

Energy-saving potential of TPV glass integrated into existing and heritage buildings: a case study comparing a typical climate series and an extreme year.

L. Ruiz-Juncos, A. Monge-Barrio, A. Sanchez-Ostiz

Abstract— Given the urgency of decarbonizing the construction sector and the challenge faced by the built heritage in urban environments and the pressing need to enhance thermal resilience, the integration of renewable energy systems such as photovoltaics can be particularly challenging due to specific restrictions aimed at preserving the aesthetic and architectural value of the heritage buildings. In this context, the integration of transparent photovoltaic glass (TPV) in architectural design can enhance the energy generation capacity of existing buildings. This approach offers a solution that minimizes alterations to the aesthetic appearance of façades and roof, making particularly suitable for heritage buildings. Additionally, it is justified by the necessity of glazing replacement to improve the energy performance of built heritage in use. This particular case study explores the potential of TPV glazing implementation in an existing and listed educational building located in an urban environment in a temperate climate (Cfb) with the goal of maximizing its electricity generation potential and level of self-sufficiency. The study compares the energy performance of the refurbished building using high performance-glazing and TPV technologies currently available on the market, in combination with passive strategies (solar protections and night cooling ventilation), given that the rooftop PV installations are not allowed due to heritage conservation plans. The results evaluate annual energy performance by distinguishing between summer and winter condition, and compares a typical climate year with an extreme year characterized by heatwave events (2022). The analysis addresses the advantages and limitations of TPV implementation in the context of decarbonization and thermal resilience of listed buildings.

Keywords—cooling, heating, heatwave, energy generation

I. INTRODUCTION

Climate change affects the thermal and energy efficiency of our built environment by causing a steady rise in average temperatures and leading to more frequent extreme weather events, including heatwaves [1]. Path to decarbonization international objectives by 2050 requires high standards of energy efficiency based on passive strategies, as promoted by the European Energy Performance Buildings Directive, EPBD [2] together with a decisive commitment to renewables implementation.

Rehabilitation of listed buildings or buildings in architectural protected areas with decarbonization objectives supposes a clear challenge to balance objectives that can be contrary [3]. A clear example is the installation of photovoltaic panels (PV) on roofs that may even be banned in some contexts. The integration of transparent photovoltaics (TPV) in windows and glazed areas represents a promising technological solution with significant potential in this context. As Traverse *et al* states TPV allows many of the surfaces of our built environment to be turned into solar harvesting arrays without impacting the function or aesthetics [4].

Although there are some TPV in the market, as Onyx or Polysolar (in the European context), the technology still faces challenges previous to be fully incorporated in the market. Firstly, the technology must address the trade-off between visual transmittance and energy generation potential, ensuring that external visibility remains uncompromised. Another major challenge of this technology lies in its carbon footprint, durability, circularity, and cost. In this regard, emerging solutions such as organic photovoltaic glazing may represent a promising area for further investigation [5].

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R-J. L. is with the University of Navarra (e-mail: lruijuncos@unav.es).
M. A. is with the University of Navarra (e-mail: amongeb@unav.es). S-O. A. is with the University of Navarra (e-mail: aostiz@unav.es).
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Finally, extreme climate events and energy blackouts make it necessary to analyse passive and active strategies in buildings in order to ensure resilience and sufficiency.

This proposal looks for analyse through a case study of a listed building in a temperate climate the required balance through passive strategies and implementation of renewables with TPV in glazed areas, with objectives of decarbonization and resilience in the built environment. A core aspect of the analysis involved determining the extent to which TPV-based systems can serve as a competitive alternative to existing, well-established technologies in architectural and energy applications.

II. METHOD

This study develops an integrated approach to assess the potential of photovoltaic windows (TPV) in an educational building where local regulations do not allow the installation of photovoltaic panels on the roof or integrated into the building envelope. TPVs are analysed in combination with passive conditioning measures in summer: solar shading devices on southwest and southeast façades and night cooling ventilation. The analysis is conducted for both current climate scenario and an extreme year due to heatwaves (2022) in Spain, where the case study is located.

The annual heating and cooling energy demands are simulated to assess the effectiveness of passive measures and to estimate the theoretical contribution of the TPV system to energy needs. This section describes the used data and methods in more detail, including: information about the case study building, such as retrofitting works, envelope, area and HVAC systems (A); the climate scenarios selection(B); description of the selected glazing and TPV systems included in the study (C); and the description of the selected renovation measures for the case study (D).

A. Case study building description

To investigate the limitations and potential of built heritage in relation to the challenges posed by decarbonisation and resilience to heatwaves, this case study focuses on a representative building located in the city of Pamplona (Spain). The building is embedded within the city's urban context. This typology occupies an entire urban block and is bordered by three vehicular streets and an urban park on the northwest façade. The architectural layout is defined by a perimeter block enclosing an open central courtyard, within which a secondary volume is attached to one of the sides. Although this annexed volume is excluded from thermal performance calculations, it is included in the simulation model to account for its impact on incident solar radiation on the courtyard-facing façades.

The historical building was constructed in 1944, and has undergone various renovation interventions, including



Figure 1 – Case study building (Source: Google Earth)

roof insulation upgrades and the replacement of approximately 70% of its windows over different phases, using various window types. The current building features four different glazing types. The properties of the original glazing (T1) and the double-glazed units installed during a subsequent phase (T2) were estimated based on visual inspection and replacement records. The glazing installed in recent refurbishment works (T3 and T4) has been characterized according to the technical datasheets provided by the manufacturer.

The main characteristics of the building under analysis are summarised in TABLE I, which includes the estimated

TABLE I
CASE STUDY BUILDING INFORMATION AND CONSTRUCTION DETAILS

Description	Parameter	Unit
Location	Pamplona	
Construction year	1944	
Number of floors	2	
Rehabilitation works	W(70%), Roof insulation	
Heated floor area	9019	m ²
Window area	956	m ²
Heating system	N. Gas	
Setpoint temperature	20-25	° C
Cooling system	No	
Mechanical ventilation	No	h
Heating Schedule	6:00-13:30 16:00- 20:30	
Scholar schedule	8:30-15:00 16:50-21:30	h
U-values		
Façade	1.6	(W/m ²)
Roof	0.2	(W/m ²)
Occupation	0.03	(students/m ²)
WWR (Window-to-Wall Ratio)		
SO, SE, NO, NE	28,35,21,24	%

thermal transmittance values of the envelope components, as well as the building's occupancy schedule and the operating hours of the heating systems. Currently, the building is not equipped with either a cooling system or mechanical ventilation. For the purposes of this study, the cooling demand will be calculated, along with a scenario in which indoor air quality is ensured through a mechanical ventilation system with and without heat recovery. The cooling demand will be assessed for the summer months during which the building is currently in operation: June and September.

TPV systems are especially relevant in the case of heritage buildings, and both the EPBD (Energy Performance of Building Directive) [6] and the CTE (Spanish Code for Construction), acknowledges the need to adapt energy efficiency requirements to the particularities of listed buildings. However, TPV solutions enable contributions that preserve the architectural integrity and aesthetics.

B. Climate

For the purposes of this study, two weather files were selected for energy simulations: ASHRAE IWE2 with the climate series 1980–2010 [7] and year 2022 (HW2022), selected for being the year with the most days affected by heat waves, specifically 41, according to AEMET, Spanish Agency of Meteorology [8]. The first heat wave of 2022 occurred very early, from June 12 to 18. Data for the weather file was taken from the Meteorological Agency of Navarra (meteo.navarra.es).

C. Glazing definition and TPV typology

A comprehensive review of the scientific literature was undertaken in the preliminary phase of this investigation to delineate the current state-of-the-art in Transparent Solar Cell (TSC) technologies and their integration into Transparent Photovoltaic (TPV) systems. The literature encompasses a significant number of reviews that map the technological trajectories of BIPV systems [9], dissect conceptual approaches to PV-integrated fenestrations [10], and detail the operational principles of transparent photovoltaic [11].

The study was designed to investigate the comparative performance of current market-available transparent photovoltaic (TPV) systems against conventional alternatives, such as standard glazing technologies.

Emphasis was placed on examining the functional viability, energy conversion potential, and technological constraints of TPV solutions—specifically PV glazing units.

Transparent photovoltaic (TPV) glass products currently available on the market have been identified and synthesized in TABLE II as an outcome of this research. For the purposes of this case study, Onyx-30 glass has been selected due to its prior use in benchmark projects (<https://onyxsolar.com>) and its proven reliability in key performance indicators such as Power Conversion Efficiency (PCE) and Visible Transmittance (VT). This glass type was chosen for offering the highest VT (30%) within the product line of the European manufacturer, in line with a PCE of 2.8%, and for its transparent aesthetic, which does not obstruct outward views. Therefore, compared to other similar TPV models available on the market, Onyx-30 offers a well-balanced combination of transparency and photovoltaic generation, allowing clear outward visibility without the perception of patterns or excessive opacity. At the same time, the product's durability ensures energy production throughout its 25-year lifespan.

As part of this research, a review of the state of the art in photovoltaic glass technologies currently undergoing laboratory testing was conducted. However, this information was not included in the present article, as laboratory-grade performance—typically achieved on small-scale samples—does not necessarily translate into products ready for real-world implementation [12]. This case study instead focuses on commercially available products that have already been installed in other building typologies.

The glasses used in this case study are detailed in TABLE III, which includes the characteristics of the glazing systems currently installed in the building, named as T1,

TABLE II
STATE-OF-THE ART REVIEW OF MARKET-AVAILABLE TPV PRODUCTS

Market-available products	Power conversion efficiency(PCE) (%)	Visible transmittance (VT) (%)	Technology	Appearance	Source
<i>Onyx-10</i>	4,0	10	A-Si		https://onyxsolar.com
<i>Onyx-20</i>	3,4	20	A-Si		https://onyxsolar.com
<i>Onyx-30</i>	2,8	30	A-Si		https://onyxsolar.com
<i>Polysolar PS-CT-72</i>	7,2	10	CdTe thin-film	grey-	https://www.polysolar.co.uk/
<i>Polysolar PS-CT-64</i>	6,4	20	CdTe thin-film	colourless	https://www.polysolar.co.uk/
<i>Polysolar PS-CT-56</i>	5,6	30	CdTe thin-film	grey-	https://www.polysolar.co.uk/
<i>Polysolar PS-CT-48</i>	4,8	40	CdTe thin-film	colourless	https://www.polysolar.co.uk/
<i>Polysolar PS-CT-40</i>	4,0	50	CdTe thin-film	grey-	https://www.polysolar.co.uk/
<i>Polysolar C-Series</i>	9,0	20	A-Si	colourless	https://www.polysolar.co.uk/
<i>Kaneka 10% laminate</i>	8,5	6,8	A-Si	grey-	https://www.kanekaenergysolutions.com/
<i>Kaneka 20% laminate</i>	7,5	13,8	A-Si	colourless	https://www.kanekaenergysolutions.com/
<i>Kaneka 30% laminate</i>	6,5	20,7	A-Si	grey-	https://www.kanekaenergysolutions.com/
<i>Kaneka 50% laminate</i>	4,5	35,4	A-Si	colourless	https://www.kanekaenergysolutions.com/
<i>Kaneka 70% laminate</i>	2,0	50,3	A-Si	Orange	https://www.kanekaenergysolutions.com/

Legend:

*Technology: (A-Si) Amorphous Silicon, (CdTe) Cadmium Telluride

TABLE III
CASE STUDY WINDOW TYPES

Window	T1	T2	T3	T4	TPV
Glazing type	Simple	Double (RPT)	Double (RPT)	Double (RPT)	Double (RPT)
Specs.			Air 4+16+6	Argon 4+16+4	Argon 4+16+4
U value	5,8	2	1,5	1,1	1,1
g value	0,85	0,6	0,6	0,6	0,4
VT	0,89	0,81	0,81	0,81	0,3
PCE	-	-	-	-	2,8%

Glazing type (RPT): thermal bridge break

VT: visual transmittance, PCE: potential coefficient efficiency

T2, T3, and T4, as well as the selected model for this study, Onyx-30, designated as TPV in the table. These glazing types are individually assigned within the energy simulation model, based on their typology and location within the building under analysis.

D. Set of renovation measures

DesignBuilder (v7.0.0.102), based on EnergyPlus (v9.4), was considered the most appropriate tool for conducting energy simulations in this study, as it includes the option to define photovoltaic glazing on windows. This feature allows the specification of optical, thermal, and energy production characteristics in accordance with the selected commercial TPV model

The software enables the integration of the building's geometric configuration, material properties, and climatic conditions. Accordingly, a set of renovation measures are performed based on the interventions examined in this article, using the existing building described in TABLE I as the baseline model.

The retrofit strategies examined in this study were chosen with the objective of ensuring their integration within the real conditions of the analysed case study, based on the following criteria: (1) replacement of glazing elements that have not yet been modernized, (2) implementation of passive measures without modifying the building envelope, and (3) assurance of adequate indoor air quality. To enable a comparative evaluation of the performance of the selected photovoltaic glazing, the interventions were divided into two major categories: A) passive measures incorporating high-performance glazing comparable to the T4 windows already installed in the building, and B) passive measures and the use of transparent photovoltaic (TPV) glazing. TABLE IV presents the various scenarios, outlining the selected window types, assumed infiltration levels, and the passive solutions applied in each case.

TABLE IV
SUMMARY OF CASE STUDIES

Cases	Windows	Description	Infiltration (n50)
E0	T1,T2,T3,T4	Current	7
Passive:			
E1.1	T2,T3,T4,T4(R)	WR	5
E1.2	T2,T3,T4,T4(R)	WR+SP	5
E1.3	T2,T3,T4,T4(R)	WR+NV	5
E1.4	T2,T3,T4,T4(R)	WR+SP+NV	5
E1.5	T2,T3,T4,T4(R)	WR+SP+NV+MV	5
E1.6	T2,T3,T4,T4(R)	WR+SP+NV+MV (HR)	5
Passive & Active			
E2.1	T2,T3,T4,TPV(R)	WR	5
E2.2	TPV	WR (all)	4
E2.3	TPV	WR (all)+NV	4
E2.4	TPV	WR(all)+NV+MV+R	4
E2.5	TPV	WR(all)+NV+MV (HR)	4

Legend:

T1,T2,T3,T4: Window types described in Table III

T4(R): remaining window renovation with T1. TPV(R): remaining window renovation with TPV.

Strategies: Solar protections, SP; window replacement, WR; natural ventilation, NV; mechanical ventilation, MV; mechanical ventilation with heat recovery, MV(HR).

The limitations of manually operated solar shading systems and night-time natural ventilation as well as security concerns must be taken into account to ensure proper performance, particularly in large institutional buildings, where poor management could significantly worsen the expected outcomes based on correct operation considered in this case study.

Within the framework established in this section, a transparent photovoltaic atrium covering the central courtyard is modelled as a stand-alone case study. The analysis is carried out in isolation, focusing solely on the energy generation of this potential structure, and compared to the generation of the photovoltaic glazing systems installed on the building's façades.

III. RESULTS

This section presents the outcomes of the energy simulations and provides a comparative analysis of the different scenarios under study. The results are organized into two categories, distinguishing between a typical meteorological year (IWECC2) and an extreme year of heatwaves (HW2022).

A. Energy performance.

Annual heating and cooling demands are calculated based on the operational schedule of this secondary education building. Heating demand is covered during the established hours from October to May, while cooling demand is considered for June and September.

TABLE V summarizes the data for each scenario assessed in this research, including the annual heating and

TABLE V
CASE STUDIES RESULTS

	E0	E1.1	E1.2	E1.3	E1.4	E1.5	E1.6	E2.1	E2.2	E2.3	E2.4	E2.5
<i>IWEC2</i>												
Heating (kWh/m ² y.)	48	36	36	36	36	69	55	38	35	35	69	54
Cooling (kWh/m ² y.)	2,9	3,4	2,1	1	0,5	0,5	0,4	2,8	2,4	0,5	0,4	0,3
Generation (kWh/m ² y.)	-	-	-	-	-	-	-	0,9	2,1	2,1	2,1	2,1
<i>YEAR 2022 (HEATWAVE)</i>												
Heating (kWh/m ² y.)	32	23	23	24	23	50	38	25	23	23	50	39
Cooling (kWh/m ² y.)	8,8	9,1	7,1	4,9	3,6	3,6	3,3	8,2	7,4	3,6	3,5	3,2
Generation (kWh/m ² y.)	-	-	-	-	-	-	-	1	2,5	2,5	2,5	2,5

cooling demands as well as the TPV energy generation associated with each configuration. In general, the scenarios yield a notable reduction in heating and cooling demand. Exceptions are observed in cases that include the integration of a mechanical ventilation system with and without heating recovery (E1.5, E1.6, E2.4, E2.5) designed to comply with indoor air quality standards established by the Spanish Technical Building Code (CTE).

Among all measures, window glazing replacement demonstrates the greatest impact on reducing heating demand under both climatic scenarios, around 26% in all scenarios (not including MV scenarios).

A comparison between the baseline scenario (E.0) and the high-performance glazing scenario with integrated solar shading and night-time ventilation (E1.4) reveals a 25% reduction in heating demand and an 83% reduction in cooling demand under the IWEC2 conditions. Under the HW2022 scenario, heating demand is reduced by 27%, while cooling demand is lowered by 59%. When comparing the baseline (E.0) to the scenario with transparent photovoltaic (TPV) glazing and natural night-time ventilation (E2.3), the reductions under IWEC2 are 27% for heating and 84% for cooling; and under the HW2022 scenario 29% for heating and 59% for cooling. Among all the measures, natural ventilation proves to be the most effective in reducing cooling demand, achieving a 66% reduction in the typical year and 44% in the heatwave year when applied alongside high-performance glazing (E1.3).

Another notable comparison involves the conventional glazing with solar shading scenario (E1.2) and the TPV glazing replacement scenario (E2.2). In the typical year, cooling demand is reduced by 28% in E1.2 and by 20% in E2.2. This indicates that solar shading is more effective in minimizing cooling demand compared with the TPV-selected solution.

Energy generation

The study scenarios incorporating transparent photovoltaic (TPV) glazing contribute to the building's electricity generation and overall energy autonomy. Accordingly, scenarios E2.1 through E2.5 include annual energy production results in kWh/m², as shown in TABLE VI. To assess the contribution of this solution to cooling

TABLE VI
COOLING DEMAND AND GENERATION (JUNE AND SEPTEMBER)

	E0	E2.1	E2.2	E2.3	E2.4	E2.5
<i>IWEC2</i>						
Cooling	26.539	25.135	21.262	4.349	3.994	3.146
Red.		5%	20%	84%	85%	88%
Generation	-	1.687	4.131	4.131	4.131	4.131
C.C %	-	7%	19%	95%	103%	131%
<i>HW2022</i>						
Cooling	78.976	73.917	66.666	32.179	31.933	28.809
Red.		6%	16%	59%	60%	64%
Generation	-	1.814	4.487	4.487	4.487	4.487
C.C%	-	2%	7%	14%	14%	16%

Legend:

E0,E2.1,E2.2,E2.3,E2.4 case studies represented in Table IV.

Cooling: cooling demand in June and September

Generation: TPV generation in June and September

Red: percentage reduction compared to E0.

CC%: percentage of cooling demand covered by on-site generation

demand, TABLE VI summarizes the energy produced only during the months of June and September. In the scenario where only the remaining non-renovated glazing is replaced with TPV (E2.1), under IWEC2 climatic conditions, the system could supply up to 7% of the total cooling demand, whereas under HW2022 conditions, the contribution would be 2%. In scenarios where the entire building is equipped with TPV glazing (E2.3), up to 95% of the cooling demand could be met during a typical year (IWEC2) when combined with night-time natural ventilation, while this share drops to 14% under heatwave conditions (HW2022).

The proposed passive measure (night-time natural ventilation) have the greatest impact on reducing cooling demand under both climatic scenarios. Scenario E2.5, which incorporates mechanical ventilation with a heat recovery system, results in the highest reduction in cooling demand—88% under the IWEC2 conditions and 64% under the HW2022 scenario. Consequently, the energy autonomy provided by the TPV glazing reaches 131% in IWEC2, and 16% in HW2022.

In order to assess the generation potential of the different façades of the building, considering its urban

context (shading from adjacent buildings), the contribution of each façade by level was analysed.

The results of this analysis are presented in TABLE VII.

TABLE VII
FAÇADE AND ATRIUM ANNUAL GENERATION CAPACITY (IWECC2)

	GF kWh	L1 kWh	L2 kWh	TOTAL kWh	GENERATION kWh/m ² glass
<i>FAÇADES</i>					
SE	1.216	1.598	2.041	4.855	15
SW	806	1.539	1.756	4.101	16
NE	352	669	887	1.907	9
NW	-	565	752	1.317	10
<i>ATRIUM*</i>				44.076	32

Legend:

Ground Floor, GF; Level 1, L1; Level 2, L2.

Façades: Southeast, SE; Southwest, SW; Northeast, NE; Northwest, NW.

*Atrium: installation of transparent photovoltaic (TPV) panels as a canopy covering over the interior courtyard, aligned with the main roof level of the building.

The southeast (SE) and southwest (SW) façades exhibit the highest annual energy yields, with each square meter of photovoltaic glazing generating 15 kWh/m² and 16 kWh/m² per year, respectively. These are followed by the northwest (NW) façade with 10 kWh/m² and the northeast (NE) façade with 9 kWh/m² annually.

An exploratory scenario was considered that disregards internal thermal implications, assuming full coverage of the interior courtyard with transparent photovoltaic (TPV) panels installed horizontally at rooftop level. Under this assumption, the projected annual energy yield amounts to 44,076 kWh, corresponding to a specific yield of 32 kWh/m² per year.

IV. DISCUSSION

This case study highlights the decarbonization potential of historic built heritage through the integration of advanced technologies, specifically transparent photovoltaic (TPV) glass, which aligns with architectural preservation requirements while enhancing on-site energy generation. The present study focused on estimating total energy demand and examining the synergetic effect of TPV glazing with passive design strategies, enhancing the building's resilience against potential power supply disruptions.

A comparative analysis is performed between the climate series 1980–2010 (ASHRAE IWECC2) and an extreme year affected by heat waves (HW2022) to evaluate the role of TPV glazing in enhancing summer resilience and supporting a potential cooling system. The findings suggest that during a heatwave year, the energy contribution may decrease substantially in relation to the total cooling demand, while in a typical year, it could

nearly meet the total cooling energy demand. A comprehensive assessment of the building's autonomy requires examining both energy generation and consumption patterns, as well as the associated energy storage requirements.

This study uniformly incorporates TPV glazing consistent with the Onyx-30 market model, featuring a power conversion efficiency (PCE) of 2.8% and a visible transmittance (VT) of 30%. This model was selected due to it having the highest VT value offered by the European manufacturer and the availability of its technical specifications. However, TPV glazing could be customized for each façade and use case, enabling an assessment of the suitability of specific PCE and VT values based on the lighting requirements of the space. This could guide future research pathways, which will be shaped by both the pace of technological innovation and its practical availability.

Limitations and future research

The present study focuses exclusively on the analysis of heating and cooling demands to assess the impact of TPV glazing. Future investigations may undertake a detailed assessment of classrooms, allowing for a more comparative evaluation between solar protection systems and TPV glazing. This approach would enable simultaneous analysis of thermal comfort, visual comfort, energy demand, and energy generation, thereby contributing to more robust decision-making processes.

In order to gain a comprehensive understanding of the comparison between TPV glazing integration and the high-performance glazing alternative, as discussed in the results, it is essential to also evaluate key aspects such as the lifespan of the components, their carbon footprint, and the life cycle cost (LCC) of each solution.

For the Onyx-30 TPV model, the cost is approximately €270/m², representing a 50% increase compared to similar glazing systems without energy-generating capabilities—excluding installation and maintenance costs. However, it is important to emphasize that this system integrates energy production, façade glazing, and solar protection, which could position it as a competitive alternative to conventional solutions.

Considering that the typical service life of TPV systems is 25 years (with 85% efficiency), the carbon footprint would include the impact of the photovoltaic film combined with the selected glazing and its associated costs. It is also advisable to assess the circularity of these components to facilitate the replacement of the photovoltaic layer at the end of its service life. These factors are of critical importance for the successful implementation of TPV systems within decarbonized architectural strategies. In this regard, emerging studies focused on organic TPV could represent a highly valuable alternative, although these technologies are still in the development and prototyping stages.

To achieve optimal performance from passive strategies, proper control is essential. In the case of solar shading, both geometric configuration and material properties are decisive. The current simulation assumes fixed, exterior-mounted solar protections, active from May through September, modelled using blinds with high reflectivity slats. These parameters suggest potential for further optimization. Likewise, natural ventilation is scheduled from midnight to 8:00 a.m. during the months of June to September, assuming full manual window operation. This assumption may be impractical in large buildings due to logistical and security constraints.

The findings of this study contribute to the ongoing discourse on the integration of transparent photovoltaic glazing (TPV) into the existing building stock and their potential contribution to both decarbonization and resilience. As an emerging technology, TPV systems have the potential to become a key component in sustainable building strategies—particularly if improvements in power conversion efficiency (PCE) can be achieved without significantly compromising visible transmittance (VT).

Glazed atrium structures reveal promising capabilities for TPV-based electricity generation, facilitating adequate lighting conditions and compatibility with the conservation of architectural heritage. Instances of this roofing typology exist in multiple heritage-listed buildings.

Finally, existing heritage architecture in densely populated urban contexts could potentially serve as “climate shelters” in response to current and future heatwave events, offering refuge to society. Therefore, incorporating strategies that enhance the building’s level of electrical self-sufficiency will contribute to a more resilient architecture in the face of extreme events or power outages, such as the one that occurred across Spain on April 28 of 2025. In this context, the strategic combination of passive and active measures emerges as a central focus for future research efforts.

V. CONCLUSION

This study aims to analyse the potential of photovoltaic glass (TPV) integrated into heritage buildings, with the objective of contributing to their decarbonization and resilience. To achieve this, a comprehensive review and analysis of the current state of the art in transparent photovoltaic technologies at commercially available products is essential. Based on this review, the study considers the incorporation of one of the most widely used market-available models in the European context (Onyx-30), prioritizing transparency over power generation, as it offers a PCE of 2.8% and a visible transmittance (VT) of 30%, with a solar heat gain coefficient (g-value) of 0.4.

The case study involves a secondary education building under heritage protection in a temperate climate, located in a densely built urban environment. The building has previously undergone selective renovations, including

roof restoration and the replacement of approximately 70% of its original windows with improved thermal glazing. Within this context, the study aims to evaluate multiple retrofit scenarios that integrate passive energy-efficiency measures with the use of either high-performance or transparent photovoltaic glazing. The objective is to optimize thermal energy demand for both heating and cooling while simultaneously exploring opportunities for on-site renewable energy generation, ultimately contributing to the building’s resilience in the face of extreme heatwave events or potential electrical grid failures. The study is conducted using a typical meteorological year (IWEC2) and an extreme year characterized by heat waves (2022) in Pamplona, a Spanish city with temperate climate (Cfb).

The main comparative results under both climate scenarios indicate that the scenario involving solar shading on the southwest and southeast façades performs similarly to the scenario in which all glazing is replaced with transparent photovoltaic glass (TPV). This is reflected in the heating and cooling demand results under both climate scenarios. In the IWEC2 scenario, the case with solar protections yields 36 kWh/m² for heating and 2.1 kWh/m² for cooling; whereas the configuration with fully integrated TPV glazing results in 35 kWh/m² for heating, 2.4 kWh/m² for cooling, and an annual generation of 2.1 kWh/m². Both scenarios are improved by the passive measure of natural night ventilation, resulting in the greatest reduction in cooling demand in both cases, which are again comparable. In the IWEC2 climate scenario, the case with solar protections and natural ventilation shows 0.5 kWh/m² for cooling; while the scenario with fully TPV-glazed façades and natural ventilation shows 0.5 kWh/m² for cooling and an annual generation of 2.1 kWh/m².

A further critical dimension of this study is the assessment of electricity generation, with the aim of evaluating the resilience of built heritage against heatwave events. To this end, the analysis focuses on cooling demands during the building’s operational months—June and September—considering the improvements introduced in each scenario that includes TPV integration.

The results show that under a typical meteorological year, cooling demand can be reduced by up to 84% in the scenario with TPV and natural ventilation, and covered up to 95% through the generated electricity during those months. However, under in a heatwave year the same scenario, the reduction in cooling demand is reduced to 64%, and TPV generation can only cover up to 14% of this demand.

In the evaluation of TPV electricity generation, data were extracted for a typical meteorological year and analysed by façade orientation and building level, in order to identify the generation potential of each surface. This methodology enables a more accurate assessment of the feasibility and efficiency of TPV deployment across different parts of the building envelope. The results show that the highest generation values are observed on the

southeast and southwest façades at the second level, with average annual outputs of 15 kWh/m² and 16 kWh/m² of glass, respectively. As an exploratory approach, a TPV-integrated atrium was simulated to enclose the internal courtyard at the roof level. This configuration was found to generate approximately 44,076 kWh annually, which corresponds to 32 kWh/m² of TPV glass per year.

The results of this study establish a framework through which the suitability of integrating transparent photovoltaic (TPV) glazing can be assessed, considering the specific context, functional requirements, and resilience objectives of heritage buildings.

This approach is particularly critical for buildings envisioned as climate refuges or as self-sufficient structures in the face of energy disruptions—such as the extended blackout experienced in Spain on April 28, 2025, where certain regions remained without power for nearly a full day. Future research efforts, supported by ongoing improvements in TPV technology—including increased power conversion efficiency (PCE), higher visible transmittance (VT), and progress in cost-effectiveness, carbon footprint reduction, and material circularity—are expected to be of considerable value and influence in the evolution of the built environment.

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