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Cultural heritage as a structural modifier of rooftop solar deployment: A building-level framework for heritage-constrained urban decarbonisation

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HIGHLIGHTS

- Heritage protection is a structural modifier of rooftop PV, not a binary barrier.
- 10.3% of protected buildings hold 31.9% of PV-suitable roof area.
- Deployable rooftop PV is 68–93% of technical, set by regulatory interpretation.
- Rooftop PV cannot reach municipal self-sufficiency under 2050 electrification.
- Deeper renovation without relaxed PV rules widens the residual electricity gap.

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ABSTRACT

Cultural-heritage protection constrains rooftop photovoltaic (PV) deployment across a large share of the European building stock, yet existing solar cadastres ignore heritage-related regulatory constraints and therefore systematically overestimate deployable capacity in historic urban environments. This study develops and applies a heritage-aware framework that integrates building-level energy-demand modelling, a geographic information system (GIS)-based rooftop PV cadastre and scenario-based interpretation of heritage regulations to assess realistic decarbonisation pathways for heritage-constrained building stocks. Applied to the Municipality of Maribor, Slovenia (27,249 buildings), the framework shows that formally protected buildings (10.3% of the stock) account for 31.9% of technically suitable rooftop area — more than three times their share. Across five heritage-based scenarios, deployable PV potential ranges from 68% to 93% of the technical baseline (≈308–422 GWh/yr against 452.55 GWh/yr), determined primarily by institutional interpretation rather than the legal framework. Under deep electrification toward 2050, rooftop PV cannot achieve municipal self-sufficiency, leaving a residual gap of 8–22% of demand; notably, deeper renovation without relaxed PV admissibility widens rather than narrows this gap, showing that renovation depth and PV admissibility are complementary policy levers. Heritage protection thus acts as a structural modifier rather than a binary barrier, providing a transferable basis for integrating heritage constraints into solar cadastres, urban energy planning and national renovation strategies.

1. Introduction

The decarbonisation of the built environment is a central pillar of European climate policy, with rooftop photovoltaic (PV) systems increasingly recognised as a key instrument for reducing energy demand and greenhouse gas emissions in the building sector [1]. At the same

Acronyms: BH, building heritage; BZ, buffer zone; COP, coefficient of performance; DHW, domestic hot water; DSM, digital surface model; EPBD, Energy Performance of Buildings Directive; EPC, Energy Performance Certificate; EU, European Union; GIS, geographic information system; HVAC, heating, ventilation and air conditioning; KOP, key observation point; LPG, liquefied petroleum gas; M, monument; NEPN, National Energy and Climate Plan (Slovenia); PV, photovoltaics; PVGIS, Photovoltaic Geographical Information System; RED, Renewable Energy Directive; SH, settlement heritage; TABULA, building typology database (EU project).

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time, heritage conservation is evolving beyond a narrow focus on material preservation toward approaches that emphasise adaptive reuse, functional relevance and long-term environmental responsibility [2]. As decarbonisation pressures intensify, historic buildings and protected settlements are increasingly being considered within low-carbon strategies. Electrification of building heating — particularly space heating and domestic hot water — is expected to substantially reshape future electricity demand across Europe, with direct implications for local decarbonisation strategies and the role of on-site renewable generation."

Yet a fundamental tension is emerging between the ambitions of urban energy transitions and the constraints imposed by cultural heritage protection. Across Europe, a substantial share of the urban building stock falls within heritage-designated areas — encompassing not only individually listed monuments but also settlement ensembles, historic urban cores, and associated buffer zones — where interventions on rooftops and facades are subject to strict regulatory oversight. International research highlights both the opportunities and limitations of PV integration in heritage-protected environments, underscoring the need for assessment frameworks that explicitly account for heritage-related constraints when evaluating realistic deployment potential [3].

This tension remains only partially reflected in existing solar assessment tools. While some municipal and regional solar web platforms display multiple thematic layers — including solar potential, existing PV installations and, in certain cases, heritage-related information — such heritage layers are typically provided as separate visual overlays rather than being analytically integrated into the estimation of deployable PV potential ([4,5]). As a result, technical rooftop PV potential is systematically overestimated in heritage-sensitive urban environments, producing a structural mismatch between modelled solar potential and realistically deployable capacity — a gap examined in detail in Section 2.1.

This mismatch has direct implications for the reliability of municipal decarbonisation planning and the credibility of renewable energy targets under key European policy frameworks, including the revised Energy Performance of Buildings Directive (EPBD) [6] and the Renewable Energy Directive (RED III) [7]. If heritage constraints are not integrated into energy planning, rooftop PV potential is systematically overestimated, leading to misalignment between decarbonisation targets and spatial reality and increased uncertainty for policymakers and building owners. Addressing this challenge requires analytical approaches that jointly consider building-level energy demand, rooftop PV potential and the regulatory conditions governing interventions in protected built environments — yet such frameworks are currently absent from both the scientific literature and planning practice.

To address this gap, this study develops and demonstrates a transferable framework for evaluating deployable rooftop PV potential in municipalities with extensive cultural-heritage protection, and for assessing how such constraints shape feasible decarbonisation pathways in the building sector. The framework combines building-level energy-demand modelling with a GIS-based rooftop PV cadastre and heritage-sensitive spatial filtering, explicitly distinguishing technical from deployable potential and evaluating their implications under current conditions and a deep-decarbonisation 2050 scenario. It is demonstrated through application to the Municipality of Maribor, Slovenia — a city with an extensive and legally complex heritage-protection system representative of many historic European cities.

Specifically, the analysis (i) quantifies current (2025) and future (2050) electricity demand under a deep electrification pathway consistent with long-term climate targets; (ii) estimates technical rooftop PV potential using high-resolution spatial data; (iii) distinguishes between technical and deployable PV capacity by incorporating heritage-protection regimes across four legally defined protection categories; and (iv) evaluates the implications of alternative regulatory interpretations for building-level and municipal electricity self-sufficiency and residual electricity gaps under current and future conditions.

By comparing baseline and fully electrified target states across five heritage-based scenarios, the study examines how regulatory constraints affect the balance between local renewable generation and electricity demand. The results provide policy-relevant insights into the gap between technical solar potential and realistically deployable capacity, contributing to more robust decarbonisation planning in heritage-rich urban environments — a challenge shared by a large number of European municipalities with historically developed building stocks.

2. Literature review

2.1. Rooftop solar energy potential: From technical to deployable capacity

2.1.1. Technical potential assessment and solar cadastres

Rooftop solar assessments typically begin with the estimation of technical PV potential, defined as the maximum electricity generation achievable under ideal geometric and radiative conditions. GIS- and LiDAR-based methodologies form the methodological backbone of such assessments: building on digital surface models and 3D city models, they compute roof orientation, tilt, usable area and inter-building shading to estimate solar irradiation at high spatial resolution, increasingly complemented by data-driven approaches ([8–10]). These methods have been widely applied to support energy-policy scenarios from neighbourhood and municipal assessments to national and EU-wide estimates of rooftop PV potential, and recent studies show that high-resolution rooftop modelling reliably identifies PV-suitable surfaces, with building typology and urban morphology strongly shaping the ability of rooftop PV to offset electricity demand ([9,11,12]).

Solar cadastres represent the principal tool for operationalising technical PV potential at urban and regional scales, combining building geometry, irradiance modelling and shading analysis to provide spatially explicit estimates of solar suitability. Their widespread adoption has been enabled by advances in 3D city modelling and LiDAR-based data acquisition [13]. Solar web platforms built on cadastral data integrate meteorological, geographical and urban-geometry information to estimate solar potential and related energy metrics, and by visualising results on two- or three-dimensional urban models, they support early identification of suitable areas for solar deployment and enable assessment of alternative energy scenarios ([4,5,14]). Recent methodological advances include automated roof segmentation, cloud-based irradiance modelling and partial integration with building-energy demand ([15–17]). For example, the Vienna solar cadastre [18] presents roof-level solar potential in graduated suitability classes and assumes on average that around 30% of suitable roof area is usable; yet, like other municipal platforms, it does not analytically integrate the city's spatial heritage-protection zones (Schutzzonen, covering roughly 8–9% of the building stock) into its deployable-potential estimates.

Despite these technological advances, existing cadastres and solar platforms remain highly heterogeneous, lacking a unified taxonomy and exhibiting wide variation in interactivity and analytical depth ([19–21]). A global review of 51 platforms shows that none explicitly incorporates cultural-heritage protection regimes, while regulatory constraints are only marginally represented, leading to systematic overestimation of deployable PV capacity in heritage-sensitive areas [13]. Even advanced systems that integrate high-resolution geometry or vegetation modelling primarily depict solar resource availability rather than legal or cultural feasibility [22].

2.1.2. Deployable potential and regulatory constraints

Technical potential rarely translates directly into deployable capacity. Structural constraints, safety requirements, administrative procedures and economic or behavioural factors substantially reduce feasible PV deployment [23]. In areas subject to cultural-heritage protection, conservation rules, legal restrictions and visual-integrity requirements often prohibit PV installation on technically suitable roofs [3], with empirical evidence from historic cities showing that heritage-related constraints can reduce deployable rooftop PV potential by more than half ([24,25]).

A limited subset of approaches extends solar cadastres toward regulation-aware frameworks by incorporating planning rules, visibility constraints or façade typologies, highlighting their relevance for heritage-sensitive environments ([26–28]). However, the systematic incorporation of cultural-heritage protection regimes into building-level PV potential mapping remains largely absent from the literature.

This literature underscores the importance of distinguishing between technical and deployable PV potential — the latter defined as the subset of technically suitable rooftop area that is legally, culturally and visually permissible. While widely recognised conceptually, this distinction is rarely operationalised in spatially explicit, building-level analyses that incorporate statutory heritage-protection regimes.

2.2. Building energy demand and electrification pathways toward 2050

Recent studies indicate that while electricity demand increases under electrification pathways, overall final energy use can decline when electrification is combined with building renovation and efficient technologies such as heat pumps and district heating ([29–31]). Accurate representation of building energy demand is critical for reliable scenario analysis. Research shows that simplified archetypes often misestimate annual and peak loads, whereas building-specific modelling better captures heterogeneity related to building typology, envelope quality and occupancy [32]. Climate change further affects electrification pathways, with declining heating demand but increasing cooling needs projected toward mid-century, altering both load profiles and their temporal alignment with PV generation ([33–35]).

Large-scale stock analyses reveal pronounced spatial variability in future electricity demand driven by renovation depth, technology choice and building characteristics [36]. Empirical evidence further indicates that older and poorly insulated buildings dominate heating demand and remain heavily dependent on fossil fuels, underscoring the importance of coordinated renovation and electrification strategies [37]. In heritage-constrained building stocks, this challenge is amplified: conservation requirements can limit both the depth of envelope renovation and the deployment of on-site renewable generation, constraining the achievable reduction in final energy demand and the growth of local PV supply simultaneously.

However, few studies explicitly link building-level PV potential with future electricity demand under electrification scenarios, and most rely on archetypes rather than individual buildings. This study addresses this gap by combining building-level energy-demand modelling with rooftop PV assessment under current conditions and a 2050 electrification pathway, with explicit treatment of heritage-related constraints on both renovation depth and PV deployment.

2.3. Cultural heritage constraints on urban solar deployment

2.3.1. Heritage protection regimes and PV admissibility in European context

Cultural heritage protection systems across Europe operate through multi-tiered regulatory frameworks that govern interventions on

Table 1

Overview of studies and heritage inventories addressing cultural heritage constraints on rooftop PV deployment and building energy assessment in European urban contexts.

Country/City	Protected buildings (ind. / spatial)	Study focus	Heritage constraint operationalisation	Spatial scale	Rooftop PV potential	Energy balance	Electr. scenarios	Building-level assessment	Reference
Slovenia (nat.)	9%/21.6%	Heritage-constrained PV potential, energy balance and electrification scenarios	Graduated categories + visibility-based	Building / national	✓	✓	✓	✓	This study
Maribor, SI	10.3%/	Heritage-constrained PV potential, energy balance and electrification scenarios	Graduated categories + visibility-based	Building / city	✓	✓	✓	✓	This study
Budapest, HU	–/–	City-scale rooftop PV potential and heritage visibility constraints	Visibility-based	City	✓	×	×	×	[44]
Swedish historic cities	–/–	Rooftop PV potential and heritage visibility constraints	Visibility-based	City	✓	×	×	×	[24]
Amsterdam Centrum, NL	86%/–	Energy retrofitting of heritage buildings for low-temperature heating transition	Graduated categories	Building / district	×	partial	×	partial	[43]
Vienna, AT	–/8–9%	Municipal solar cadastre (Solarpotenzialkataster); heritage protection zones (Schutzzonen)	Platform / inventory (no heritage integration in PV potential)	City	✓	×	×	×	[18,45]
Germany (nat.)	3%/–	Heritage inventory and monument protection statistics	Inventory only	National	×	×	×	×	[38]
England, UK	2%/–	Heritage inventory and listed building statistics	Inventory only	National	×	×	×	×	[39]
Netherlands, (nat.)	1%/–	Heritage inventory and monument protection statistics	Inventory only	National	×	×	×	×	[40]
Czech Republic (nat.)	1%/–	Heritage inventory including urban heritage reservations and zones	Inventory only	National	×	×	×	×	[41]
France (nat.)	<1%/–	Heritage inventory (monuments historiques)	Inventory only	National	×	×	×	×	[42]

Notes: Notes: ind. = individually listed buildings as share of total building stock; spatial = share including settlement heritage areas and buffer zones or equivalent spatial protection regimes; — = data not reported or not available; partial = energy demand modelled at building archetype level rather than individual building level. Heritage constraint operationalisation refers to how protection regimes are translated into analytical constraints: inventory only = heritage data not integrated into energy or PV assessment; binary exclusion = protected buildings fully excluded from PV or renovation potential; graduated categories = protection categories translated into differentiated constraint levels; visibility-based = PV admissibility determined by line-of-sight analysis from key observation points. National-level shares reflect country-wide averages and may substantially underestimate the share of heritage-affected buildings in historically developed urban cores, as illustrated by the contrast between the national Slovenian share (~9%) and the Amsterdam Centrum district share (~86%).

historically significant buildings and areas. While specific categories and administrative procedures vary between national systems, most distinguish between individually listed monuments, registered building heritage, settlement-level designations and associated buffer zones — with regulatory strictness typically declining from monument to buffer zone level. Across these categories, the admissibility of rooftop PV installations is shaped by statutory protection regimes, conservation principles and visual-impact considerations [3].

The spatial extent of heritage protection varies considerably across European countries and urban contexts (Table 1). National inventories indicate that individually listed buildings account for approximately 3% of the building stock in Germany [38], around 2% in England [39], and roughly 1% in both the Netherlands [40] and the Czech Republic [41], while France lists fewer than 0.1% as monuments historiques [42]. These figures, however, systematically underestimate true regulatory exposure, since spatial protection regimes — encompassing settlement heritage areas, historic urban cores and buffer zones - extend constraints to a substantially larger share of buildings without individually listing them. In Slovenia, the share of formally protected objects amounts to approximately 9% of the national building stock, rising to over 21% when settlement heritage areas and buffer zones are included. At the urban scale, the contrast can be even more pronounced: in Amsterdam Centrum, approximately 86% of residential buildings are subject to at least one level of heritage protection [43], compared to 10.3% of all buildings in the Municipality of Maribor.

Despite the recognised importance of heritage constraints for urban energy transitions, existing studies addressing their intersection with rooftop PV potential and building energy demand remain limited in analytical scope (Table 1). Studies explicitly quantifying the impact of heritage protection on deployable PV capacity are confined to a small number of cases — notably Budapest [25] and Swedish historic cities [24] — both adopting visibility-based constraint operationalisation without linking PV potential to building-level energy demand or electrification scenarios. Studies addressing energy retrofitting of heritage buildings, such as Dang et al. [43], operate at archetype rather than individual building level and do not assess rooftop PV generation or electricity self-sufficiency implications.

The magnitude of constraint depends critically on how regulations are interpreted and applied — ranging from near-complete exclusion to conditional permission subject to visibility and compatibility criteria — highlighting regulatory interpretation as a key determinant of deployable solar potential in heritage-sensitive environments ([24,25]).

2.3.2. Visual impact, reversibility and approval frameworks

The assessment of rooftop PV installations in heritage contexts is typically governed by criteria related to visual impact, architectural compatibility, material reversibility and effects on protected views and urban silhouettes. These criteria are applied by competent heritage authorities and translated into approval decisions that determine where PV systems may legally be installed ([3,46]). In practice, approval outcomes depend not only on formal regulatory categories but also on institutional interpretation, administrative capacity and the availability of design guidance for heritage-compatible PV integration. This is illustrated by the case of Amsterdam Centrum, where a three-tier protection system (orde 1–3) translates directly into differentiated constraints on both energy retrofitting measures and rooftop interventions, with the most restrictive tier requiring approval from the municipal architectural committee before any works may begin [43].

Visibility-based assessment approaches — which evaluate PV admissibility on the basis of whether roof surfaces are visible from key public viewpoints — represent a promising middle ground between strict prohibition and unrestricted deployment ([24,28]). Such approaches can retain a substantial share of technical PV potential while preserving the visual integrity of historic urban environments, and their operationalisation through GIS-based visibility analysis offers a transparent and reproducible basis for regulatory decision-making. Beyond formal regulation, capacity-building within heritage authorities and early coordination between energy planners, designers and heritage professionals may be as important as regulatory reform for enabling inclusive PV deployment.

2.3.3. Gaps in heritage-aware solar assessment

The systematic integration of heritage constraints into solar cadastres and building-level PV assessment remains largely absent from both the literature and planning practice, where such constraints are typically ignored or treated as binary exclusions rather than graduated, spatially differentiated modifiers of deployable capacity [13]. As shown in Table 1, studies that do address heritage constraints in solar assessments are limited in number and analytical scope — none combining heritage-aware PV assessment with building-level energy demand modelling and scenario-based electrification pathways across a complete municipal building stock.

This gap is particularly consequential for urban energy planning in heritage-rich environments, where conservation requirements simultaneously constrain both on-site renewable generation and the depth of achievable envelope renovation, thereby shaping both the supply and demand sides of the local energy balance. The interaction between these dual constraints and the electricity demand implications of deep electrification pathways has not been systematically examined at the municipal scale. Addressing this gap requires analytical frameworks that move beyond technical solar potential and explicitly integrate heritage-related constraints into building-level PV assessments alongside scenario-based renovation and electrification pathways — the approach developed in the present study and described in Section 3.

2.4. Research gap and contribution of this study

The reviewed literature points to a consistent and consequential gap: while the importance of distinguishing between technical and deployable rooftop PV potential is widely recognised, this distinction is rarely operationalised in spatially explicit, building-level analyses that incorporate statutory heritage-protection regimes. Existing solar cadastres and assessment frameworks systematically overestimate feasible PV capacity in heritage-sensitive environments, and few studies link heritage-constrained PV potential with building-level energy demand under future electrification scenarios. As a result, municipal decarbonisation planning in heritage-rich cities lacks a reliable analytical basis for estimating realistic renewable energy contributions from the existing building stock.

The novelty of this study is conceptual and integrative rather than methodological: while it builds on established GIS-based PV assessment and building-level energy-demand modelling, it combines them in a way not previously realised in the literature, directly addressing the gap identified above. The study makes three specific contributions.

- First, it operationalises the widely recognised but rarely applied distinction between technical and deployable PV potential at the building level, using four statutory heritage-protection categories rather than a binary protected/unprotected classification.
- Second, it links this heritage-constrained deployable potential with building-level energy demand under current conditions and a deep-decarbonisation 2050 pathway across a complete municipal building stock — a combination absent from existing studies.
- Third, it conceptualises heritage protection as a structural modifier of deployable PV potential and reveals the interaction between renovation depth and PV admissibility as a novel analytical and policy insight.

Together, these contributions provide an integrated analytical foundation for more realistic and policy-relevant assessments of rooftop solar potential in heritage-constrained urban environments, supporting better-informed decarbonisation planning at both municipal and national scales.

We use the term structural modifier to denote this role of heritage protection. Rather than reducing deployable rooftop PV potential uniformly across the building stock (a linear reduction) or excluding a fixed set of buildings (a binary barrier), heritage protection reshapes the entire distribution of deployable capacity. Because protection regimes concentrate spatially on the largest and most productive roofs in historically developed cores, they remove a disproportionate share of high-value rooftop area, shift the building-level distribution of electricity self-sufficiency, and simultaneously constrain the depth of envelope renovation. Heritage protection thus modifies both the magnitude and the distribution of feasible PV deployment, and its effect depends on how regulations are interpreted rather than on the legal framework alone.

3. Methodology

The overall analytical workflow is summarised in Fig. 1. Starting from a common set of spatial and building-stock datasets, the framework first models building-level energy demand (A) and technical rooftop PV potential (B); a heritage-constraints layer (C) then translates technical into deployable potential, which is evaluated across five heritage scenarios (D) and a 2050 electrification and renovation pathway (E). The resulting energy balance and self-sufficiency are assessed at building and municipal level, including seasonal resolution (F). Each module is detailed in the subsections below,

3.1. Study area and building dataset

The study focuses on the Municipality of Maribor, Slovenia, selected as a representative case of a mid-sized European city combining an extensive and legally complex cultural-heritage protection system with a large and heterogeneous building stock. The municipality encompasses a historically layered urban core with post-war residential areas and dispersed non-residential buildings, resulting in diverse building types, roof geometries and conservation contexts relevant for rooftop PV deployment.

The building dataset was compiled from national building footprints [47] and validated using OpenStreetMap data [48]. High-resolution LiDAR point clouds, rasterized into a 1 × 1 m grid, were used to derive digital surface models with and without vegetation, supporting roof segmentation, shading analysis and solar-exposure modelling. Cultural-heritage constraints were identified using the national heritage registry [49], while infrastructure cadastres were applied to correct LiDAR artefacts related to overhead powerlines.

Buildings were classified through a multi-step process. Each building was first assigned to a heritage-protection regime based on the categories described in Section 3.1.1. Typological classification was then derived from national building-use records, resulting in 13 building types and seven construction periods (Table 2). Data from the national Energy Performance Certificate (EPC) Registry [50] were linked to the building stock where available, while buildings without EPCs were characterised using representative national typologies.

The resulting building-level database integrates physical attributes relevant for energy and PV modelling — such as roof geometry, height, shading context and envelope characteristics — with cultural-protection attributes required for assessing deployable PV potential. This dataset provides the consistent input basis for the building energy-demand assessment described in Section 3.2 and the subsequent analysis of electrification scenarios, rooftop PV potential and building-level self-sufficiency.

3.1.1. Heritage protection system

Rooftop PV deployment in Slovenia is governed by a multi-tiered heritage-protection system that directly shapes the regulatory context for interventions on culturally significant buildings and areas. Four protection categories are distinguished in the national heritage register, differing in regulatory strictness and in their implications for the admissibility of rooftop PV installations.

The most restrictive regimes apply to monuments of national or local significance (M) and registered building heritage (BH), where visible rooftop PV installations are generally discouraged or prohibited, with exceptions limited to fully concealed or non-visible roof surfaces. Less restrictive categories comprise settlement heritage areas (SH), where PV installation is typically restricted on visually exposed roof planes while limited placement may be permitted on less visible segments subject to

Table 2
Building typologies and construction periods used in the analysis.

Category	Classes
Building typologies	Single- and two-dwelling residential buildings, Multi-apartment residential buildings, Private office buildings, Educational and research buildings, Accommodation and food service buildings, Retail and service buildings, Cultural buildings, Healthcare buildings, Social residential buildings, Public administration buildings, Sports facilities and Agricultural buildings
Construction periods	0–1945, 1946–1970, 1971–1980, 1981–2002, 2003–2008, 2009–2022, 2023-today

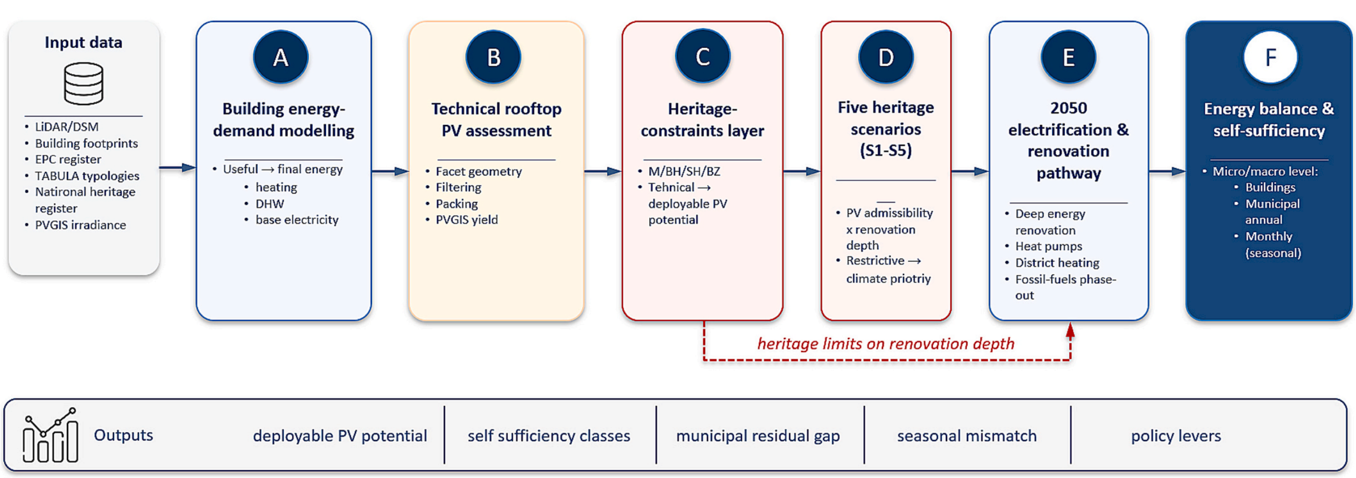

Fig. 1. Analytical workflow of the heritage-constrained rooftop-PV and self-sufficiency framework. Input datasets (left) feed six sequential modules (A–F); the bottom bar lists the resulting outputs. The figure shows the analytical sequence rather than the order of subsections (the 2050 electrification pathway, module E, is described in Section 3.3). The dashed arrow denotes the interaction by which heritage protection constrains both PV admissibility and achievable renovation depth.

minimal visual impact and material compatibility, and buffer zones (BZ), where PV deployment is generally allowed provided that key viewpoints, urban silhouettes and the perception of protected structures are not adversely affected. Regardless of category, all interventions in registered cultural heritage areas require prior authorisation from the Institute for the Protection of Cultural Heritage of Slovenia (ZVKDS).

At the national level, approximately 9% of the building stock is formally designated as protected objects. When settlement heritage areas and buffer zones are included, this share rises to over 21% — a pattern reflecting the dominance of spatial heritage regimes over individual monument listings as the primary regulatory context for rooftop PV deployment. In the Municipality of Maribor specifically, heritage designations cover a substantial share of the urban fabric, with particular concentration in the historic city core and adjoining residential and public-sector areas. These protection categories are directly translated into the scenario-based constraint framework described in Section 3.5 and 3.6.

3.2. Building energy demand assessment

The current energy demand of each building was estimated as useful energy demand for space heating and cooling at the individual-building level. A hierarchical approach was applied, prioritising measured or certified data where available and relying on typology-based modelling to ensure full coverage of the building stock.

For buildings with an EPC, useful energy demand for heating ($Q_{H,nd}$) and cooling ($Q_{H,nc}$) was taken directly from the EPC database, as these values reflect building-specific envelope characteristics, installed systems, renovation status and local climatic conditions. For buildings without an EPC, energy demand was estimated using typology-based methods. Residential buildings were assigned to TABULA building typologies based on construction period and building type, providing representative thermo-physical parameters and typical system configurations [51]. Non-residential buildings were modelled using an extended national typology derived from a large sample of EPC calculations, covering the main functional categories and representative envelope and system characteristics. Heating and cooling demand was thus determined as a function of construction period, building type, documented renovation status and the presence of renewable-energy measures.

To enable comparison between building-level electricity consumption and rooftop PV generation, final energy use was estimated separately for electricity, space heating and domestic hot water (DHW). Where available, final electricity consumption was taken directly from EPC records; otherwise, it was estimated using typology-specific values calibrated to observed consumption patterns. Heating and DHW energy carriers were assigned using a multi-source approach. In the 2025 baseline, approximately 40% of buildings located within the service area of the district-heating network were assumed to be connected, reflecting observed conditions in Maribor [52]. Additional system information was obtained from EPCs and the national registry of combustion appliances, covering biomass and decentralised fossil fuel-based systems. For buildings without verified system data, heating technologies were assigned based on distributions derived from the municipal energy balance, ensuring consistency between building-level allocations and the local energy mix. The resulting workflow for assigning heating and DHW energy carriers is illustrated in Fig. 2.

3.2.1. Final energy demand

For each building, useful energy demand for space heating and DHW was converted into final energy use by applying technology-specific generation efficiencies and a system-level loss factor. $Q_{H,d}$ and $Q_{DHW,nd}$ denote the useful energy demand for space heating and DHW, respectively. For a given building i, the corresponding final energy use was calculated as:

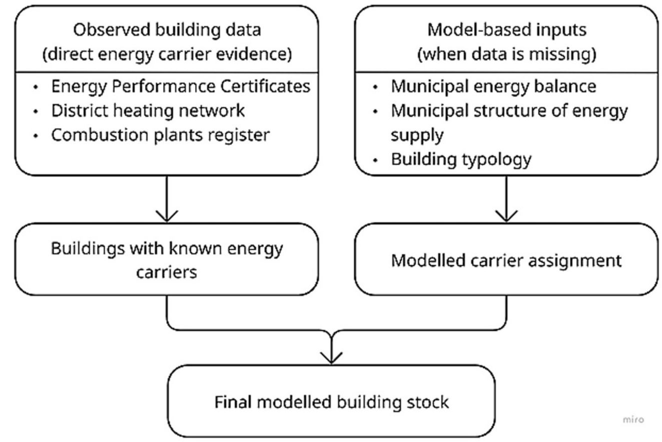

Fig. 2. Workflow for assigning heating and DHW energy carriers to the building stock.

$$Q_{H,final,i} = \frac{Q_{H,nd,i}}{\eta_{H,i} \times \eta_{sys}}; Q_{DHW,final,i} = \frac{Q_{DHW,nd,i}}{\eta_{DHW,i} \times \eta_{sys}}$$

where $\eta_{H,i}$ and $\eta_{DHW,i}$ denote the generation efficiencies (or coefficient of performance (COP) values for heat pumps) of the heating and DHW systems assigned to building i. A system-level loss factor $\eta_{sys} = 0.95$ was applied to account for typical distribution, storage and circulation losses within the building.

In addition to electricity used for heating and DHW in electrically supplied buildings, electricity demand for uses other than heating, ventilation and air conditioning (non-HVAC) — including lighting, appliances, equipment and process-related loads — was estimated using expert-based electricity-intensity values (kWh/m^2·yr) assigned according to building function (Table 3). These intensities reflect typical consumption patterns in Slovenian residential, commercial, agricultural and public-service buildings and provide a consistent baseline for comparing building-level electricity demand with rooftop PV generation potential. Although buildings are classified into 13 dominant-use types, individual buildings may contain parts with different functional uses and corresponding electricity-demand profiles; this internal functional diversity was accounted for through the applied electricity-intensity values and data harmonisation procedures.

It is important to note that the 2025 baseline electricity demand reflects current energy-use patterns, in which a substantial share of

Table 3
Non-HVAC electricity intensity classes by consumption range.

Intensity range (kWh/m^{2}a)	Building functions/spaces
0–10	Woodshed; Parking bay; Cellar; Terrace/balcony/loggia; Garage; Bike/boat storage; Auxiliary agricultural space; Storage/drying/laundry room; Crop storage area; Technical room; Tank/silo space
10–20	Stable; Apiary; Cemetery-related facility; Shared sanitary rooms; Common areas; Archive; Religious facility; Pastoral activity space
20–40	Vineyard cottage; Greenhouse; Mountain hut/lodge; Dwellings (single-family, two-dwelling, multi-apartment); School/kindergarten; Sports hall; Housing unit; Assisted-living dwelling; Service space; Education/research space
40–60	Office space; Public administration office; Museum/library
60–80	Cultural and recreational buildings; Exhibition hall/fairground; Bank/post/insurance
80–100	Industrial space; Retail area; Telecommunications facility; Hangar/depot/cargo terminal
100–120	Accommodation facility; Power plant; Entertainment venue (casino, circus, nightclub, dance hall); Food-service facility
120–150	Healthcare treatment space; Hospital/health centre

buildings continue to rely on non-electrical energy carriers — district heating, biomass and fossil fuels — for space heating and DHW. As a result, present-day building-level electricity demand remains relatively modest, which has direct implications for the interpretation of self-sufficiency outcomes under current conditions, as discussed in Section 4.3.

3.3. Future scenario: 2050 electrification and renovation pathway

3.3.1. Building renovation and heating demand reduction

By 2050, the building stock is assumed to undergo deep energy renovation, leading to a pronounced reduction in useful energy demand for space heating. Target post-renovation heating demands of 25 kWh/m^2·yr for residential buildings and 35 kWh/m^2·yr for non-residential buildings were adopted as reference performance levels, consistent with the national Long-term Building Renovation Strategy [53] and the Integrated National Energy and Climate Plan (NEPN) [54].

However, the extent to which these targets can be achieved varies across the building stock and is explicitly constrained by cultural-heritage protection. While non-heritage buildings are assumed to reach the full target performance, heritage-protected buildings are renovated only to the extent permitted under the respective heritage-based scenarios defined in Section 3.6. Renovation measures considered include roof insulation, façade treatment and window replacement; the admissibility of each measure under different heritage categories is specified in the scenario matrix presented in Table 5. Consequently, reductions in useful and final heating demand are scenario-dependent and systematically lower for buildings subject to stricter conservation regimes, reflecting the dual role of heritage protection in simultaneously constraining on-site renewable generation and limiting achievable demand reduction.

The assumed pre- and post-renovation U-values and heating-demand targets for each measure are summarised in Table 4. Each renovation measure is admissible only to the extent permitted by the heritage-based scenarios (Table 5): for heritage-protected buildings, the achievable post-renovation U-values — and hence the resulting heating demand — are constrained by the measures allowed under the respective protection category, so that the full target performance is reached only where all three measures are permitted.

3.3.2. Transformation of energy carriers and electrification

The 2050 scenario assumes a near-complete phase-out of fossil fuels for space heating and DHW. Within existing district-heating zones, approximately 80% of buildings within district-heating zones are assumed to be connected by 2050, reflecting the expansion targets of the municipal energy concept [55]. This represents policy ambitions and economic feasibility and a substantial increase from the 40% share assumed in the 2025 baseline. Outside these areas, a broad transition to electric heat pumps is assumed, replacing oil- and liquefied petroleum gas (LPG)-based systems and becoming the dominant decentralised heating technology. By NEPN, in low-density rural areas, biomass boilers are assumed to remain in use, with ageing systems replaced by modern, high-efficiency units.

Table 4
Renovation measures with assumed pre- and post-renovation U-values and resulting heating-demand targets by building type.

Renovation measure	Parameter	Pre-renovation (typical)	Post-renovation target
Roof / top-ceiling insulation	U [W/m^2K]	~0.4–1.0	0.15
Façade (external wall) insulation	U [W/m^2K]	~1.0–1.5	0.15
Window replacement	U [W/m^2K]	~2.5–3.5	1.00
Resulting useful heating demand — residential	$Q_{H,nd}$ [kWh/m^2yr]	building-specific	25
Resulting useful heating demand — non-residential	$Q_{H,nd}$ [kWh/m^2yr]	building-specific	35

The combined effects of deep renovation and heating-system substitution result in a marked reduction in final energy demand per building. Although electricity demand for heating increases due to electrification, it remains substantially lower than in the baseline as a consequence of reduced heating needs and high system efficiencies. The resulting building stock is characterised by low final energy consumption, strong reliance on low-carbon district heating where available, widespread electrification elsewhere, and limited continued use of biomass in rural settings.

The 2050 electrification and renovation assumptions described in this section define a common energy-system baseline applied across all subsequent scenarios. Differences between scenarios therefore reflect alternative interpretations of heritage-related constraints on rooftop PV deployment and building renovation, rather than divergent assumptions regarding the broader electrification pathway. This scenario structure provides the basis for assessing future rooftop PV self-sufficiency, municipal energy balances and the interaction between renovation strategies, heritage constraints and local decarbonisation pathways, as examined in Sections 3.6 and 3.7.

3.4. Technical rooftop solar potential assessment

The technical rooftop solar potential was assessed using a GIS-based workflow integrating detailed 3D building geometry, high-resolution elevation models and spatially explicit solar radiation data. Roof facets were derived from cadastral building footprints and a digital surface model (DSM), enabling the calculation of orientation, tilt, effective area and shading from surrounding buildings, vegetation and terrain. Solar irradiance was modelled using the Photovoltaic Geographical Information System (PVGIS) [50], providing hourly and annual global radiation for each roof segment based on locally representative meteorological data.

Roof segments were filtered to exclude sections with unfavourable orientation, insufficient annual irradiation, or areas below the minimum usable threshold. Specifically, roof surfaces with a tilt above 60°, an annual global irradiation below 800 kWh/m^2·yr, or a usable area smaller than 10 m^2 were excluded from further analysis ([12,22]). Flat and low-slope roofs were retained as PV-suitable rather than excluded: for multi-apartment residential and non-residential buildings — which dominate the flat-roof stock — a flat roof was assumed, and the PV-suitable area was estimated using a standard flat-roof mounting layout, with inter-row spacing reflected in the packing factor. The tilt and orientation criteria were applied to the pitched-roof segments derived from the digital surface model, so that low-slope roofs were not removed by the lower tilt limit.

For all roof segments that passed these suitability filters, a packing factor of 80% was applied to account for inter-row spacing, maintenance access and structural constraints [12]. Importantly, this factor is applied to net suitable area rather than gross roof area: because unfavourably oriented, shaded, low-irradiation and undersized segments are already excluded at the filtering stage, the 80% packing factor is not directly comparable with the 30–60% usable-area fractions commonly applied to gross roof area in studies that do not perform explicit upstream filtering. Expressed relative to total gross roof area, the deployable module area in our analysis corresponds to approximately 42%, consistent with values reported in the literature. PV generation was modelled assuming monocrystalline silicon modules with a nominal efficiency of approximately 21% and an installed power density of about 0.2 kWp per m^2 of usable module area. Annual yield per roof facet was derived from PVGIS-modelled in-plane irradiance [50], applying a performance ratio of around 0.83 that accounts for temperature losses (power temperature coefficient ≈ −0.38%/°C) as well as inverter and balance-of-system

Table 5
Heritage–compatibility matrix for rooftop PV and renovation measures.

Scenario	Description		PV	Roof TI	Facade TI	Windows
S1 – Restrictive scenario	Strict conservation; no visible alterations allowed in protected areas	M	χ	χ	χ	χ
		BH	χ	χ	χ	χ
		SH	χ	χ	χ	χ
		BZ	χ	χ	χ	χ
S2 – Trend-aligned scenario	Reflects current conservation practice with selective allowances.	M	χ	χ	χ	χ
		BH	~	~	~	~
		SH	~	~	~	~
		BZ	✓	✓	✓	✓
S3 – Permissive scenario	Enables broad renovation while keeping strict monument protection.	M	χ	χ	χ	χ
		BH	~	✓	✓	✓
		SH	~	✓	✓	✓
		BZ	✓	✓	✓	✓
S4 – Visibility-based scenario	PV allowed where not visible from key public viewpoints; visibility assessed via GIS.	M	χ	χ	χ	~
		BH	~	~	~	~
		SH	~	~	~	~
		BZ	~	~	~	~
S5 – Climate-priority scenario	Strong decarbonisation priority; aesthetic impact mitigated through architectural integration.	M	~	~	~	✓
		BH	✓	✓	✓	✓
		SH	✓	✓	✓	✓
		BZ	✓	✓	✓	✓

X = prohibited, ✓ = allowed, ~ = conditionally allowed (e.g. only on non-visible/secondary surfaces, or with strict design integration).
M = Monument, BH = Building heritage, SH = Settlement heritage, BZ = buffer zones.

losses (≈14%).

This workflow yields a spatially explicit estimate of technically suitable rooftop PV potential at the individual-building level across the entire municipal building stock. The resulting technical potential represents an upper-bound estimate of rooftop PV generation under current building geometry and irradiation conditions, before any regulatory, heritage or visual constraints are applied. Heritage-related filtering of this technical potential is described in Section 3.5, while the scenario-based operationalisation of heritage constraints is presented in Section 3.6.

3.5. *Cultural heritage constraints on rooftop PV deployment*

Cultural-heritage protection represents a key constraint on rooftop PV deployment, particularly in historically sensitive urban areas. To operationalise these constraints within the solar assessment, all buildings were classified according to the four heritage-protection categories defined in Section 3.1.1 (M, BH, SH and BZ) using spatial data from the national heritage registry [49].

All heritage categories were translated into a unified GIS-based constraint layer and spatially overlaid with rooftop geometry and solar potential derived from the technical assessment described in Section 3.4. This spatial integration enabled the identification of heritage-affected roof segments at the individual-building level, distinguishing between roof surfaces subject to regulatory oversight and those outside any protection regime. For buildings within settlement heritage areas and buffer zones, where protection applies to entire settlement ensembles rather than individual structures, the constraint layer captures both directly designated buildings and those affected by spatial proximity to protected areas.

Scenario-specific exclusion rules were then applied to reflect different interpretations of heritage regulations. Depending on the scenario, these rules range from full exclusion of all rooftop PV on buildings classified as monuments, to selective exclusion of visually exposed roof planes on buildings classified as building heritage or located within settlement heritage areas or buffer zones, to visibility-based exclusion of roof surfaces visible from key observation points (KOP) identified through GIS-based line-of-sight analysis. The translation of these exclusion rules into operational scenario assumptions is described in detail in Section 3.6.

This integration of heritage constraints enables the calculation of heritage-filtered deployable rooftop PV potential at the building level, clearly distinguishing it from purely technical potential and providing a more realistic basis for assessing feasible PV deployment in culturally sensitive environments. The difference between technical and deployable potential — quantified across scenarios in Section 4.2 — represents the regulatory reduction attributable to heritage protection under alternative interpretations of conservation requirements.

3.6. *Heritage-based scenarios for PV deployment and building renovation*

While the preceding sections quantify technical rooftop PV potential and identify buildings subject to cultural-heritage protection, these elements alone do not capture how conservation rules shape the feasibility of building renovation or how such constraints affect long-term decarbonisation outcomes. In heritage-rich areas, restrictions on envelope interventions — such as roof insulation, façade treatment or window replacement — can limit not only PV deployment but also achievable reductions in energy demand, thereby influencing future electricity consumption and self-sufficiency simultaneously.

To address this, a set of five heritage-based scenarios was developed to translate the protection regimes defined in Section 3.1.1 into explicit, operational assumptions regarding the admissibility of rooftop PV installations and building renovation measures across the four heritage categories. Each scenario represents a distinct regulatory interpretation, ranging from strict conservation practice to climate-oriented approaches that prioritise decarbonisation objectives while maintaining heritage-compatible design integration. The scenario structure is summarised in Table 5.

The restrictive scenario (S1) assumes strict conservation, prohibiting all visible envelope interventions — including PV installation and energy renovation — across all heritage categories. The trend-aligned scenario (S2) reflects current conservation practice, allowing limited interventions on non-monument heritage buildings while maintaining strict restrictions for monuments; PV deployment and renovation measures are conditionally permitted in BH and SH categories, and fully permitted in BZ. The permissive scenario (S3) enables broad envelope renovation across BH, SH and BZ categories — including roof insulation, façade treatment and window replacement — but continues to apply conditional restrictions on PV installation in BH and SH, identical to S2. This design reflects a deliberate analytical choice: S2 and S3 isolate the effect of renovation depth from PV admissibility, allowing separate assessment of their respective contributions to self-sufficiency and the municipal energy balance. As a result, deployable PV rooftop area is identical between S2 and S3, while electricity demand differs due to deeper renovation in S3. The visibility-based scenario (S4) introduces spatial differentiation by permitting PV and renovation measures only on roof and façade surfaces not visible from key public viewpoints, identified through GIS-based line-of-sight analysis. The climate-priority scenario (S5) prioritises decarbonisation objectives, allowing PV deployment and renovation across most heritage categories subject to architectural integration requirements.

For each scenario, technically suitable rooftop PV areas were filtered according to the applicable heritage rules described in Section 3.5, resulting in the calculation of heritage-adjusted deployable PV potential. In parallel, scenario-specific renovation allowances informed the building energy-demand assumptions applied in the 2025 baseline and 2050 electrification pathway described in Section 3.3. This integrated treatment enables systematic evaluation of how heritage regimes simultaneously constrain on-site renewable generation and energy-demand reduction, providing a robust basis for assessing building-level and municipal self-sufficiency under alternative regulatory interpretations.

For scenario S4, PV admissibility was determined through a GIS-based line-of-sight (viewshed) analysis. KOPs were defined by experts on the basis of local visual and cultural significance — including principal public spaces, panoramic viewpoints and approaches from which protected structures and the urban silhouette are most prominently perceived. Their spatial distribution is shown in Fig. 3 ($N = 39$). From each KOP, visibility to all roof surfaces was computed using the 1×1 m digital surface model, with surrounding buildings, terrain and vegetation as obstructions; surfaces visible from one or more KOPs were excluded from PV deployment, while non-visible surfaces were admissible, consistent with visibility-based heritage-PV assessments ([22,26]).

3.7. *Energy balance and self-sufficiency analysis*

To evaluate the implications of rooftop PV deployment and building electrification under different heritage-based scenarios, an energy-balance framework was applied at both building and municipal levels. The analysis compares final electricity demand with heritage-adjusted rooftop PV potential for two reference states: the current baseline (2025) and a fully decarbonised target state (2050). Intermediate years were not modelled, as renovation timing is uncertain, whereas compliance with long-term performance targets by 2050 is assumed. This two-

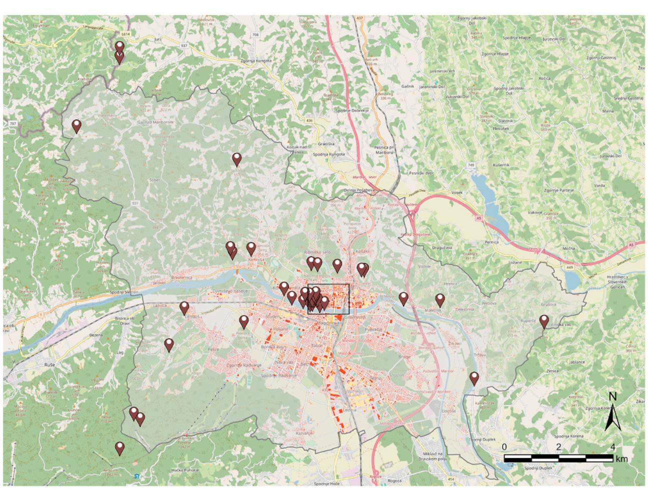

Fig. 3. Expert-defined Key Observation Points (KOPs) used in the visibility-based scenario (S4), shown against the cultural-heritage protection regimes across the Municipality of Maribor. KOPs represent public vantage points of high visual and cultural significance, including elevated locations on the urban perimeter from which the historic skyline is visible. The black rectangle marks the historic core, which is shown in greater detail in Figs. 4 and 6.

state comparison provides a clear assessment of the structural change in the electricity balance resulting from deep renovation and electrification, independent of transition pathway assumptions.

For each building, annual final electricity demand was calculated as the sum of electricity used for space heating, domestic hot water and other electrical end uses, following the methods described in Sections 3.2 and 3.3. Annual electricity demand was then compared with rooftop PV generation derived from the technical assessment (Section 3.4) and subsequently reduced according to the applicable heritage scenario (Section 3.6), enabling quantification of on-site electricity coverage under current and future conditions.

Building-level electricity self-sufficiency was defined as the ratio of locally generated PV electricity to total annual electricity demand:

$$\mathrm{SS_i} = \frac{\mathrm{E_i^{PV}}}{\mathrm{E_i^{el}}}$$

where E ∼ i ∼ ˆPVˆ denotes the heritage-adjusted annual PV generation of building i, and E_i^{el} its final electricity demand. Values of $SS_i \geq 1$ indicate theoretical full self-sufficiency on an annual basis. It should be noted that this indicator reflects annual energy quantities and does not account for temporal matching between PV generation and demand; actual self-sufficiency under hourly or seasonal profiles would typically be lower, particularly for buildings with high heating demand concentrated in winter months.

At the municipal scale, electricity demand and PV generation were aggregated across all buildings to assess collective self-sufficiency and system-level outcomes. Residual dependence on external electricity supply was captured using a gap-to-decarbonisation indicator, defined as the share of final electricity demand not covered by on-site PV generation:

$$\mathrm{Gap} = 1 - \frac{\sum_i \mathrm{E_i^{PV}}}{\sum_i \mathrm{E_i^{el}}}$$

This indicator quantifies the minimum share of municipal electricity demand that must be met through sources other than on-site rooftop PV — including grid-supplied renewable electricity, off-site generation, storage or demand-side flexibility measures. It complements building-level self-sufficiency by capturing aggregate system-level outcomes and providing a policy-relevant metric for assessing the contribution of rooftop PV to municipal decarbonisation targets under current conditions and a fully electrified future building stock.

To complement the annual self-sufficiency indicator, a monthly energy-balance analysis was carried out for a representative sample of buildings ($n = 8$) spanning the main building-use types and all four heritage-protection categories. Monthly rooftop PV generation was obtained by distributing annual generation according to the PVGIS-derived monthly irradiation profile for Maribor. Monthly electricity demand under the 2050 pathway was decomposed into a temperature-independent component (base electricity and domestic hot water, distributed uniformly) and a heat-pump space-heating component distributed in proportion to heating-degree-days (base 18 °C) and modulated by a temperature-dependent COP. Monthly self-sufficiency was defined as the ratio of monthly PV generation to monthly demand.

4. Results

4.1. *Building stock and heritage constraints overview*

The building stock of the Municipality of Maribor comprises 27,249 buildings, providing approximately 2.87 million m^2 of rooftop area that is technically suitable for PV installations (Table 6). Residential buildings (single−/two-dwelling and multi-apartment) represent 66.6% of the stock by count (18,142 buildings) and 54.6% of technically suitable rooftop area, while non-residential buildings account for 33.4% and

Table 6
Building stock and technically suitable rooftop area for PV installations in the Municipality of Maribor.

Building type	Number of buildings [–]	PV-suitable rooftop area [m^2]
Single- and two-dwelling residential buildings	16,074	590,515
Multi-apartment residential buildings	2068	978,577
Private office buildings	684	227,012
Educational and research buildings	195	177,402
Accommodation and food service buildings	248	71,816
Retail and service buildings	548	386,797
Cultural buildings	62	65,412
Healthcare buildings	71	55,198
Social residential buildings	62	60,014
Public administration buildings	39	20,672
Sports facilities	77	61,115
Agricultural buildings	7121	180,524
Total	27,249	2,875,055

45.4%, respectively. Single- and two-dwelling residential buildings dominate in terms of building numbers, accounting for almost four-fifths of all buildings, whereas multi-apartment residential buildings contribute the largest share of PV-suitable rooftop area due to their substantially larger roof surfaces. Non-residential buildings represent a smaller share of the total stock but display pronounced differences in rooftop availability — retail and service buildings, office buildings and agricultural buildings provide comparatively large PV-suitable roof areas relative to their counts, while public administration, healthcare and cultural buildings contribute only marginally to the overall rooftop area.

A substantial share of the building stock is subject to cultural-heritage protection regimes. In total, 2818 buildings fall under at least one heritage category, representing 10.3% of all buildings in the municipality. Critically, these buildings account for approximately 916,268 m^2 of PV-suitable rooftop area — corresponding to 31.9% of the total technically suitable rooftop area. This disproportionate share reflects the spatial concentration of large-roofed buildings within historically developed urban areas, where heritage designation frequently applies to entire settlement ensembles or buffer zones rather than individual monuments.

The distribution of heritage protection is highly uneven across building types (Table 7). Particularly high shares of protected buildings are observed among cultural buildings (91%), public administration buildings (76%) and educational and research buildings (56%). Elevated protection shares are also found in healthcare buildings (43%), accommodation and food service buildings (41%) and multi-apartment residential buildings (44%). These patterns primarily reflect the spatial concentration of these building types within historically developed urban areas. In contrast, single- and two-dwelling residential buildings (6%) and agricultural buildings (8%) exhibit comparatively low shares of heritage protection despite their numerical dominance in the overall building stock. Fig. 4 provides a spatial overview of the cultural heritage protection regimes across the urban fabric of Maribor.

This asymmetry has important implications for deployable rooftop PV potential: heritage-related constraints disproportionately affect building types with relatively large rooftop areas per building — particularly multi-apartment residential, public and cultural buildings — amplifying their relevance beyond what building counts alone would suggest.

The share of heritage-protected buildings in Maribor (10.3%) is broadly consistent with national-level protection rates reported for other European countries, which typically range from approximately 1% to 3% for individually listed buildings (Table 1). However, as observed elsewhere in historically developed urban cores — most notably in Amsterdam Centrum, where approximately 86% of residential buildings fall under heritage protection [43] — the share of protected buildings alone provides an incomplete picture of regulatory exposure, since spatial heritage regimes concentrate disproportionately in areas with large-roofed buildings of high PV potential. The finding that 10.3% of buildings in Maribor account for 31.9% of technically suitable rooftop area illustrates this asymmetry and suggests it may be a structural feature of heritage-constrained urban building stocks more broadly. The scenario-based quantification of these constraints on deployable PV potential is presented in Section 4.2. Agricultural buildings, although numerous (7121 buildings, 26% of the stock), are predominantly auxiliary structures with low electricity demand; they contribute about

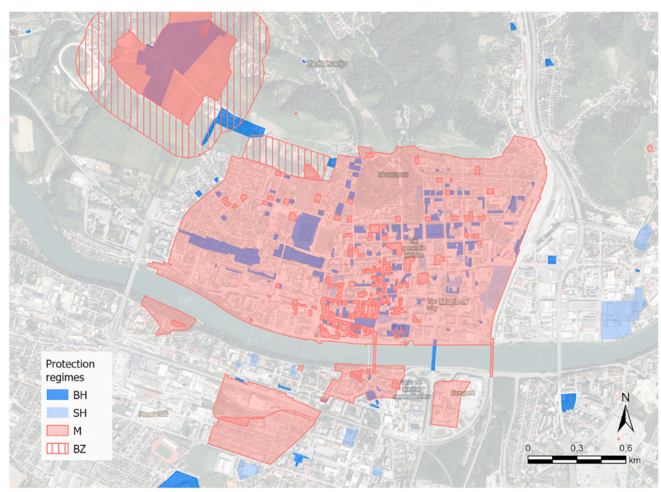

Fig. 4. Spatial extent of cultural heritage protection regimes in the historic centre of Maribor.

Table 7
Distribution of buildings and PV-suitable rooftop area by heritage category and building type in Maribor.

Building type	Number of buildings [–]				PV-suitable rooftop area [m^2]			
	BH	M	SH	BZ	BH	M	SH	BZ
Single- and two-dwelling residential buildings	79	713	28	38	5405	29,606	1147	1691
Multi-apartment residential buildings	279	551	62	4	144,592	206,392	75,488	1103
Private office buildings	37	87	25	2	18,289	38,918	20,381	222
Educational and research buildings	32	42	7	2	37,938	53,784	7932	473
Accommodation and food service buildings	15	34	4	1	11,234	17,510	531	151
Retail and service buildings	30	61	13	0	15,569	61,268	13,302	0
Cultural buildings	11	15	13	0	6832	22,623	29,840	0
Healthcare buildings	5	10	3	0	3106	4527	3309	0
Social residential buildings	10	15	2	0	10,786	12,292	2456	0
Public administration buildings	7	7	2	0	4960	10,006	702	0
Sports facilities	4	14	3	0	12,404	10,797	4981	0
Agricultural buildings	73	421	20	37	4074	8058	536	1054

6% of technically suitable rooftop area and only 1.5% of protected rooftop area.

4.2. Scenario-based reduction of deployable rooftop PV potential

Building on the structural constraints identified in Section 4.1, this section examines how different heritage-based scenarios translate regulatory frameworks into reductions of deployable PV potential. While the technically suitable rooftop area provides an upper-bound estimate of 2.87 million m^2 and 452.55 GWh/year of annual generation, the extent to which this potential can be realised in practice depends on how heritage protection regimes are operationalised under alternative assumptions regarding PV admissibility and visibility.

Across the five scenarios, deployable rooftop PV potential ranges from 68% to 93% of the technical baseline, corresponding to approximately 308–409 GWh of annual PV generation at the municipal scale (Table 8). Under the restrictive interpretation of heritage regulations (S1), nearly one third of the technical rooftop PV potential is rendered non-deployable, reducing the available rooftop area to 1.96 million m^2 and limiting annual PV generation to approximately 308 GWh. The trend-aligned (S2) and permissive (S3) scenarios yield identical deployable PV areas and generation values — 2.12 million m^2 and 309 GWh/year respectively — reflecting the deliberate methodological design described in Section 3.6, whereby these scenarios differ in renovation depth rather than PV admissibility. The visibility-based scenario (S4) produces closely aligned outcomes to S2 and S3, retaining approximately 74% of technical potential, while the climate-priority scenario (S5) retains more than 90% of the technical rooftop area, approaching the upper bound of feasible PV deployment under current building geometry and irradiation conditions.

Beyond aggregate capacity, scenario assumptions also affect the distribution of PV opportunities across the building stock. Under scenarios S1 through S4, approximately two thirds of buildings retain some deployable PV potential, whereas this share increases to 90% under the climate-priority scenario. This indicates that regulatory interpretation shapes not only the magnitude of rooftop PV deployment but also its inclusiveness at the building level — a distributional dimension that has direct implications for the equity of decentralised energy transitions in heritage-sensitive urban environments.

Taken together, these results demonstrate that the gap between technical and deployable rooftop PV potential in Maribor is primarily determined by the interpretation of heritage regulations rather than by technical constraints alone. The range between the most restrictive and most permissive scenarios — approximately 100 GWh/year — represents the regulatory space within which heritage authorities and energy planners can operate, highlighting the central role of institutional interpretation in shaping urban solar deployment outcomes.

Table 8
Scenario-based deployable rooftop PV potential in the Municipality of Maribor.

Scenario	Deployable PV rooftop area (m^2)	Share of technical area (%)	Deployable PV generation (GWh/yr)	Buildings with deployable PV (%)
Technical baseline	2,873,321	100%	452.55	100%
S1 – Restrictive scenario	1,957,433	68%	308.30	68%
S2 – Trend-aligned scenario	2,121,024	74%	309.01	68%
S3 – Permissive scenario	2,121,024	74%	309.01	68%
S4 – Visibility-based scenario	2,117,629	74%	308.30	68%
S5 – Climate-priority scenario	2,666,993	93%	409.22	90%

4.3. Building-level electricity self-sufficiency under heritage-constrained scenarios

Building-level electricity self-sufficiency outcomes reported in this section refer to the entire municipal building stock under current conditions (2025), including both heritage-protected and non-protected buildings. Heritage-based scenarios therefore affect only a subset of buildings, while most retain access to their full technical rooftop PV potential. Self-sufficiency patterns thus reflect the combined influence of regulatory constraints and the structural characteristics of the building stock.

Across all building groups and scenarios, a substantial share of buildings attains high or full electricity self-sufficiency under current conditions. This outcome is primarily explained by the present energy-use structure, in which many buildings rely on non-electrical energy carriers — district heating, biomass and fossil fuels — for space heating and domestic hot water, as described in Section 3.2. As a result, present-day electricity demand remains relatively modest, allowing rooftop PV to cover annual electricity needs for many buildings even under restrictive regulatory conditions. This finding underscores that high self-sufficiency levels observed under current conditions reflect structural features of the present-day energy system rather than the intrinsic solar potential of the building stock.

Scenario-dependent differences nevertheless emerge for specific building groups (Fig. 5). Under the restrictive scenario (S1), a larger share of residential and public-sector buildings exhibits very low self-sufficiency, particularly in heritage-sensitive urban areas where regulatory constraints exclude the largest roof surfaces from PV deployment. More permissive scenarios (S2–S4) shift buildings toward intermediate self-sufficiency classes, while the climate-priority scenario (S5) substantially reduces the proportion of buildings with minimal PV contribution and expands the share achieving full theoretical self-sufficiency.

The distributional analysis reveals clear differences across building groups. Residential buildings show the strongest sensitivity to regulatory assumptions, reflecting both their numerical dominance and heterogeneous exposure to heritage protection — a large subset of multi-apartment residential buildings is located within heritage-designated areas and therefore directly affected by scenario assumptions. Public-sector buildings remain constrained across all scenarios by high demand relative to available roof area, with heritage restrictions further limiting their already modest self-sufficiency potential. Service buildings exhibit limited variation across scenarios, reflecting lower exposure to heritage constraints and more favourable roof-to-demand ratios. Agricultural buildings consistently achieve the highest self-sufficiency levels due to large roof surfaces, low electricity demand and minimal exposure to heritage protection regimes.

These findings indicate that heritage regulations produce differentiated self-sufficiency outcomes across the building stock rather than uniform limitations, with distributional consequences for which buildings and building owners can benefit from decentralised PV generation. The spatial dimension of these outcomes is illustrated in Fig. 6, which shows building-level self-sufficiency across the municipality under current conditions. The implications of deep renovation and electrification for building-level and municipal self-sufficiency are examined in Section 4.4.

4.4. Municipal electricity balance under current and 2050 conditions

At the municipal scale, the electricity balance reflects the combined effects of building renovation, electrification of end uses and heritage-

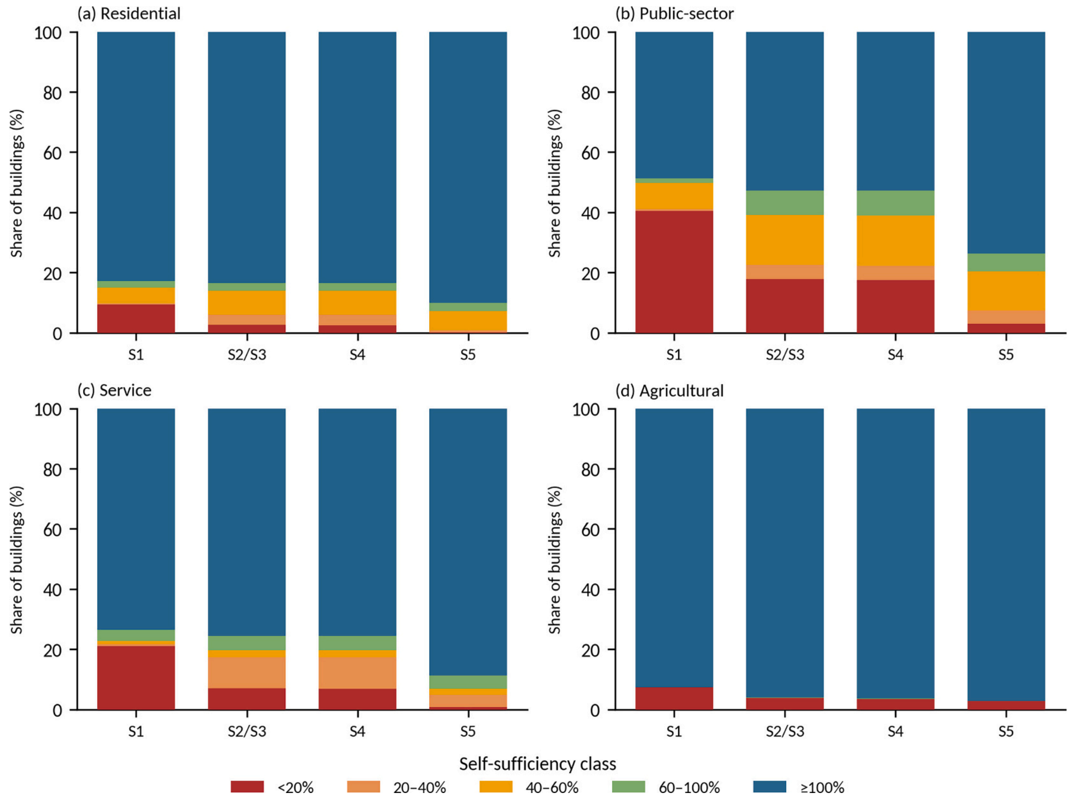

Fig. 5. Distribution of buildings across electricity self-sufficiency classes under heritage-constrained scenarios (2025), shown separately for (a) residential, (b) public-sector, (c) service, and (d) agricultural buildings. Electricity self-sufficiency is defined as the ratio of annual on-site photovoltaic generation to total annual electricity demand. The self-sufficiency classes represent the following coverage levels: Class 1: <20%, Class 2: 20–40%, Class 3: 40–60%, Class 4: 60–100%, and Class 5: ≥100% (theoretical annual self-sufficiency).

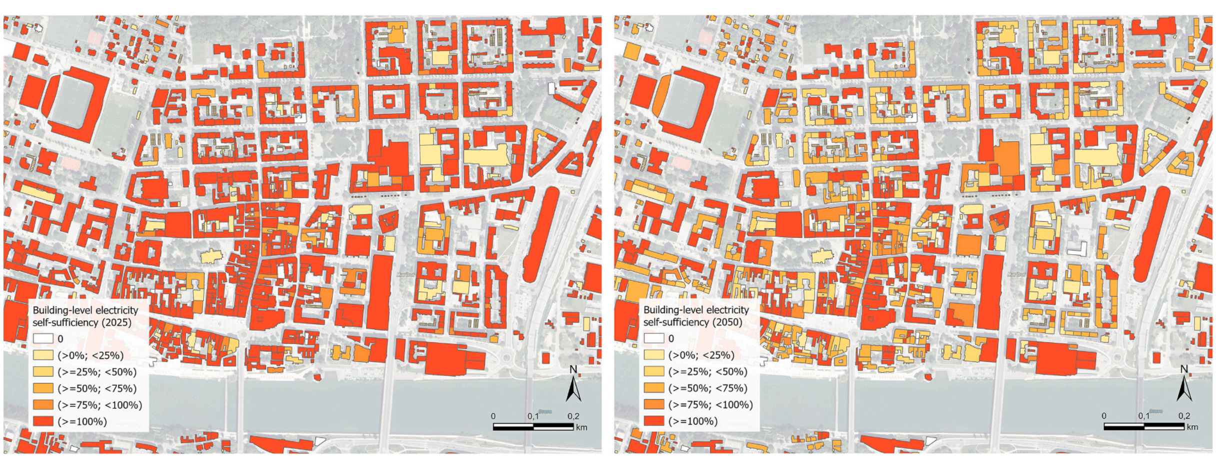

Fig. 6. Spatial distribution of building-level electricity self-sufficiency in Maribor in 2025 (left) and 2050 (right).

related constraints on rooftop PV deployment across the building stock. This section presents total electricity demand, deployable rooftop PV generation and the resulting residual electricity gap for the baseline year 2025 and the decarbonised target state in 2050, summarised in Table 9 and illustrated in Fig. 7.

In 2025, electricity demand and deployable PV generation are identical across all scenarios, reflecting observed energy-use patterns and the current early stage of rooftop PV deployment across the municipal building stock. Total electricity demand amounts to approximately 224.5 GWh/year, while deployable PV generation is estimated at 7.1 GWh/year — approximately 3% of total demand. This low share reflects the early stage of rooftop PV deployment in Maribor rather than a technical constraint, and should be interpreted as the starting point of a transition rather than a measure of solar potential. The resulting residual gap of approximately 217 GWh/year, corresponding to 97% of total demand, confirms strong current dependence on grid-supplied electricity across the municipal building stock.

By 2050, both total electricity demand and deployable rooftop PV generation vary across scenarios, reflecting differences in heritage-constrained renovation depth, electrification extent and PV admissibility. Deployable rooftop PV generation increases markedly across all scenarios compared to the 2025 baseline, driven by assumed widespread PV deployment on technically suitable rooftops. The highest generation levels are achieved under the climate-priority scenario (S5), where

Table 9
Municipal electricity demand, deployable rooftop PV generation, and residual electricity gap under heritage-constrained scenarios in 2025 and 2050.

Year	Scenario	Total electricity demand (GWh/yr)	Deployable PV generation (GWh/yr)	Residual gap (GWh/yr)	Residual gap (%)
2025	Baseline	224.5	7.1	217.4	97%
2050	S1 – Restrictive	368.3	308.7	59.6	16%
2050	S2 – Trend aligned	390.5	334.8	55.7	14%
2050	S3 - Permissive	428.9	334.8	94.1	22%
2050	S4 – Visibility-based	386.5	334.3	52.2	14%
2050	S5 – Climate priority	459.4	422.0	37.4	8%

deployable PV reaches approximately 422 GWh/year, reducing the residual electricity gap to about 37 GWh/year — roughly 8% of total demand. More restrictive scenarios yield lower PV deployment and retain larger residual gaps, ranging from approximately 14% under S2 and S4 to 16% under S1.

A notable feature of the 2050 results is that the permissive scenario (S3) produces a higher residual gap — 94.1 GWh/year, or 22% of demand — than the more restrictive S1, S2 and S4 scenarios. This seemingly counterintuitive outcome reflects the deliberate methodological design of S3, which enables broad envelope renovation across heritage categories while maintaining the same PV admissibility rules as S2. As a result, deeper renovation in S3 drives more extensive electrification of previously fossil-fuel-dependent heritage buildings, substantially increasing electricity demand without a corresponding increase in deployable PV generation. This finding illustrates that renovation depth and PV admissibility must be considered jointly rather than independently when assessing decarbonisation outcomes in heritage-constrained building stocks.

Despite substantial improvements across all scenarios, none achieves a net municipal electricity surplus by 2050. Even under the most permissive assumptions, increased on-site generation remains insufficient to fully offset demand growth associated with electrification. At the municipal scale, surplus generation within unconstrained parts of the building stock is absorbed by aggregate demand rather than producing a net excess. This finding is robust across all five scenarios and indicates that the persistence of the municipal electricity gap is primarily a system-level outcome driven by electrification dynamics rather than by heritage constraints alone — heritage protection influences the scale of the gap but not its qualitative character.

Overall, the results demonstrate that rooftop PV can substantially reduce municipal dependence on external electricity supply under deep decarbonisation pathways, but cannot deliver full electricity self-sufficiency at the municipal scale. The policy implications of this finding — and the complementary measures required to close the residual gap — are examined in the Discussion.

4.5. Seasonal mismatch between rooftop PV generation and electrified demand

The preceding sections assess self-sufficiency on an annual basis. Because deep electrification shifts a large share of building energy demand to electricity and concentrates it in the heating season, the annual indicator may overstate the effective contribution of rooftop PV. To examine this, a monthly energy-balance analysis was carried out for a representative sample of eight buildings spanning the main building-use types — single−/two-dwelling and multi-apartment residential, education, healthcare, office and agricultural buildings — and all four heritage-protection categories (M, BH, SH, BZ). The results are shown in Fig. 8.

At the level of the sample, rooftop PV generation and electricity demand are strongly anti-correlated in time. Generation peaks in summer, when monthly self-sufficiency exceeds 100% (reaching approximately 200% in July) and on-site production is in surplus, whereas demand peaks in winter, when heat-pump space-heating coincides with minimum PV output and monthly self-sufficiency falls to 14–17%. Although the sample attains an annual self-sufficiency of about 65% — computed here using technical PV potential as a conservative upper bound — this figure masks a pronounced seasonal deficit: roughly 42% of annual electricity demand occurs in the winter months (December–February), during which rooftop PV covers only about 20% of demand. The shoulder months (April and September) mark the transition between surplus and deficit.

This temporal pattern is consistent across building types, although its magnitude varies with the roof-area-to-demand ratio: agricultural buildings, with large roofs and low, non-electrified demand, remain in surplus for most of the year, whereas multi-apartment residential, healthcare and other demand-intensive buildings exhibit deep winter deficits even where annual self-sufficiency appears moderate (Fig. 8b–e). The seasonal gap is structurally more severe for heritage-constrained buildings, whose deployable PV area — and hence summer surplus available for nothing in winter — is reduced relative to their electrified demand.

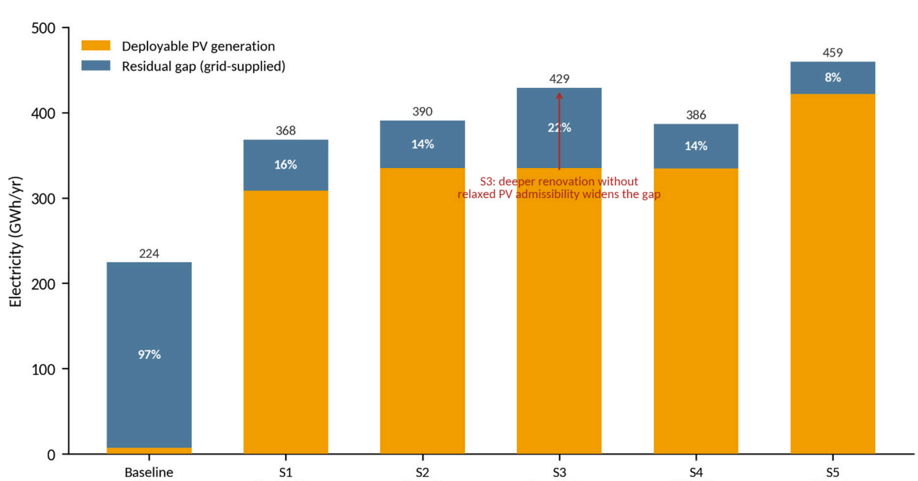

Fig. 7. Municipal electricity balance under heritage-constrained renovation and rooftop PV scenarios (2025 and 2050).

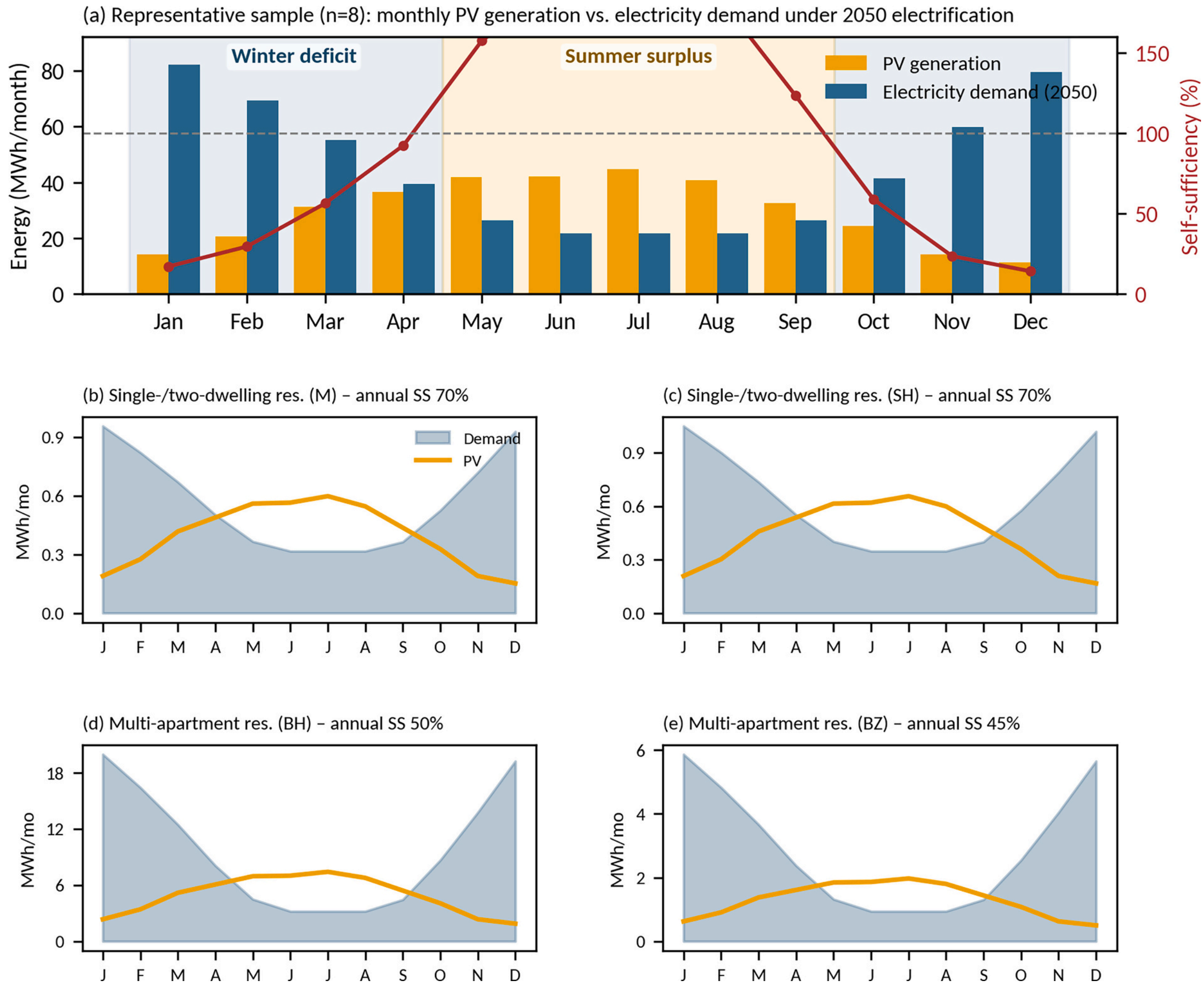

Fig. 8. Seasonal mismatch between rooftop PV generation and electrified electricity demand for a representative sample of buildings in Maribor under the 2050 pathway. (a) Aggregate monthly PV generation, electricity demand and self-sufficiency for the sample ($n = 8$); (b–e) monthly profiles for selected individual buildings across building types and heritage categories. PV generation is based on technical rooftop potential; monthly demand combines base electricity, domestic hot water and heat-pump space heating distributed by heating-degree-days and a temperature-dependent COP.

These results confirm that annual self-sufficiency is an incomplete indicator under deep electrification, and that the residual gap identified at the municipal scale (Section 4.4) is concentrated in winter. Closing this gap therefore depends primarily on inter-seasonal flexibility — electricity storage, demand-side management and exchange with the wider grid — rather than on additional rooftop PV capacity alone, an implication examined further in Section 5.

5. Discussion

5.1. Heritage constraints as a structural modifier of deployable PV

The results show that cultural-heritage protection does not act as a binary barrier to rooftop PV but as a structural modifier that reshapes where and to what extent deployment is feasible. In Maribor, only 10.3% of buildings are formally protected, yet these account for 31.9% of technically suitable rooftop area — more than three times their share of the stock. This asymmetry reflects the spatial concentration of large-roofed buildings (multi-apartment residential, public and cultural facilities) in historically developed cores, where protection typically applies to settlement ensembles and buffer zones rather than individual monuments. Assessments based on the share of protected buildings therefore systematically understate the regulatory impact on deployable capacity, because heritage constraints filter out a disproportionate share of the most valuable rooftop area before any technical or economic criteria are applied.

This pattern is unlikely to be specific to Maribor. At the national level, designated heritage buildings represent roughly 9% of the Slovenian stock, rising to over 21% once settlement heritage areas and buffer zones are included, confirming that spatial regimes — not individual listings — constitute the dominant regulatory context for rooftop PV. The comparative data in Table 1 suggest the same blind spot is pan-European: although the share of protected buildings ranges from below 1% to over 86% [43], the structural asymmetry between building counts and rooftop area is likely to recur wherever spatial heritage regimes concentrate in dense historic cores. Solar cadastres and municipal energy plans should therefore represent heritage protection not as a simple exclusion criterion but as a graduated, spatially differentiated constraint layer distinguishing monument, building-heritage, settlement-heritage and buffer-zone categories.

Crucially, the magnitude of this modification is governed by institutional interpretation rather than the legal framework itself. Across the five scenarios, deployable potential spans a regulatory range of approximately 100 GWh/yr — equivalent to nearly 22% of municipal electricity demand — without any change to the underlying legislation. Restrictive interpretations confine PV to a small subset of buildings, whereas visibility-based ([24,28]) and climate-priority approaches retain most technical potential and broaden participation from about two-thirds to 90% of buildings. This points to regulatory flexibility, clearer procedural guidance and capacity-building within heritage authorities — rather than binary choices between strict conservation and unrestricted deployment — as the most productive policy levers.

5.2. Self-sufficiency, electrification and the municipal energy balance

At the building level, heritage constraints produce differentiated rather than uniform self-sufficiency outcomes, concentrating multi-apartment residential and public-sector buildings in heritage-sensitive areas in the lowest self-sufficiency classes. The high self-sufficiency observed under current conditions is, however, largely an artefact of the present energy-use structure: because many buildings still rely on district heating, biomass or fossil fuels for heat, present-day electricity demand is low enough to be covered by limited PV. This masking effect disappears under the 2050 electrification pathway, when heat-pump heating sharply raises electricity demand and the distributional consequences of heritage constraints become pronounced — an equity dimension that will intensify as electrification progresses.

The temporal analysis (Section 4.5) further qualifies the annual indicator. PV generation and electrified demand are strongly anti-correlated in time: monthly self-sufficiency exceeds 100% in summer but falls to 14–17% in winter, when heat-pump demand coincides with minimum PV output, and roughly 42% of annual demand occurs in the winter months. Annual self-sufficiency therefore overstates the effective contribution of rooftop PV, and the residual gap is structurally concentrated in winter.

Aggregated municipally, these dynamics yield a robust conclusion: rooftop PV alone cannot deliver electricity self-sufficiency under deep decarbonisation, with a residual gap ranging from about 8% of demand under the climate-priority scenario to 22% under the permissive scenario. A counterintuitive but policy-critical result is that the permissive scenario (S3) produces a larger residual gap than more restrictive scenarios: enabling deeper envelope renovation without simultaneously relaxing PV admissibility drives more extensive electrification of previously fossil-fuelled heritage buildings, raising demand without a corresponding increase in deployable generation. The persistence of the gap across all scenarios indicates that it is primarily a system-level outcome of electrification dynamics; heritage protection influences its scale (the S1–S5 difference is ~22 GWh/yr) but not its qualitative character.

This result has a direct and somewhat counterintuitive policy implication. In heritage-constrained building stocks, deep envelope renovation electrifies previously fossil-fuelled buildings and raises their electricity demand, yet where PV admissibility is not relaxed in parallel (as in S3), this additional demand cannot be met on site and is instead transferred to the grid. A renovation-first strategy — encouraged by efficiency-focused instruments such as the EPBD — may therefore increase grid dependence and winter peak demand in precisely those historic areas where on-site generation is most restricted, even as it reduces final energy use and carbon emissions. The implication is not that renovation should be slowed, but that renovation and PV admissibility must be sequenced and enabled jointly: relaxing envelope-renovation rules while maintaining restrictive PV rules shifts heritage buildings from fossil-fuel dependence to structural grid dependence, with consequences for both system balancing (Section 4.5) and the electricity-cost exposure of their occupants. Coordinated relaxation of renovation and PV constraints — together with storage and demand flexibility — is required to avoid this trade-off.

5.3. Policy implications and transferability

These findings carry concrete implications across governance levels. Solar cadastres and renewable-energy targets built on technical rooftop potential systematically overestimate feasible deployment in heritage-rich areas; heritage-adjusted, deployable-potential assessment should therefore become a standard planning input, and the scenario framework developed here offers a practical template for testing how sensitive decarbonisation trajectories are to regulatory interpretation. This is directly relevant to current EU instruments: the European Solar Rooftops Initiative [56], operationalised through the rooftop-solar obligation of the recast EPBD (in force since May 2024), introduces a phased, legally binding requirement to install rooftop PV — on public and commercial buildings above 250 m^2 (2026–2027) and on new residential buildings (2029–2030) — yet allows heritage-related exemptions without any systematic method for deciding where, within protected stocks, deployment remains feasible. By distinguishing technical from deployable potential at the building level across graduated heritage categories, the framework fills this gap: it identifies which protected buildings can realistically comply, which warrant exemption, and under which regulatory interpretation compliance could be extended, turning a binary ‘exempt/obliged’ decision into a graduated, evidence-based one. Neither the revised EPBD nor RED III currently addresses this interaction explicitly, risking misalignment between policy ambition and spatial reality.

The framework is transferable to any municipality with a multi-tiered heritage system and building-level spatial data. Its four protection categories (M, BH, SH, BZ) follow a declining-strictness logic structurally analogous to systems across Central and Western Europe, so application elsewhere requires city-specific datasets but no methodological adaptation. While the absolute magnitude of heritage constraints varies between cities — from low-listing contexts such as France to highly protected cores such as Amsterdam Centrum [41] — the structural asymmetry between protected building share and protected rooftop area documented here is likely a general feature of heritage-constrained stocks. Comparative studies across cities with contrasting protection profiles would further validate the framework and support standardised heritage-aware solar cadastres at European scale.

Comparison with previous works underlines both the consistency and the novelty of the approach. Visibility-based studies of historic cores report that heritage constraints can reduce deployable rooftop PV by more than half under restrictive interpretations ([22,23]). Our municipal-scale reductions are smaller (deployable potential of 68–93% of the technical baseline) because the analysis covers a complete stock in which only 10.3% of buildings are protected; restricting attention to protected buildings yields reductions of comparable order, confirming consistency once scope is accounted for. At the same time, the framework quantifies features not previously captured: the asymmetry between the share of protected buildings (10.3%) and of protected rooftop area (31.9%); the building-level distribution of self-sufficiency; and the counterintuitive S3 result, whereby deeper renovation without relaxed PV admissibility widens the residual gap — effects that archetype-level retrofit studies (e.g. [41]) cannot resolve.

Several limitations should be acknowledged. The analysis is based on a static representation of the building stock and a deterministic definition of the five heritage scenarios; it captures the structural effect of heritage protection on deployable potential, but not the gradual evolution of the stock, of protection regimes, or of PV and renovation technologies toward 2050. The visibility scenario (S4) relies on KOP defined by domain experts, which introduces a degree of subjectivity. The deployable-potential estimates are also an upper bound with respect to factors not modelled explicitly — most importantly distribution-grid hosting capacity, which in dense urban areas limits how much decentralised PV can be absorbed locally and tends to be most acute in historically developed cores, where ageing infrastructure spatially coincides with the highest concentration of heritage protection; heritage and grid constraints may therefore compound, the former restricting where PV can be installed and the latter how much generation can be used. Together with on-site storage, demand-side flexibility and the costs of deep renovation in protected buildings, this reinforces the need to couple rooftop PV with storage, increased self-consumption, demand-side flexibility and coordinated grid reinforcement, particularly in historic environments [57]. Finally, the seasonal analysis was conducted at monthly resolution for a representative sample of eight buildings rather than hourly for the full stock, so it characterises the seasonal mismatch but not sub-daily balancing or self-consumption dynamics. Future work should extend the framework toward hourly, stock-wide co-simulation coupling rooftop PV with storage and demand response, incorporate a dynamic building-stock and grid-capacity model, and test transferability to other European cities with differing protection regimes and urban morphologies — refining the quantitative estimates while preserving the study's central, transferable contribution: the treatment of cultural-heritage protection as a structural modifier of deployable rooftop PV potential.

6. Conclusions

This study developed and demonstrated a heritage-aware analytical framework that explicitly distinguishes technical from deployable rooftop PV potential, integrating building-level energy-demand modelling, a GIS-based rooftop PV cadastre and scenario-based interpretation of cultural-heritage regulations. Applied to the Municipality of Maribor, Slovenia, it quantifies the gap between theoretical solar potential and realistically deployable capacity under current conditions and a deep-decarbonisation 2050 pathway.

Three findings stand out. First, cultural-heritage protection acts as a structural modifier rather than a binary barrier: although only 10.3% of buildings are protected, they hold 31.9% of technically suitable rooftop area, and deployable potential ranges from 68% to 93% of the technical baseline — a regulatory space of roughly 100 GWh/year governed by institutional interpretation rather than the legal framework itself. Second, heritage constraints produce differentiated, not uniform, self-sufficiency outcomes; the high self-sufficiency seen today is largely an artefact of the present, still partly fossil-based energy structure, and the distributional (equity) consequences will intensify as electrification deepens. Third, rooftop PV alone cannot deliver municipal self-sufficiency under deep electrification: a residual gap of 8% (climate-priority) to 22% (permissive) of demand persists in 2050, and the permissive scenario's larger gap shows that renovation depth and PV admissibility must be treated as complementary, not independent, policy levers.

Taken together, these results establish that heritage protection must be integrated explicitly — as a graduated, spatially differentiated constraint — into solar cadastres, municipal energy plans and national renewable-energy strategies, and into EU instruments such as the rooftop-solar obligation of the recast EPBD. Approaches based solely on technical rooftop suitability systematically overestimate feasible PV deployment in heritage-rich environments, a challenge shared by many European cities with historically developed building stocks.

Future work should extend the framework toward hourly, stock-wide co-simulation coupling rooftop PV with storage and demand-side flexibility, incorporate the economic dimension of heritage-compatible PV, and apply the framework comparatively across European cities with contrasting protection regimes — refining the quantitative estimates while preserving the central, transferable contribution: the treatment of cultural-heritage protection as a structural modifier of deployable rooftop PV potential.

CRediT authorship contribution statement

Gašper Stegnar: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Jure Čižman:** Visualization, Validation, Methodology, Investigation. **Tadej Bevk:** Validation, Methodology, Investigation, Formal analysis. **Maja Debevec:** Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Damjana Gantar:** Validation, Software, Project administration, Funding acquisition, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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