pumps, with rooftop PV as a separately reported component	**Scenario 2** (integrated)
006_EEM_PV_NEW	Rooftop PV only (2,577 kWp, 2,834,783 kWh/year), applied to the baseline building stock	Separate PV assessment, the source of the PV component in both scenarios
Zvijezda_Public_Lighting	194 public lighting luminaires, LED retrofit	Separate assessment outside the building energy balance

Key features of the modelling approach include:

- Building-by-building data structure: Each of the 234 buildings in the district is represented with attributes such as use type, floor area, conservation status, heating system, and energy demand (derived or assumed).
- Energy flow calculations: Final and primary energy demand were computed by end-use (heating, DHW, lighting, appliances) and by fuel type, with energy conversion factors taken from the national 2021 methodology for building energy audits.
- Scenario differentiation: For each decarbonisation strategy, the model applied specific technical measures, e.g. heat pump SCOP, CTS supply efficiency, PV sizing, and RES shares.

Scenarios 1 and 2 are mutually exclusive. They describe two different heating pathways for the same building stock: centralised geothermal district heating, or decentralised heat pumps. Each scenario is compared with the baseline on its own, and their results are never added together. Both scenarios include

the same envelope refurbishment and the same rooftop PV systems. The only difference between them is the heating supply. Separating the building measures from PV. The results of individual measures have not been added twice when calculating the overall scenario impacts. In each integrated model, the effect of the measures is calculated in two separate parts:

- Building renovation and heating system (envelope + geothermal DH or heat pumps): savings from the lower energy demand of the buildings.
- Rooftop PV: on-site electricity production, taken directly from the PV assessment (model 006).

Impact estimates: The model outputs included reductions in primary/final energy, CO_2 emissions, estimated investment costs, and calculated payback periods.

The model was calibrated using available consumption data, certificates, and survey inputs. Due to data limitations, some values are based on reasonable assumptions and averages, as documented in the methodology section of this report.

7.2. GIS Integration

To support spatial visualisation, communication, and cross-sectoral planning, a QGIS-based geospatial platform was used to represent energy data and simulate the impact of proposed measures.

Main steps in GIS integration included:

- Importing building-blocks-level data from Excel to QGIS using georeferenced block and parcel layers.
- Assigning attributes: Each building-block polygon was linked to calculated energy and emissions values, baseline and scenario data, and technical renovation indicators (e.g. insulation applied, PV installed, heating type changed).
- Creating thematic layers for:
  - CO_2 emissions per building block
  - Energy use intensity (kWh/m²)
  - Heating system types (current vs. scenario)
  - PV capacity (on-site and virtual)

This combined Excel-GIS workflow ensures that all scenarios are spatially explicit, analytically traceable, and digitally reproducible. It also provides a strong basis for future updates as better data become available and as implementation progresses.

8. Governance and Institutional Framework

Defines the roles and responsibilities of stakeholders involved in the planning, coordination, financing, and execution of the action plan. Includes municipal departments, utilities, private sector partners, and community actors. Aligns implementation with local urban and regulatory plans (e.g. GUP, UPU, conservation rules).

8.1. Integration of Citizen Feedback

Citizen feedback collected within the ZEB4ZEN project gives additional insight into the social and practical conditions that affect the implementation of energy efficiency and decarbonisation measures

in Karlovac. The citizen survey documented in Deliverable D.4.1.1 was carried out online between 28 November and 30 December 2025 and received 53 responses. About 13% of respondents live within the historic centre (Zvijezda) and 87% outside it. Nearly all respondents (92%) have considered renovating their home or building to improve energy efficiency. The most frequently reported barrier was high renovation cost, named by 83% of respondents. Lack of access to financial support followed at 49%, and lack of information at 23%. Heritage protection requirements (13%) and unresolved ownership or legal relationships (11%) were mentioned less often. Some open responses described how hard it is to reach agreement among co-owners in multi-apartment buildings. None of the respondents identified rented accommodation as a barrier. Although 70% of respondents said they were aware of existing financial incentives, almost half still considered this support inaccessible. This points to a gap between knowing that programmes exist and being able to use them. Willingness to invest depends strongly on support: 85% would renovate if financial support were available. However, 47% said they could personally cover no more than 25% of the costs. About 11% considered their household energy poor, and 66% were not familiar with support programmes for energy-poor citizens.

Flooding was by far the most frequently identified environmental problem in the city (91% of respondents), followed by waste management (66%) and air pollution (49%). Respondents showed broad support for water management measures (68%), energy renovation of buildings (66%), bicycle lanes and pedestrian zones (66%) and the installation of renewable energy sources (64%). These findings are relevant to the implementation of the Energy Action Plan. The proposed building renovation and renewable energy measures require technical assessment, but they also depend on investment affordability, the accessibility of funding schemes and decision-making in co-owned buildings. Clear information on available funding, simpler access to financial incentives, and support for building representatives and co-owner communities could help address the main barriers identified by survey participants. In the historic centre, early consultation with heritage conservation authorities remains important. The survey findings are consistent with several implementation challenges addressed by the Energy Action Plan. However, the available documentation does not establish that specific technical measures were directly modified as a result of the survey. Citizen feedback is therefore considered complementary evidence for identifying implementation barriers and informing future stakeholder engagement activities. Given the limited number of respondents and the sample's composition, the survey results should be interpreted as indicative rather than representative of the entire population of Karlovac. Of the respondents, 83% hold a university degree, 98% are employed, and only a small share live in the historic centre.

8.2. Integration of the Energy Action Plans into the 3D Enviroment

The Energy Actions Plans for the city of Karlovac have been implemented into the 3D DRONODAT platform, that enables the geographical representation and interactive exploration of energy efficiency and decarbonization measures proposed for the pilot neighborhoods, facilitating the visualization and communication of the planned interventions. Figure 7 shows the 3D environment including the spatial representation of photovoltaic installations on buildings, supported by a timeline showing the long-term implementation horizon.

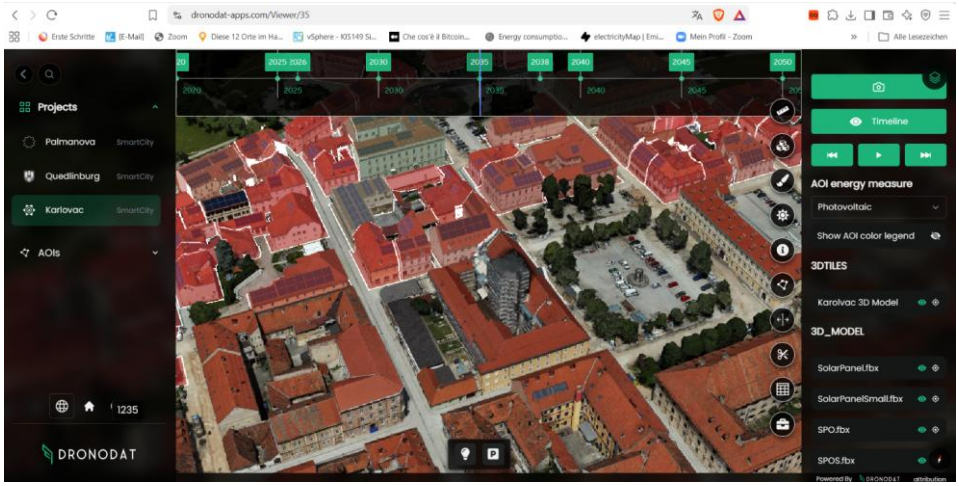


Figure 7 3D visualisation including building-level spatial representation and the implementation timeline

9. Conclusion and Strategic Outlook

The transformation of Zvijezda into a low-carbon, energy-efficient neighbourhood is both feasible and desirable, given the maturity of available technologies and the alignment with EU and national climate objectives. Both scenarios lead to substantial decarbonisation, but the decision between centralised and decentralised approaches depends on factors such as funding model, technical capacity, community preferences, and long-term urban energy vision.

C. GREEN AND DIGITAL ENERGY ACTION PLAN FOR QUEDLINBURG, GERMANY

10. Decarbonisation Strategy Scenario: Building Renovation with Heat Pumps

10.1. Scenario Overview

This scenario for Quedlinburg focuses on a decentralised approach to decarbonisation, based on deep energy renovation of buildings combined with the introduction of high-efficiency heat pumps as the primary heating technology. The strategy targets residential building blocks and aims to significantly reduce energy demand, greenhouse gas emissions, and operational costs, while increasing the share of renewable energy in final consumption. The approach is based on building-level interventions, allowing flexibility in implementation and adaptation to the specific technical and ownership conditions of the building stock. This makes it particularly suitable for heterogeneous urban areas with varying building typologies and renovation states. Three quartiers (blocks) have been considered in the analysis: 1, 16 and 17 (see Figure 8). According to the Heritage Management Plan database, these blocks contain a total of 216 buildings. This figure represents the building stock considered in the initial inventory and heritage-related assessment. The quantitative energy renovation and heat pump scenario covers a subset of 97 buildings, with a total useful floor area of approximately 44,446 m². The proposed interventions are distributed across Block 1 (37 buildings), Block 16 (31 buildings) and Block 17 (29 buildings).

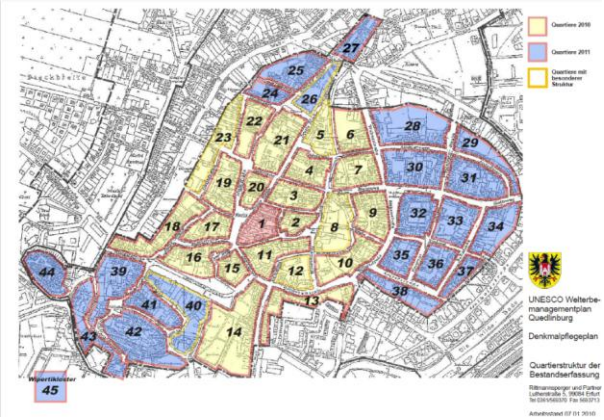


Figure 8 Map of Quedlinburg and quartiers identification

Scope of the Assessment and Data Availability

The assessment focuses on three selected urban blocks within the historic city of Quedlinburg, identified as Blocks 1, 16 and 17. According to the Heritage Management Plan database, these blocks comprise a total of 216 buildings.

The quantitative assessment of energy efficiency and decarbonisation measures was carried out for a subset of 97 buildings, representing approximately 44,446 m² of useful floor area. These buildings were selected based on the availability of sufficient technical data to perform the energy calculations and evaluate the proposed interventions.

Consequently, the selection of these 97 buildings should not be interpreted as a comprehensive technical feasibility assessment of the entire building stock. Buildings excluded from the quantitative analysis were not necessarily considered unsuitable for energy renovation or heat pump installation.

The estimated energy savings, CO_2 emission reductions and investment requirements therefore refer exclusively to the 97 buildings included in the model. Further data collection and building-specific assessments would be necessary to extend the analysis to the remaining buildings.

Energy Baseline and Reference conditions

The energy baseline for the three selected urban blocks was established using historical electricity and natural gas consumption data covering the period 2020–2023. Due to data protection requirements, the consumption data were provided at street level rather than for individual buildings (see Table 10).

Average consumption values over the available reference period were used to establish the benchmark conditions for the subsequent energy efficiency and decarbonisation assessments. These reference conditions formed the basis for estimating the effects of building envelope renovation and the replacement of conventional heating systems with electrically driven heat pumps.

The energy baseline was finalised by 31 March 2026. The remaining scenario calculations and implementation roadmap were subsequently consolidated, and the Energy Action Plan was technically finalised on 15 May 2026.

Table 10 Overview of Energy Consumption in the three analysed districts of Quedlinburg

		Gas					Power				
Quartier	Straße	G - 2020	G - 2021	G - 2022	G - 2023	G - Averag	P - 2020	P - 2021	P - 2022	P - 2023	P - Averag
1	Breite Straße	210.934 kWh	247.786 kWh	219.393 kWh	207.343 kWh	221.364 kWh	33.873 kWh	20.578 kWh	40.758 kWh	30.985 kWh	31.549 kWh
1	Hölle	45.480 kWh	40.250 kWh	28.253 kWh	2.638 kWh	29.155 kWh	4.426 kWh	1.981 kWh	2.350 kWh	5.807 kWh	3.641 kWh
1	Markt	551.516 kWh	449.249 kWh	585.211 kWh	402.284 kWh	497.065 kWh	270.649 kWh	218.286 kWh	316.853 kWh	329.067 kWh	283.714 kWh
1	Pölle	247.378 kWh	294.006 kWh	302.477 kWh	240.833 kWh	271.174 kWh	61.017 kWh	40.947 kWh	46.447 kWh	45.079 kWh	48.373 kWh
1	Schuhhof	65.748 kWh	77.940 kWh	65.697 kWh	62.395 kWh	67.945 kWh	9.032 kWh	11.163 kWh	11.873 kWh	10.984 kWh	10.763 kWh
1	Stieg	176.114 kWh	214.116 kWh	191.902 kWh	127.411 kWh	177.386 kWh	30.242 kWh	30.626 kWh	32.673 kWh	25.423 kWh	29.741 kWh
16	Blasiistraße	902.655 kWh	901.195 kWh	1.175.255 kWh	732.403 kWh	927.877 kWh	219.903 kWh	220.953 kWh	255.285 kWh	158.462 kWh	213.651 kWh
16	Carl-Ritter Straße	82.821 kWh	83.268 kWh	103.616 kWh	105.227 kWh	93.733 kWh	5.138 kWh	4.543 kWh	7.354 kWh	6.963 kWh	6.000 kWh
16	Hohe Straße	160.920 kWh	177.276 kWh	146.253 kWh	132.413 kWh	154.216 kWh	29.943 kWh	20.547 kWh	19.959 kWh	26.586 kWh	24.259 kWh
16	Markt	119.653 kWh	130.248 kWh	102.630 kWh	92.798 kWh	111.332 kWh	31.623 kWh	31.725 kWh	21.541 kWh	22.140 kWh	26.757 kWh
16	Word	19.063 kWh	22.790 kWh	3.179 kWh	713 kWh	11.436 kWh	4.159 kWh	2.473 kWh	1.705 kWh	1.582 kWh	2.480 kWh
16	Wordgasse	55.698 kWh	69.567 kWh	60.175 kWh	66.702 kWh	63.036 kWh	28.609 kWh	3.549 kWh	42.445 kWh	33.519 kWh	27.031 kWh
17	Blasiistraße	316.482 kWh	331.548 kWh	292.209 kWh	272.782 kWh	303.255 kWh	70.051 kWh	57.343 kWh	61.679 kWh	63.088 kWh	63.040 kWh
17	Hohe Straße	246.080 kWh	289.702 kWh	319.230 kWh	249.876 kWh	276.222 kWh	42.360 kWh	59.607 kWh	70.067 kWh	45.649 kWh	54.421 kWh
17	Markt	504.110 kWh	637.412 kWh	680.198 kWh	404.865 kWh	556.646 kWh	187.278 kWh	149.797 kWh	216.654 kWh	147.806 kWh	175.384 kWh

In addition to it, the data base of the Heritage Management Plan was used for the identify previous interventions on individual buildings (see Figure 9). The database covers a total of 216 buildings and includes three main categories of information:

- Identification data (district, address, and buildings number),
- Administrative data (building use, number of residents, and ownership structure), and
- Building data (building condition, roof type, renovation status, and maintenance condition).

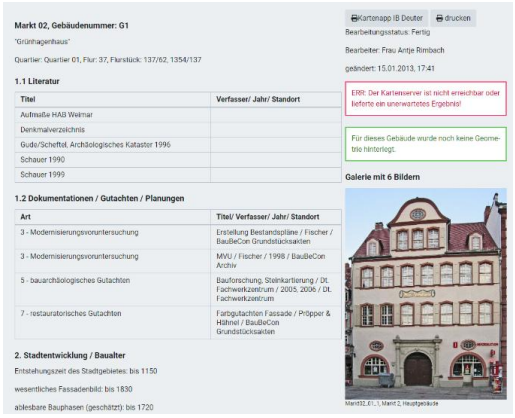


Figure 9 Example of the Heritage Management Plant

The distribution of buildings across the three districts shows that District 16 has the highest number of buildings (85), followed by District 17 (68) and District 1 (63). Residential and commercial buildings represent the predominant use categories, with 113 and 98 buildings, respectively. Administrative buildings, garages and storage facilities, and special-purpose buildings account for smaller shares. Table 11 provides an overview of the distribution of buildings by use category in each district. The quantitative energy assessment was conducted for 97 buildings for which sufficient technical data were available, as explained in the scope of the assessment. The building-use inventory and the quantitative energy assessment therefore represent different levels of analysis.

Table 11 Distribution of buildings by use category across the three districts of Quedlinburg, based on the Heritage Management Plan

District	Total Buildings	Residential Buildings	Commercial Buildings	Administrative Buildings	Garages & Storage	Special-Purpose Buildings
1	63	36	19	6	2	0
16	85	41	49	5	13	0
17	68	36	30	0	20	0
Total	216	113	98	11	35	1

10.2. Technical Measures

Thermal Envelope Refurbishment

The renovation of the building envelope represents the foundation of the scenario. Measures include:

- External wall insulation (according to structural and architectural feasibility)
- Roof and attic insulation to reduce heat losses
- Replacement of windows with high-efficiency glazing systems

- Floor or basement ceiling insulation

These interventions significantly reduce heating demand and improve indoor thermal comfort, while also enabling more efficient operation of heat pumps.

Heat Pump Systems Implemantation

Existing fossil fuel-based heating systems are replaced with electric heat pumps (air-to-water or ground-source, depending on site conditions).

- Systems are dimensioned according to reduced building heat demand after renovation
- Average Seasonal Coefficient Of Performance (SCOP) assumed at high efficiency levels or calculated considering the air temperature of 2006.
- In some cases, hybrid systems may be used to cover peak loads

The electrification of heating is a key element of the decarbonisation pathway, particularly when combined with renewable electricity sources. In particular, the combination of improved thermal insulation and electrically driven heat pumps offers an effective approach to reducing fossil fuel consumption and improving the overall energy efficiency of the building stock. Air-to-water heat pumps are particularly relevant as an alternative to conventional gas boilers, as they can provide space heating and domestic hot water using electricity and ambient thermal energy. Their efficiency depends on several factors, including outdoor temperature, required supply temperature, and the thermal performance of the buildings. Improving building insulation and reducing heating supply temperatures can significantly enhance heat pump performance, particularly during the winter months. Nevertheless, the large-scale deployment of heat pumps requires careful assessment of electricity grid capacity, winter peak loads, and the compatibility of existing heating distribution systems. These aspects are particularly important for developing an integrated and technically feasible decarbonisation strategy that respects the architectural and cultural heritage of the city.

Integration of Heritage Protection Requirements and WP1-WP3 Results

The development of the Quedlinburg Energy Action Plan takes into account the specific characteristics of the historic building stock and the requirements associated with cultural heritage protection. The Heritage Management Plan database provided information on building conditions, previous renovation activities, roof characteristics and maintenance status, supporting the assessment of potential energy efficiency interventions. The energy consumption data and building-related information collected and analysed within the project provided the basis for defining the reference conditions and evaluating the proposed decarbonisation measures. The Energy Action Plan builds on this information to assess the potential contribution of thermal insulation and heat pump technologies to reducing energy consumption and CO_2 emissions. The proposed interventions must be adapted to the architectural and conservation requirements of individual buildings. In particular, external wall insulation, window replacement and the installation of heat pump equipment may be subject to restrictions concerning historic façades, original building components, visual appearance and the placement of technical installations. Alternative solutions, including internal insulation or less visually intrusive technical configurations, may therefore need to be considered on a building-specific basis. The quantitative scenario results represent the potential energy and environmental benefits of the proposed measures. They do not constitute confirmation that each intervention has already been assessed or authorised by the responsible heritage conservation authorities. The Energy Action Plan provides a basis for subsequent technical planning, stakeholder consultation and heritage compatibility assessments before individual investments are implemented.

Renewable Energy Integration

The scenario assumes the integration of renewable electricity, primarily through:

- On-site photovoltaic systems (where applicable)

- Potential participation in local or regional renewable energy schemes

One potential measure to support the energy transition in historic urban districts is Building-Integrated Photovoltaics (BIPV). BIPV involves integrating solar modules directly into the building envelope, including roofs, façades, and even windows. The main advantage is that these photovoltaic systems can be visually unobtrusive, blend into the existing architecture, and simultaneously serve as construction materials. This makes it possible to generate renewable electricity while minimising the visual impact on the historic urban landscape. Another promising technological development in this field is perovskite solar cells. These technologies offer the potential for high conversion efficiency, low production costs, and flexible applications. For example, perovskite solar cells can be manufactured as thin, lightweight layers, making them particularly suitable for integration into different building surfaces. The combination of BIPV and perovskite solar cell technologies opens up new opportunities for solar energy generation in historic city centres, where architectural preservation and visual integration are essential requirements. In this context, the Design Regulations of the World Heritage City of Quedlinburg (Gestaltungssatzung) provide a regulatory framework for integrating solar technologies into the historic building stock. According to Section 13a(4), photovoltaic installations visible from public spaces may be permitted under specific conditions, including the use of modules whose colour matches the existing roof covering, matt and low-reflective surfaces, and architectural integration into the roof structure[1]. These requirements are particularly relevant for BIPV solutions, as they encourage the use of visually compatible photovoltaic technologies while preserving the architectural character of the historic city centre. However, compliance with these design requirements does not automatically guarantee approval, as installations remain subject to the applicable heritage conservation regulations. Such solutions could contribute to a more efficient, visually compatible, and sustainable integration of renewable energy into the historic built environment. Furthermore, locally generated photovoltaic electricity could be partially used to supply electrically driven heat pumps, thereby reducing electricity purchases from the grid, operational costs, and potentially associated greenhouse gas emissions.

Photovoltaic systems, including BIPV, are considered potential complementary measures for future implementation. Their installation is subject to technical feasibility and heritage conservation requirements. The quantitative energy, environmental and economic results reported in Table 12 refer exclusively to thermal insulation and heat pump measures and do not include additional benefits or investment costs associated with photovoltaic installations.

10.3. Strategic Impact

The proposed scenario transforms the Quedlinburg building stock towards a low-carbon, energy-efficient system by:

- Eliminating fossil fuel-based heating at building level
- Reducing dependence on external energy sources
- Increasing resilience through electrification and efficiency
- Contributing to EU climate neutrality objectives

The combination of thermal insulation and heat pumps proves to be a robust and scalable solution, applicable across different building types and adaptable to local constraints. The electrification of heating is a key element of the decarbonisation pathway, particularly when combined with renewable electricity sources. However, the electrification of heating systems will lead to an increase in electricity demand. Considering the weather conditions of 2006 and the coefficient of performance (COP) of modern air-to-

[1] Welterbestadt Quedlinburg (2024). Gestaltungssatzung der Welterbestadt Quedlinburg, § 13a – Anlagen zur Nutzung solarer Strahlungsenergie. Adopted by the City Council on 5 December 2024, effective from 30 December 2024.

water heat pumps, an additional electricity demand of approximately **1.3 GWh per year** is estimated if all existing gas boilers are replaced with electrically driven heat pumps. The highest electricity demand for heating is expected during January and February (see **Error! Reference source not found.**). Nevertheless, the electrification of heating systems could result in **annual energy savings of more than 3 GWh** compared to the baseline scenario, primarily due to the higher efficiency of heat pumps compared to conventional gas boilers.

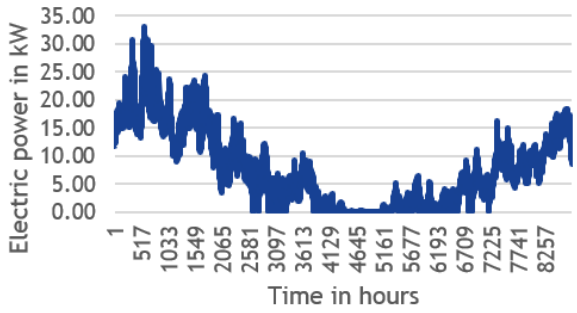


Figure 10 Electricity demand for supply heat pump based heating system

10.4. Phasing and Implementation Timeline

The implementation is structured in phases aligned with investment cycles and renovation priorities:

PHASE 1 (2025-2030) Focus on priority buildings (mainly Block 1), achieving:

- ~754,623 kWh/year final energy savings
- ~129 tCO_2/year emissions reduction

The first phase focuses on the most suitable and priority buildings, primarily located in Block 1. These buildings are characterised by relatively favourable technical conditions for renovation and early adoption of heat pump systems. During this phase, the emphasis is on achieving quick wins in energy savings while establishing the technical and organisational framework for broader implementation. Early investments enable a reduction in energy demand and emissions, while also providing practical experience for scaling up the measures in later phases.

PHASE 2 (2030-2040) Expansion to additional buildings, continuing energy demand reduction across the stock.

In the second phase, the renovation programme expands to a larger share of the building stock, including additional buildings within Block 1 and gradually extending to other blocks. This phase represents the core period of implementation, where the majority of thermal insulation measures are applied and heat pump systems are installed at scale. The focus is on maximising cumulative energy savings and reducing emissions through systematic renovation. At the same time, lessons learned from the initial phase contribute to improved efficiency in project delivery and cost optimisation.

PHASE 3 (2040-2050)

Completion of renovation and full deployment of heat pump systems across Blocks 16 and 17, delivering the largest cumulative savings. This gradual rollout enables balanced investment planning and alignment with building renovation cycles.

The final phase completes the transformation of the building stock, with a particular focus on Blocks 16 and 17, which are implemented later due to technical, financial, or organisational constraints. This phase ensures full coverage of the planned measures, optimising system performance and achieving the highest levels of energy efficiency and decarbonisation. By the end of the period, the majority of buildings are expected to operate with significantly reduced energy demand and fully electrified heating systems based on heat pumps. Table 12 summarizes the energetic, ecological and economic KPIs of the energy action plan of the city of Quedlinburg.

Table 12 Energetic, ecological and economic KPIs of the energy action plan for the city of Quedlinburg

BLOCK / Year of EE measures implementation	No. of Buildings	Useful Area [m2]	Investiment CAPEX [€]	OPEX savings [€/year]	Final energy savings [kWh/year]	Primary energy savings [kWh/year]	CO2 savings [t/year]	Mean building-level simple payback period [years]
BLOCK 1	**37**	**15.818**	**6.916.770**	**126.513**	**1.199.221**	**1.201.963**	**204**	**53,49**
2025	*18*	*10.333*	*4.518.047*	*80.188*	*754.623*	*759.171*	*129*	*55,56*
2030	*19*	*5.485*	*2.398.723*	*46.325*	*444.598*	*442.792*	*75*	*51,53*
BLOCK 16	**31**	**13.821**	**5.723.925**	**140.775**	**1.316.041**	**1.328.512**	**222**	**41,84**
2040	*20*	*10.008*	*4.378.124*	*116.681*	*1.078.376*	*1.095.088*	*182*	*36,35*
2045	*11*	*3.813*	*1.345.801*	*24.094*	*237.665*	*233.424*	*40*	*51,82*
BLOCK 17	**29**	**14.807**	**3.454.442**	**103.800**	**1.064.505**	**1.025.406**	**165**	**36,97**
2045	*11*	*5.521*	*948.278*	*24.503*	*268.379*	*250.379*	*39*	*38,09*
2050	*18*	*9.286*	*2.506.164*	*79.297*	*796.126*	*775.027*	*126*	*36,28*
TOTAL:	**97**	**44.446**	**16.095.137**	**371.088**	**3.579.767**	**3.555.881**	**591**	**44,82**

The proposed decarbonisation scenario combines thermal insulation measures for building envelopes with the installation of electrically driven heat pumps and PV building integration. The assessment covers 97 buildings, representing approximately 44,446 m² of useful floor area.

The estimated total investment for these two categories of measures amounts to €16.10 million. Once all interventions have been implemented, the model projects annual final energy savings of approximately 3.58 GWh, primary energy savings of 3.56 GWh, CO_2 emission reductions of 591 tonnes, and operating cost savings of approximately €371,000 per year.

The mean building-level simple payback period is approximately 44.82 years, while the programme-level simple payback, calculated as the ratio between total investment and aggregate annual operating cost savings, is approximately 43.37 years.

The reported results are modelled estimates rather than measured post-implementation performance. The economic assessment does not include discount rates, financing costs, future energy price developments or equipment replacement costs. Consequently, the calculated payback periods should be interpreted as preliminary economic indicators rather than a comprehensive investment feasibility assessment.

Implementation Timeline

The implementation years shown in Table 12 represent the assumed schedule used for the scenario calculations. In particular, measures assigned to 2025 are part of the modelled implementation pathway and should not be interpreted as investments already completed in that year.

The actual implementation of the proposed measures will depend on the availability of financing, building-specific technical assessments, decisions by the respective property owners and compliance with applicable heritage conservation requirements.

10.5. GIS Integration

To facilitate the geographical representation of energy-related information and support integrated urban energy planning, a geospatial analysis was carried out using QGIS. The platform enables the visualisation of existing energy consumption patterns and the spatial assessment of potential improvements resulting from the proposed decarbonisation measures.

The GIS implementation was structured around the following activities:

- Data integration: Energy-related datasets developed in Excel were transferred into QGIS and associated with georeferenced building-block and parcel geometries.
- Spatial data enrichment: Each building-block polygon was assigned relevant attributes, including energy consumption, CO_2 emissions, baseline conditions, and projected scenario results. Additional information describing renovation interventions, such as thermal insulation, photovoltaic installations, and heating system replacements, was also incorporated.
- Development of thematic maps: Dedicated GIS layers were generated to illustrate:
    - CO_2 emissions at building-block level.
    - Specific energy consumption expressed in kWh/m².
    - Distribution of heating technologies under existing and proposed conditions.
    - Installed and planned photovoltaic capacity, including on-site and virtual PV systems.

The City of Quedlinburg, as an Associated Partner of the ZEB4ZEN project, will play a key role in supporting the implementation of the Green and Digital Energy Action Plan at the local level. The Municipality is expected to facilitate coordination among relevant stakeholders, including heritage conservation authorities, building owners, energy utilities, technology providers and regional institutions. Particular attention should be given to ensuring that energy efficiency measures, electrification of the heating sector and building-integrated photovoltaic systems comply with the specific requirements for the protection of Quedlinburg's UNESCO World Heritage status. Cooperation with the Magdeburg-Stendal University of Applied Sciences, as a ZEB4ZEN project partner, can support the transfer of technical knowledge, the evaluation of

decarbonisation scenarios and the identification of suitable funding opportunities. Stakeholder engagement, particularly involving private building owners and local energy suppliers, will be essential to encourage the adoption of proposed measures. Furthermore, the Municipality will promote the integration of energy-related data and monitoring activities into existing urban planning and heritage management processes, supporting the long-term implementation and periodic updating of the Energy Action Plan. During the implementation phase, particular attention should be given to the involvement of building owners, landlords and tenants, as well as to the provision of information on financial support mechanisms and heritage-compatible renovation solutions. These activities should be coordinated with the responsible municipal and heritage conservation authorities.

10.6. Integration of Citizen Feedback

Citizen feedback collected within the ZEB4ZEN project provides additional insights into the social and practical conditions affecting the implementation of energy efficiency and decarbonisation measures in Quedlinburg. The citizen survey documented in Deliverable D.4.1.1 involved 15 respondents. Among the reported barriers to energy renovation, approximately 33% of respondents identified heritage protection requirements, while 27% highlighted renovation costs. Furthermore, 60% of respondents reported living in rented accommodation. These findings are relevant to the implementation of the Energy Action Plan. The proposed thermal insulation and heat pump measures require not only technical assessment but also consideration of investment affordability, property ownership arrangements and compliance with heritage conservation requirements. In particular, the relatively high proportion of tenants among respondents highlights the importance of involving property owners and landlords in the implementation process. Financial incentives, information on available funding opportunities and early consultation with heritage conservation authorities may help address some of the barriers identified by survey participants. The survey findings are consistent with several implementation challenges addressed by the Energy Action Plan. However, the available documentation does not establish that specific technical measures were directly modified as a result of the survey. Citizen feedback is therefore considered complementary evidence for identifying implementation barriers and informing future stakeholder engagement activities.Given the limited number of respondents, the survey results should be interpreted as indicative rather than representative of the entire population of Quedlinburg.

10.7. Integration of the Energy Action Plans into the 3D Enviroment

The DRONODAT digital visualisation platform was used to support the spatial representation and interactive exploration of energy-related information for the historic urban area of Quedlinburg.

The platform provides a three-dimensional representation of the urban environment, structured around the three selected neighbourhood blocks (Quartals 1, 16 and 17). Users can navigate through the historic building stock, select individual streets and explore the corresponding energy consumption data.

The integration includes historical electricity and natural gas consumption data covering the period 2020-2023, which were used to establish the energy baseline of the Quedlinburg Energy Action Plan. These data can be explored through interactive charts and tables linked to the geographical representation of the selected areas.

The digital environment therefore complements the quantitative energy assessment by connecting historical consumption patterns with the spatial characteristics of the historic neighbourhood. This functionality provides a basis for communicating the energy conditions of the selected urban blocks and supporting the subsequent planning and assessment of energy efficiency and decarbonisation measures. Figure 11 illustrates the DRONODAT 3D environment for Quedlinburg, showing the geographical representation of Quartal 1 and the historical electricity and gas consumption data for Breite Straße.



Figure 11 3D visualization representing quartier 1 (Breite Strasse) and the corresponding energy consumptions

11. Conclusion and Strategic Outlook

The Green and Digital Energy Action Plan for Quedlinburg provides a quantitative assessment of the potential for improving energy efficiency and reducing CO_2 emissions in selected parts of the historic urban area. The analysis focuses on Blocks 1, 16 and 17, comprising an inventory of 216 buildings, of which 97 were included in the quantitative energy assessment based on the availability of sufficient technical data.

The proposed decarbonisation scenario combines thermal insulation measures with the installation of electrically driven heat pumps. The estimated investment amounts to approximately €16.10 million. Once fully implemented, the proposed measures are expected to achieve annual final energy savings of

approximately 3.58 GWh, primary energy savings of 3.56 GWh and CO_2 emission reductions of 591 tonnes. The estimated annual operating cost savings amount to approximately €371,000.

Despite these potential energy and environmental benefits, the economic assessment indicates significant investment challenges. The programme-level simple payback period is approximately 43.37 years under the assumptions adopted in the model. Consequently, implementation will require further economic assessment and consideration of suitable financing mechanisms, public incentives and investment support.

The historic character of Quedlinburg represents an additional consideration. Energy renovation measures must respect the architectural characteristics of protected buildings and comply with applicable heritage conservation requirements. In particular, the suitability of insulation solutions and the installation of heat pump equipment must be evaluated individually, taking into account technical conditions, conservation restrictions and the potential visual impact of the interventions.

The findings of the citizen involvement activities further highlight the importance of addressing renovation costs, heritage protection requirements and the involvement of building owners and tenants. These considerations should inform future stakeholder engagement and implementation planning.

The Energy Action Plan was technically finalised on 15 May 2026. It provides a strategic basis for subsequent building-specific feasibility studies, consultation with heritage conservation authorities, investment planning and the progressive implementation of energy efficiency and decarbonisation measures.

The next steps should focus on validating the proposed interventions at building level, identifying suitable financing opportunities, engaging property owners and relevant municipal stakeholders, and establishing a monitoring framework to assess the energy and environmental performance of implemented measures.

BLOCK / Year of EE measures implementation	No. of Buildings	Useful Area [m2]	CAPEX [€/year]	OPEX savings [€/year]	Final energy savings [kWh/year]	Primary energy savings [kWh/year]	CO2 savings [t/year]	Simple payback period [years]
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BLOCK 16	**31**	**13.821**	**5.723.925**	**140.775**	**1.316.041**	**1.328.512**	**222**	**41,84**
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2045	*11*	*3.813*	*1.345.801*	*24.094*	*237.665*	*233.424*	*40*	*51,82*
BLOCK 17	**29**	**14.807**	**3.454.442**	**103.800**	**1.064.505**	**1.025.406**	**165**	**36,97**
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2050	*18*	*9.286*	*2.506.164*	*79.297*	*796.126*	*775.027*	*126*	*36,28*
TOTAL:	**97**	**44.446**	**16.095.137**	**371.088**	**3.579.767**	**3.555.881**	**591**	**44,82**

12. Decarbonisation Strategy Scenario 1: Building Renovation and Geothermal District Heating

12.1. Scenario Overview

Commented [PL8]: Please clarify the technical feasibility assumptions underlying the geothermal district heating scenario. In particular, indicate whether the availability of a suitable geothermal resource, the feasibility of the distribution network and the required heritage approvals have been verified or are still assumptions. Please distinguish a modelled decarbonisation scenario from an investment-ready solution.

The proposed decarbonisation strategy for the pilot site in historic centre of Zamość combines energy renovation of buildings with the gradual transition to a renewable-based district heating system supplied by geothermal energy. The scenario has been developed for urban fabric, where interventions must preserve the historical and architectural value of buildings while significantly reducing energy consumption and greenhouse gas emissions. The scenario supports the Development Strategy of the City of Zamość 2020-2030, which calls for continued thermal modernisation of buildings, modernisation of heat networks and wider use of renewable energy (see the strategy integration section of the Zamość chapter).

The strategy builds upon the building-level analyses carried out within Deliverables D.1.2.1 and D.1.2.2 and integrates them into a neighbourhood-scale approach. Priority is given to improving the thermal performance of building envelopes, followed by the replacement of fossil-fuel heating systems through connection to a geothermal district heating network. The proposed solution enables substantial decarbonisation while minimising visible interventions on protected buildings and reducing the need for individual heating installations. The scenario supports the long-term objective of transforming the historic centre into a low-carbon heritage district that combines cultural preservation with modern renewable energy infrastructure.

Status of the geothermal option: this is a modelled planning scenario, not a confirmed local investment. A technology-specific feasibility study, evidence of an exploitable geothermal resource, a network connection concept and the necessary conservation and administrative approvals have not been established for this scenario. These matters, together with detailed conformity with municipal plans, require further verification before the pathway can be treated as implementable. General support for renewable heat and district heating in the City Strategy does not itself confirm a geothermal project.

12.2. Technical Measures

The scenario consists of the following EE measures:

- Deep renovation of residential and public buildings using heritage-compatible insulation solutions, improved windows where conservation regulations permit, and optimisation of building envelopes.
- Gradual connection of renovated buildings to a geothermal district heating network replacing existing natural gas and other fossil-fuel based heating systems. Geothermal supply remains conditional on confirmation of the resource, network feasibility and conservation approval. Until connection, coal-fired and other high-emission sources should be replaced first, in line with the City Strategy, which recommends network gas and renewable heat for this purpose.
- Installation of modern district heating substations with smart metering and energy management functions.
- Modernisation of internal heating installations to improve distribution efficiency and compatibility with lower supply temperatures.

The district heating system provides a centralised renewable heat source that significantly simplifies operation and maintenance while improving energy security and reducing local air pollution.

Table 13 Decarbonisation Strategy Scenario 1: Building Renovation with Geothermal District Heating

Building ID	Year	CAPEX [€]	OPEX savings [€/year]	Final energy savings [kWh/year]	Primary energy savings [kWh/year]	Production [kWh/year]	CO2 savings [t/year]	Simple payback period [years]
1	2030	978.354	31.227	350.862	496.542	0	145	31
2	2030	56.104	1.956	21.976	30.702	0	9	29
3	2030	54.026	1.724	19.375	27.420	0	9	31
4	2030	78.961	2.753	30.930	43.208	0	13	29
5	2030	286.753	9.153	102.836	145.535	0	42	31
6	2030	27.013	862	9.687	13.710	0	4	31
7	2030	27.013	942	10.581	14.782	0	4	29
8	2030	47.792	1.666	18.721	26.153	0	7	29
9	2030	162.078	5.650	63.487	88.691	0	25	29
10	2030	96.970	3.380	37.984	53.063	0	15	29
11	2030	58.611	2.044	22.958	32.073	0	10	29
12	2030	207.792	7.244	81.394	113.707	0	32	29
13	2030	173.160	5.527	62.100	87.884	0	26	31
14	2030	169.697	5.416	60.857	86.126	0	25	31
15	2030	155.844	5.433	61.046	85.280	0	24	29
16	2030	169.697	5.916	66.472	92.861	0	27	29
TOTAL:		**2.749.864**	**90.892**	**1.021.266**	**1.437.738**	**0**	**416**	**30**

Table 14 Scenario 1: KPI`s

INDICATOR	VALUE
Heating Supply Type:	Geothermal District Heating
Primary Energy Needs [kWh/y]:	3.295.969
Final Energy Needs [kWh/y]:	2.398.742
CO_2 Emissions [t CO2/y]:	600
Useful Area [m2]	7.940
Specific Primary Energy Needs [kWh/m2/y]:	415,11
Specific Final Energy Needs [kWh/m2/y]:	302,11
Specific CO_2 Emissions [kg CO2/m2/y]:	75,57
Primary Energy Savings [kWh/y]:	1.437.738
Final Energy Savings[kWh/y]:	1.021.266
CO_2 Emissions Savings [t CO2/y]:	416
OPEX Savings [€/year]:	90.892

Commented [PL9]: Please add a concise comparison of the geothermal district heating and ground-source heat pump scenarios, explaining why the heat pump scenario achieves greater final energy savings while the district heating scenario achieves greater modelled CO_2 reductions. Please document the assumed emission factors, conversion efficiencies and energy supply conditions, and verify that both scenarios use the same baseline and assessment boundaries.

Investment (TI, Geoth) (2024) [€]:	2.749.864
Simple Payback Period [years]:	30,25

Comparison of the two modelled pathways[2]

Both scenario workbooks use the same pilot baseline of 16 buildings and 7,940 m² of useful area, with annual final energy demand of approximately 2,398,742 kWh, primary energy demand of 3,295,969 kWh and CO_2 emissions of 600 t. Scenario 1 combines renovation with geothermal district heating; Scenario 2 combines renovation with heat pumps. The results below describe the modelled pilot and are not city-wide forecasts.

Scenario 1 produces modelled annual savings of approximately 1,021,266 kWh of final energy (42.6%), 1,437,738 kWh of primary energy (43.6%) and 415.6 t CO_2 (69.3%). Its estimated capital cost is EUR 2.750 million, annual operating-cost savings are approximately EUR 90,892 and simple payback is 30.25 years. Scenario 2 produces approximately 1,829,149 kWh of final energy savings (76.3%), 1,865,822 kWh of primary energy savings (56.6%) and 264.5 t CO_2 savings (44.1%), at an estimated capital cost of EUR 1.364 million, annual operating-cost savings of approximately EUR 135,954 and simple payback of 10.03 years.

The different rankings follow the workbook assumptions. The geothermal heat-supply option is assigned a zero operational CO_2 factor, whereas the heat-pump option uses an electricity CO_2 factor of 0.597 kg CO_2/kWh and a heat-pump efficiency coefficient of 4. A zero factor for geothermal heat is a modelling assumption, not evidence that an actual Zamość heat supply would have no operational or lifecycle emissions. Heat pumps reduce delivered energy substantially, but their calculated emissions depend on the electricity factor. Resource availability, achievable seasonal performance, network losses, supply emissions, prices and investment costs require validation before an investment decision.

12.3. Phasing and Implementation Timeline

Implementation is proposed through several coordinated phases:

PHASE 1

Detailed engineering studies and permitting. This phase is aligned with the 2030 horizon of the City Strategy.

Preparation of district heating infrastructure.

Renovation of priority public buildings.

Pilot connection of selected buildings to the geothermal network.

PHASE 2

Extension of district heating infrastructure throughout the historic centre.

Large-scale renovation of residential buildings.

Progressive replacement of existing fossil-fuel heating systems.

PHASE 3

Completion of network expansion.

Optimisation of system operation using digital monitoring.

Integration with additional renewable electricity sources where feasible.

[2] Source: Zamość action-plan workbooks 003_EEM_TI_GEOTH_Zamosc_Action_Plan.xlsx and 005_EEM_TI_HP_Zamosc_Action_plan.xlsx; detailed calculation workbooks 003_EEM_TI_Geoth_DH_Zamosc_AP.xlsx and 005_EEM_TI_HP_Zamosc_AP.xlsx. The comparison retains their numerical assumptions and does not establish a preferred or municipally approved scenario

This phased implementation reduces investment risks while allowing gradual adaptation of residents and public institutions.

Table 15 Scenario 1: Decarbonization Roadmap 2020 - 2050

Year	Primary Energy Needs	Final Energy Needs	CO2 Emissions
2020	3.295.969	2.398.742	600
2030	2.698.097	1.975.599	425
2035	2.497.917	1.833.773	368
2040	2.210.383	1.627.950	286
2045	1.858.231	1.377.476	184

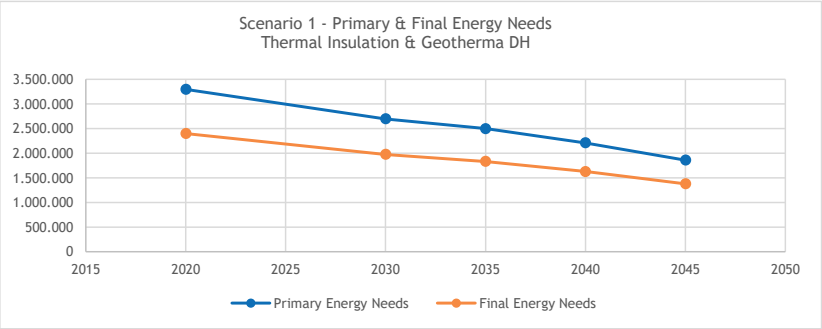


Figure 12: Scenario 1: Primary & Final Energy Needs

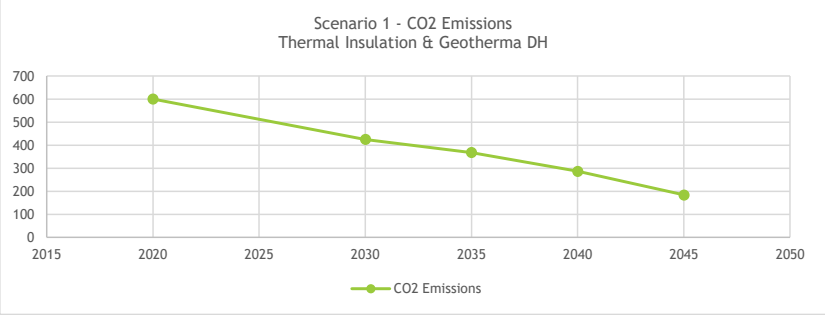


Figure 13: Scenario 1: CO2 Emissions

Table 16 Scenario 1: Primary / Final Energy & CO2 Savings

Year:	Primary Energy Savings [kWh/y]	Final Energy Savings [kWh/y]	CO2 Emissions Savings [t/y]
2030	597.872	423.143	175
2035	200.180	141.825	57
2040	287.535	205.823	82
2045	352.152	250.474	102
TOTAL:	**1.437.738**	**1.021.266**	**416**

12.4. Strategic Impact

The proposed scenario contributes simultaneously to climate neutrality, heritage preservation and urban resilience.

Expected strategic benefits include:

- significant reduction of final and primary energy demand;
- reduction of CO_2 emissions;
- replacement of fossil fuels with renewable geothermal energy;
- improved indoor comfort and building durability;
- reduced local air pollution;
- increased energy security through centralised renewable heating;

13. Decarbonisation Strategy Scenario 2: Building Renovation and Shallow ground-source heat pumps

13.1. Scenario Overview

The second scenario represents a decentralised decarbonisation pathway based on building renovation combined with shallow ground-source heat pump systems. This option is intended for buildings or areas where connection to a district heating network may not be technically or economically feasible. This pathway is consistent with the City Strategy, which promotes renewable heat when individual heat sources are modernised.

Following improvements to the thermal performance of buildings, heating demand is reduced sufficiently to enable efficient operation of high-performance ground-source heat pumps. The scenario allows each building to operate independently while maintaining compatibility with strict heritage protection requirements. The approach provides flexibility for phased implementation and enables gradual replacement of conventional heating systems without requiring large-scale energy infrastructure investments.

Rationale for the choice of technology: as Zamość is a historic city, photovoltaic installations cannot be placed on every building. The project partner from Croatia, which prepared the predictions, therefore identified heat pumps as an alternative renewable energy source. This choice is supported by analyses presented in 2017 by the Polish Geological Institute – National Research Institute (PIG-PIB)[3], which concluded that the geological and hydrogeological conditions of the city of Zamość, at a depth of approximately 75 m, offer good potential for ground-source heat pumps (translated from Polish). These results were promising but general in nature, so ground-source heat pumps are treated here as an alternative renewable source, and their use at individual sites must be confirmed by local investigations, including borehole locations and archaeological and conservation requirements. The calculated building savings are auxiliary and indicative.

[3] Polish Geological Institute – National Research Institute, Geotermia w Zamościu, Geothermal4PL project: https://www.pgi.gov.pl/geothermal4pl/o-projekcie/1108-aktualnosci-geothermal/10116-geotermia-w-zamosciu.html

13.2. Technical Measures

The scenario includes:

- Deep renovation of building envelopes using conservation-compatible solutions.
- Installation of vertical borehole heat exchangers where geological conditions permit.
- Deployment of high-efficiency ground-source heat pumps for space heating and domestic hot water preparation.
- Modernisation of internal heating systems to low-temperature operation.

Where possible, borehole fields may be shared between neighbouring buildings to optimise land use and reduce installation costs.

Table 17 Decarbonisation Strategy Scenario 2: Building Renovation and Shallow ground-source heat pumps

Building ID	Year	CAPEX [€]	OPEX savings [€/year]	Final energy savings [kWh/year]	Primary energy savings [kWh/year]	Production [kWh/year]	CO2 savings [t/year]	Simple payback period [years]
1	2030	485.166	47.291	638.468	649.247	0	92	10
2	2030	27.822	2.873	38.443	39.399	0	6	10
3	2030	26.791	2.611	35.257	35.852	0	6	10
4	2030	39.157	4.043	54.105	55.449	0	8	10
5	2035	142.201	13.861	187.133	190.293	0	27	10
6	2035	13.396	1.306	17.628	17.927	0	2	10
7	2035	13.396	1.383	18.510	18.969	0	2	10
8	2035	23.700	2.447	32.748	33.562	0	4	10
9	2040	80.374	8.298	111.058	113.817	0	16	10
10	2040	48.087	4.965	66.445	68.096	0	10	10
11	2040	29.065	3.001	40.161	41.159	0	6	10
12	2040	103.044	10.638	142.382	145.920	0	21	10
13	2045	85.870	8.370	113.003	114.911	0	16	10
14	2045	84.153	8.202	110.743	112.613	0	16	10
15	2045	77.283	7.979	106.787	109.440	0	16	10
16	2045	84.153	8.688	116.278	119.168	0	17	10
TOTAL:		**1.363.657**	**135.954**	**1.829.149**	**1.865.822**	**0**	**264**	**10**

Table 18 Scenario 2: KPI`s

INDICATOR	VALUE
Heating Supply Type:	Shallow ground-source heat pumps
Primary Energy Needs [kWh/y]:	3.295.969
Final Energy Needs [kWh/y]:	2.398.742
CO_2 Emissions [t CO2/y]:	600
Useful Area [m2]	7.940
Specific Primary Energy Needs [kWh/m2/y]:	415,11
Specific Final Energy Needs [kWh/m2/y]:	302,11
Specific CO_2 Emissions [kg CO2/m2/y]:	75,57
Primary Energy Savings [kWh/y]:	1.865.822

Final Energy Savings[kWh/y]:	1.829.149
CO_2 Emissions Savings [t CO2/y]:	264
OPEX Savings [€/year]:	135.954
Investment (TI, HP) (2024) [€]:	1.363.657
Simple Payback Period [years]:	10,03

13.3. Phasing and Implementation Timeline

Implementation is foreseen in three consecutive phases:

PHASE 1

Geological investigations. This phase is aligned with the 2030 horizon of the City Strategy.

Feasibility studies.

Demonstration installations on representative pilot buildings.

PHASE 2

Progressive installation of ground-source heat pump systems in suitable residential and public buildings.

Optimisation of internal heating systems.

PHASE 3

Large-scale deployment across the historic district.

Digital optimisation of system operation.

Integration with future renewable electricity generation and energy communities where appropriate.

Table 19 Scenario 2: Decarbonization Roadmap 2020 - 2050

Year	Primary Energy Needs	Final Energy Needs	CO2 Emissions
2020	3.295.969	2.398.742	600
2030	2.516.022	1.632.468	489
2035	2.255.271	1.376.450	453
2040	1.886.279	1.016.404	401
2045	1.430.147	569.593	336

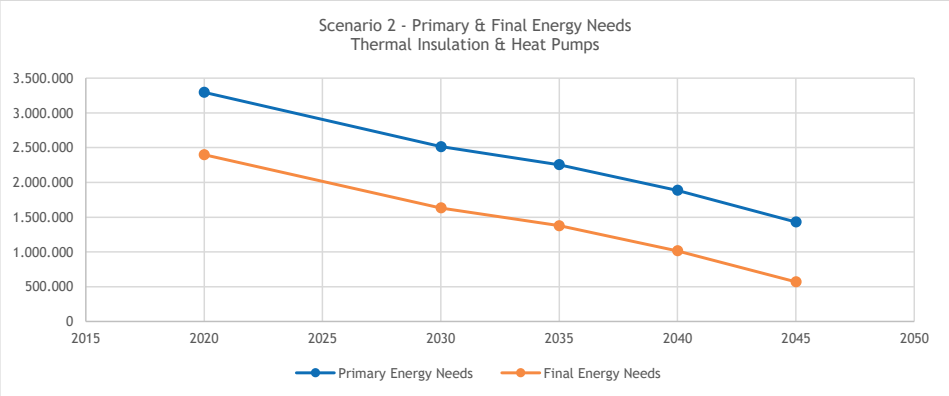


Figure 14: Scenario 2: Primary & Final Energy Needs

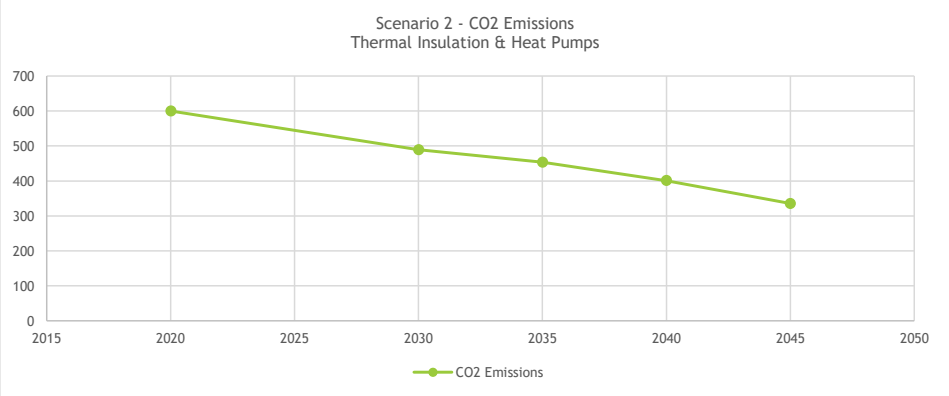


Figure 15: Scenario 2: CO2 Emissions

Table 20 Scenario 2: Primary / Final Energy & CO2 Savings

Year:	Primary Energy Savings [kWh/y]	Final Energy Savings [kWh/y]	CO2 Emissions Savings [t/y]
2030	779.947	766.274	111
2035	260.750	256.019	36
2040	368.992	360.045	53
2045	456.132	446.811	65
TOTAL:	**1.865.822**	**1.829.149**	**264**

13.4. Strategic Impact

The decentralised scenario provides an alternative pathway towards climate neutrality while preserving the historical character of Zamość pilot.

Its principal benefits include:

- high energy efficiency through ground-source heat pumps;

- major reductions in greenhouse gas emissions;
- elimination of fossil-fuel heating systems;
- flexible implementation adapted to individual buildings;
- compatibility with heritage conservation requirements;
- improved resilience through distributed energy systems;
- creation of a scalable model for historic urban districts lacking district heating infrastructure.

14. Public Lightning

The public lighting system in Zamość pilot has already undergone significant modernisation through the replacement of conventional luminaires with energy-efficient LED technology. As a result, the system already achieves substantially lower electricity consumption and maintenance requirements compared to traditional lighting solutions.

Based on the available information, no additional public lighting measures are proposed within this Energy Action Plan. Further optimisation, such as the implementation of adaptive lighting controls, smart lighting management systems or additional efficiency improvements, would require more detailed technical information on the existing infrastructure, operational profiles and control systems, which is currently not available.

Consequently, public lighting is not considered a priority intervention within the present Action Plan. Nevertheless, future updates of the plan may include additional measures once more comprehensive technical data become available and opportunities for further digitalisation and optimisation can be assessed. The inventory nevertheless shows 10 high-pressure sodium luminaires, representing 39% of installed power, which should be reviewed first in any such update.

Table 21 Public Lightning – Electricity consumption, Zamość

No	TECHNOLOGY	Lamp Power [W]	No. of Lamps	Installed Power [W]	Share	Installed Power [kW]	Working Hours [h/y]	Electricity Consumption [kWh/y]
1	LED 36W	36	28	1.008,00	39,33%	1,008	4100	4.132,80
2	LED 20W	20	16	320,00	12,49%	0,32	4100	1.312,00
3	LED 25W	25	3	75,00	2,93%	0,075	4100	307,50
4	HST (High Presure Sodium) 100W	100	10	1.000,00	39,02%	1	4100	4.100,00
5	LED 40W	40	4	160,00	6,24%	0,16	4100	656,00
	TOTAL:		**61**	**2.563,00**	**100,00%**	**2,563**		**10.508,30**

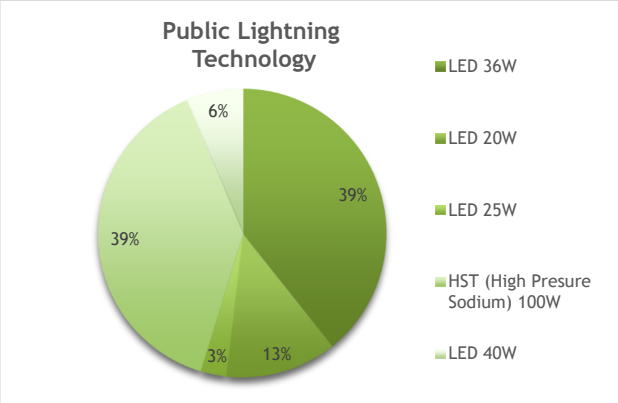


Figure 16 Public Lightning - technology, Zamość

15. Transportation

The transport sector represents an important component of neighbourhood decarbonisation due to its contribution to overall energy consumption and greenhouse gas emissions. However, detailed local transport data for the Zamość pilot area, such as traffic counts, vehicle kilometres travelled and modal split, are currently not available. Therefore, the proposed transport measures should be considered indicative and primarily intended to demonstrate the potential contribution of sustainable mobility measures to achieving a zero-emission neighbourhood.

Table 22: Fuel consumption, Zamość

FUEL	Share	Fuel Consumption [kWh/y]	Assumed number of vehicles
Gasoline	53,20%	425.295,57	56
Diesel	38,70%	309.378,54	41
LPG	1,10%	8.793,71	1
Electricity	7,00%	55.959,94	7
TOTAL:	**100,00%**	**799.427,76**	**105**

According to the available baseline assessment, approximately 7% of the vehicle fleet is already electrified, while the remaining energy consumption is associated with conventional gasoline, diesel and LPG vehicles. Since electric vehicles do not contribute to direct fossil fuel consumption within the transport sector, only conventional vehicles are considered when estimating the effects of the proposed transport measures.

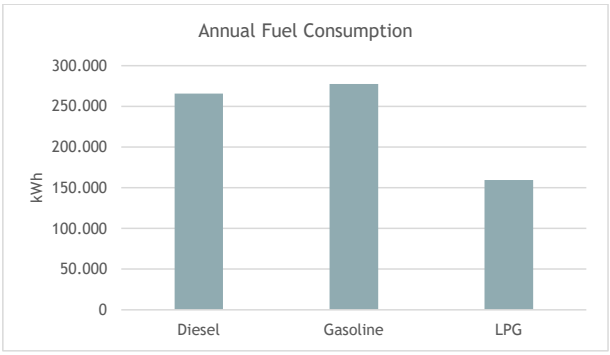


Figure 17: Estimation of fossil fuel consumption in traffic, Zamość pilot

For the purpose of estimating future energy savings and CO_2 emission reductions, the same calculation methodology applied for the Karlovac pilot will be used. The assessment assumes progressive reductions in fossil-fuel vehicle traffic resulting from the implementation of sustainable mobility measures, while maintaining a transparent and comparable approach across all pilot sites.

The indicative transport transition foresees a gradual introduction of traffic management measures. In the medium term, restrictions on heavy goods vehicles can reduce traffic-related energy consumption and emissions while improving environmental quality within the historic centre. In the longer term, access restrictions for conventional petrol, diesel and LPG vehicles could further accelerate decarbonisation, complemented by increased use of public transport, walking and cycling. These measures support the City Strategy's direction of making public transport more competitive, modernising the bus fleet to environmental standards and extending cycling routes. They should also be reconciled with the city's electromobility strategy and sustainable urban mobility plan.

The long-term vision is the establishment of a pedestrian-priority historic centre with limited access for motorised traffic, preserving accessibility for residents, emergency services and other authorised users. These measures are expected to improve air quality, reduce noise levels, enhance the attractiveness of public spaces and contribute to the overall climate neutrality objectives of the Zamość neighbourhood.

Table 23 Indicative energy reduction in transport

Year	Transport Measure in Zamosc	Traffic Reduction [%]	Energy consumption [kWh/y]	Energy reduction [kWh/y]	CO2 emissions [tCO2/y]	CO2 emission savings [tCO2/y]
2025	No measures	0%	702.617	0	192,61	0
2030	Traffic ban for trucks	30%	491.832	210.785	135,11	57,50
2040	Traffic ban for petrol, diesel and LPG vehicles	80%	98.366	393.466	27,02	108,09
2050	Pedestrian-priority zone	100%	0	98.366	0,00	27,02

16. Integration of the Development Strategy of the City of Zamość 2020-2030

The Development Strategy of the City of Zamość 2020–2030 provides the policy context for the pilot. The assessment below refers to its objectives, implementation tasks and governance provisions. The energy calculations cover 16 buildings and 7,940 m² of useful area and must not be extrapolated to the whole city.

- Energy efficiency and heat supply: operational objective 2.1 and its implementation tasks support thermal modernisation, wider renewable-energy use, replacement of old heating systems, connection of selected buildings to the municipal heat network and improved energy management (pp. 75–76). Both pilot scenarios are consistent with these general directions through demand reduction and cleaner heat supply.
- Heritage protection: the Strategy supports conservation and renovation of historic properties and protection of the Old Town environment (pp. 77–78). Building-envelope works, external equipment, ground works and new network infrastructure therefore require site-specific heritage assessment and the applicable approvals; general strategic alignment does not settle their acceptability.
- Sustainable mobility: the Strategy includes walking and cycling infrastructure, public transport, low-emission vehicles and measures affecting traffic and parking (pp. 76–77). The pilot mobility proposals can contribute to these directions, but their detailed design, timing and implementation remain subject to municipal verification.
- Digital planning and participation: the Strategy includes digitalisation of public information and ICT-supported public participation (p. 78). CityAtlas can support these aims by making building information spatially accessible and helping explain proposed interventions. The platform does not replace statutory planning procedures, technical designs or consultation.
- Implementation and monitoring: the Strategy assigns coordination to the municipal department responsible for city development and external funding and describes cross-department cooperation, public participation, project selection and monitoring (pp. 94–100). The proposed pilot governance below follows this general approach without creating new municipal commitments.
- The Strategy provides a basis for discussing renovation and renewable heat, but is not treated here as approval of geothermal district heating or a specific heat-pump installation. The long-term pilot pathways also extend beyond its 2030 horizon. Their technology choices, investment schedules, financing and detailed conformity with city planning and heritage requirements need further verification.
- Source: Development Strategy of the City of Zamość 2020–2030, strategic objectives (p. 71), implementation tasks (pp. 75–78) and implementation and monitoring arrangements (pp. 94–100). Full municipal strategy: official BIP document.

This review establishes broad policy compatibility only. It does not confirm an exploitable geothermal resource, available network capacity, permissible drilling locations, individual property-owner consent or technology-specific approvals. These conditions must be verified through subsequent technical, conservation and municipal assessment before implementation.

16.1. Governance and Institutional Framework

A proposed implementation framework should distinguish municipal decision-making, technical support and building-owner responsibilities. The City of Zamość would coordinate consistency with municipal strategies, public-space and infrastructure planning, stakeholder consultation and the preparation of investment decisions through its competent departments. This reflects the coordination and monitoring approach in the City Strategy (pp. 94–100); the allocation of specific pilot tasks and resources remains to be agreed by the municipality.

Lublin University of Technology contributes the pilot documentation, the analytical 3D model and CityAtlas as technical and communication resources. This contribution can support interpretation of building information, comparison of modelled pathways and discussion with municipal partners. It does not confer

authority to approve investments, certify geological resources or replace the competent design and conservation bodies.

For any selected measure, building owners or managers, the relevant heat and electricity operators and competent heritage and administrative authorities should be involved according to their responsibilities. A subsequent preparation stage should confirm ownership and consent, technical feasibility, approvals, funding and procurement arrangements before a delivery schedule is adopted. Monitoring should distinguish the existing baseline, modelled benefits and measured post-implementation results, with responsible data owners agreed for energy use, emissions assumptions, costs and heritage constraints.

16.2. Integration of Citizen Feedback

Citizen feedback is considered through two separate evidence sources. The common ZEB4ZEN questionnaire contains 19 Zamość responses and identifies high renovation costs (100%), difficulty accessing financial incentives (74%) and insufficient information (37%) as barriers. These findings support attention to affordability, understandable technical guidance and information on possible support, while the small voluntary sample limits generalisation.

A separate city-led consultation on the Municipal Programme for the Care of Monuments for 2026–2029 received 273 responses. The mayoral invitation was issued on 15 September 2025 with a response deadline of 15 October 2025. Internal insulation was supported by 43.2% of respondents, opposed by 16.5%, with 40.3% undecided. Heat pumps were supported by 43.2%, opposed by 23.4%, with 33.3% undecided. For photovoltaics, 26.4% selected courtyard-facing roof surfaces in the Old Town, 38.5% selected locations outside the historic area, and 35.2% opposed the proposed installations. These results are reported in the municipal Google Forms export of 27 October 2025, Questions 26–28 (pp. 93–95).

The municipal consultation broadens the local context but is not pooled with the 19-response project survey and does not establish approval of either Energy Action Plan scenario. The undecided responses and differences between technologies support further explanation of visual impacts, conservation conditions, running costs and financial support. Before selecting investments, building-specific options should be discussed with owners and relevant stakeholders and checked against municipal strategy and heritage requirements. CityAtlas can provide a common visual reference for this dialogue; no completed technology-specific approval process is claimed here.

16.3. Integration of the Energy Action Plans into the 3D Environment

For the Zamość pilot, the digital environment supporting the interpretation and communication of the Energy Action Plan is provided by CityAtlas, developed at Lublin University of Technology. The platform combines a three-dimensional representation of the historic urban area with structured building-level information. The model was prepared using terrestrial laser scanning and terrestrial and UAV photogrammetry, with individual buildings represented as separate objects linked to their corresponding descriptive data. The building information is organised into five categories: administrative, cultural heritage, technical, energy, and socio-economic data. Users can select individual buildings to inspect their parameters and apply filters to identify groups of objects meeting specific criteria. The results are displayed within the 3D model (see Figure 18), allowing building characteristics and energy-related information to be examined together with their location and surrounding historic urban fabric. In relation to the Energy Action Plan, CityAtlas provides a spatial framework for understanding existing building conditions and discussing the proposed renovation and heating pathways. Information concerning building use, technical condition, heritage characteristics and available energy parameters can be explored within the same environment.

This supports the identification of buildings requiring further assessment and helps explain how energy interventions relate to the characteristics and constraints of the historic neighbourhood.



Figure 18 Live preview of the CityAtlas interface — analysis colouring and simulation on the 3D model.

The quantitative assessment of the decarbonisation scenarios is documented in the accompanying Excel calculation models. CityAtlas complements this assessment through the spatial presentation and exploration of building information, supporting communication between technical partners, municipal stakeholders and other users involved in subsequent planning activities.

The documentation and analytical approach underlying the Zamość model is also described in Wac, M. and Szostak, B. (2026), Digital Tool Supporting the Documentation and Analysis of Cultural Heritage: The Case of the Analytical 3D Model of the Zamość Fortress, Computer Assisted Methods in Engineering and Science, 33(1), 27–49 (DOI 10.24423/cames.2025.1943). The paper acknowledges ZEB4ZEN support and provides a scientific reference for combining 3D documentation with structured building information. Public communication of the platform is supported by city-atlas.com and the CityAtlas demonstration video.

17. Conclusion and Strategic Outlook

The Zamość pilot sets out two alternative pathways combining heritage-compatible building renovation with a change in heat supply. Under the workbook assumptions, geothermal district heating gives the larger modelled CO_2 reduction, while heat pumps give the larger delivered-energy reduction and shorter simple payback. These differences depend on the assumed supply emission factors, performance, prices and capital costs; they should guide further assessment rather than be read as a confirmed investment ranking.

The City Strategy supports energy efficiency, cleaner heating, digital information and heritage protection. Detailed conformity of individual interventions still requires verification, together with geothermal resources, network feasibility, drilling or equipment locations, conservation approvals and owner consent. The next preparation stage should validate these conditions and the financial assumptions before selecting a scenario, committing funding or fixing an implementation timetable.

The two citizen-feedback sources underline affordability and the need for clear information, while the municipal consultation also shows substantial uncertainty about some technologies. Lublin University of

Technology can support subsequent dialogue through the documented building model, CityAtlas and the published Zamość case study. The pilot therefore provides an analytical and communication basis for further municipal planning; it does not establish that the proposed energy infrastructure has been approved or built.

D. GREEN AND DIGITAL ENERGY ACTION PLAN FOR PALMANOVA, ITALY

18. Existing Conditions and Baseline Assessment

18.1. Urban and Heritage Context

Palmanova is a UNESCO Renaissance fortress city located in the Friuli Venezia Giulia Region, Italy. Its unique nine-pointed star-shaped urban layout represents one of the most significant examples of military urban planning in Europe. The historic insula analysed within the ZEB4ZEN project contains municipal buildings, educational facilities, administrative premises and cultural heritage assets that require careful balancing between energy efficiency improvements and heritage conservation requirements.

The Municipality has committed to reducing greenhouse gas emissions and improving the energy performance of public assets in line with European climate objectives, regional energy policies and local sustainability strategies.

Due to its unique Renaissance urban structure and heritage value, energy renovation measures must be carefully designed to preserve architectural integrity while improving energy performance. The proposed approach prioritises non-invasive solutions and compatible technologies, ensuring consistency with heritage conservation requirements.

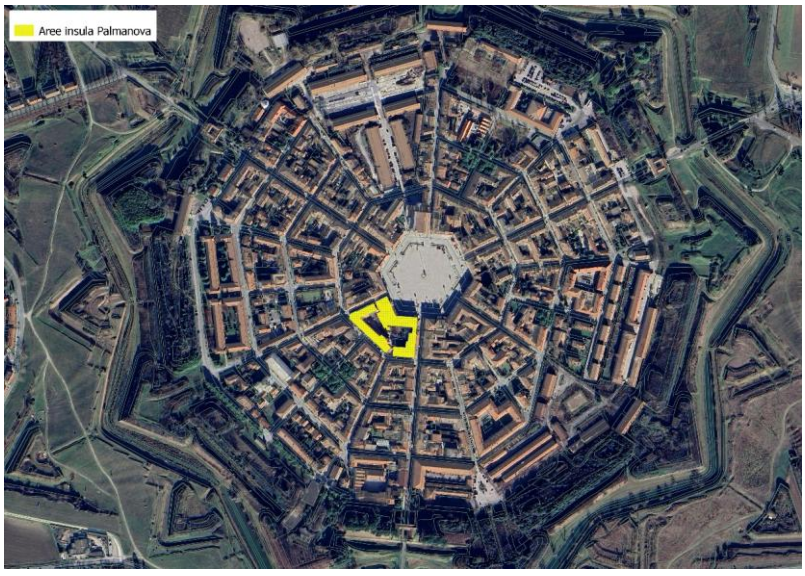


Figure 19: Map of Palmanova with the analysed insula

18.2. Building Stock Characteristics

The analysed building stock consists of six private and public buildings with a total conditioned floor area of 8,171 m². Main characteristics include:

- Ageing building envelopes with limited thermal insulation.
- Conventional heating systems with relatively low efficiency.
- High heating energy demand.
- Significant opportunities for electrification and energy performance improvement.
- Absence of integrated digital energy monitoring systems.

18.3. Energy and Emissions Baseline

Table 24 The baseline assessment identified the following annual performance indicators

INDICATOR	BASELINE
Final Energy Consumption [kWh/year]	1.365.785
Primary Energy Consumption [kWh/year]	1.951.325
Energy Costs [€/year]	575,273
CO_2 Emissions [tCO_2/year]	293

Heating demand represents the largest share of overall energy consumption.

18.4. Digital Representation and Energy Data Management

The energy assessment was performed using the ZEB4ZEN energy modelling framework, integrating building-level technical data, energy consumption information and decarbonisation calculations.

The proposed digital approach foresees the progressive integration of:

- building energy databases;
- smart metering systems;
- digital monitoring dashboards;
- GIS-based visualization of municipal assets;
- KPI tracking and reporting tools.

18.5. KPIs and Impact Summary

Table 25 KPIs and impact summary

INDICATOR	VALUE
Primary Energy Needs [kWh/y]	1.951.325
Final Energy Needs [kWh/y]	1.365.785
CO_2 Emissions [tCO_2/y]	293

Conditioned floor area [m²]	8.170,91
OPEX [€/y]	575,273

19. Integration of Existing City Strategies into the Palmanova Green and Digital Energy Action Plan

The proposed measures for Palmanova are consistent with:

- European Green Deal
- Fit for 55 Package
- REPowerEU Strategy
- Italian National Energy and Climate Plan (PNIEC)
- Regional Energy Strategy of Friuli Venezia Giulia
- Local sustainable urban development objectives

The Action Plan contributes to:

Energy Efficiency

Deep renovation of municipal buildings through thermal envelope improvements and reduction of heat losses.

Electrification of Heating

Replacement of conventional heating systems with high-efficiency heat pumps.

Digitalisation

Implementation of digital energy monitoring systems to support data-driven management of municipal assets.

Decarbonisation

Reduction of fossil fuel consumption and greenhouse gas emissions in public buildings.

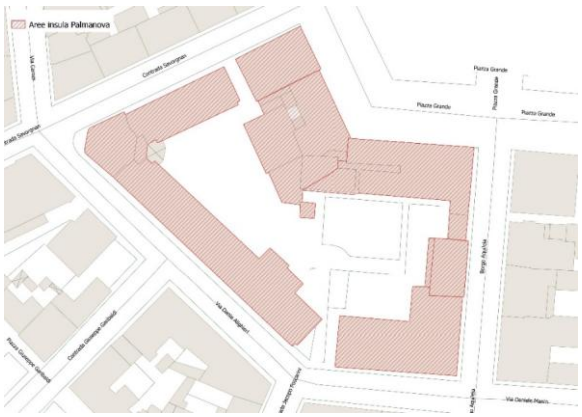


Figure 20: Map detail of Palmanova insula

20. Analasys Limitations and Assumptions

The assessment is based on the best available data at the time of preparation.

Key assumptions include:

- standard operating conditions for public buildings;
- typical occupancy schedules;
- heat pump seasonal performance values according to current technology standards;
- current electricity emission factors;
- average energy price assumptions;

Results should therefore be interpreted as strategic planning values and updated during detailed project design and implementation.

21. Decarbonisation Strategy: Public Buildings Renovation with Heat Pumps and Digital Energy Management

21.1. Scenario Overview

The proposed decarbonisation strategy focuses on the renovation of municipal buildings through a combination of:

- building envelope refurbishment;
- electrification of heating systems;
- deployment of high-efficiency heat pumps;
- digital monitoring and control solutions.

The objective is to create a highly efficient, low-carbon building portfolio while improving indoor comfort and reducing operating costs.

21.2. Technical Measures

Measure 1 – Building Envelope Renovation

- Thermal insulation improvements.
- Roof insulation upgrades.
- High-performance window replacement where applicable.
- Reduction of transmission losses.

Measure 2 – Heat Pump Deployment

- Replacement of conventional heating systems.
- Installation of electric heat pumps.
- Optimisation of heating system efficiency.
- Preparation for future renewable electricity integration.

Measure 3 - Digital Energy Management

- Smart metering.
- Building energy monitoring.
- Energy performance dashboards.
- Continuous KPI tracking.

21.3. KPIs and Impact Summary

Table 26 Target Scenario

INDICATOR	VALUE
Primary Energy Needs [kWh/y]:	1.093.122
Final Energy Needs [kWh/y]:	457.029
CO_2 Emissions [t CO_2/y]:	117
OPEX [€/year]:	180,084

Table 27 Achieved reductions

INDICATOR	REDUCTION
Primary Energy Savings [kWh/y]:	858.203
Final Energy Savings [kWh/y]:	908.756
CO_2 Reduction [t CO_2/y]:	176
OPEX Savings [€/year]:	395,189

Table 28 Percentage Improvement

INDICATOR	REDUCTION
Primary Energy Consumption [kWh/y]:	-44%
Final Energy Consumption [kWh/y]:	-66,5%
CO_2 Emissions [t CO_2/y]:	-60,1%

21.4. Action plan

Table 29: Proposed energy efficiency measures and key indicators

MEASURE	Year	CAPEX [€]	Annual OPEX Savings [€]	Final energy savings [kWh/year]	Primary energy savings [kWh/year]	CO2 savings [t/year]	Simple payback [years]
Building Envelope Renovation	2025	3.573,466	395,189	908.756	858.203	176	From 6 to 16 years, depending on each building
Heat Pump Installation	2025			included	included	included	

Digital Energy Monitoring	2025 - 2026			operational optimisation	operational optimisation	additional monitoring benefits	

22. Implementation Roadmap and Milestones

The roadmap outlines the proposed timeline for implementing renovation measures. The implementation roadmap presented outlines a sequence of **planned future measures** scheduled for execution, not actions already completed.

Commented [PL10]: Please explain the main implementation dependencies for the proposed renovation, heat pump and digital monitoring measures, including heritage approvals, technical design, investment financing and building ownership responsibilities. Clarify that the roadmap represents planned implementation rather than measures already completed. Please also indicate how the proposed measures comply with the conservation requirements of Palmanova's historic urban fabric.

Period	Main Activities
2025	Detailed design and procurement
2025-2026	Building renovation works
2025-2026	Heat pump installation
2026	Digital monitoring deployment
2026 onwards	Monitoring and optimisation

The successful execution of the proposed measures relies on several interconnected key dependencies:

Technical design and sequence:

- Detailed technical design and procurement must precede physical works.
- Thermal envelope upgrading and consequently HVAC system sizing must be co-designed to ensure optimal heat pump performance and efficiency.
- Digital monitoring infrastructure depends on the prior installation and commissioning of the heat pump and envelope improvements.

Heritage and regulatory approvals: authorization from the competent Heritage Authority (Soprintendenza Archeologia, belle arti e paesaggio) is a mandatory prerequisite for starting envelope works and outdoor heat pump unit installations, given the heritage constraints.

Investment financing: securing the required capital expenditure (€3,573,466 CAPEX) and final procurement validation must occur before awarding construction contracts.

Building ownership and governance responsibilities: clear delegation of responsibilities between building owners, municipal departments, and operators is required for access permissions, tenant coordination during works, and long-term facility management.

Palmanova is a UNESCO World Heritage site with strict urban and architectural conservation rules. The proposed interventions respect heritage requirements. First of all, external visual integrity is maintained by prioritizing interior thermal insulation or invisible, non-disruptive solutions, preserving original facades and historic fenestration. To prevent visual impacts on the historic streetscape, heat pumps integration will consider outdoor units, piping, and mechanical infrastructure concealed within internal courtyards, service areas, or dedicated acoustic and visual enclosures. Moreover, the deployment of digital monitoring relies on low-impact, non-destructive wireless or micro-cabling technologies, respecting historic masonry without altering structural integrity.

23. Scenario Calculations and GIS Integration Overview

The scenario calculations were performed using the ZEB4ZEN Excel-based energy modelling methodology.

The digital component of the Action Plan should include:

- GIS mapping of municipal buildings.
- Building energy performance database.
- Monitoring of energy consumption and emissions.
- Tracking of renovation measures.
- Reporting of KPIs through digital dashboards.

This approach ensures transparency, replicability and continuous improvement of municipal energy management.

24. Governance and Institutional Framework

The Municipality of Palmanova will act as the coordinating body responsible for planning, procurement, monitoring and reporting activities. Cooperation with regional authorities, energy agencies, technology providers and funding institutions will be essential to ensure successful implementation. Stakeholder engagement activities should accompany the implementation phase in order to increase awareness, promote behavioural change and maximise long-term energy savings. Monitoring and reporting activities should be integrated into regular municipal asset management processes.

24.1. Integration of Citizen Feedback

Citizen feedback collected within the ZEB4ZEN project provides additional insights into the social and practical conditions affecting the implementation of energy efficiency and decarbonisation measures in Palmanova.

The citizen survey documented in Deliverable D.4.1.1 involved 99 respondents, a statistically significant sample. Almost 71% of respondents have considered renovating their home to improve energy efficiency (through insulation, windows, heating systems, RES, heat pumps), but they have faced barriers to energy renovation: 44% of respondents identified heritage conservation restrictions, while 66% highlighted renovation costs.

Furthermore, in Palmanova 89% of respondents report interest in solutions that enable the use of renewable energy sources within the city walls. Additionally, 72% indicate that the city's historical character is very important when considering energy-efficient or climate-adaptation measures.

These findings are relevant to the implementation of the Energy Action Plan, as they confirm that citizens understand the importance of the conservation of the historical city center and, at the same time, they are aware of the need to renovate buildings and to improve energy efficiency.

Consequently, the proposed measures require not only technical assessment but also consideration of investment affordability and compliance with heritage conservation requirements.

In particular, financial incentives, information on available funding opportunities and early consultation with heritage conservation authorities may help address some of the barriers identified by survey participants.

24.2. Integration of the Energy Action Plans into the 3D Environment

The ZEB4ZEN project uses the DRONODAT digital visualisation environment to support the spatial representation and communication of energy efficiency and decarbonisation measures developed for the pilot neighbourhoods. Figure 21 shows the 3D environment representing the heat pump measure, together with a timeline and an energy saving visualization.

The visualisation demonstrates that selected measures associated with the Energy Action Plans have been incorporated into the digital environment. Verification of the complete correspondence between the final Energy Action Plan datasets and the information available in the platform requires confirmation from the responsible technical partners.

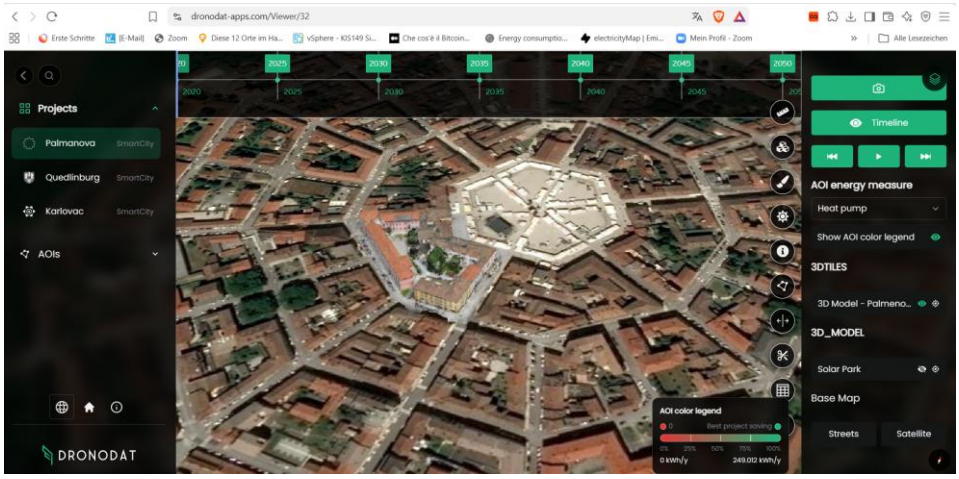


Figure 21 3D/VR Environment for the city of Palmanova

25. Conclusion and Strategic Outlook

The proposed Green and Digital Energy Action Plan demonstrates that significant energy and emissions reductions can be achieved through targeted renovation of municipal buildings combined with electrification and digitalisation measures.

The implementation of building envelope improvements, heat pump systems and digital energy management tools is expected to deliver:

- 66,5% reduction in final energy consumption;
- 44% reduction in primary energy consumption;
- 60,1% reduction in CO_2 emissions;
- annual savings of almost € 400 (€ 395,189).

The Action Plan therefore represents a practical and financially viable pathway towards the decarbonisation of Palmanova's building stock and supports the Municipality's contribution to European climate neutrality objectives.