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Potentials and Limits of Photovoltaic Systems Integration in Historic Urban Structures: The Case Study of Monument Reserve in Bratislava, Slovakia

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Abstract: In the context of the current energy crisis and climate change, the importance of discussions on how to incorporate monument protection into sustainable strategies that mitigate the human impact on the environment and implement renewable sources while preserving cultural values is raised. Through the case study of the Monument Reserve in Bratislava, Slovakia, this article presents the potentials and limits of the integration of photovoltaic systems in historic urban structures that directly affect their feasible participation in smart city and positive energy district concepts by means of energy cooperativeness. This study highlights the most current recommendations and basic principles on how to assess their visual impact and select the most appropriate solutions. Using the datafication process, it analyzes the irradiance of pitched and flat roof polygons of the set area based on their characteristics such as the normal vector azimuth and slope of the rooftops. For this purpose, a 3D morphological model in LOD3 detail and the open-source solar irradiation model *r.sun* implemented in GRASS GIS/QGIS were used. The data obtained provided an estimate of the output potential to endow the city's power grid and were compared to the electricity consumption of the particular city district. Furthermore, these data are suitable for designing a customized technical and aesthetic solution for the integration of photovoltaics with respect to cultural sustainability, as well as for decision- and policy makers.

Keywords: solar energy; PV systems; historic urban structure; renewable sources; cultural heritage; sustainability; smart city concept; datafication

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1. Introduction

Architecture and construction as the main substances of the city have always reflected global phenomena. One of the biggest challenges humanity faces is determining the ways to develop the world's cities into resilient, intelligent, and sustainable habitats that will overcome various issues associated with energy sources, climate change, urbanization, transport, social segregation, immigration, security, lack of water, waste management, etc. To achieve sustainability, it is inevitable to consider the diversity and interdependence of these aspects, as well as the latest projections by the United Nations (UN) that suggest the global population could grow to around 8.5 billion in 2030, 9.7 billion in 2050, and 10.4 billion in 2100. The share of urban dwellers is projected to represent two-thirds of the global population in 2050. Although cities occupy only about 2% of the total land surface, they are responsible for 60–80% of global energy consumption, 60% of resource consumption, 70% of global carbon emissions, and 70% of global waste. Therefore, cities are predominantly considered a problem [1–5].

The 2030 Agenda adopted by the UN introduces 17 Sustainable Development Goals (SDG-s) with 169 associated targets, among which sustainable cities and communities, responsible consumption and production, and climate actions are listed [6]. Other related international strategic documents on sustainability can be mentioned as well, such as the EU Adaptation Strategy to Climate Change [7], the European Green Deal [8], the Climate and Environmental Emergency [9], or the Paris Agreement [10]. These goals based on win–win cooperation can be partially achieved through design strategy measures, for instance, by reducing heat losses, ensuring efficient electricity use, optimizing solar gains, visualization and control of energy flows, and finally, selecting a renewable energy source (RES), such as photovoltaic (PV) systems [11].

In the European Union (EU), approximately 75% of the building stock is considered energy inefficient [12]. Eurostat estimates that 22.69% of dwellings in the EU were built before 1945 (generally considered as historic buildings), while in Slovakia the share is approximately 14.38% [13]. Therefore, historic buildings and cultural heritage, as a material testimony and evidence of the force of civilization, precious, unique, and irreproducible memories play a non-negligible role within this frame of reference [14] (Table 1).

Table 1. Breakdown of dwellings by construction year in Slovakia and the European Union. Data available for 2014 [13].

	Unit	<1945	1945–1969	1970–1979	1980–1989	1990–1999	2000–2010	>2010
Slovakia	%	14.38	32.21	23.34	17.63	5.12	5.81	1.50
EU	%	22.69	26.19	15.98	12.54	9.34	9.56	3.69

1.1. Global Approach to Energy-Efficient Retrofitting of Historic Buildings in the Context of Cultural Sustainability

The energy-efficient retrofitting of historic buildings poses various challenges, mainly related to the impingement of their heritage significance as a combination of the heritage values assigned to a building and its setting [15,16]. It prompts the question of the vulnerability, viability, and preservation of human merits and common cultural heritage in the full richness of their authenticity for future generations, as advocated by the authors of the Venice Charter of 1964 [17]. In the background of globalization, cities as human-made settlements concentrate culture and form their (urban) image, which could be assessed through the prism of historical stratigraphy and references/buildings from past times. The main objective must be to enhance cultural sustainability and protect cultural identity that can be understood as a process in which a given community identifies itself with the cultural heritage of its ancestors and safeguards and otherwise slows its extinction due to the preservation of cultural continuity for descendants under the best possible conditions [18]. In this context, Pisello et al. introduced a methodology for the energy assessment of historic buildings and the decision on the best energy approach. It involved the following three steps [19,20]:

(i) Elaboration of the energy model of the building (i.e., with Energy Plus), considering the current status of the structure, both in terms of architectural and technical elements;
(ii) Simulation of the year-round energy performance of the building in terms of heating and cooling primary energy requirements before the energy retrofit;
(iii) Proposition of a new integrated configuration of the energy systems, considering all the architectural and technical constraints due to the historical value of the pilot case study building.

In areas of high cultural heritage, the integration of PV modules should not distort the fabric or architectural and aesthetic expression of the existing building envelope, its tangible and intangible, documentary, artistic, technical, functional, and experience values, etc. [21]. The sustainable use and preservation of historic buildings require broad and long-term compromises between social, economic, and environmental aspects while respecting a need to reduce energy demands using nearly Zero Energy Building (nZEB) solutions.

It is obvious that authenticity and identity limit each new intervention. However, they should not act as a counterpoint to all new encroachments but as part of a complex articulation of material space [22]. In this regard, some researchers argue that cultural heritage is primarily about the preservation of timeless values, which, without a proper relationship with new technologies, could be endangered to the point where society will solve the energy efficiency of the ruins in the future [23]. The decision process is multidisciplinary and involves both qualitative and quantitative analysis, in fact [24]. In historical buildings, it is necessary to find a balance among the requirements of the building, the occupants, and the objects exhibited while considering the well-being of people, which usually does not correspond to the supreme conditions of objects and collections [25]. Their environmental sustainability and energy efficiency could be certified through the most diffused environmental sustainability assessment method developed by the Green Building Council (GBC), such as GBC Historic Building®, which introduces a new topic called Historic Value (that pays close attention to the principles and different stages of the restoration process, while improving overall environmental performance), in addition to the already existing LEED® thematic areas to make the rating system customary to the historical context [26].

The current state of knowledge on the protection of environmental and cultural heritage is already evident from the Convention Concerning the Protection of the World Cultural and Natural Heritage adopted in 1972 [27], the Nairobi Recommendations of 1976 [28], the Washington Charter of 1987 [29], the Nara Document on Authenticity of 1994 [30], and many others. Specifically, it is Article 11 of the Convention for the Protection of the Architectural Heritage of Europe adopted in 1985 (also known as the Granada Convention) that states that, due regard being had for the architectural and historical character of the heritage, each Party undertakes fostering the use of protected properties in light of the needs of contemporary life and the adaptation when appropriate of old buildings for new uses [31].

At the national level, the fulfillment of these obligations and recommendations is supervised by heritage and public authorities such as the Monuments Board of the Slovak Republic established in 2002 and its subordinate local bodies. They outline the correct guidelines, policies, and financial incentives; control their implementation in a conscious way; and force designers to improve the architectural qualities of existing buildings or assess PV compatibility on architectural heritage sites, protected landscapes, architectural heritage monuments, traditional buildings, their extensions, or within historic building elements.

As the rate of use of RES and the integration of photovoltaics vary from country to country, the national legislative frameworks and their complexity also differ. In addition to them, there exist various international guidelines, databases, catalogues, and research projects demonstrating the possible integration of photovoltaic technologies owing to their innovative architectural design, aesthetic appeal, flexibility, multifunctionality, cost reduction, and technological development, as well as even awards and prizes regarding the integration of photovoltaic technologies in cultural heritage and built environment, as those listed by Lucchi [32]. As she affirms, the prevalent strategy, especially in the last decade, is the use of building-integrated photovoltaic (BIPV). The implementation levels can be structured in aesthetic, technological, and energy integration. Such documents, protocols, outputs, and best practices lay the basis for updating approaches to the use of RES and PV in many countries.

1.2. Scope

This study aimed to evaluate the potentials and constraints of the implementation of photovoltaic systems in historical urban structures based on the case study of Monument Reserve in Bratislava, Slovakia. Part of this study was to verify the potential of datafication through which attributes and processes were converted to dates and data flows to create predictive analysis [33]. The authors of this article are fully aware of the challenges that await heritage preservation in relation to the current global energy crisis and adaptation to climate change. They assume that the issue of RES, including the integration of PV systems and related technical equipment, will raise and affect historic preservation strategies. Therefore, the article compares various scenarios of PV systems integration based on the analyses of roof polygons' solar potential and introduces the tools and recommendations that can be applied in areas of great cultural values while having minimal/visually acceptable aesthetic impact on the built environment.

In the context of the article topic, the Directive 2018/2001 introduces the concept of prosumers/producers, the energy-independent users who can be remunerated for electricity produced and supplied to the network. Therefore, it opens possibilities for the integration of PV systems into the building heritage as the consumer becomes an active part of the national grid's energy supply [34,35]. This approach is calculated in four scenarios through the power output potential of selected roof polygons in the final Section 4.4. Such calculations/estimates also correlate with the concept of the smart city and the energy cooperativeness of urban structures, thus contributing to urban decarbonization and mitigating the occupation of creditworthy agricultural land by solar farms. On-site/near the point of consumption photovoltaic electricity generation reduces power losses through transmission over long distances. In recent years, the Positive Energy District (PED) concept has emerged in which a district generates more local renewable energy than energy consumed from the outer-district boundaries while maintaining a net-zero carbon emission balance. Furthermore, the solar potential of heritage buildings can be implemented in virtual PEDs, which open the spatial frontiers of districts to allow off-site renewable generation [36–39], (Figure 1).

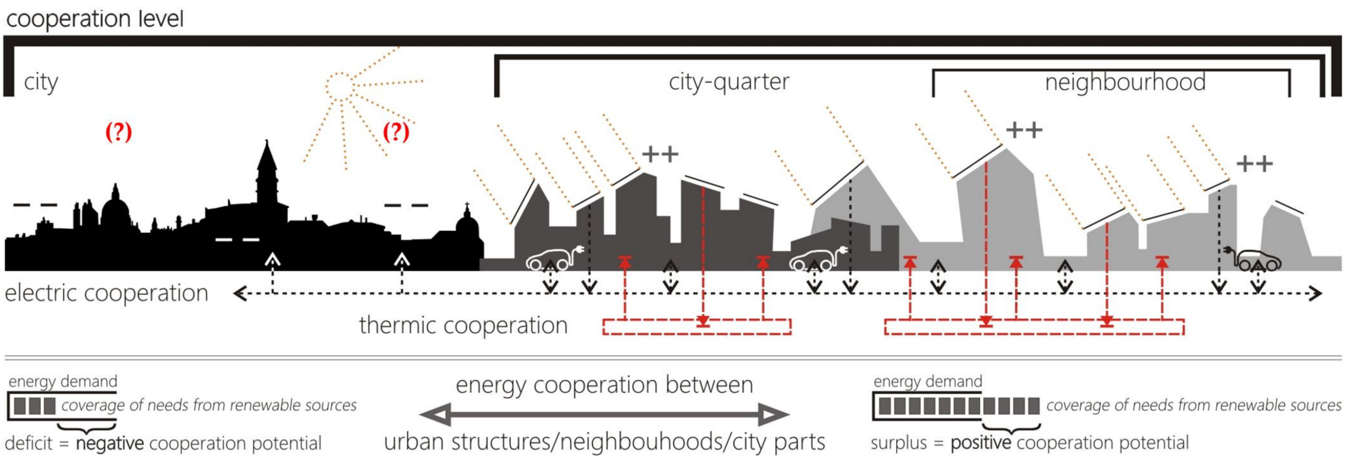


Figure 1. The concept of synergic energy cooperation of urban structures/neighborhoods/city quarters. The energy potential of overproduction or deficiency may be related to electrical energy as the electric cooperation indicator (ECI), to thermic energy through the thermic cooperation indicator (TCI), or to any other related commodity. Alternatively, it can be expressed as the daily or annual average specification of the total energy demands (kWh/d(a)). The electric/thermic cooperation indicator also offers the unitary value (uECI/uTCI) related to the number of units (e.g., dwellings). This illustration and indicators have previously been introduced by Legény and Morgenstein [40].

2. Framework

2.1. Review of the Current State-of-Art and Valid Legislation Framework in Bratislava, Slovakia

Bratislava, the capital of Slovakia, was declared an urban protected monument area as early as 1954 [41]. It comprises 5 districts and 17 boroughs, while the subject of research interest was the main part of the City District I—Old Town. Its history documents many immovable national cultural monuments (INCM) listed by the Monuments Office of the Slovak Republic in the Register of National Cultural Monuments (Table 2).

Table 2. Numbers of INCM by Bratislava city districts [42].

City District	INCM in Total	Buildings	Other [1]
I.	1308	951	357
II.	34	26	8
III.	73	58	15
IV.	124	105	19
V.	36	24	12
In total	1575	1164	411

[1] This column includes cemeteries, memorials, fountains, statues, etc.

In addition to the valid basal national legislation on cultural heritage and international conventions adopted by the Slovak Republic, the preservation of monuments in Bratislava is regulated by the Regional Monument Board—Bratislava. In 2015, it issued a binding document titled the Principles of heritage area protection: Heritage zone Bratislava—central urban area (hereafter mentioned as a strategic document) [43]. The criteria for evaluating the quality of the urban structure within the document have become the degree of preservation and the stylistic characteristics of the urban structure, as well as its degree of homogeneity, compared to the traditionally built urban compact structures until the middle of the twentieth century. Based on the factor of creation and the degree of preservation of the historical structure, the Heritage Zone (HZ) was divided into six areas and six sectors with specific subsectors. These principles outline strict borders of the HZ and Monument Reserve (MR), define the protected spot and linear views, or identify the INCM in the heritage zone (Figure 2).

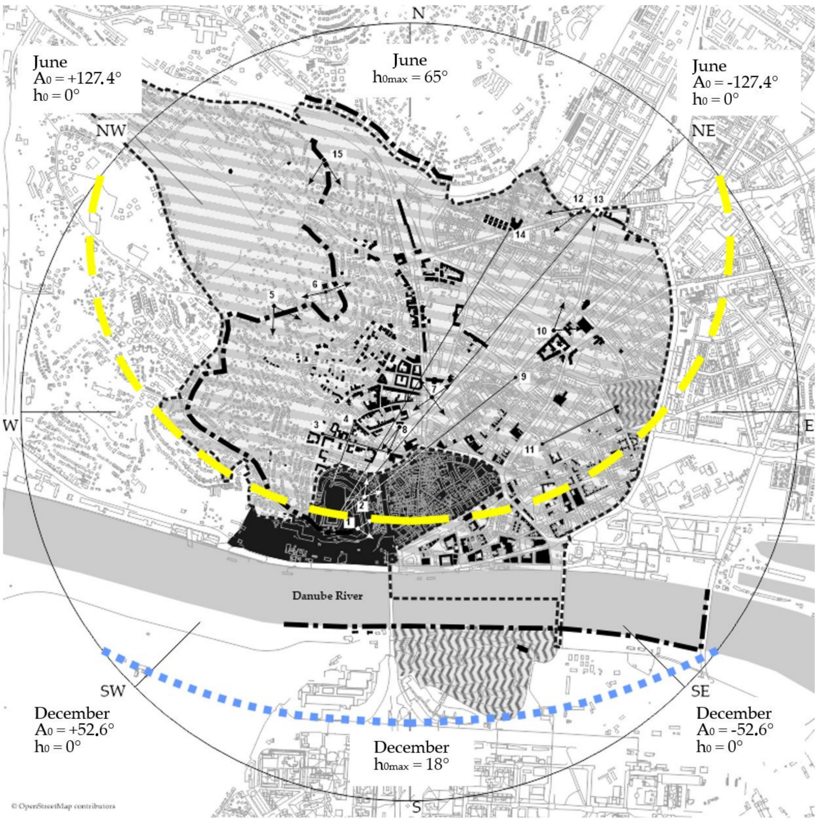


Figure 2. Demarcation of the HZ boundary (dashed line), the territory of the MR (black area), protected spot views (arrows with numbers) and linear views (dashed-dot lines) within the strategic document. The picture also illustrates the maximum/minimal azimuth (A_o) and sun height (h_0) during the summer and winter period. Figure elaborated by the authors, with modifications based on the Regional Monument Board—Bratislava [43].

Unfortunately, the issue of PV integration is only marginally mentioned in this strategic document. According to its section CH.1.5.4, RES devices (photovoltaics, solar panels, etc.) and other technical devices such as air-conditioning units can be installed on buildings within the territory of the monument zone only in visually unexposed and inaccessible positions. In the case of INCM, their placement is permissible only in exceptional cases if there is no deterioration, denial, or disturbance of the historical values of the object. Sections G.1.6 and G.1.7 of the strategic document devoted to the fifth facade—roof landscape, silhouettes, skylines, and valuable views—conclude that the roof, especially its covering, is a part of the building that undergoes regular maintenance, and, therefore, the degree of authenticity of the roof elements is the lowest. Coverings were changed often with an emphasis on the financial situation of the owner, and therefore the degree of heterogeneity of coverings is relatively high within the framework of traditional construction. Today, ceramic, concrete, and fiber–cement tiles of terracotta and gray color prevail. In the case of metal sheets, they were often provided with paints of different colors, combined with coverings of different types of materials and types of templates. Despite that, the rate of interventions in MR shall reach minimal levels, and their impact must be precisely assessed case-to-case.

2.2. Principles and Recommendations Applicable

Due to the lack of detailed recommendations on the integration of PV devices in historical structures in Slovakia and the common historical background and similar developments with the Czech Republic (they formed a sovereign state—Czechoslovakia—in 1918–1939 and 1945–1993), the authors of the article analyzed the very novel methodological statement on the evaluation of plans for the installation of photovoltaic and other solar devices in cultural monuments, heritage protected areas, and protected zones of cultural monuments, which has been issued by the National Heritage Institute of the Czech Republic (NHICZ) in 2022 in relation to the energy crisis [44].

On the one hand, it confirms the fact that in the Monument Reserve and in territories listed in the UNESCO register, the placement of PV modules is generally undesirable. Possible exceptions relate to very specific cases, e.g., new buildings or atypical solutions within the restoration of modern architecture. All such installations must be assessed individually, as a complex, and within the context of the given territory. In such a case, the placement of this device is possible only in situations where its rejection would not be justified. On the other hand, this document highlights the basic recommendation on how to deal with PV integration in historical structures based on their types. According to the European Standard EN 50583-1/2, building-integrated photovoltaic (BIPV) systems are prerequisite for the integrity of the functionality, and, in the case of structurally bound modules, they are dismountable, including the adjacent construction product, and they would have to be replaced by an appropriate construction product. In contrast, building-attached photovoltaics (BAPVs) are mounted on a building envelope and do not fulfill the following criteria: (i) mechanical rigidity or structural integrity; (ii) primary weather impact protection from rain, snow, wind, and hail; (iii) energy economy, such as shading, daylighting, or thermal insulation; (iv) fire protection; (v) noise protection; (vi) separation between indoor and outdoor environments; (vii) security, shelter, or safety [45,46]. At the same time, the Czech document delivers the approach that the suitability of such intervention should always be adequately and precisely assessed and verified through the visual and building substance impact study (Figures 3–6, Table 3).

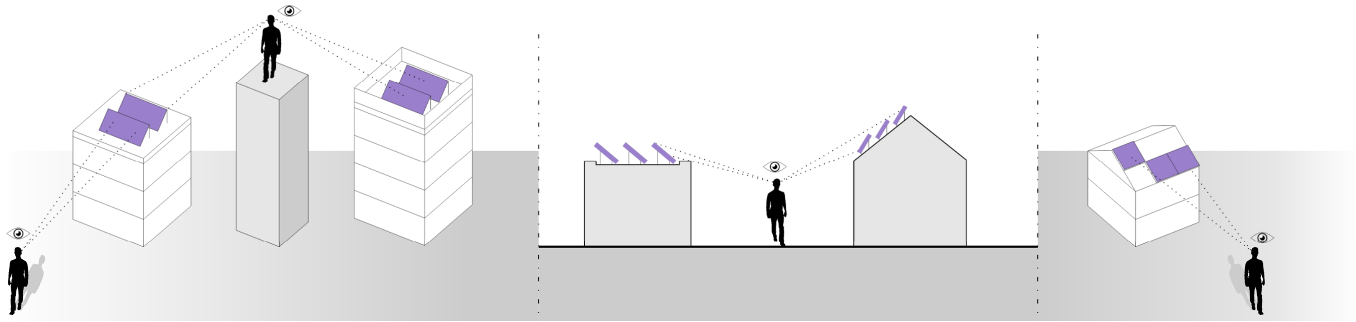


Figure 3 panels: **(a)** **(b)** **(c)** **(d)** **(e)**

Figure 3. Illustration of visually unsuitable solutions in situations where the methodological statement considers the possibility of placing PV modules: (**a**) The flat roof of the building is visible from the normal horizon and publicly accessible space (e.g., from elevated natural places or when situated in a valley position, etc.); (**b**) The flat roof of the building is visually perceived from an elevated horizon and publicly accessible buildings, from church towers, terraces, etc.; (**c**) Flat roof without existing attic gable or existing attic gable of insufficient height; (**d**) A pitched roof with installed panels at a different slope compared to the slope of the existing roof planes; (**e**) A pitched roof with BAPV/BIPV panels of varying, disparate placement, size, or type. Figure elaborated by the authors, with modifications based on the NHICZ [44].

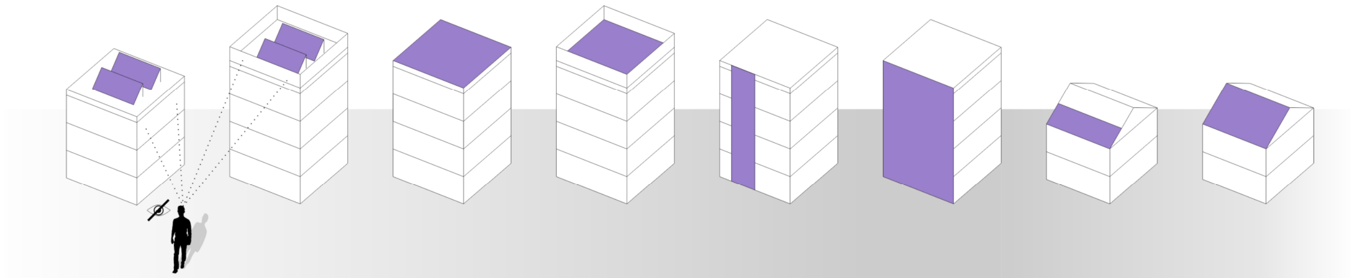


Figure 4 panels: (**a**) (**b**) (**c**) (**d**) (**e**) (**f**) (**g**) (**h**)

Figure 4. Illustration of visually suitable solutions in 3D display: (**a**) The flat roof of the building is not visible from a normal or elevated horizon (e.g., due to the height of the building, the ruggedness of the terrain without elevated places, or the location of buildings next to each other without accessible dominant position); (**b**) The flat roof of the building is not visually perceived from a normal or elevated horizon (e.g., due to the existing attic gable); (**c**) Flat roof of a modern building without attic gable; (**d**) Flat roof of a modern building with an existing attic gable; (**e**) Flat façade of a modern building; (**f**) Semitransparent BIPV modules integrated within the existing façade system of a modern building; (**g**) A pitched roof covered with building-attached photovoltaics (BAPVs) on a building with an existing roof of a nontraditional composition and color, without visual impact perceivable from a public or semipublic space, or when viewed from a height from publicly accessible places, or a pitched roof supplemented with a built-in photovoltaic device (BIPV) (e.g., solar tiles) of a conceptually arranged location, in color and size that does not contrast with the local traditional covering without visual impact from a public or semipublic space.; (**h**) A pitched roof covered with BAPVs on a building with existing roofing of a nontraditional composition and color, without visual application from a public or semipublic space, or when viewed from a height from publicly accessible places or a pitched roof in the full area formed by a BIPV device on a building with an existing covering of a nontraditional composition and color without visual impact perceivable from a public or semipublic space. Figure elaborated by the authors, with modifications based on the NHICZ [44].

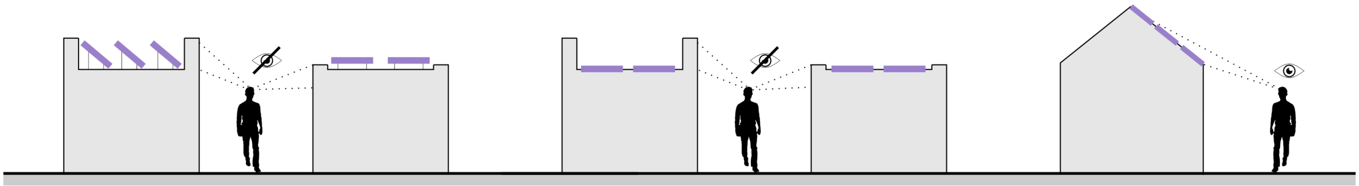


Figure 5. Illustration of visually suitable solutions articulated in sections: (**a**) A flat roof with an existing attic gable of sufficient height for BAPV integration with a slope that is different from the slope of the existing roof planes; (**b**) A flat roof with an existing attic gable of sufficient height for BAPV application with a slope identical to the existing roof plane; (**c**) A flat roof with an existing attic gable with BIPVs; (**d**) A flat roof without attic gable and integrated BIPVs; (**e**) A pitched roof with partially installed BIPVs in the same slope as the existing roof plane or BIPVs fully installed in the existing roof plane and enabling the reversibility of the original covering character in the future. Figure elaborated by the authors, with modifications based on the NHICZ [44].

Figure 6. Examples of the low visual impact BIPV modules: (**a**) Solar tiles in the color of typical roofing, Solarti Company [47]; (**b**) Tesla solar roof tiles—Tuscan, slate, and textured glass tiles [48]; (**c**) Solar shingles, United Solar Ovonic Corporation [49].

Table 3. PV systems' entry rate into the construction of objects or the structure of the territory and modifications or changes related to their integration.

Type of PV System	Subtype of PV System	Description	
		Pros (+)	**Cons (−)**
Lean to	-	Simple design, structurally noninvasive intervention. Do not change the material substance of buildings.	Causes a change in the visual perception of object and territory. *
Partially embedded / / building-attached photovoltaics (BAPVs)	-	Minimal (but not zero) intervention into the material substance of the object and degree of reversibility.	Change in the volume and silhouettes of the building. *

Table 3. *Cont.*

Type of PV System	Subtype of PV System	Description	
		Pros (+)	Cons (−)
Embedded/building integrated photovoltaics (BIPVs)	Systems replacing the entire structural element of a building.	The integration follows the existing material substance and volume. The silhouette of the building is retained.	Reversibility of the intervention. *,**
	Systems replacing part of the building	The integration follows the existing material substance and volume.	Reversibility of the intervention. *,**
	Semitransparent systems	The volume of the construction remains preserved and is reversible.	Change the original transparency of the glass. *

* The rate, effect, and suitability of invasiveness/intervention should always be adequately and precisely assessed and verified through the visual impact study. ** Some authorities on cultural heritage preservation consider BIPVs as an irreversible intervention, but according to the CENELEC mentioned above, BIPV devices are dismountable, including the adjacent construction product, and they would have to be replaced by an appropriate construction product. The reversibility of the intervention varies from case to case.

3. Materials and Methods

3.1. Study Area

The study evaluated the solar roof potential of existing buildings in the Monument Reserve in Bratislava, Slovakia, using the open-source solar irradiance and irradiation model—r.sun—developed by Hofierka et al. that was implemented in GRASS GIS/QGIS software [50]. For this purpose, the 3D morphological model of the study area in LOD 3 detail of the buildings provided by the Eurosense Company was used. Since the irradiance of the objects' surfaces for the reference year and the given location, as well as their albedo values, were not available during the calculation, the preset values of the online r.sun radiation model were used [51]. In this study, the albedo value (α) was set at 0.2 and the Linke turbidity factor (TL) at 3.0. Possible discrepancies resulting from the default settings of the radiation model only slightly affected the final correlation between the irradiance of the roof polygon (RP) and its geometry. This distortion could manifest itself in the difference between the solar energy conversion potential calculated for clear-sky values and the real irradiance affected by weather and environmental conditions. This deviation was corrected in the final steps by comparing the irradiance calculated using r.sun with the irradiance calculated using PVGIS [52]. Raster maps of diurnal irradiance, in which one pixel corresponded to an area of 0.5×0.5 m, were calculated for 12 reference days of the year, specifically on the 15th day of each month. Using the GRASS GIS/QGIS application, the irradiance values were supplemented with data regarding the geometry of the RPs such as the size, slope, and azimuth of the normal vector. Finally, they were classified into groups attributed to traditional urban blocks with inner courtyards and other types of development (Figures 7 and 8).

The aesthetic and visual impact of RES devices on the landscape and in the vicinity of sites of cultural heritage is crucial for planning and decision making. It can be assessed through various methods. Among many other parameters, the contrast of color, form, line, texture, and scale are generally evaluated [53]. Lingfors et al. refer to a target-based method for assessing visibility from the perspective of the building envelope, rather than possible vantage points on the ground. Their study confirmed that, if the public domain is chosen, the nonvisible roof surfaces doubled compared to the case if the entire ground/terrain was chosen [54]. In relation to this, the study also investigated traditional urban blocks with inner courtyards.

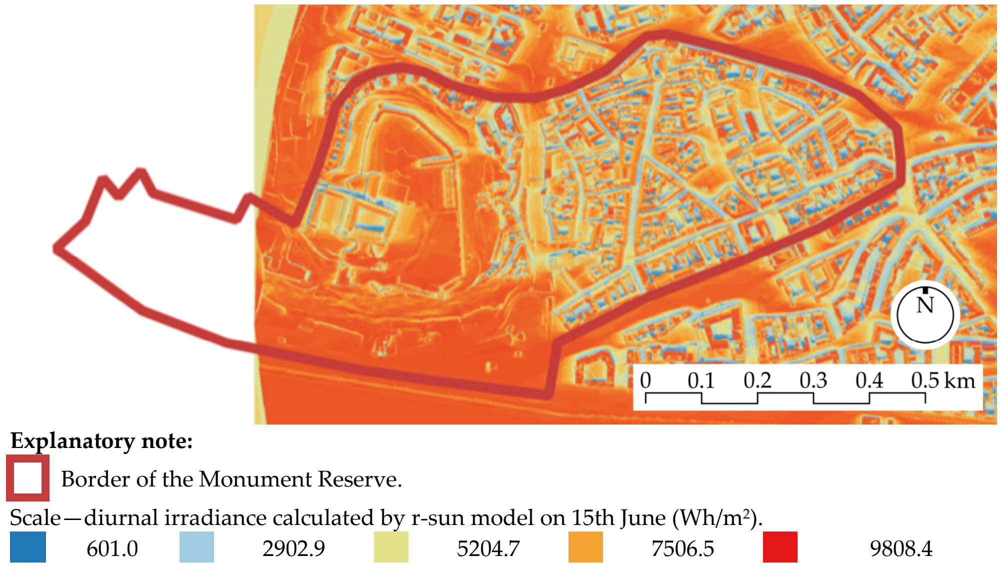


Figure 7. The 15th of June diurnal irradiance of the investigated territory of the Monument Reserve in Bratislava, Slovakia. The missing substance on the left is currently under construction and was not analyzed.

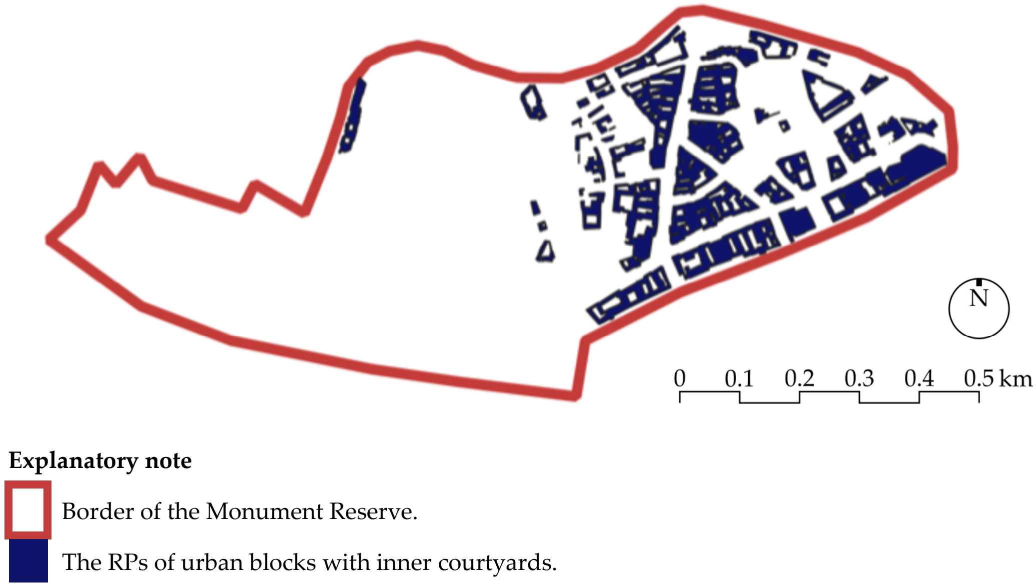


Figure 8. Traditional urban blocks with inner courtyards that are relevant for a nonvisible integration of PV appliances perceived by the passerby.

The RPs datasets were further postprocessed in the MS Excel program. In this phase, the monthly irradiance values for all eligible polygons located in the investigated MR were calculated as multiples of the reference day. The average value of 30,437 days was used as the duration of the month. Subsequently, the seasonal and annual irradiance values were enumerated. Data were further analyzed using statistical methods and tools.

3.2. Classification of Roof Plane Polygons

The number of roof plane polygons (Σ RPs) in the Monument Reserve was 9150. In the first step, the minimum polygon area of 5 m^2 appropriate for the integration of the PV modules was determined. Polygons of size below this set limit were evaluated as ineffective in terms of technical properties of PV modules, such as their anchoring to the structure, standardized factory dimensions, prevalent rectangular shapes, etc. This authorial limitation in the RP size had only a 3.92% impact on annual irradiance of all RPs but reduced their number by 53.92% (Table 4).

Table 4. RPs analysis according to annual irradiance and a minimum of 5 m^2 applicable area.

Area Interval (m^2)	Annual Irradiance (MWh)	(%)	Area (m^2)	(%)	Σ RPs	(%)
All polygons	306,194	100	259,211	100	9150	100
<0, 5)	12,017	3.9	9976	3.9	4934	53.9
<5, max.>	294,178	96.1	249,235	96.2	4216	46.1

In the next step, the RPs analyzed were categorized according to their slope into two groups. The first included flat RPs within a slope interval of 0° to 10°, and the second, covered pitched RPs with slopes of 10° to 90°. Their degree of representation in the RPs area under consideration is shown in Table 5.

Table 5. RPs analysis according to the slope of the roof.

Slope Interval (°)	Annual Irradiance (MWh)	(%)	Area (m^2)	(%)	Σ RPs	(%)
All polygons	294,178	100	249,235	100	4 216	100
<0, 10)	77,785	26.4	55,121	22.1	844	20.0
<10, 90>	216,393	73.7	194,115	77.9	3 372	80.0

Subsequently, all pitched RPs were analyzed in terms of their geometric properties that affected their irradiance values, such as the area of the surface, slope, or azimuth of the normal vector of the specific polygon. Later, the RPs were ranked in series according to their size, from the smallest (0) to the largest (1). The series numbers were expressed as normalized values in the interval 0 to 1. Figure 9 shows the correlation between the slope and the area of the pitched RPs. The X-axis represents the normalized series of pitched RPs according to the area, while the primary Y-axis indicates their slope. In addition, the secondary Y-axis expresses the pitched RPs area. The arithmetic mean (AM) of all pitched RPs slopes was calculated at 41.66°, and later, the standard deviation was derived from the slope values. Then, the 50% prediction interval (PI) was established, with the lower bound of 30.69° and the upper bound of 52.63°. From this figure, it is apparent that the slope of the RPs correlates to some extent with their area. Therefore, this correlation and its effect on solar gains were analyzed in the next steps.

Similarly to the previous one, Figure 10 shows the relationship between the normal vector azimuth and the area of the pitched RPs. The primary Y-axis depicts the normal vector azimuth of pitched RPs (0°—north, 90°—east, 180°—south, 270°—west); the secondary Y-axis articulates their area.

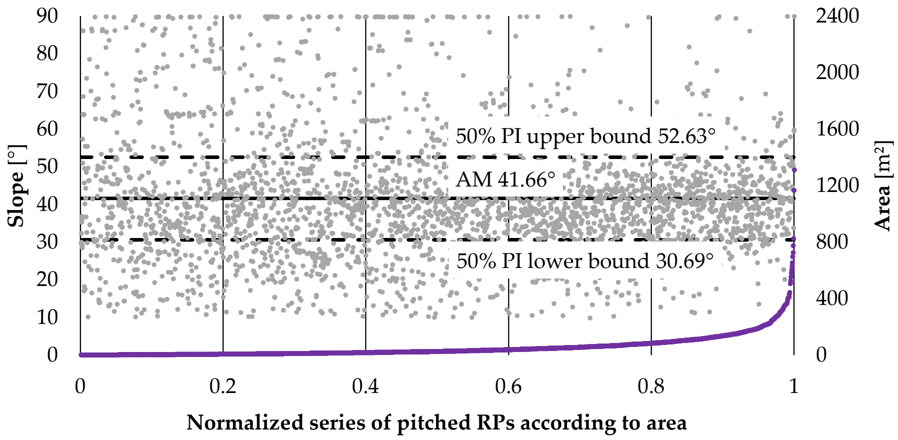


Figure 9. Relation between the slope and the area of the pitched RPs.

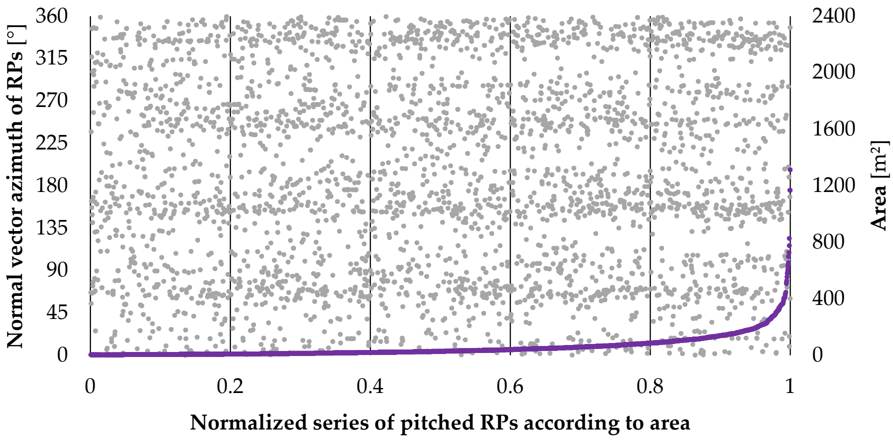


Figure 10. Relation between the normal vector azimuth of RPs and the area of the pitched RPs.

The higher density of values near the lines with an azimuth of 70°, 160°, 250°, and 340° were compared with the 3D morphological model of the Monument Reserve in Bratislava, Slovakia (Figure 11).

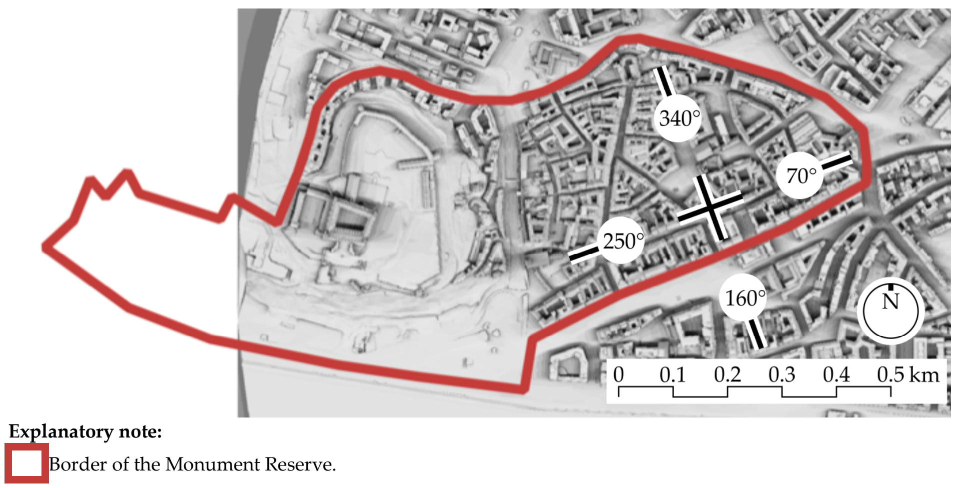


Figure 11. The 3D morphological model of the buildings provided by the Eurosense. Main roads pattern azimuth.

Based on the comparison of Figures 10 and 11, it is obvious that the variety of roof planes in examined historical urban structure has a certain level of order that arises from the street pattern. The degree of disorder was analyzed by apportioning the pitched RPs' normal vector azimuth in fourth intervals symmetrical to the prevalent azimuth of 70°, 160°, 250°, and 340°. For each interval, the AM and 50% PI bounds were calculated (Table 6, Figure 12).

Table 6. Statistical characteristic of pitched RPs based on the prevalent azimuth.

Interval	Prevalent Azimuth (°)	Azimuth Interval (°)	AM (°)	50% PI (°)
I	70	<25, 115)	73.6	±14.1
II	160	<115, 205)	163.5	±13.1
III	250	<205, 295)	254.7	±14.5
IV	340	<295, 385)	343.2	±13.5

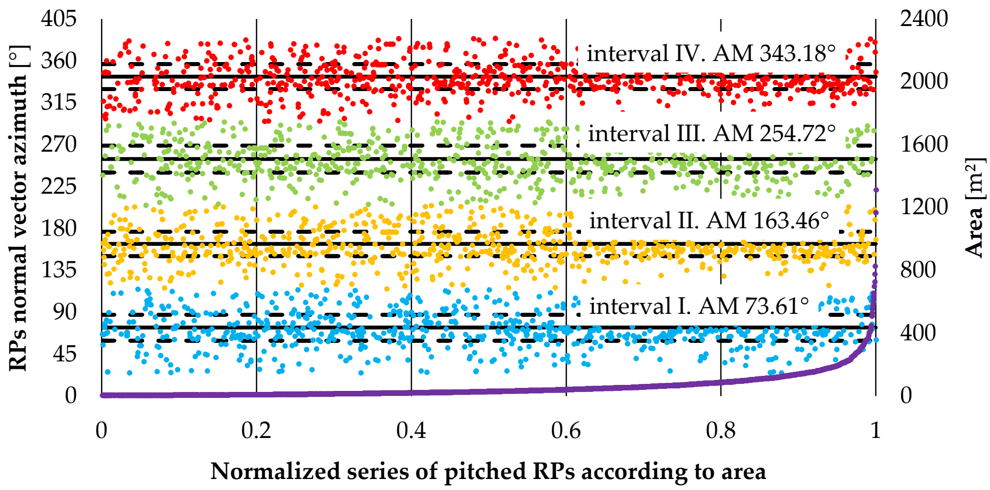


Figure 12. The degree of disorder of the pitched RPs normal vector azimuth analysis.

Resulting from the geometry characteristics of pitched RPs, the elaborated RPs dataset identified twenty groups (A–E/I–IV), which were sorted out according to four intervals of their prevalent normal vector azimuth (I—IV) and five intervals of the normalized series of pitched RPs based on their area (A–E) (Table 7).

Table 7. Groups of pitched RPs dataset divided by their geometric characteristics.

			RPs Normal Vector Azimuth of RPs			
			I	II	III	IV
		Interval	<25, 115)	<115, 205)	<205, 295)	<295, 385)
Normalized series of pitched RPs according to area	A	(0.0, 0.2)	Group A-I.	Group A-II.	Group A-III.	Group A-IV.
	B	<0.2, 0.4)	Group B-I.	Group B-II.	Group B-III.	Group B-IV.
	C	<0.4, 0.6)	Group C-I.	Group C-II.	Group C-III.	Group C-IV.
	D	<0.6, 0.8)	Group D-I.	Group D-II.	Group D-III.	Group D-IV.
	E	<0.8, 1.0>	Group E-I.	Group E-II.	Group E-III.	Group E-IV.

4. Results

The previous classification and analyses of the RPs provided the basis for the next major steps of investigation. The study highlights the possible integration of PV modules in the Monument Reserve in Bratislava, Slovakia, through the reciprocal relations of the geometric and irradiance characteristics and their AM/PI values of each twenty pitched

RP groups (A–E/I–IV), as presented in Table 7. According to development types, these 20 groups were examined in three main categories. The first category (A–ALL) calculated the potential of solar gains of all RPs in the study area. The second (B–IN) provided information on the solar potential of RPs of urban blocks with inner courtyards suitable for nonvisible integration of PV perceived by passersby. Finally, the third category (C–OTHER) examined the solar potential of RPs complementary to RPs of urban blocks with inner courtyards. The rooftops within all three categories reached a size of more than 5 m^2.

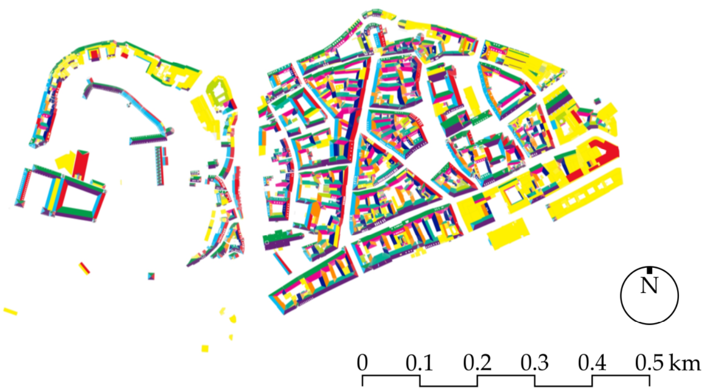
4.1. Pitched Roofs

Based on detailed results, as presented in Appendix A, it is obvious that the coherence of slope and normal vector azimuth (NVA) were in an inverse ratio to area. It means that smaller RPs had a higher level of declination to prevalent values. This decrease in the coherency of smaller RPs was in direct proportion to the decrease in annual irradiation (AI) of the area. Therefore, it was possible to assume that the smaller areas were more shaded by the surrounding buildings. The total annual irradiance of RPs (Σ RPs AI) decreased significantly in an interval of a third of 20% of the smallest RPs with an average area of 30 m^2. This trend was continuous with all RPs smaller than this interval (Tables A1–A5).

4.2. Flat Roofs

In parallel to the pitched-roof polygons, flat RPs were also investigated. In this case, the area of flat roofs (FR) was assumed only to be a relevant geometric characteristic. Other attributes such as slope and normal vector azimuth of polygons were not applicable. The analysis confirmed that the flat RPs did not affect the annual irradiance (AI) of the area; respectively, no correlation was affirmed. A higher dispersion of AI values compared to pitched RPs was affected by the shading of the surrounding buildings (Table A6).

The data stemmed from the analysis shown in Tables A1–A6 were visualized in 3D color model of RPs according to the groups (A–E/I–IV) (Figure 13).



Explanation: RPs are colored according to the groups below.

Interval	A	B	C	D	E	A	B	C	D	E
I.	A-I./i	B-I./i	C-I./i	D-I./i	E-I./i	A-I./c	B-I./c	C-I./c	D-I./c	E-I./c
II.	A-II./i	B-II./i	C-II./i	D-II./i	E-II./i	A-II./c	B-II./c	C-II./c	D-II./c	E-II./c
III.	A-III./i	B-III./i	C-III./i	D-III./i	E-III./i	A-III./c	B-III./c	C-III./c	D-III./c	E-III./c
IV.	A-IV./i	B-IV./i	C-IV./i	D-IV./i	E-IV./i	A-IV./c	B-IV./c	C-IV./c	D-IV./c	E-IV./c
FR.	A-FR./i	B-FR./i	C-FR./i	D-FR./i	E-FR./i	A-FR./c	B-FR./c	C-FR./c	D-FR./c	E-FR./c

Figure 13. Division of RPs into groups according to Tables A1–A6, where *i* means the subcategory of RPs of blocks with inner courtyards, c represents the subcategory of complementary roof polygons to RPs of urban blocks with inner courtyards, and FR symbolizes flat roofs.

4.3. Identification of Suitable RPs for PV Integration

To identify the suitability of RPs for PV integration, all RP groups and subgroups were characterized with the following three values:

(i) The threshold of annual irradiance of RPs (AM–PI) AI calculated as the lower bound of 50% probability interval (PI). It meant that 75% or RPs in a particular group reached a higher and 25% a lower values of annual irradiance than this threshold;
(ii) Sum of the area of all RPs within the group (Σ RPs);
(iii) Sum of the annual irradiance of all RPs within the group (Σ RPs AI).

To better assess the groups/subgroups of RPs according to the threshold of annual irradiance, the four-level scale was set. AM established the scale's midthreshold, and the scale's first- and third-quarter thresholds were calculated as the upper and lower bounds of 50% PI. Based on this scale, the RPs were sorted by 25% intervals into four division arrays from the first 25% of the best irradiated RP groups (dark orange), to the second 25% (orange), to the third 25% (light orange), to the fourth 25% of the worst irradiated RP groups of gray color (Table 8, Figure 14).

Table 8. Array of geometric and irradiance characteristics of all RP groups and subgroups according to Tables A1–A6.

Group	**A-I./i**	**A-II./i**	**A-III./i**	**A-IV./i**	**A-I./c**	**A-II./c**	**A-III./c**	**A-IV./c**	**A-FR/i**	**A-FR/c**
(AM–PI) AI (kWh/m^2)	665.9	718.7	591.9	513.7	616.5	917.3	752.2	494.3	1239.2	1205.9
Σ RPs area (m^2)	410.8	448.7	444.1	436.3	757.2	727.2	748.5	664.2	264.7	1208.8
Σ RPs AI (MWh)	402.9	526.0	433.3	343.0	680.7	936.3	824.6	499.6	391.9	1796.0
Group	**B-I./i**	**B-II./i**	**B-III./i**	**B-IV./i**	**B-I./c**	**B-II./c**	**B-III./c**	**B-IV./c**	**B-FR/i**	**B-FR/c**
(AM–PI) AI (kWh/m^2)	655.5	1057.4	734.9	521.5	564.0	984.4	804.9	411.5	1433.3	983.1
Σ RPs area (m^2)	1155.5	1056.8	1167.2	1016.8	1677.6	1288.9	1369.2	1686.1	396.0	2053.0
Σ RPs AI (MWh)	1088.4	1506.4	1270.4	739.3	1499.5	1757.8	1506.8	1102.6	664.4	2618.4
Group	**C-I./i**	**C-II./i**	**C-III./i**	**C-IV./i**	**C-I./c**	**C-II./c**	**C-III./c**	**C-IV./c**	**C-FR/i**	**C-FR/c**
(AM–PI) AI (kWh/m^2)	666.6	1059.9	912.9	469.5	624.8	887.0	813.9	396.5	1221.0	1039.9
Σ RPs area (m^2)	2390.3	3260.4	2457.8	2973.0	2469.7	2176.9	2641.4	2283.5	903.6	4006.5
Σ RPs AI (MWh)	2261.6	4552.5	3035.2	2136.4	2276.2	2721.2	2941.7	1492.1	1389.2	5318.1
Group	**D-I./i**	**D-II./i**	**D-III./i**	**D-IV./i**	**D-I./c**	**D-II./c**	**D-III./c**	**D-IV./c**	**D-FR/i**	**E-FR/c**
(AM–PI) AI (kWh/m^2)	810.1	1332.3	1054.0	471.3	830.8	1265.4	985.0	600.0	1011.2	975.5
Σ RPs area (m^2)	4887.9	5177.4	5397.4	5249.8	5564.7	6295.0	5312.9	5341.0	1380.0	7100.1
Σ RPs AI (MWh)	5251.5	8061.3	6872.2	3534.0	5923.8	9567.2	6497.2	4173.8	1728.6	9287.9
Group	**E-I./i**	**E-II./i**	**E-III./i**	**E-IV./i**	**E-I./c**	**E-II./c**	**E-III./c**	**E-IV./c**	**E-FR/i**	**E-FR/c**
1-11 (AM–PI) AI (kWh/m^2)	774.0	1383.8	1037.0	620.5	900.3	1332.0	1016.9	515.2	1159.7	1120.8
Σ RPs area (m^2)	8918.6	12358.3	8954.6	11535.1	18094.2	19059.7	13453.8	22806.0	1911.6	35896.3
Σ RPs AI (MWh)	8779.5	19569.6	10787.1	9208.2	20652.9	29436.4	16374.8	15169.2	2911.4	51678.6

According to the geometry characteristics of the RP groups (pitched roofs, flat roofs, inner (i) and complementary (c) to the RPs of traditional urban blocks with inner courtyards), all data regarding the sum of the annual irradiance of the RPs (ΣAI, (GWh)) and the area of the sum of the RPs (ΣA, (*1000 m^2)) were combined. Furthermore, to illustrate the level of energy and the areal impact on RPs by photovoltaics, these summarized values were also classified by the scale of the best RP irradiance (best 25%, 50%, 75%, 100%), the increase in the irradiance and area values were compared to the scale categories (ICB 25%, 50%, 75%), and finally, they were compared to the values of all RPs (CTA ratio). Subsequently, based on the relation between the energy contribution potential and the visual impact, all sections were divided into three categories regarding the suitability of PV integration as follows: (i) RPs highly applicable for PV integration; (ii) RPs applicable for PV integration with an additional investigation on an architectural scale; (iii) RPs not applicable for PV integration (Table 9, Figure 15).

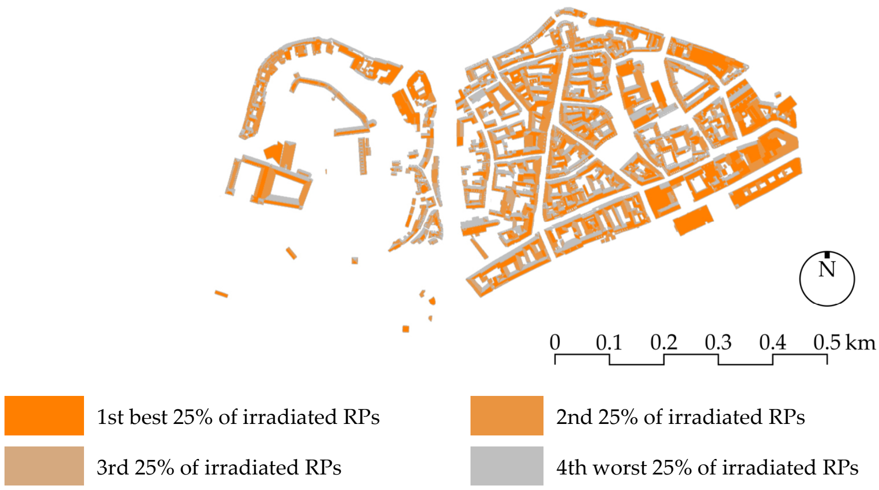


Figure 14. RP divisions according to the four-level annual irradiation scale.

Table 9. Irradiance and area values summarized by RP division.

RPs		Pitched/I RPs/i		Pitched/c RPs/c		All Pitched RPs		Flat/I RPs/i		Flat/c RPs/c		All Flat RPs		All RPs	
		CTA	(%)	CTA	(%)	CTA	(%)	CTA	(%)	CTA	(%)	CTA	(%)	CTA	(%)
All	ΣA	79.7	32.0	114.4	45.9	194.1	77.9	4.9	1.9	50.3	20.2	55.1	22.1	249.2	100.0
	ΣAI	90.4	36.3	126.0	42.8	216.4	73.6	7.1	2.4	70.7	24.0	77.8	26.4	294.2	100.0
best	ΣA	27.3	10.9	25.4	10.2	52.6	21.1	3.5	1.4	37.1	14.9	40.6	16.3	93.2	37.4
25%	ΣAI	40.6	13.8	39.0	13.3	79.6	27.0	5.4	1.8	53.5	18.2	58.8	20.0	138.4	47.0
best	ΣA	38.7	15.5	66.4	26.6	105.1	42.2	4.9	1.9	50.3	20.2	55.1	22.1	160.2	64.3
50%	ΣAI	54.4	18.5	87.9	29.9	142.3	48.4	7.1	2.4	70.7	24.0	77.8	26.4	220.1	74.8
ICB	ΣA	11.4	4.6	41.1	16.5	52.5	21.1	1.4	0.6	13.2	5.3	14.5	5.8	67.0	26.9
25%	ΣAI	13.8	4.7	48.9	16.6	62.8	21.3	1.7	0.6	17.2	5.9	19.0	6.4	81.7	27.8
best	ΣA	52.9	21.2	76.7	30.8	129.7	52.0	-	-	-	-	-	-	184.8	74.1
75%	ΣAI	68.9	23.4	99.1	33.7	168.1	57.1	-	-	-	-	-	-	245.9	83.6
ICB	ΣA	14.3	5.7	10.3	4.1	24.6	9.9	-	-	-	-	-	-	24.6	9.9
50%	ΣAI	14.6	4.9	11.2	3.8	25.8	8.8	-	-	-	-	-	-	25.8	8.8
best	ΣA	79.7	32.0	114.4	45.9	194.1	77.9	-	-	-	-	-	-	249.2	100.0
100%	ΣAI	90.4	30.7	126.0	42.8	216.4	73.6	-	-	-	-	-	-	294.2	100.0
ICB	ΣA	26.8	10.7	37.7	15.1	64.5	25.9	-	-	-	-	-	-	64.5	25.9
75%	ΣAI	21.4	7.3	26.9	9.1	48.3	16.4	-	-	-	-	-	-	48.3	16.4

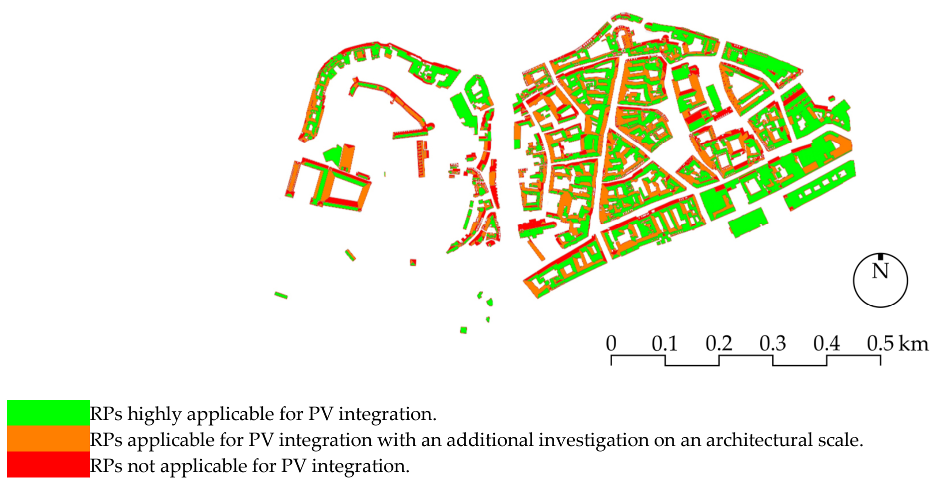


Figure 15. Division of RPs regarding the suitability of PV integration.

4.4. Scenarios Calculation

The previous complex analytical datasets and the identified roof polygons that are, highly applicable (hap) or applicable for PV integration in Monument Reserve (MR) with an additional investigation on an architectural scale (ap) were involved in the final step of the study in scenario simulations. First, data on irradiation under the clear sky calculated by the r-sun model were compared with data provided by PVGIS under the typical meteorological year (TMY), in particular, PVGIS-SARAH2 based on measurements from 2005 to 2020 [52]. Then, the annual irradiance (AI) of the ten largest RPs of each of four azimuth intervals (which were with high probability not shaded by surroundings) calculated by r-sun were compared with the AI of PVGIS. The PVGIS/*r-sun* reduction factor and PV efficiency losses due to angle of incidence, spectral effects, temperature, and low irradiance were enumerated (Table A7). RP data essential to simulate four scenarios of power output potentials (POP) were derived for three types of solar cells: i) non-multijunction cells under laboratory conditions such as crystalline Si cells, thin-film cells, emerging cell technologies with a median efficiency value of 22% (Non-MJC); ii) multijunction cells under laboratory conditions with a median efficiency value of 39% (MJC); and iii) building integrated PV referring to Tesla solar roof tiles with efficiency of 7% (BIPV) [48,55]. The area reduction factor was established according to spatial and aesthetic limits and energy conversion losses were estimated. The scenario with the highest power output potential and relatively low visual impact on Monument Reserve is highlighted in Table 10 in gray cells.

Table 10. RP data essential to simulate four scenarios of PV integration on pitched or flat roofs within blocks with inner courtyards (i) and complementary RPs (c) in MR.

							Cell Type/Efficiency		
							NonMJC	**MJC**	**BIPV**
							22%	**39%**	**7%**
	Area ($\times$1000 m^2)	**AI (GWh)**	**Area Reduction Factor**	**PVGIS R-Sun Reduction Factor**	**PV Efficiency Losses (%)**	**Conversion Losses (%)**	**POP (GWh)**	**POP (GWh)**	**POP (GWh)**
Pitched RPs/i/hap	65.9	94.9	0.8	0.79	11.1	14	10.1	17.9	3.2
Pitched RPs/c/hap	25.4	39.0	0.8	0.79	11.1	14	4.1	7.3	1.3
Pitched RPs/i/ap	132.6	159.3	0.5	0.79	11.1	14	10.6	18.8	3.4
Pitch RPs/c/ap	66.4	87.9	0.5	0.79	11.1	14	5.8	10.4	1.9
Flat RPs/i/hap	8.3	12.4	0.8	0.79	11.1	14	1.3	2.3	0.4
Flat RPs/c/hap	87.4	124.2	0.8	0.79	11.1	14	13.2	23.4	4.2
Total	386.0	517.8						65.6	

To comprehend and assess the power output potential (POP) of the roof polygons within the Monument Reserve in the context of the Bratislava City, the City District I–Old Town with an area of 9.59 km^2 and annual power consumption (PC) of buildings at the level of 352.5 GWh per year was selected as a reference. This PC value was derived as an arithmetic mean of PC values measured between 2000 and 2019 and accessed through the city open data website [56]. On the contrary, the area of the Monument Reserve addressed is 0.55 km^2. The comparison presented in Table 11 refers to the area of the territory, since the area is one of the determinants in capturing the energy of the sun.

Table 11. Four different scenarios of PV integration in MR compared to the power consumption of buildings within Bratislava City District I–Old Town.

Bratislava City District I (BAI)					
Area: 9.59 km^2 Annual BAI power consumption: 352.5 GWh Annual BAI power consumption per area: 36.76 GWh/km^2					
Monument Reserve (MR)					
Area: 0.55 km^2					
Scenario	**RPs Included**	**Annual MR POP (GWh)**	**MR POP Compared to BAI PC (%)**	**MR POP Per Area (GWh/km^2)**	**MR POP Per Area Compared to BAI PC Per Area (%)**
I.	Flat RPs, Non-MJC	14.5	4%	26.4	72%
II.	Flat RPs, Non-MJC Pitched RPs/i, Non-MJC	35.2	10%	64.0	174%
III.	Flat RPs, MJC pitched RPs/i, MJC	62.4	18%	113.5	309%
IV.	Flat RPs, MJC Pitched RPs/i, MJC Pitched RPs/c, BIPV	65.6	19%	119.3	324%

5. Discussion and Conclusions

This study investigated the solar potential of roof polygons within the Monument Reserve, Bratislava. Since this topic does not correspond to the current standards of monument preservation approaches applied in monument reserves, it may seem controversial, indeed. However, the data obtained confirmed the justification that it is relevant to open up the in-depth discussion on PV integration in historical urban structures in order to bequeath a heritage asset to future generations. The current energy crisis brings with it a change in thinking about energy, not only through the threats resulting from anthropogenic global climate change, but also through energy self-sufficiency, which has become a tool of power struggle [57].

The authors of this article are of the opinion that the cultural heritage will survive only if it meets the energy requirements and is energetically sustainable. Therefore, the issue of PV applicability in the built environment becomes crucial even in the context of historical and preserved structures. In fact, to take part in the responsibility for global issues and participate in resilience and sustainable development strategies, a balance is necessary between monument preservation, technological innovations, and advanced engineering/architecture/urban solutions that respect the cultural values of historic buildings.

The four scenarios presented the power output potentials (POPs) of the roof polygons calculated with three types of cells/systems and their efficiency, which is crucial and will most likely only increase henceforward. Another prospect represents flexible solar foils or solar clear glass inventions that are applicable to transparent surfaces such as windows. These innovations can enhance the transformation of buildings into the solar power generators in the future. Based on the results provided in Table 11, the potential for power generation of MR according to specific scenarios can cover from 4% to 19% of the total power consumption of buildings located in BAI City District, respectively, from 72% to 324% of their PC related to an area of 1 km^2.

The detailed quantitative analysis of RPs in MR, Bratislava, showed that, at first sight, the high variety of rooftops based on geometrical characteristics located in the historical urban structure could be sorted into several groups of RPs with a significant prediction of their characteristics. In the case of the analysis performed, it meant that of the total of 9150 RPs, of which 4216 RPs were suitable for PV integration, it was possible to drop to 20 groups of pitched RPs and 5 groups of flat RPs due to an affiliation with inner RPs of urban blocks with inner courtyards, which were further divided into 50 subgroups.

These data and set methodology are suitable for designing a customized technical and aesthetical solution of possible PV integration for RPs executed with higher effectiveness. Furthermore, this type of data can be used by decision- and policy makers. It is precisely the datafication process as part of the quantitative research method that is recommended as a tool to create predictive analysis for decision making while operating with many stakeholders or quantitative (physical, economic, environmental) and qualitative (cultural, social, aesthetic) parameters [58,59]. In a future generation of the data model that was used, it is needed to improve the quality of the data and analytics tools to increase the reliability of the results.

The elaborate datasets and the evaluation method can be perceived as a 'live data model' that keeps data in flow vertically and horizontally. This means, on the one hand, that any new information with higher precision can be transferred in a vertical direction, from urban scale to separate polygon and vice versa. On the other hand, the data with higher accuracy can be transferred in horizontal direction—between RPs with similar characteristics (in group of RPs) and any new characteristic added into the data model. For instance, real-time and on-site measurements of irradiance, light intensity, or other physical parameters such as albedo, reflectivity, normalized difference vegetation index, relative humidity, etc., which affect the formation of urban heat islands, are also within the scope of the authors' research. Therefore, further research can aim at refinement of calculations or examining the solar potential of other city parts/districts in the context of smart city/PEDs concepts and mutual energy flows. In collaboration with experts, other prospects in this issue after consolidation represent the calculation of financial return and costs related to PV, examination of stability of the power grid affected by the PV installed, designing of conductors and protection devices, technological solutions associated with the connection of such PV systems to the existing power grid, etc. These aspects and parameters were not examined by the authors of the article mainly due to the volatility of current tariffs affected by the energy crisis, average costs of PV systems, or rapid development of their efficiency. In fact, before the energy crisis, the average cost of a solar panels dropped by 90% from 2010 to 2020 [60], while the fossil gas energy prices were four to six times higher than the new PV energy capacity in Europe in 2021 [61].

To raise awareness of the laid public and owners of immovable national cultural monuments in whom the burden of ownership of a cultural monument and the associated energy and maintenance costs are projected, such data could be applied in visualization tools such as solar cadasters or other more extensive data presenting applications to ensure responsible user behavior or to implement various incentive models to exploit the use of photovoltaics to counteract climate change with respect to cultural values. Such a discussion may result in the future modification/reconfiguration of the current valid legislation or in the creation of new regulatory principles in the form of textual guidelines and maps that will categorize the specific sites in Slovakia/Bratislava according to the suitability and types of PV systems. Hopefully, in the end, the city will not be perceived as a problem but as a solution.

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Appendix A

Table A1. Evaluation of the 1st 20% of pitched RPs by area.

Category/Group		Group A-I. (1st 20%) (Azimuth 70°)		Group A-II. (1st 20%) (Azimuth 160°)		Group A-III. (1st 20%) (Azimuth 250°)		Group A-IV. (1st 20%) (Azimuth 340°)	
			PI		**PI**		**PI**		**PI**
A–ALL	RPs count	163.0		161.0		165.0		150.0	
	AM NVA (°)	71.2	14.8	161.7	13.8	255.3	15.1	340.1	15.1
	AM RPs slope (°)	43.4	11.7	43.5	14.0	44.4	14.4	43.0	13.3
	Σ RPs area (m^2)	1083.6		1462.4		1257.9		842.6	
	AM RPs area (m^2)	7.1	1.0	7.3	1.1	7.2	1.0	7.3	1.0
	Σ RPs AI (MWh)	1083.6		1462.4		1257.9		842.6	
	AM RPs AI (kWh/m^2)	936.7	304.8	1241.9	402.4	1059.1	369.7	761.2	258.4
B–IC	RPs count	57.0		61.0		63.0		60.0	
	AM NVA (°)	73.1	12.7	163.0	11.5	255.9	14.4	341.5	15.6
	AM RPs slope (°)	40.5	13.0	45.9	15.3	47.0	16.6	41.3	13.9
	Σ RPs area (m^2)	410.8		448.7		444.1		436.3	
	AM RPs area (m^2)	7.2	1.1	7.4	1.2	7.0	1.0	7.3	1.1
	Σ RPs AI (MWh)	402.9		526.0		433.3		343.0	
	AM RPs AI (kWh/m^2)	1003.8	337.9	1174.7	456.1	982.1	390.2	763.9	250.2
C–OTHER	RPs count	106.0		100.0		102.0		90.0	
	AM NVA (°)	70.2	15.8	160.9	15.1	255.0	15.6	339.2	14.8
	AM RPs slope (°)	44.9	10.9	42.1	13.2	42.7	12.8	44.1	12.8
	Σ RPs area (m^2)	757.2		727.2		748.5		664.2	
	AM RPs area (m^2)	7.1	1.0	7.3	1.0	7.3	1.0	7.4	1.0
	Σ RPs AI (MWh)	680.7		936.3		824.6		499.6	
	AM RPs AI (kWh/m^2)	900.6	284.1	1282.8	365.5	1106.7	354.5	759.4	265.1

Table A2. Evaluation of the 2nd 20% of pitched RPs by area.

Category/Group		**Group B-I. (2nd 20%) (Azimuth 70°)**		**Group B-II. (2nd 20%) (Azimuth 160°)**		**Group B-III. (2nd 20%) (Azimuth 250°)**		**Group B-IV. (2nd 20%) (Azimuth 340°)**	
			PI		**PI**		**PI**		**PI**
A–ALL	RPs count	186.0		151.0		168.0		177.0	
	AM NVA (°)	74.4	13.8	163.3	14.1	254.8	13.4	341.9	14.4
	AM RPs slope (°)	43.6	12.4	41.7	13.2	44.2	12.2	43.9	12.4
	Σ RPs area (m^2)	2833.1		2345.8		2536.4		2702.9	
	AM RPs area (m^2)	15.2	2.4	15.5	2.2	15.1	2.2	15.3	2.2
	Σ RPs AI (MWh)	2587.9		3264.2		2777.2		1841.8	
	AM RPs AI (kWh/m^2)	907.6	305.6	1371.1	353.3	1098.7	326.6	684.4	232.0
B–IC	RPs count	78.0		68.0		77.0		68.0	
	AM NVA (°)	74.6	13.7	164.1	15.4	255.1	13.1	342.4	13.9
	AM RPs slope (°)	37.3	10.9	38.8	12.9	43.0	13.4	39.0	11.1
	Σ RPs area (m^2)	1155.5		1056.8		1167.2		1016.8	
	AM RPs area (m^2)	14.8	2.3	15.5	2.0	15.2	2.3	15.0	2.3
	Σ RPs AI (MWh)	1088.4		1506.4		1270.4		739.3	
	AM RPs AI (kWh/m^2)	936.2	280.7	1404.5	347.1	1097.5	362.6	729.8	208.4
C–OTHER	RPs count	108.0		83.0		91.0		109.0	
	AM NVA (°)	74.3	14.0	162.8	13.1	254.5	13.7	341.5	14.7
	AM RPs slope (°)	48.1	12.6	44.1	13.2	45.2	11.1	47.0	12.7
	Σ RPs area (m^2)	1677.6		1288.9		1369.2		1686.1	
	AM RPs area (m^2)	15.5	2.4	15.5	2.3	15.0	2.1	15.5	2.1
	Σ RPs AI (MWh)	1499.5		1757.8		1506.8		1102.6	
	AM RPs AI (kWh/m^2)	887.0	323.0	1343.8	359.4	1099.8	294.9	656.1	244.6

Table A3. Evaluation of the 3rd 20% of pitched RPs by area.

Category/Group		**Group C-I. (3rd 20%) (Azimuth 70°)**		**Group C-II. (3rd 20%) (Azimuth 160°)**		**Group C-III. (3rd 20%) (Azimuth 250°)**		**Group C-IV. (3rd 20%) (Azimuth 340°)**	
			PI		**PI**		**PI**		**PI**
A–ALL	RPs count	158.0		178.0		167.0		174.0	
	AM NVA (°)	72.8	13.8	163.5	13.9	253.1	15.6	343.6	12.4
	AM RPs slope (°)	41.1	11.1	41.8	11.3	40.7	11.2	44.4	13.3
	Σ RPs area (m^2)	4860.0		5437.3		5099.2		5256.5	
	AM RPs area (m^2)	30.8	4.0	30.5	4.1	30.5	3.9	30.2	3.8
	Σ RPs AI (MWh)	4537.8		7273.7		5976.9		3628.5	
	AM RPs AI (kWh/m^2)	929.4	284.2	1330.7	343.1	1163.4	302.9	692.2	256.6
B–IC	RPs count	76.0		106.0		83.0		80.0	
	AM NVA (°)	73.3	12.1	163.8	12.2	252.4	15.2	338.3	8.9
	AM RPs slope (°)	39.0	11.4	37.4	10.4	36.6	11.9	42.0	13.7
	Σ RPs area (m^2)	2390.3		3260.4		2457.8		2973.0	
	AM RPs area (m^2)	31.5	4.0	30.8	3.9	29.6	3.7	31.6	3.8
	Σ RPs AI (MWh)	2261.6		4552.5		3035.2		2136.4	
	AM RPs AI (kWh/m^2)	956.3	289.8	1383.7	323.8	1228.3	315.4	724.0	254.5

Table A3. *Cont.*

Category/Group		Group C-I. (3rd 20%) (Azimuth 70°)		Group C-II. (3rd 20%) (Azimuth 160°)		Group C-III. (3rd 20%) (Azimuth 250°)		Group C-IV. (3rd 20%) (Azimuth 340°)	
			PI		PI		PI		PI
C–OTHER	RPs count	82.0		72.0		84.0		64.0	
	AM NVA (°)	72.2	15.2	163.0	16.1	253.7	16.0	336.6	9.4
	AM RPs slope (°)	43.0	10.6	48.3	11.2	44.8	9.8	47.3	12.7
	Σ RPs area (m^2)	2469.7		2176.9		2641.4		2283.5	
	AM RPs area (m^2)	30.1	3.9	30.2	4.4	31.4	4.1	28.5	3.5
	Σ RPs AI (MWh)	2276.2		2721.2		2941.7		1492.1	
	AM RPs AI (kWh/m^2)	904.5	279.7	1252.6	365.7	1099.3	285.4	654.8	258.3

Table A4. Evaluation of the 4th 20% of pitched RPs by area.

Category/Group		Group D-I. (4th 20%) (Azimuth 70°)		Group D-II. (4th 20%) (Azimuth 160°)		Group D-III. (4th 20%) (Azimuth 250°)		Group D-IV. (4th 20%) (Azimuth 340°)	
			PI		PI		PI		PI
A–ALL	RPs count	173.0		185.0		177.0		172.0	
	AM NVA (°)	76.1	13.6	165.2	12.7	255.1	13.3	345.9	13.0
	AM RPs slope (°)	38.6	8.8	37.9	7.5	37.3	7.9	40.4	9.6
	Σ RPs area (m^2)	10,452.7		11,472.5		10,710.3		10,590.7	
	AM RPs area (m^2)	60.4	8.5	62.0	8.6	60.5	8.6	61.6	9.1
	Σ RPs AI (MWh)	11,175.4		17,628.5		13,369.4		7707.9	
	AM RPs AI (kWh/m^2)	1062.2	240.8	1529.1	234.1	1247.0	227.6	733.0	200.1
B–IC	RPs count	82.0		82.0		89.0		86.0	
	AM NVA (°)	73.6	12.5	164.1	11.2	252.9	11.0	349.3	11.6
	AM RPs slope (°)	35.5	9.2	36.6	6.9	35.6	7.8	41.9	11.0
	Σ RPs area (m^2)	4887.9		5177.4		5397.4		5249.8	
	AM RPs area (m^2)	59.6	9.5	63.1	8.5	60.6	7.9	61.0	9.0
	Σ RPs AI (MWh)	5251.5		8061.3		6872.2		3534.0	
	AM RPs AI (kWh/m^2)	1064.6	254.6	1557.4	225.1	1275.6	221.6	683.3	211.9
C–OTHER	RPs count	91.0		103.0		88.0		86.0	
	AM NVA (°)	78.4	14.3	166.2	13.8	257.4	15.1	342.6	14.0
	AM RPs slope (°)	41.5	8.0	38.9	7.8	39.0	7.8	38.9	7.9
	Σ RPs area (m^2)	5564.7		6295.0		5312.9		5341.0	
	AM RPs area (m^2)	61.2	8.8	61.1	8.6	60.4	9.3	62.1	9.1
	Σ RPs AI (MWh)	5923.8		9567.2		6497.2		4173.8	
	AM RPs AI (kWh/m^2)	1059.9	229.1	1506.5	241.1	1218.2	233.1	782.6	182.6

Table A5. Evaluation of the 5th 20% of pitched RPs by area.

Category/Group		Group E-I. (5th 20%) (Azimuth 70°)		Group E-II. (5th 20%) (Azimuth 160°)		Group E-III. (5th 20%) (Azimuth 250°)		Group E-IV. (5th 20%) (Azimuth 340°)	
			PI		**PI**		**PI**		**PI**
A–ALL	RPs count	149.0		181.0		137.0		200.0	
	AM NVA (°)	73.2	14.4	163.3	11.2	255.4	15.4	343.9	12.5
	AM RPs slope (°)	41.3	8.3	40.9	6.7	40.3	6.0	41.2	7.7
	Σ RPs area (m^2)	27,012.9		31,417.9		22,408.4		34,341.1	
	AM RPs area (m^2)	181.3	95.6	173.6	82.4	163.6	59.5	171.7	82.6
	Σ RPs AI (MWh)	29,432.4		49,006.0		27,161.8		24,377.4	
	AM RPs AI (kWh/m^2)	1046.7	200.6	1561.9	205.9	1227.2	200.5	725.3	171.5
B–IC	RPs count	61.0		85.0		64.0		80.0	
	AM NVA (°)	71.3	12.5	165.5	12.6	255.4	13.9	343.0	10.9
	AM RPs slope (°)	40.2	8.0	39.6	5.0	39.8	5.6	37.2	6.3
	Σ RPs area (m^2)	8918.6		12,358.3		8954.6		11535.1	
	AM RPs area (m^2)	146.2	44.2	145.4	40.5	139.9	36.3	144.2	38.1
	Σ RPs AI (MWh)	8779.5		19,569.6		10,787.1		9208.2	
	AM RPs AI (kWh/m^2)	987.6	213.6	1569.9	186.1	1226.9	189.9	791.8	171.3
C–OTHER	RPs count	88.0		96.0		73.0		120.0	
	AM NVA (°)	74.6	15.6	161.3	9.7	255.4	16.8	336.2	8.4
	AM RPs slope (°)	42.0	8.5	42.1	7.9	40.8	6.4	43.9	8.1
	Σ RPs area (m^2)	18,094.2		19,059.7		13,453.8		22,806.0	
	AM RPs area (m^2)	205.6	116.4	198.5	103.9	184.3	71.5	190.0	100.3
	Σ RPs AI (MWh)	20,652.9		29,436.4		16,374.8		15,169.2	
	AM RPs AI (kWh/m^2)	1087.6	187.3	1554.8	222.8	1227.4	210.6	681.0	165.7

Table A6. Evaluation of flat RPs.

Category/Group		Group A-FR (1st 20%)		Group B-FR (2nd 20%)		Group C-FR (3rd 20%)		Group D-FR (4th 20%)		Group E-FR (5th 20%)	
			PI		**PI**		**PI**		**PI**		**PI**
A–ALL	RPs count	169.0		134.0		135.0		114.0		167.0	
	Σ RPs area (m^2)	1208.8		2053.0		4006.5		7100.1		35,896.3	
	AM RPs area (m^2)	7.2	1.0	15.3	2.3	29.7	3.9	62.3	9.5	214.9	140.7
	Σ RPs AI (MWh)	1796.0		2618.4		5318.1		9287.9		51,678.6	
	AM RPs AI (kWh/m^2)	1498.7	292.8	1283.6	300.5	1327.2	287.4	1302.7	327.2	1396.5	275.6
B–IC	RPs count	35.0		27.0		31.0		22.0		10.0	
	Σ RPs area (m^2)	264.7		396.0		903.6		1380.0		1911.6	
	AM RPs area (m^2)	7.6	1.0	7.4	2.4	29.1	3.9	62.7	9.5	191.2	127.3
	Σ RPs AI (MWh)	391.9		664.4		1389.2		1728.6		2911.4	
	AM RPs AI (kWh/m^2)	1490.1	251.0	1676.7	243.4	1530.8	309.8	1278.2	266.9	1425.4	265.7
C–OTHER	RPs count	106.0		100.0		102.0		90.0		90.0	
	Σ RPs area (m^2)	757.2		727.2		748.5		664.2		664.2	
	AM RPs area (m^2)	7.1	1.0	7.3	1.0	7.3	1.0	7.4	1.0	7.4	1.0
	Σ RPs AI (MWh)	680.7		936.3		824.6		499.6		499.6	
	AM RPs AI (kWh/m^2)	900.6	284.1	1282.8	365.5	1106.7	354.5	759.4	265.1	759.4	265.1

Table A7. Comparison.

Azimuth Interval Mid-Value (°)	Azimuth (°)	Slope (°)	Area (m^2)	AI r-sun (kWh/m^2)	AI PVGIS (kWh/m^2)	Changes in Output (%)	Changes in Output AM (%)	Changes in Output MEDIAN (%)	Ratio PVGIS /r-sun	Ratio AM	Ratio MEDIAN
70	88.5	31.7	88.2	1517.7	1201.2	−11.4	−11.5	−11.5	0.8	0.8	0.8
	64.5	12.9	91.7	1516.9	1205.7	−12.1			0.8		
	92.1	15.2	99.4	1462.9	1271.1	−11.6			0.9		
	99.1	37.9	108.8	1414.1	1239.9	−11.1			0.9		
	79.2	50.4	143.8	1752.2	1040.0	−11.5			0.6		
	107.1	36.4	146.2	1511.9	1291.1	−11.0			0.9		
	102.5	41.4	191.0	1405.9	1244.8	−11.1			0.9		
	50.3	19.1	192.9	1390.9	1117.8	−12.5			0.8		
	102.7	31.2	214.5	1636.0	1282.9	−11.5			0.8		
	95.6	37.7	404.4	1398.8	1222.4	−11.2			0.9		
160	189.3	30.9	88.4	2062.9	1501.1	−10.7	−10.8	−10.7	0.7	0.7	0.7
	154.9	11.3	113.9	2044.6	1384.9	−11.2			0.7		
	161.3	16.3	116.7	1968.9	1425.2	−11.0			0.7		
	171.2	31.2	124.0	1978.7	1500.1	−10.7			0.8		
	189.2	30.1	148.5	1959.8	1498.9	−10.7			0.8		
	154.8	28.9	171.1	1985.6	1472.4	−10.7			0.7		
	153.9	27.1	172.0	1999.2	1465.6	−10.8			0.7		
	156.7	28.4	176.0	1971.7	1474.1	−10.8			0.8		
	161.9	25.4	282.6	2031.5	1472.7	−10.8			0.7		
	173.1	35.1	320.5	1977.9	1507.3	−10.6			0.8		
250	218.1	41.7	93.8	1641.3	1439.8	−10.7	−10.9	−10.9	0.9	0.8	0.8
	220.4	26.1	100.9	1963.7	1433.9	−10.9			0.7		
	244.4	25.8	105.9	1764.8	1352.9	−11.1			0.8		
	221.1	29.0	114.7	1998.8	1436.0	−10.9			0.7		
	230.5	33.8	119.2	1762.8	1406.1	−10.8			0.8		
	251.0	31.6	128.2	1638.0	1316.5	−11.1			0.8		
	233.6	28.8	129.4	1666.4	1391.7	−10.9			0.8		
	216.8	33.4	130.4	1650.5	1451.3	−10.8			0.9		
	218.7	31.3	161.4	1713.2	1444.1	−10.8			0.8		
	230.4	29.7	221.5	1793.1	1406.6	−10.9			0.8		
340	337.2	29.2	91.1	1200.2	931.5	−13.8	−13.1	−13.0	0.8	0.7	0.8
	334.2	17.7	94.3	1302.4	1071.8	−13.0			0.8		
	305.9	30.5	105.4	1190.1	1037.4	−12.7			0.9		
	297.0	32.2	106.9	1214.1	1068.0	−12.3			0.9		
	335.5	11.6	112.5	1423.0	1150.1	−12.6			0.8		
	302.6	89.5	134.5	1587.8	545.1	−12.5			0.3		
	336.6	23.5	136.3	1191.4	1007.9	−13.3			0.9		
	352.9	13.6	195.3	1345.50	1110.4	−12.9			0.8		
	325.9	25.0	230.8	1889.37	1009.5	−13.2			0.5		
	331.9	49.0	348.8	1437.63	708.5	−14.3			0.5		
ALL							−11.6	−11.1		0.8	0.8

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