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Photovoltaic potential estimation of natural and architectural sensitive land areas to balance heritage protection and energy production

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ABSTRACT

The study aims at defining a methodology for estimating the photovoltaic potential of natural and heritage sensitive land areas, balancing heritage protection and energy production thanks to the involvement of Public and Heritage Authorities. This method is applied to the Como Land Area (Italy) for verify its feasibility in territories with heterogeneous morphologies, landscapes, and constraints. First, "*urban area typology*" and their "*recurring buildings typologies*" are identified using local sources and tools with the support of the Public Authorities for considering similar shapes, features, materials, roof geometries, and orientations as well as future policy developments. Then, heritage-compatible photovoltaic technologies and suitable surfaces are selected for one "*recurring buildings typology*" respecting original appearance, values, and meanings thanks to the enquires with the local Heritage Authority. Considering these recommendations, the photovoltaic potential in covering energy and building needs is estimated considering the impact of urban geometries, self-shadings, heritage and territorial constraints. Energy profiles are generated using stochastic models calibrated to include occupant diversity and cultural factors. An average index for the photovoltaic potential reduction due to the heritage-compatibility is found respectively of 21% and 16% compared with the maximum theoretical potential achievable in the building envelope and in the roof.

1. Introduction

Renewable energy sources (RES) can significatively contribute to the zero-carbon transition of the existing building stock through the reduction of energy needs [1], increasing also building renovation rates [2,3], environmental resilience [4,5], cleaner production [6], and quality of life [7]. Furthermore, RES are crucial to face the worldwide climatic situation [8,9], and to mitigate carbon emissions [10]. Withing RES, photovoltaic (PV) technologies are promising solutions for promoting the energy transition towards low-carbon systems, thanks to the easily integration into existing roofs and façades [10], and to the on-site energy production [11]. Traditionally, PV applications in buildings are divided in Building Attached Photovoltaics (BAPV) and Building Integrated Photovoltaics (BIPV) [12]. BAPV systems are mounted directly on the building envelope for generating electricity [12,13] while BIPV systems are multifunctional elements that substitute the existing building component [13,14] for providing both electrical supply and additional functions (e.g., noisy and thermal insulation, weatherproofing, fire protection, daylighting, shading, mechanical resistance, structural integrity, and security) [13–16]. Otherwise, PV applications must move from individual buildings to urban contexts to guarantee a sustainable development from social, environmental, and economic points of views [17]. Cities and urban districts represent an ideal scale for incorporating PV systems in the existing building stock, to produce localized energy demand exploiting existing spaces, infrastructures, and networks [10]. This also improves their energy performances, according to the Sustainable Development Goals (SDGs) defined by the United Nation (UN) n. 7, 11, and 13 [18].

In existing areas, the European regulations require significant PV implementation to face the recent energy crisis and to support the energy transition [6]. This aspect could have a negative impact especially on the preservation of their traditional features and natural values [19]. On the contrary, these territories represent "[…] *the single biggest potential sector for energy savings*" [20] with a crucial role to fulfil the EU targets [6]. Besides, the progress on aesthetical aspect and energy performance of innovative PV systems can favor large-scale solar applications in urban contexts [21,22]. Despite this, PV applications in natural and architectural sensitive contexts have several acceptability barriers, related to information (i.e., lack of knowledge, training and capacity

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Nomenclature

Acronyms

PV	Photovoltaics
BIPV	Building Integrated Photovoltaic
BAPV	Building Attached Photovoltaic
RES	Renewable Energy Sources
DIVA	Radiance, Data-Interpolating Variation Analysis
CBDM	Climate Based Daylight Modelling
GIS	Geographic Information System
SDGs	Sustainable Development Goals
UN	United Nations
BSM	Building Stock Modelling
SHF	Single-Family House
MFH	Multifamily House
OB	Occupants' Behavior
CREST	Centre for Renewable Energy Systems Technology
ISTAT	Italian National Institute of Statistics
UK	United Kingdom
TMY	Typical Meteorological Year
3D	Three Dimensions
DBTR	Lombardia Regional Topographic Database
DUSAF	Lombardia Regional Database "Land use and coverage
PGT	Territorial Governance Plan
SIBA	Regional Architectural Heritage Information System
SIRBEC	Regional Information System of Cultural Heritage
PTC	Spina Verde territorial control plan

building) [23,24], economy (i.e., high cost, initial investment, long payback period) [11,23–27], policies (i.e., complexity, lack of financial incentives) [28–30], technical performances (i.e., visual impact, energy performance) [11,30–34], and human resources (i.e., lack of technical experts and marketing professionals) [23,24]. Furthermore, some doubts for their application in dense urban areas concern the reduction of solar radiation potential due to mutual shadings, especially compared with isolated constructions [35–37]. Application barriers are higher in heritage and natural contexts, due to their fragility, and well-recognized values [38]. Otherwise, PV benefits in these contexts are recognized in scalability, versatility, reliability, on-site production, self-consumption coverage, energy peak shaving, and low maintenance costs [19].

2. Theoretical background

Studies on the integration of PV systems refers mainly to heritage and historic buildings rather than urban and natural areas. Design and evaluation criteria for PV integration on heritage buildings are deeply investigated by national or local guidelines, as clearly synthetized by the recent literature [19,38]. These criteria are "*universally recognized*" thanks to the reference to the architectural restoration theories [38]. Otherwise, slowly differences pertain to the scale of cultural heritage (building, town, or landscape), and to the protection level (e.g., protected or vernacular building) [19]. Higher integration levels refer to PV integration in protected landscapes, and to damaged buildings [38]. General criteria can be synthetized as [38]:

- "*Visual compatibility*" for preserving the original visual appearance in terms of sizes, proportions, colors, and features.
- "*Material compatibility*" for conserving original materials, and construction techniques as well as for reducing material losses.
- "*Minimum intervention*" for reducing the impact of PV integration on original surfaces, both guarantee the preservation of original materials and aesthetic apparencies.
- "*Reversibility*" for underdoing the PV intervention without damaging the original building.
- "*Durability*" of the PV intervention for preventing structural, hygrothermal, electrical, energy-efficiency risks.
- "*Balance between preservation and energy production*" for dimensioning the PV systems according to energy needs.

These criteria are applicable also at urban level [19], despite only few studies are specifically referred to PV integration or to PV potential estimation in heritage cities and towns. On the contrary, several studies concern the PV potential evaluation of existing urban areas without a specific attention to heritage features. Tools are divided in solar cadasters and bottom-up models. Solar cadasters provide information on the PV potential of building surfaces (i.e., roofs, façades) for supporting informed decision-makings through web-based 2 dimensional (2D), or orthophoto maps [21]. They have a deterministic approach focused on the PV potential of individual standard buildings, neglecting the presence of heritage constraints [33,34], the potentials of aggregated buildings [10,21], and the geometric regularity of the arrangements [21]. Otherwise, bottom-up models assess the PV potential of the entire building stock. In this case, statistical and technological data are clustered to define "*representative buildings*" characterized by similar shapes, features, sizes, materials, roof geometries and orientations [35]. Several studies refer to the impact of urban forms on PV potential estimation in existing cities and districts [10,21,34–41]. To this purpose, Geographic Information System (GIS) techniques are matched with simulation tools (i.e., Radiance, Data-Interpolating Variation Analysis (DIVA), Climate Based Daylight Modelling (CBDM), CitySim, etc.) for spatial and non-spatial data management, cluster creation, queries interactions, and digital solar mapping [36].

Only few studies refer to heritage towns, focusing mainly on PV visibility assessment using target-based approaches [42,43], and standard PV integration criteria [44] for rooftops [42–44], and vertical façades [42,43]. Target-based visibility assessments, particularly, develop specific algorithms for the PV potential optimization in existing towns, considering the visual impact of PV technologies from public spaces as the most significant criterion for selecting available envelope surfaces [42,43]. First, the LESO-QSV (Quality-Sensitivity-Visibility) assesses the criticity of the PV installations in heritage territories [43] combining PV visibility and heritage sensibility. Due to the high sensibility of heritage towns, a careful selection of PV geometry, materiality, and pattern is needed. Second, the "*target-based method*" evaluates the PV visibility only on heritage elements, according to their compatibility [42]. The comparison of these two approaches on the historical center of Geneve in Switzerland showed that respectively 50% and 64% of roofs can be used for PV installations [42]. Thus, the evaluation of heritage values increases the compatibility of PV system in protected areas.

The major gaps highlighted by the literature are: (i) lack of decision-making processes for PV estimation of architectural sensitive urban areas, considering their outstanding values, territorial and architectural constraints; (ii) PV potential calculations are applied mainly to heritage buildings rather than to urban areas; (iii) urban studies refers only to historic towns while natural land areas are not analysed; (iv) urban morphologies and mutual shadows between buildings are neglected despite their high impact on energy production; (v) Heritage and Public Authorities are not involved despite they important role in real decision-making processes and workflows, despite their important role in decision-making is always recognized [22,32,42]; and (vi) lacks in the evaluation of the PV potential of aggregated buildings, and the geometric regularity of the arrangements [30]. Current literature is not based on real workflows for heritage areas. The definition of a real methodology for balancing heritage protection and PV production is fundamental for the energy transition at international level for minimizing the aesthetical impact of PV systems on traditional urban settings, also respecting historic features, and heritage values [22,30,32].

To overcome these gaps, the present study aims at defining a methodology for the PV potential estimation in natural and architectural sensitive land areas, considering both natural and heritage values and constraints with the support of local Heritage and Public Authorities as well as the impact of urban morphologies, aggregated buildings, and mutual shadows. In this way, the present study overcomes all the gaps highlighted by the literature as: (i) the decision-making process estimates the PV potential of architectural sensitive (ii) urban and (iii) natural land areas; (iv) the impact of urban morphologies and shadows is considered; and (v) Heritage and Public Authorities are involved in all the process. Thus, the study serves as a roadmap for integrating PV technologies in urban planning, architectural design, authorizative, and decision-making process for the traditional building stocks. The methodology is applied to the Province of Como, an important natural and architectural sensitive land area in the northern part of Italy. The use of a real case study permits to verify its applicability, suitability, and replicability in real contexts, also simplifying the decision-making process according to real needs and skills.

The study is structured in two main sections:

- Section 3 that aims at developing the methodological framework for the estimation of the PV potential in natural and heritage sensitive areas.
- Section 4 that aims at presenting qualitative and quantitative results in the Como Land Area, to verify the applicability of this methodology in real contexts, also describing its replicability in similar or different contexts.

3. Methodology

According to the definition of the United Nation Educational, Scientific and Cultural Organization (UNESCO) [45,46], "*cultural heritage*" is classified in: "*monuments*" (e.g., paintings, sculptures, architectural and archaeological works, inscriptions, etc.); "*groups of buildings*" (e.g., separated or connected buildings with a value for architecture, homogeneity, or place in the landscape); and "*sites*" (e.g., works of man or combined works of nature and man, and archaeological sites). The present study concerns all the categories of "*cultural heritage*", involving vernacular districts, historic and traditional towns, traditional building stocks, and historic buildings in protected landscapes.

The proposed methodology simulates a real and replicable decision-making process founded on a cross-disciplinary approach that involves urban planning, heritage conservation, environmental sustainability, building physics, and energy simulation techniques, procedures, and tools. This methodology balances three main elements: (i) conservation of heritage and natural values; (ii) definition of human behavior and electric needs; (iii) estimation of PV potential. The novelty of the study concerns:

- Development of a simple, logical, and replicable methodology for real PV planning and authorization processes in sensitive areas, considering urban, buildings and heritage constraints.
- Integration of different tools (e.g., GIS, focus group, simulation models) and sources (e.g., territorial/heritage databases, maps, photos).
- Involvement of the local Public Authority for clustering urban areas and building typologies considering local morphologies, planning criteria, policies, and future urban developments.
- Involvement of the local Heritage Authority for defining heritage-compatible PV technologies, considering heritage values, constraints, conservation levels, and modifications of the original building appearance.
- Evaluation of the impact of urban geometries, self-shading between buildings, heritage and territorial constraints that affect the total PV production in dense historic contexts.
- Identification of the local hourly electricity demand profile using stochastic international models calibrated to the local energy habits, technical features of market available PV technologies, local weather, and morphological conditions.
- Definition of average values for the reduction of the PV potential due to the heritage-compatibility.

The methodology is structured in five phases (Fig. 1):

- Phase 1: Urban and building mapping.
- Phase 2: PV heritage compatibility assessment.
- Phase 3: Energy profiles calculation.
- Phase 4: PV potential estimation of heritage-compatible scenario.
- Phase 5: Comparison with maximum theoretical PV production.

Each phase is detailed below.

3.1. Phase 1: Urban and building mapping

Urban and building mapping aims at identifying the buildings suitable for PV installation. It is structured in the following phases:

- Urban area typologies mapping.
- Building typology mapping.
- Database of building typology.

Urban mapping aims at recognizing the recurring "*urban area typology*", defined as urban areas characterized by the presence of similar urban and environmental features in terms of morphology, urban and population density, land use, landscape type, infrastructures, urban and heritage protection levels. The typology of the urban area impact also on the built environment, as the territorial morphology influences urban forms, architectural features, and building materials selection in a specific area. Thus, the study of the urban historical evolution also allows the identification of "*recurring building typologies*" [33,47,48,49] or "*archetypes*" [50,51] for each urban area, defined as buildings characterized by similar features, shapes, dimensions, ages, functions, constructive techniques, thermal properties, climate data, indoor temperature, or use of appliances [33]. Urban and building mapping is based on the collection and the analysis of statistical information, territorial and urban plans, municipal cartography, building regulations, heritage records, online tools. Table 1 shows data to be analyzed at international level (phase, aspect, data), and specific sources considered for the study area (specific source, type, and reference).

Urban aspects consider traditional urban parameters, such as urban densities, land uses, landscape types, for having an overview of urban morphology and constraints. Visual data are added for reflecting the potential visual impact of PV systems as suggested by the literature [42,43]. Heritage aspects consider landscape, and monumental constraints according to the general UNESCO classification of heritage value to have a replicable procedure. To verify its applicability at Italian level, the heritage constraints are classified according to the Legislative Decree 42/2004 [60] in:

- Area of public interest refers to physical-geographical elements (marine coasts and banks, rivers, mountains, volcanoes, glaciers, natural parks and reserves, wetlands), land uses (woods, forests, and civic uses), and historical evidence (botanical gardens, archeological sites) [60, art. 142].
- Landscape preservation constraint concerns immovable natural artifacts with an outstanding heritage value or geological singularity, traditional towns, panoramic beauties, palaces, gardens, and parks of uncommon beauty [60, art. 136].

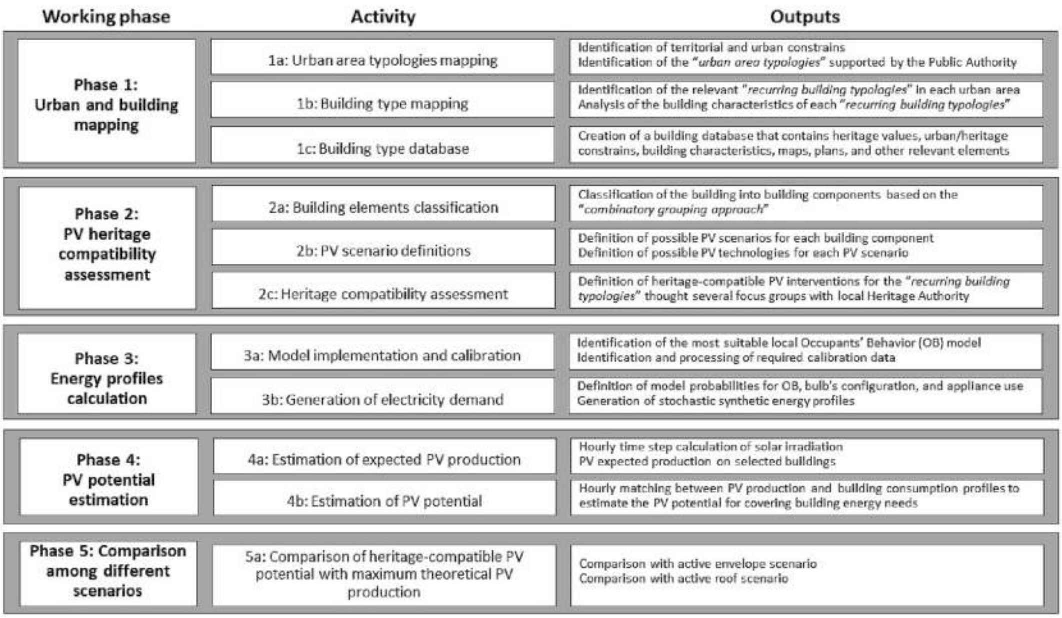

Fig. 1. Methodology for the PV potential estimation in heritage sensitive areas and heritage buildings (Source: Authors' elaboration).

Table 1
Data to be analyzed and specific sources for the Como Land Area (Source: Authors' elaboration).

Data to be analyzed International level Phase	Aspect	Data	Lombardy Region Specific source	Type	Reference
Urban area typology mapping	Urban aspects	Urban density	Regional Topographic Database (DBTR)	Webtool	[52]
		Land uses	Regional Database "Land use and coverage (DUSAF)	Webtool	[53]
			Territorial governance and control plan (PGT)	Document	[54]
		Landscape type	DUSAF	Webtool	[53]
			Geographic Viewer 3D	Webtool	[55]
			Geoportal Como	Webtool	[56]
		Urban characteristics	PGT	Document	[54]
		Visual data	Google Maps – On site visits	Webtool	[57]
	Heritage aspects	Landscape constrains	Regional Architectural Heritage Information System (SIBA)	Webtool	[58]
		Monumental and historical constrains	Vincoli in rete	Webtool	[59]
Building typology mapping	Heritage aspects	Landscape constrains	SIBA	Webtool-	[58]
		Monumental and historical constrains	Regional Information System of Cultural Heritage (SIRBEC) sheets	Webtool	[61]
			Vincoli in rete	Webtool	[59]
	Building Aspects	Buildings general description	Spina Verde territorial control plan (PTC)	Document	[62]
			PGT	Document	[54]
		Construction density	Cadaster	Webtool	[63]
		Building plant	Cadaster	Webtool	
		Year class Building Use Conservation state	Only general information on PGT	No exhaustive data	[54]
		Building height and number of stories	Geographic Viewer 3D	Webtool	[55]
		Cartography, metadata	Geoportal Como	Webtool	[56]
		Roof and façade typology and materials	Google Maps Geographic Viewer 3D	Webtool	[5755]

- Architectural heritage constraint for historic and monumental architectural heritage includes buildings and urban spaces of artistic or historical interest [60, art. 10].

This Italian classification also reflects the legislative framework of other Countries (e.g., France, Austria, Germany, Switzerland). The interaction between urban and heritage aspects permits the identification of the recurring "*urban area typologies*". Different sources for urban and building aspects are present, ensuring the quality of information. Otherwise, data and tools are generally not integrated. Local Public Authorities should be involved in specific focus groups for considering and integrating in correct way all the data. Also, their direct knowledge of the local territory allows the identification of "*recurring building typologies*" for each "*urban area typology*". To this purpose, building typology mapping analyses heritage and building features of all the buildings present in the territory (e.g., historical period, materials, height, housing density, architectural elements, presence of heritage constraints, etc.) through GIS tools. Collected data should be inserted in a database to give an overview of the building stock. The parameters to be considered for each building typology are type, use, year class, heritage and landscape constraints, conservation state, construction density, number of stories, features of the envelope (e.g., roof typology and materials). Hence, this database is at the basis of the PV potential estimation in the historic built environment because it clearly supports the definition of possible PV integration scenarios that respects original values and mandatory constraints as well as considers conservation levels (as low levels change the materiality and the appearance of original values), energy needs (estimated by the number of house-holders), urban geometries (as PV production changes according to urban shadow), and building features (as PV selection is influenced by building sizes, dimensions, proportions, colors, …).

3.2. PV heritage compatibility assessment

The evaluation of heritage compatibility of the widest range of possible PV solutions for the "*recurring buildings typologies*" is structured in the following steps:

- Classification of the buildings into building elements.
- PV scenario definitions, concerning both collection and selection of PV technologies.
- Heritage compatibility assessment of PV scenarios through the realization of focus groups with the local Heritage Authority.

The classification of the buildings into building elements is based on the "*combinatory grouping approach*" introduced by the Italian standard UNI 8290–1 [64]. This approach is valid for the residential sector, but it can be also applied to other functions [64]. This standard categorizes the building systems in three homogeneous levels:

- Classes of technological units composed by groups of singular building components [64].
- Technological units realized by groups of building components characterized by technological-compatible functions for obtaining specific requirements [64].
- Classes of technical elements composed by building components «(…) *capable of performing, completely or partially, functions proper to one or more technological units*» [64].

The first two levels represent the constructive working to meet users' requirements, while the third level provides the technical products classes available on the market [64].

Then, for each class of technical element is defined the widest range possible of PV scenarios. Two different PV approaches are considered [65]:

- Approach 1, based on the use of conventional PV modules mounted directly on the building element for generating electricity.
- Approach 2, based on the use of innovative multifunctional PV systems that replace the existing building component providing energy and constructive functions, such as mechanical resistance, structural integrity, daylight, security, thermal insulation, acoustic control, fire, or weather protection [66,67].

These two approaches are selected for evaluating their differences in terms of aesthetic integration and energy performance, as they can be both applied to historic buildings respecting heritage conservation issues [38,68]. In some cases, only approach 2 is feasible, as conventional PV technologies are not transparent (thus not applicable on windows for scenarios 5, 14), or walkable (thus not applicable on pavements for scenario 7). Then, the possible PV technologies are identified for each approach, according to research projects [69–82], case studies [30,32], and contexts awards [83] on PV integration in heritage buildings and landscapes. Based on this information, 24 possible PV scenarios are identified, as illustrated below (Table 2).

This matrix (Table 2) supports Public and Heritage Authorities in the selection of possible PV interventions, focusing on the whole building envelope, not only on roofs as traditionally appears. Then, it is important to know that any intervention on cultural heritage that modifies its external appearance must be internationally authorized by the Heritage Authority [84]. Thus, the heritage-compatibility of PV technologies on

Table 2
Possible scenarios for PV integration in buildings (Source: Authors' elaboration).

Class of technological unit	Technological unit	Class of technical element		PV approach	PV technology	PV scenario number
Building envelope	Vertical	Façade	External	1	Opaque, recognizable (blue)	1
				2	Opaque, hidden-colored	2
			Internal	1	Opaque, recognizable (blue)	3
				2	Opaque, hidden-colored	4
		Vertical window		2	Semi-transparent, uniform	5
	Inferior horizontal	Basement		–	–	–
		Horizontal window		2	Semi-transparent, uniform	6
	Exterior horizontal	Pavement		2	Opaque, hidden-colored, walkable	7
	Superior horizontal	Roof	Flat	1	Opaque, recognizable (blue)	8
				2	Opaque, hidden-colored	9
			Tilted	1	Opaque, recognizable (blue)	10
					Opaque, recognizable (red PV tile + blue PV cells)	11
				2	Opaque, hidden-colored	12
					Opaque, recognizable (red PV tile + blue PV cells)	13
		Dormer or skylight		2	Semi-transparent, uniform	14
External partition	Vertical	Solar shading		1	Semi-transparent, visible PV cells (blue)	15
				2	Semi-transparent, uniform	16
		Balustrade and parapet		1	Semi-transparent, visible PV cells (blue)	17
				2	Semi-transparent, uniform	18
		Lift		1	Semi-transparent, visible PV cells (blue)	19
				2	Opaque, hidden-colored	20
	Horizontal	Balcony		–	–	–
		Canopy		1	Semi-transparent, visible PV cells (blue)	21
				2	Semi-transparent, uniform	22
	Vertical and horizontal	Greenhouse		1	Semi-transparent, visible PV cells (blue)	23
				2	Semi-transparent, uniform	24
	Sloped	Staircase		–	–	–
		Flight		–	–	–

specific buildings must be defined with the support of focus groups with the local Heritage Authority that help the designers to consider original architectonic appearance of traditional features, heritage values, and conservation levels. The compatibility between heritage values and PV systems should be carefully assessed case-by-case, pondering risks, and benefits (section 4.2) [32].

3.3. Energy profiles calculation

The estimation of the PV potential, meaning in this study the PV capability to cover the energy needs, requires hourly profiles of the buildings' electricity demand. This data is directly influenced by OB, defined by the occupant's presence and actions (OPA). Traditionally, these profiles are derived from standard and fixed schedules and occupant-related power densities [85]. Nevertheless, the literature showed that this OB representation is oversimplified, since it describes the occupants as homogeneous and passive agents, although they are diverse and actively interacting with the building and its systems [85]. To integrate advanced OB models, it is necessary to identify the relevant OB, select the most suitable modelling approach, and adapt available models considering both the development and deployment contexts [85]. Regarding the first point, electricity use in the Italian residential sector is mainly due to appliances use [85]. Space heating and domestic hot water demand are serviced by other energy sources, such as natural gas [86]. While this is expected to change with boilers being replaced by heat pumps in the following years, in this study a conservative perspective is considered hence, only the appliances are considered. Additionally, occupancy is a prerequisite for these actions, so it is also included.

Regarding the modelling approach, the OB research field explored several strategies such as data-based, stochastic, probabilistic, and agent-based models [87]. Ongoing research in the field is working towards defining systematic guidelines for choosing the most suitable approach and key aspects [85]. The characteristics of the key performance indicators (KPI) that are being studied and the spatial resolution of the problem are two main points to analyze. When assessing the PV potential in the region, it becomes highly important the amount of electricity used, and the time of this use. This data is affected by the people's diversity (i.e., people's lifestyles, socio-cultural background, etc.). Further, it is necessary to balance the accuracy and complexity of the models. Thus, for regional and local context, it is not feasible to consider agent-based models, which are computationally expensive to simulate all the agents (i.e., occupants). Considering these points, stochastic models are chosen as the most suitable approach. The well-established and validated Centre for Renewable Energy Systems Technology (CREST) demand model is selected for generating the electricity demand profiles [88,89]. Despite being developed for the United Kingdom (UK) context, its structure allows being calibrated for the local context extracting, adapting, and implementing occupancy, appliance use, and electricity use. Occupancy and appliance use models are based on an inhomogeneous in time, first-order Markov chain model that uses probability matrices to define states representing occupancy (i.e., combined stated of presence distinguishing whether the occupant is active or inactive), and the given activities (e.g., watching TV, cooking). Then active occupancy and activities are mapped to defined appliances (e.g., TV, oven), and to estimate their consumption. As for the lighting system, a survival model is used to estimate the number of switch-on events, their duration, and power consumption. This model can be adapted to other Countries to consider local specificities and habits. In the present paper this model is adapted to the Italian context, but it can be adapted to worldwide contexts. Here, the methodology is showed in detail to be perfectly replicable in all Countries. National statistics are gathered from different sources (for example in Italy, national sources are the Italian National Institute of Statistics (ISTAT) [86], the Italian Time Use Survey (TUS) [90]), and published monitoring campaigns [91]. Table 3 summarizes the main parameters and sources of the models that are specific to the UK and need to be transferred to national level.

Table 3
Model parameters (Source: Authors' elaboration).

Parameter	UK statistic sources	IT statistic sources	Use
Number of Occupants	User-defined	ISTAT [86]	Occupancy model Appliance model
Initial state probability matrix	UK TUS	Italian TUS [90]	Occupancy model
Transition state probability matrix	UK TUS	Italian TUS [90]	Occupancy model
Activity probability distribution	UK TUS	Italian TUS [90]	Appliance model
Appliance's Ownership	UK context [88]	ISTAT [91]	Appliance model
Appliance's use	UK context [88]	ISTAT [91]	Appliance model
Bulb's configuration	UK context [88]	None	Lighting model

One of the main differences between the UK model and the one adapted for Italy concerns the definition of the household number of occupants. In the Italian case, for each simulation, the number of occupants is sampled randomly considering national statistics of household size [92]. Italian TUS [90] aims at identifying how Italian population uses its time, registering daily activities of 50.000 people, and 20.000 families in the period 2013–1014. The survey contains the weekly and daily diary of activities, connected with individual background (e.g., sex, age, study level, …). The use of this database permits to calibrate the user behavior, considering specific cultures. In this case, a python script is realized to automatically elaborate more than 50 million of data to define the energy profile. Additionally, the Italian TUS [90] is processed for deriving the probability matrices for the initial state and the transition state for occupancy, and probability distributions for the activities being performed at each time step. The electric appliances included in this model are fridge, freezer, vacuum, computer, printer, TV, kitchen HOB, oven, microwave, dishwasher, washing machine, dryer. The ownership statistics, main power features and use characteristics are adapted using different sources [86,91,93]. For the bulbs configuration (i.e., the number of bulbs per household), it is assumed that the differences between the Italian and the UK contexts are not significant. This step is important for individuating general energy needs connected to statistical data on user behavior at national level.

3.4. PV potential estimation

The PV potential of heritage-compatible PV interventions is evaluated with a Python tool script created by Eurac Research to optimize PV systems since the buildings' early design stage [94]. This tool is based on the stochastic approach of the ray-tracing procedure to calculate the incoming irradiation by the software DAYSIM. Due the use of a ray-tracing technique, the simulation depends on simulation parameters (e.g., number of rays traced from each measurement position), and is less dependent by the complexity of the shape compared to deterministic approaches. Thus, it permits to simulate both simple and complex shapes typical of historic buildings, as well as the effects of partial shading and reflections from nearby buildings, and site morphologies (e.g., presence of mountains, lakes, and so on). The tool starts calculating the hourly irradiation on selected building surfaces. It divides these surfaces in a grid and places a sensor in the center of each portion. For each sensor, the hourly plane of array irradiance is calculated using the ray-tracing simulation software RADIANCE [95]. The resulting hourly irradiation profile is considered to calculate the expected PV production, also taking into account specified PV system features. The PV production profile is finally compared to the building electric demand profile, allowing the estimation of their matching, thus of the directly self-consumed energy portion.

In this study, the performance indicators evaluated are::

- Expected annual PV production [kWh].
- Expected self-sufficiency [%] referring to the PV contribution to supply the building electric demand, considering the portion of PV electricity directly self-consumed.

To this purpose, for each building, the following input data are considered:

- Local weather data for a typical meteorological year (TMY) in the format "Energy Plus Weather".
- Geometric 3-Dimentions (3D) building including the surroundings (landscape morphology, buildings, close district).
- Surfaces available for PV installation.
- Possible PV integration scenarios according to the suggestion of the Heritage Authority.
- Technical features of the PV modules, in terms of photovoltaic efficiency, performance ratio.
- Hourly profile of the building energy demand, containing electric consumptions of devices and systems.

The software defines the cloud of points that indicates the coordinates and the directions of the potential PV positions. For each position and direction, it calculates the hourly irradiation (or irradiation matrix) using the DAYSIM tools for Radiance. A complete description of the functioning of this tool is given by [94]. The tool suggests the optimal PV system configuration for each building (thus, position, and number of PV panels), considering specific heritage constraints, and PV features suggested by the Heritage Authority. It is a preliminary suggestion, since it requires assumptions and default inputs, to be performed in the first phases of the building design process.

3.5. Comparison with maximum theoretical PV potential

The tool is further applied to evaluate the "maximum theoretical PV potential" in the 10 reference palaces assuming two different approaches:

- Active envelope, considering the whole building envelope as able to produce energy.
- Active roofs, considering the building roof, both flat and tilted as able to produce energy.

For both the approaches, an efficiency based on current average efficiencies of commercial crystalline silicon modules is assigned to the surfaces.

The simulation results, in terms of average self-sufficiency, are compared to the heritage-compatible PV technologies integration scenario. The objective is to identify an indicator reflecting the impact of integrating heritage compatible technologies in the buildings under study, to be generalized and used as support to the PV potential evaluation in other centers similar to the Como land area.

4. Results

The results of the single phases are presented in the following sections. As mentioned before (section 2), the study is applied to the Como Land area in Italy. This wide territorial area has heterogeneous urban, landscape, building, and heritage features, and is composed of nine municipalities: Colverde, San Fermo della Battaglia, Montani Lucino, Como, Brunate, Maslianico, Cernobbio, Moltrasio, Carate Urio (Fig. 2).

4.1. Phase 1: Urban and building mapping

The urban area typologies mapping analyses several urban datasources at local level (Table 1), to cluster the urban areas in specific "*urban area typologies*". First, all the three national urban heritage protection levels are present in the area (Fig. 3).

From the discussion with the local Public Authority (in this case both with Regional, Provincial Authorities to consider different constraints, needs, and approaches), the municipality of Como results the most representative area because it collects the highest concentration of all urban and heritage protection levels. Therefore, since Como is

Fig. 2. The territorial area: (a) aerial view (Source © Elena Lucchi).

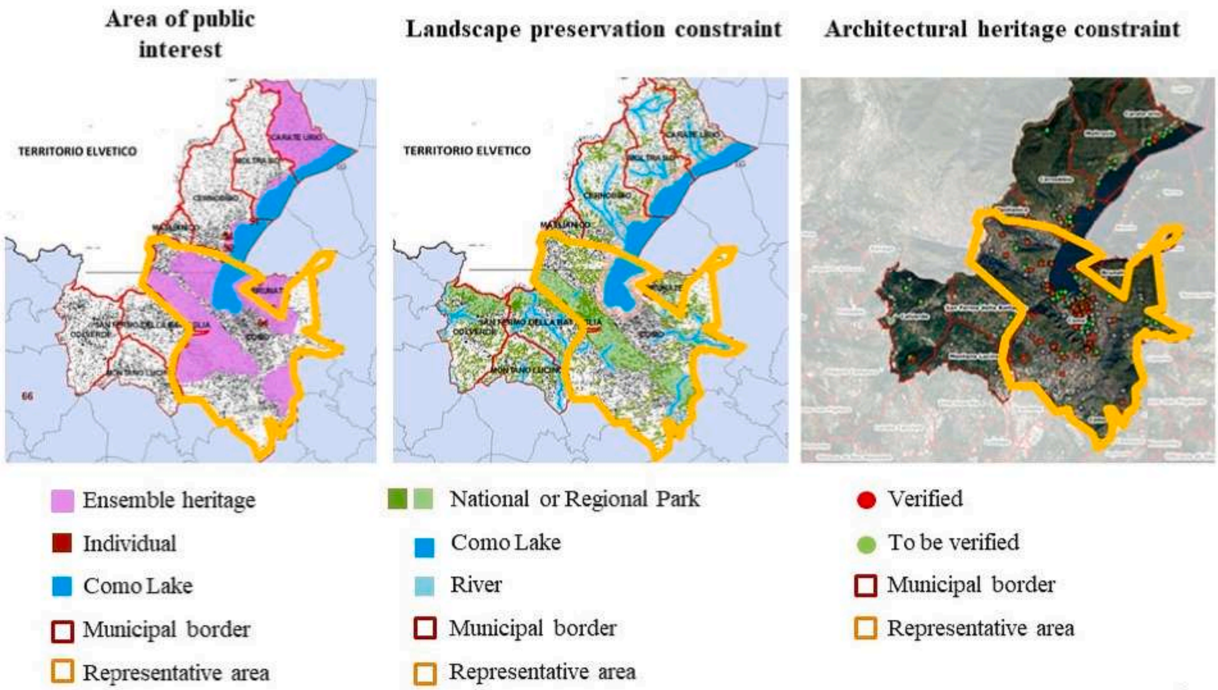

Fig. 3. Urban heritage protection levels identified in the territory (Source: Authors' elaboration).

considered as fully representative of the specificities of the area and with a high number of documentary sources, it has been selected for identifying urban densities, land uses, and landscape types through the support of GIS tools [52,53,56]. Como municipality presents the following characteristics (Fig. 4):

- Three urban density levels: dense, middle-dense, and low-dense.
- Four main land use types: residential, agricultural, industrial, and woodland.
- Two main landscape type: green and tree-covered areas, urbanized areas.

The interaction among these data permits the identification of four main "*urban area typologies*" (Table 4, and Fig. 5): (i) historical centers; (ii) regional parks; (iii) rural areas; and (iv) industrial areas.

Historical centers, regional parks, and rural areas are full of protected buildings with landscape or/and architectural values. The historical center is full of landscape (e.g., traditional town, lake's palaces and gardens of uncommon beauty) and architectural protection constraints (e.g., city's palaces, urban monuments) as well as of areas of public interest (e.g., lake bank, river, archeological site). The regional park "Spina Verde" is classified as agricultural area. It is selected as representative rather than other rural areas for the presence of

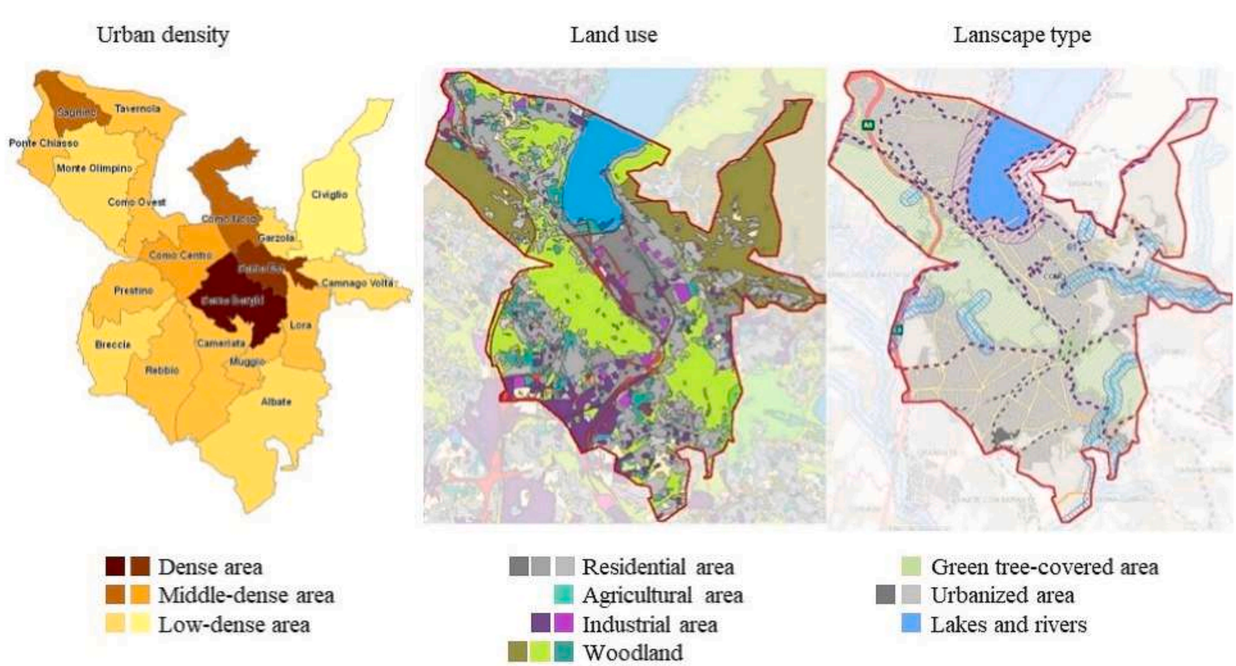

Fig. 4. Urban density, land use, and landscape type identified in the representative area (Source: Authors' elaboration).

Table 4
Urban area typologies within Como (Source: Authors' elaboration).

Area typology	Description	Selected area
Area 1 Historical centers	Parts of the territory composed by dense urbanized areas with residential use, subject both to landscape and architectural heritage preservation constraints	Como historical center, composed by the districts: Porta Torre, San Rocco, Città Murata, Santissima Annunciata, Borgo Vico, San Giuliano, Sant'Agostino e San Vitale
Area 2 Regional parks	Area of considerable public interest, characterized by low-dense areas, residential use and subject to landscape preservation constraints	Spina Verde Regional Park
Area 3 Rural areas	Area with agricultural interest that represents a symbolic value of rural civilization. They are characterized by low density areas generally subject to landscape preservation constraints	Spina Verde Regional Park
Area 4 Industrial areas	Areas of industrial civilization that have been transformed in the last 15 years and, therefore, are subject to a reduced protection level. They are generally located in middle-dense areas with industrial use.	Ex Ticosa, torrente Cosia and Camerlata

landscape preservation constraints, and of sites with symbolic value of rural civilization, such as rural dwellings and vernacular buildings for agricultural activities (about 63%) as well as old churches, and archeological ruins. Several industrial areas are present, including "disused industrial areas" subject or not to preservation, such as areas with historical evidence of industrial settlements subject to monumental preservation (e.g., Ex Ticosa and Torrente Cosia), and industrial areas with productive buildings without any historical value (e.g., Camerlata). Although a major part of industrial areas is not subject to heritage constrains, they are included for their high PV potential.

The "*recurring building typologies*" identified in the four "*urban area typology*" are (Fig. 6): (i) palaces; (ii) villas; (iii) rural buildings and farmhouses; (iv) industrial buildings; (v) public buildings; (vi) single-family house (SHF), multifamily house (MFH), and apartment blocks.

Palaces and villas are the most common types. They embody the historic places of residence. Palaces are mainly located in the dense historic town, and are characterized by high heritage values, architectural heritage constraints, and residential functions. Villas are also widespread over the territory with the aspect of residence of panoramic or agricultural value. These suburban buildings are not protected with architectural heritage constraints, but are sited in landscape constraints areas and are usually surrounded by large parks and gardens. Rural buildings indicate old farmhouses, although most of them have lost their original function. They are protected only by landscape constraints. Industrial buildings include protected and not protected productive buildings. These building can be identified as industrial archeology, as in the most cases are not used anymore and are characterized by high damage levels. Public buildings refer to the public construction with a special function not included in the previous categories. Lastly, residential buildings without historical-artistic or landscape values, are identified as apartment blocks, SHF, and MFH. All the different types of buildings within the areas are analyzed to identify morphological and typological recurrences. The parameters examined and associated with each type are year class, conservation state, building use, number of stories, construction density, heritage and landscape constrains, roof and façade typology and materials. Several data are available for the constructions placed in the historical centers of Como, while other areas have lower information on conservation state, year class, and building use (Table 5).

As a result of the analysis, a database is produced to map all the data for all the building types identified, except the apartment blocks, SHF and MFH typologies that are already collected in the "TABULA web tool" [96]. Information collected includes images, architectural elements, and heritage and landscape constrain. A total number of 63 buildings are analyzed, classified, and included in the database. This database gives a complete and reliable view of the state of art of the historic built environment, including the critical analyses of the heritage compatibility of PV (Fig. 7).

This instrument help Public and heritage Authorities in the evaluation of values, constraints, and acceptability of PV systems in natural and heritage sensitive areas.

4.2. PV heritage compatibility assessment in the selected buildings

According to the building stock analysis, palaces are selected as a representative "*recurring building typology*" for their high presence on the territory as well as for their significant heritage values and good conservation levels. Palaces have both heritage and urban constraints as well as high conservation levels. On the contrary, villas, residential buildings and rural buildings have only landscape constraints while industrial buildings can be protected or not. Villas and residential buildings have good conservation levels, while the other two typologies are damaged, abandoned, and/or significantly modified losing their original appearance. Public buildings have different typologies and functions (kindergarten, school, municipium), thus it is difficult to recognize a significative "*recurring building typology*". Also, palaces are selected because their PV potential is reduced compared to other building typologies for the presence of strictly heritage constraints, shadows, and urban morphologies due to their urban location. Otherwise, the other typologies are mainly isolated buildings located near parks, gardens, or on the lakeside. Otherwise, palaces are used only as residential buildings, with high energy consumption. Consequently, they are a representative typology for estimating the PV potential applying the present methodology.

Heritage compatibility assessment of PV systems is realized on all the palaces present in the area, considering their shapes, features, sizes, materials, roof geometries, and orientations [35]. Here, the application of PV integration criteria suggested by international guidelines for heritage buildings and areas are not appropriate, as they report general principles without discussing their integration on specific buildings [19,22,32,38,97,98]. PV integration scenarios (section 3.2) in these palaces are evaluated with the support of the local Heritage Authority of the Lombardy Region through five focus groups that simulate the standard authorization process in protected buildings, with the aid of visual materials, GIS tools, and on-site visits [19]. These focus groups are structured in the following way: (i) the first one discussed PV acceptability on architectural heritage for understanding barriers, potentials, and challenges [84]; (ii) other three focused on guidelines, case studies, and PV products for collecting universally recognized criteria [19]; and (iii) the last concerned PV integration in the selected buildings (Table 6). The last focus group was conducted through a detailed assessment of the database realized, evaluating heritage values and constraints, building additions, and modifications, and conservation state. To this purpose, also an on-site visit to these buildings was provided with the support of the local heritage Authority. These activities allow the identification of admitted, not allowed, and to be specifically evaluated interventions, according to the Italian legislation [60]. The replicability of these results is showed by [19,38]. The results are presented below (Table 6).

PV interventions on façades (scenarios 1 ÷ 4), and solar shadings (scenarios 15, 16) are not compatible with traditional shapes, colors, materials, and constructive features of these old palaces. Intervention on roof could be realized considering only compatible PV technologies (scenarios 8 ÷ 13). Interventions on windows, skylights (scenarios 5, 6, 14), and canopies (scenario 22) are allowed respecting the aesthetical appearance of the original building. Furthermore, conventional PV

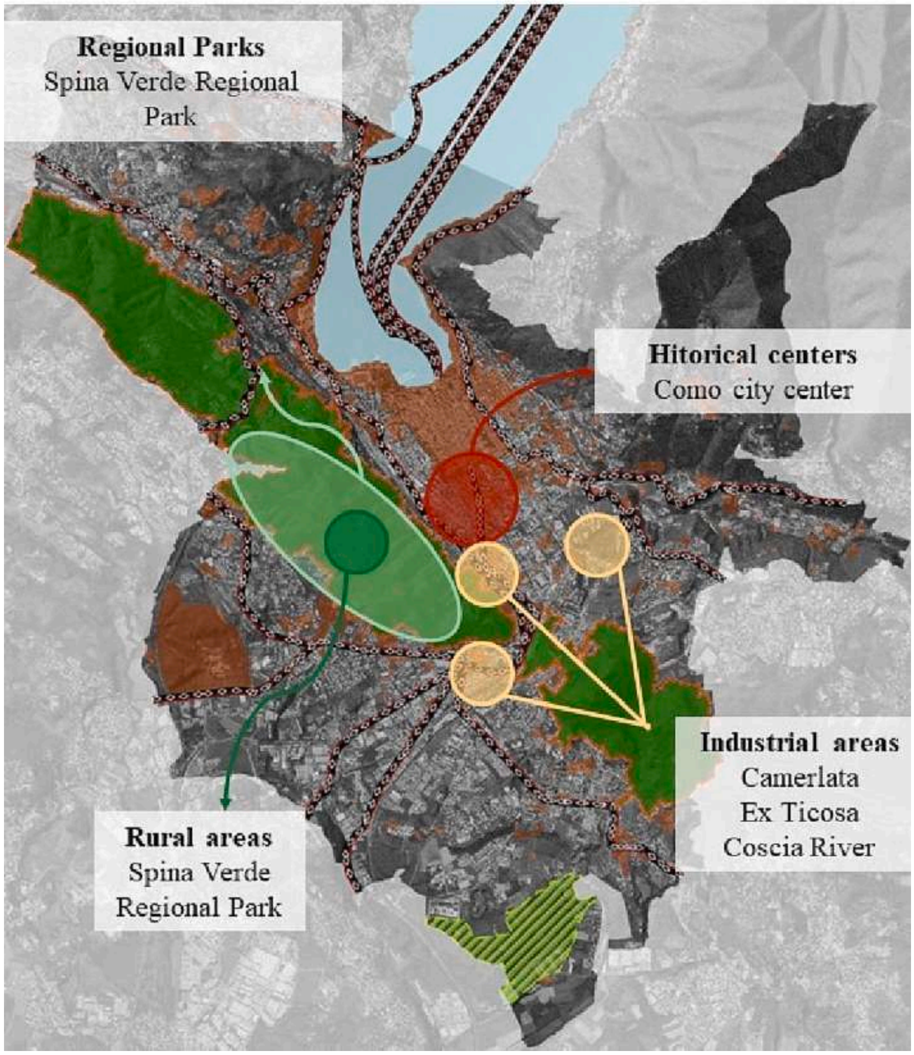

Fig. 5. Map of urban area typologies.

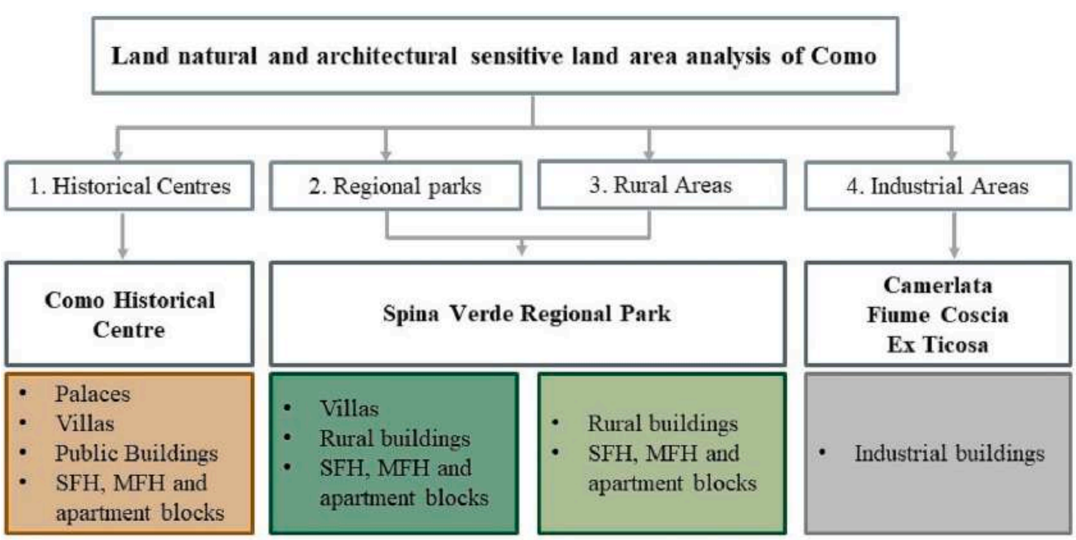

Fig. 6. Urban area and Building typologies mapped within the Como municipality (Source: Authors' elaboration).

Table 5
Example of the data collected in the database (Source: Authors' elaboration).

Area type	Building type	Number	Data collected	Examples
Historical centers	Palace Villa Public buildings (e.g., kindergarten, church)	10 11 1	Images Denomination Address Year class Heritage constraints Urban constraints Conservation level Number of stories Features of the roof Building use	
	SFH, MFH, and apartment blocks	Tabula web tool	–	–
Regional parks	Villa Rural building and farmhouses	13 10	Images Denomination Address Year class Heritage constraints Urban constraints Conservation level Number of stories Features of the roof Building use	
	SFH, MFH, and apartment blocks	Tabula web tool	–	–
Rural areas	Rural building and farmhouses	5	Images Denomination Address Year class Heritage constraints Conservation level Number of stories Features of the roof Building use	
	SFH, MFH, and apartment blocks	Tabula web tool	–	–
Industrial areas	Industrial buildings (e.g., mills and production buildings)	13	Images Denomination Address Year class Heritage constraints Conservation level Number of stories Features of the roof Building use	

technologies are forbidden in the selected case studies (Table 6, scenarios 1, 3, 8, 10, 11, 15, 17, 19, 21, 23). This is due to the presence of blue colors, high reflectance, standard shapes, and dimensions that are not compatible with traditional terracotta clay tiles, plaster façades, wooden or marble balconies, and transparent windows. Otherwise, innovative PV technologies (e.g., hidden-colored PV panels or tiles, semi-transparent uniform modules) should be evaluated case-by-case by the local Heritage Authority for verifying the match with their aesthetic appearance and original geometries, colors, patterns, and texture (Table 6, scenarios 12, 13, 18, 20, 22, 24,). In general, colored PV modules are compatible with traditional constructive technologies of the area: terracotta is suggested for clay roof tiles, anthracite or grey for stones, and white for plasters. PV frames should be minimized, also guarantying their match both with PV panels, and original roof's colors. Also, semi-transparent uniform PV modules can be evaluated for window glasses and greenhouses (Table 6, scenarios 5, 24). Here, both solar concentrators and thin-film PV can be used, respecting shapes, and colors of the original building element. The allowed innovative PV technologies are taken as reference for the next part of the study (sections 4.4-4.5), which previously requires the calculation of the buildings' hourly electric profiles.

4.3. Energy profiles calculation in the selected buildings

Advanced OB modelling strategies are adapted and implemented to generate synthetic electricity demand profiles tailored for the building archetypes of Como. Since OB is influenced by environmental, time-related, contextual, physiological, psychological, social, cultural, and random factors, the UK models are transferred to the Como's context (section 3.4). First, it is assumed there are no significant differences between Italian and Como's lifestyle, especially considering data accuracy and resolution [86,90,91]. The number of households is defined stochastically, using national statistical data, and considering the probability of having a specific number of members (from 1 to 6). The results of this calculation on the selected buildings and their number of households are summarized below (Table 7).

The following steps are performed to estimate the electricity demand profiles for each building. First, for each household of a building, an initial configuration is randomly sampled considering model probabilities so that, the number of occupants, bulb's configuration and appliance present in the house are defined. Then, the profiles for the one-year electricity demand of each apartment are generated. Finally, the demand from all single apartments in a building is aggregated to estimate the demand of the building. Due to the stochastic nature of the models, it is necessary to generate multiple synthetic profiles for each building. In this case, 20 profiles are generated for each apartment and averaged to estimate the most expected profile. As example of this calculation, a snapshot of 5 synthetic profiles corresponding to building 6 is presented (Fig. 8).

Further information on the electricity demand profiles assigned to the ten case studies (i.e., one profile for each building) are summarized in Table 8.

4.4. PV potential estimation of the area

The PV potential estimation is performed for the 10 palaces of the Como Land area with the PV tool previously introduced (section 3.4) to evaluate the PV contribution in covering buildings' consumption considering the electricity produced and directly self-consumed according to the tailored energy profiles (section 4.3). Only allowed interventions (section 4.2) are considered. To this purpose, for each building, the following input data are considered:

- Local weather data for a TMY, including hourly solar irradiation and ambient temperature [99].
- Geometric 3-Dimentions (3D) building including:
- Buildings and close district, generated from Google Map and [100].
- Surrounding landscape morphology including the hills and the Como Lake, imported from Google Earth [100].
- Surfaces available for PV installation, defined starting from the building stock (section 3.1), and the PV integration scenarios (Table 6).
- List of all PV positions (P) (section 4.2), associating hourly irradiation and temperature at each position.
- Technical features of the PV modules [101,106] related to number of modules (n), module efficiency (η), color, dimension (A),

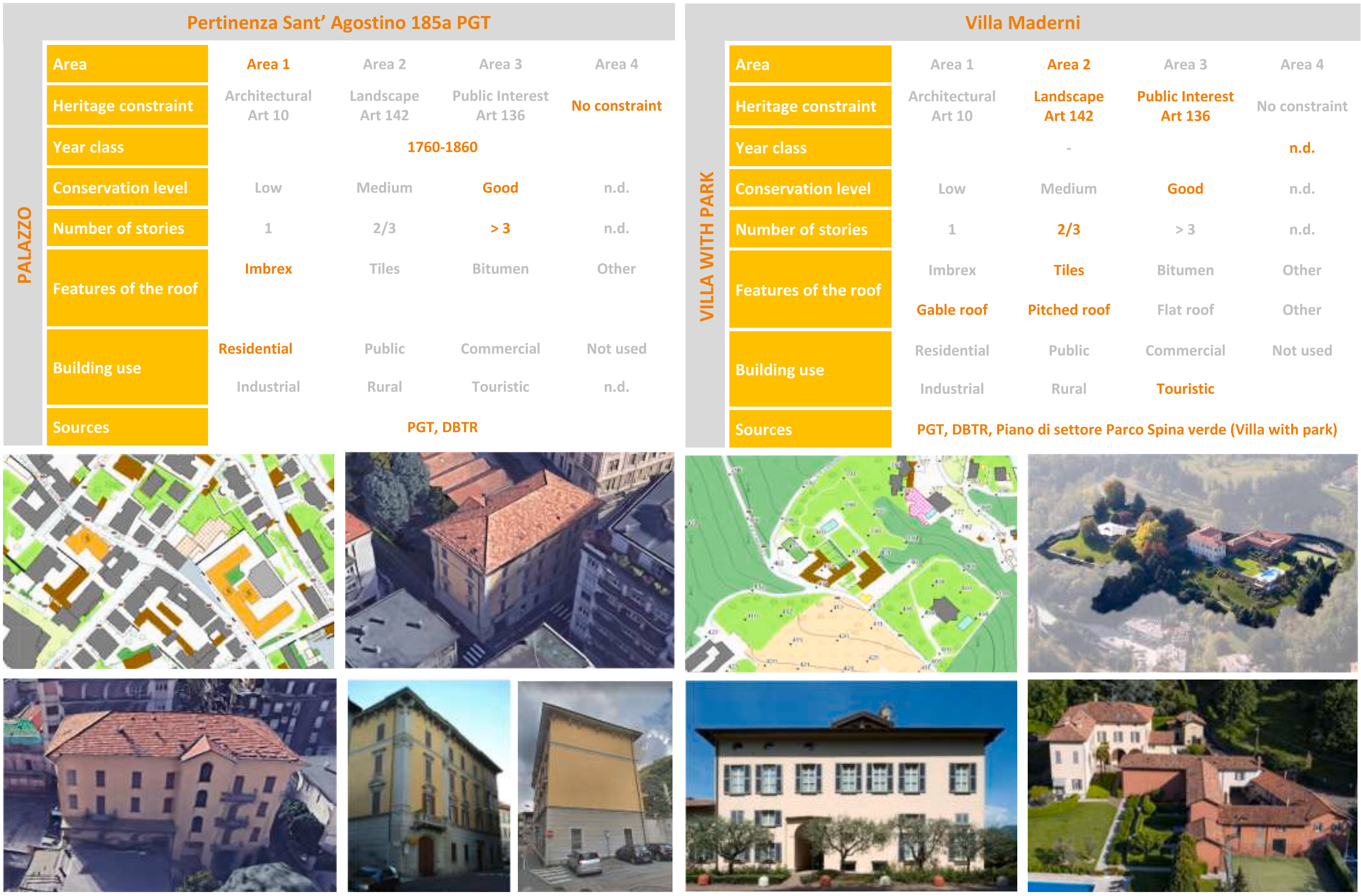

Fig. 7. Example of the database for a Palace and a Villa in Como (Source: Authors' elaboration).

Table 6
Recommendations of the local heritage Authorities for integrating PV technologies in the selected buildings (Source: Authors' elaboration).

Scenario number	5	6	7	10	17	27	38	43	45	46
1	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
2	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
3	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
4	-	-	-	-	-	-	🟥	🟥	🟥	🟥
5	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟥	🟥	🟥
6	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	🟩	-	-	-	-	-
8	-	-	-	-	-	-	🟥	-	-	-
9	-	-	-	-	-	-	🟩	-	-	-
10	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
11	🟥	🟥	🟥	🟥	🟥	-	🟥	🟥	🟥	🟥
12	🟨	🟨	🟨	🟨	🟥	🟥	🟨	🟥	🟥	🟥
13	🟨	🟨	🟨	🟨	🟨	-	🟨	🟨	🟨	🟨
14										
15	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
16	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
17	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
18	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟥	🟥	🟥
19	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
20	-	-	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	🟥	🟥	-	-
22	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟥	🟥	🟥
23	🟥	🟥	🟥	🟥	-	🟥	-	-	-	-
24	🟨	🟨	🟨	🟩	-	🟨	-	-	-	-

Note: 🟩 = Allowed 🟨 = To be specifically evaluated 🟥 = Not allowed - = Absence of the building element

Table 7
Number of Households for each reference building (Source: Authors' elaboration).

<table>
<tr><th rowspan="2">Picture</th><th colspan="10">Building number</th></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>5</td><td>6</td><td>7</td><td>10</td><td>17</td><td>27</td><td>38</td><td>43</td><td>45</td><td>46</td></tr>
<tr><td>Number of Households</td><td>2</td><td>3</td><td>3</td><td>4</td><td>8</td><td>10</td><td>4</td><td>4</td><td>2</td><td>2</td></tr>
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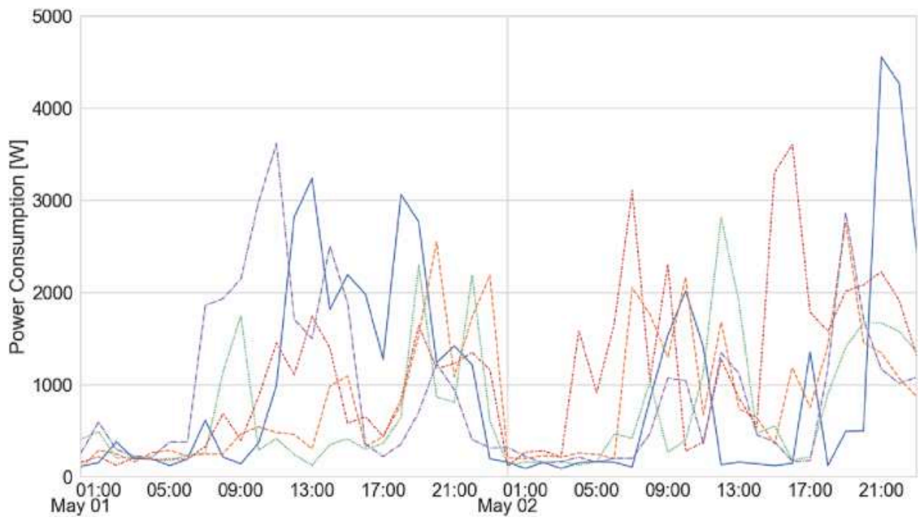

Fig. 8. Reference electricity demand profiles for building number 6 (Source: Authors' elaboration).

Table 8
Details of the electricity demand profiles assigned to the buildings selected for the PV potential evaluation (Source: Authors' elaboration).

Building number	5	6	7	10	17	27	38	43	45	46
Maximum hourly average power [kW]	3.9	4.4	4.4	5.9	11.0	13.2	5.9	5.9	3.9	3.9
Annual average power [kW]	1.0	1.4	1.4	1.9	3.7	4.5	1.9	1.9	1.0	1.0
Annual cumulative energy demand [kWh]	9,124	12,428	12,428	16,867	32,317	39,278	16,867	16,867	9,124	9,124

Table 9
Technical features of the heritage compatible PV technologies considered in the simulations (Source: Authors' elaboration).

Class of technical element		PV technology PV type	Color	Custom dimension	Frameless	Nonvisible strings	Efficiency [%]
Window, dormer, skylight		Semi-transparent, uniform [107]	–	yes	yes	–	2.8
Pavement		Opaque hidden-colored [108]	Grey	yes	yes	yes	12.5
Roof	Flat	Opaque hidden-colored [109]	Basalt grey	yes	yes	yes	12.5
	Tilted	Opaque hidden-colored [109]	Terracotta	yes	yes	yes	13.6
——		Opaque hidden-colored (red PV tile + red PV cells) [110]	Terracotta	no	yes	yes	10
Balustrade, parapet, canopy, greenhouse		Semi-transparent, uniform [107]	–	yes	yes	yes	3.4

Notes: the characteristics of the products are listed in the products' datasheets 107–110

Table 10
Further assumptions related to PV system technical parameters (Source: Authors' elaboration).

Parameter	Value
Performance Ratio	0.8 [102]
Linear annual efficiency losses [%]	0.75 [103,104]
Temperature coefficient [%/C]	0.5 [105]

performance ratio of the system (PR) (do not include the correction for the operating temperature), annual degradation (Table 9).

- Hourly profile of the building energy demand (section 4.3).
- Further assumptions related to PV system technical parameters (Table 9).

The annual electric consumption of each building and the PV power installed in the available surfaces calculated from these data are reported. Also, the PV potential estimation results are provided in terms of expected annual cumulative PV production and self-sufficiency.

Table 11
Results of the PV potential estimation considering the integration of heritage-compatible PV technologies (Source: Authors' elaboration).

Building number	Installed PV power [kWp]	Annual PV production [kWh]	Self-sufficiency [%]
5	5.4	4541	31
6	5.8	4726	29
7	8.3	6889	34
10	15.8	13,975	39
17	16.7	14,780	32
27	21.3	18,498	33
38	40.7	40,734	46
43	12.8	12,303	37
45	18.3	15,891	44
46	4.5	3881	31

Table 11 reports the cumulative PV power installed on the available surfaces, the estimated expected annual cumulative PV production, and the self-sufficiency percentage (calculated considering the PV electricity produced and directly self-consumed only).

The average self-sufficiency is 35.6%, with values in the range 29–46%. Surfaces available for PV installation, admitted interventions (on windows, roof integrated, parapet, canopy, and greenhouse), and number of stakeholders (2–3) are very similar in buildings 5, 6, 7. This is reflected on the self-sufficiency that is in the range 29–34%. In building 17 is allowed only the installation of PV systems on pavement, and PV tiles, and the number of stakeholders is higher (8). These strictly constraints have not significative impact on energy production, and self-sufficiency (32%). Otherwise, building 27 is the only where is allowed the installation of a conventional attached PV on the flat roof hidden by the parapet. Furthermore, it has other allowed interventions (windows, parapet, canopy, and greenhouse) and 10 stakeholders. The presence of this kind of roof improves the PV power, but without any impact on self-sufficiency (33%). Building 38 has higher energy production and self-sufficiency (46%) thanks to the presence of a flat roof, high available PV surfaces, and few stakeholders (4). In buildings 43, 45, and 46 is possible only the installation of PV tiles, but the self-sufficiency resulted high (31–44%) thanks to the low number of stakeholders (2–4). These results are possible because the simulation tool optimizes the intervention according to the input data.

These results were presented to the local Heritage Authorities in anther focus group, to show the energy potential of new PV technologies for boosting their applicability at local level. Heritage Authorities were really satisfied for the aesthetic possibilities and the solar potential of innovative PV technologies that resulted higher compared to the expectation based on their current knowledge.

4.5. Comparison with maximum theoretical PV potential of the area

As introduced in section 3.4, the same simulation tool is used to evaluate the maximum theoretical PV potential in two further scenarios (both assigning a 20.4% efficiency to the surfaces), and keeping the assumptions listed in Table 10 [101], considering as active surfaces respectively the whole building envelope and only the roofs (Table 12).

The simulations show ranges of self-sufficiency respectively of 40 ÷ 49% (average 44.9%) and 38 ÷ 48% (average 42.5%) considering the whole building envelope and the roof as active surfaces. The low difference reveals that, in the cases under study, building components like façades, windows, external pavements, balustrades and canopies provide a low contribution to the self-sufficiency indicator with respect to the roof. Fig. 9 compares the performance, in terms of self-sufficiency, reached in the three simulated scenarios.

Following, Table 13 highlights the percentage variation of heritage-compatible PV technologies' potential, even in terms of self-sufficiency, with respect to the maximum theoretical PV potential considering whole envelope surfaces or roof surfaces only.

Summarising results reported in Table 11 and Table 12, the self-sufficiency average values in the three scenarios are 36% (heritage-compatible PV potential), 45% (maximum theoretical PV potential of whole envelope), 43% (maximum theoretical PV potential of roof). These results were presented to the local Heritage Authorities in anther focus group, to show the energy potential of new PV technologies for boosting their applicability at local level. Heritage Authorities were really satisfied for the aesthetic possibilities and the solar potential of innovative PV technologies that resulted higher compared to the expectation based on their current knowledge.

Thus, the PV potential reached by integrating heritage compatible PV technologies in the 10 Como's buildings is in the range 6–31% (average 21%) lower than the maximum theoretical PV potential of the whole building envelopes and 4–29% (average 16%) lower than the maximum theoretical PV potential of the building roofs. This variation is also illustrated in Fig. 9 and Table 13.

5. Conclusions

The study aims at defining a methodology for estimating the photovoltaic potential of natural and architectural sensitive areas to balance heritage protection and energy production with the support of local Heritage and Public Authorities. The proposed methodology simulates a real and replicable decision-making process, permitting the identification of recurring urban and building typologies (sections 3.1 and 4.1), the selection of heritage-compatible photovoltaic technologies (sections 3.2 and 4.2), and the discussion of the correlated energy benefits (sections 3.4, 4.4 and 4.5) compared to energy consumptions (sections 3.3 and 4.3). The impact of integrating heritage compatible PV technologies is evaluated comparing the resulting PV potential (self-sufficiency, i.e., potential photovoltaic contribution in covering the building energy demand, considering the electricity produced and directly self-consumed only) to the maximum theoretical PV potential achievable in the considered buildings. This method is applied to the Como Land area for verifying its suitability with a real case study as well

Table 12
Results of the maximum theoretical PV potential estimation (Source: Authors' elaboration).

Building number	Annual electric consumption [kWh]	Maximum theoretical PV potential scenarios					
		Whole envelope surfaces			Roof surfaces		
		Annual PV power [kWp]	PV production [kWh]	Self-sufficiency [%]	Annual PV power [kWp]	PV production [kWh]	Self-sufficiency [%]
5	9124	39.2	29,587	46	12.5	10,885	40
6	12,428	17.1	14,007	41	17.1	14,007	41
7	12,428	22.8	18,542	43	17.8	15,044	42
10	16,867	126.2	80,071	48	35.3	31,634	45
17	32,317	81.6	66,128	45	25.7	23,884	38
27	39,278	99.8	74,157	44	33.5	31,914	39
38	16,867	109.1	98,499	49	82.7	83,616	48
43	16,867	62.7	39,158	45	30.7	29,790	44
45	9124	42.4	36,792	48	42.4	36,792	48
46	9124	11.4	9380	40	10.7	9179	40

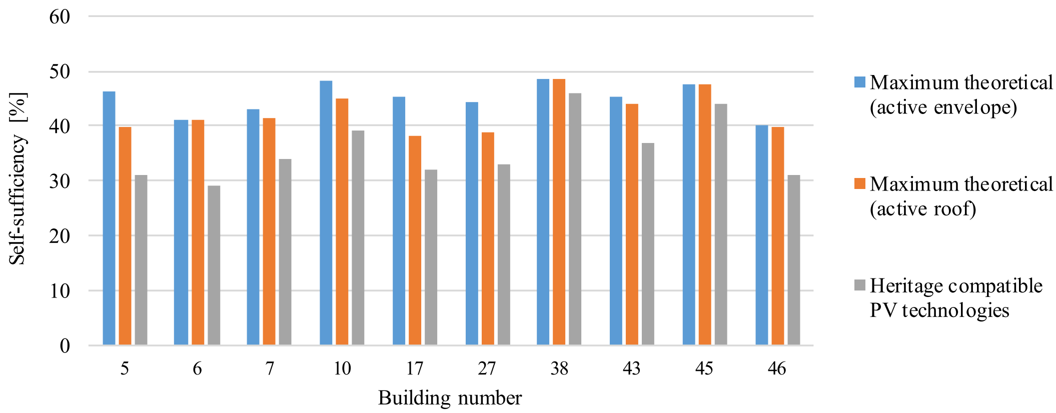

Fig. 9. Comparison between the different scenarios' results in terms of self-sufficiency (Source: Authors' elaboration).

Table 13
Percentage variation of heritage-compatible PV technologies' potential with respect to the maximum theoretical PV potential considering whole envelope surfaces or roof surfaces only.

Building number	Heritage-compatible scenario self-sufficiency variation [%]	
	with respect to Whole envelope maximum theoretical PV potential	with respect to Roof maximum theoretical PV potential
5	−0.33	−0.23
6	−0.29	−0.29
7	−0.21	−0.19
10	−0.19	−0.13
17	−0.29	−0.16
27	−0.25	−0.15
38	−0.06	−0.04
43	−0.18	−0.16
45	−0.08	−0.08
46	−0.23	−0.23
Average	**−0.21**	**−0.17**

as its replicability in others territorial contexts. Results show that the self-sufficiency achieved by integrating heritage-compatible photovoltaic technologies is 21% and 17% lower if compared to the performance achieved in the maximum theoretical photovoltaic potential scenario, respectively installing PV on the whole envelope and on the building roof. This methodology is replicable in other contexts thanks to the use of:

- Rational decision-making processes that can be easily replicated by Designers, Public and Heritage Authorities.
- Sources and maps usually available at territorial, regional, municipal, and local level.
- Universally recognized design criteria for photovoltaic integration in cultural heritage.
- Stochastic models than can be adapted to local habits and behaviors.
- Free design tools, easy to be used for early-design simulations.

Some general key-findings useful for the estimation of the photovoltaic potential on natural and sensitive areas are highlighted by this study:

- Photovoltaic integration on architectural and natural sensitive areas need solid criteria and proper assessment methodology that consider heritage protection issues, new technologies developments, and local engagement. Thus, historic centers and towns should be not excluded by solar cadasters, as usually appears both in the literature and in the practice.
- Photovoltaic compatibility assessment on sensitive areas (and buildings) needs a multidisciplinary team composed by conservators, architects, engineers, landscape designers, Heritage and Public Authorities.
- Importance of having a deep knowledge of urban and building values, constraints, features, materials, also thanks to the early-stage involvement of the local heritage Authorities for identifying tailored PV solutions that respect the heritage significance of the buildings.
- The support of Public Authorities is important for integrating different data and tools, and for selecting the "*urban area typology*" to respect also territorial, and landscape values.
- The support of Heritage Authorities is important for tailoring the photovoltaic integration considering specific heritage values (and not only heritage constraints).
- Heritage compatibility of photovoltaic interventions should be evaluated on all the building elements, not only on roofs.
- Innovative photovoltaic modules have a lower impact than conventional photovoltaic thanks to their aesthetic aspects, thus they can be compatible with traditional architectural features, especially on roofs, windows, balustrades, canopies, and greenhouses.
- To estimate the solar potential or sizing of integrated photovoltaic, it is important to adequately estimate the electricity demand which is highly influenced by the occupants' behavior. To this purpose, stochastic models can be used to include the occupant's diversity and better account for the occupant-related uncertainty (e.g., environmental, contextual, socio-economic, cultural, psychological, and physiological).
- Reduced time-step (e.g., hourly) based tools, like the one applied in this study, are preferable to evaluate the expected performance of integrated photovoltaic systems as they allow assessing the system self-sufficiency, meaning how buildings can reduce their energy demand using electricity directly from photovoltaic (e.g., east and west orientation produces energy during morning and afternoon, period with high energy consumption).
- Tailored PV interventions can improve the architectonic quality of heritage buildings and areas, especially on damaged context or in high modified buildings.

The limitation of this study concerns the focus on one representative building archetype (palaces) characterized by valuable heritage values, strictly urban and heritage constraints, good conservation levels, and high energy consumptions. Results are not replicable on other building typologies. Thus, future works will compare all building archetypes (e.g., rural buildings, historic villas, XX Century buildings, industrial archeology) using the present replicable methodology, to calculate the index for the solar photovoltaic potential estimation in different parts of historical towns (e.g., high- or low-density districts, rural areas, historical parks, and gardens) on the basis of the urban and building mapping. A GIS map will be realized to define specific indexes to be used for the evaluation of the PV potential of natural and architectural sensitive land areas to balance heritage protection and energy production. This could support the Public Authorities in the definition of solar cadasters at local level.

Future scope of the work concern:

- Definition of simplified indexes for the reduction of the photovoltaic potential due to heritage-compatibility for supporting realization of solar cadaster in historic centers.
- Economic calculations for verifying the costs of the integration of innovative technologies in sensitive areas.
- Comparison among the photovoltaic potentials of different archetypes, climates, and constraints.

CRediT authorship contribution statement

Elena Lucchi: Conceptualization, Methodology, Validation, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition, Project administration. **Jennifer Adami:** Investigation, Software, Writing – original draft, Visualization. **Alessia Peluchetti:** Investigation, Data curation. **Juan Camilo Mahecha Zambrano:** Visualization, Investigation, Writing – original draft.

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

The data that has been used is confidential.

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