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Posted Date: 6 March 2026

doi: 10.20944/preprints202603.0490.v1

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Article

The Techno-Economics of Selected PV Solutions on Building Facades, with Case Studies

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Abstract

The increasing prevalence of rooftop photovoltaics on European buildings has sparked interest in using façades and balconies as alternative surfaces for generating solar energy. This study examines the technical and economic performance of building-integrated photovoltaic (BIPV) installations on façades and balconies under real operating conditions. Four case studies from Poland are analysed using a combination of measured energy production data and simulations performed with the PVGIS tool. The analysis focuses on annual and seasonal energy yield, self-consumption potential, system costs, simple payback time and the role of module-level power electronics (MLPE) in mitigating the effects of shading and non-optimal orientations. The results demonstrate that, while façade-mounted PV systems generally have lower annual yields than optimally tilted rooftop installations, balcony and façade BAPV systems with MLPE can achieve high self-consumption rates, short payback periods (3–10 years) and favourable winter performance. These findings demonstrate that BIPV and BAPV systems on façades should be assessed using distinct technical and economic criteria, and highlight their potential to extend prosumer participation to apartment dwellers, thereby supporting a more inclusive urban energy transition.

Keywords: BAPV; BIPV; roof top PV; PV efficiency; BESS; PV façade; prosumerism

1. Introduction

The integration of photovoltaic (PV) systems into the built environment is increasingly recognized as a critical strategy for decarbonizing building energy use and supporting global renewable energy targets [1–5]. Buildings account for a substantial share of global energy consumption and associated greenhouse gas emissions, prompting the exploration of on-site renewable generation technologies such as rooftop and façade photovoltaics (PV) [6–10]. Conventional rooftop PV installations, positioned at tilt angles optimized for annual solar incidence, have long dominated building-mounted PV solutions due to their relatively high annual energy yields and established techno-economic performance. However, the limited availability of roof space, particularly in dense urban environments and in multi-storey or high-rise buildings, has stimulated growing interest in using vertical building façades for PV deployment. In this context, two main approaches can be distinguished: building-integrated photovoltaics (BIPV), where PV elements replace conventional building envelope components and are architecturally integrated into the façade, and building-applied photovoltaics (BAPV), where standard, commercially available PV panels are mounted onto existing façades without major architectural modifications. Compared to BIPV, BAPV solutions offer greater flexibility, lower investment costs, and simpler installation procedures, while significantly expanding the usable surface area for on-site renewable energy generation [11,12].

A substantial body of literature has investigated façade-mounted photovoltaic systems primarily within the framework of building-integrated photovoltaics (BIPV), with strong emphasis on architectural integration, multifunctionality and coupled thermal–electrical behavior. Yu et al. [13]

provide a comprehensive review of façade-based BIPV-T systems, discussing design configurations, heat transfer mechanisms, and combined thermal and electrical performance, thereby establishing a solid technical foundation for integrated façade solutions. Similarly, Polcovnicu [14] and Bot et al. [15] present broad state-of-the-art reviews covering materials, system typologies, and performance metrics of BIPV façades, highlighting the technological diversity of integrated photovoltaic building envelopes.

Several studies focus explicitly on architectural and urban design aspects of façade photovoltaics. Attoye et al. [16] provide a comprehensive overview of customization potentials and barriers to the adoption of BIPV façades, with particular emphasis on architectural integration, façade morphology, and stakeholder acceptance. The authors classify façade-based BIPV applications into several dominant typological categories: (I) curtain wall and cladding systems, in which photovoltaic panels replace conventional façade cladding elements and are integrated into single-layer or curtain wall envelopes; (II) solar glazing and window systems, where semi-transparent or translucent PV panels are incorporated into glazing units to simultaneously provide electricity generation, daylighting, and visual connection with the exterior; (III) external façade devices and accessories, such as photovoltaic sunshades, sunscreens, spandrel panels, balcony parapets, and elements of visual or acoustic shielding, which allow for incremental integration into existing buildings but typically rely on customized module formats and non-standard mounting solutions; and (IV) advanced and innovative envelope systems, including double-skin façades, active or responsive skins, and façades with rotating or movable PV elements, which aim to dynamically optimize solar exposure and building performance at the expense of increased system complexity and cost. Xiang et al. [17] investigate façade-integrated photovoltaics in residential high-rise buildings, identifying balconies as promising yet challenging PV application areas due to mutual shading effects and impacts on interior daylight. Using simulation-based daylight and solar radiation analyses combined with architectural design strategies for a Norwegian case study, the authors show that optimized balcony arrangements can balance façade aesthetics, indoor daylight performance, and energy productivity, with combined façade and rooftop PV systems covering up to 60% of household electricity demand. Tian et al. [18] examine curved solar balconies integrated with flexible photovoltaic-thermal (PV/T) systems, addressing the limited research on non-flat BIPV/T façade elements. Their modeling and parametric analysis demonstrate that curved, south-facing PV/T balcony systems can improve electrical yield and thermal performance compared to flat configurations, particularly under conditions dominated by direct solar radiation.

From a performance and implementation standpoint, Bošnjaković et al. [19] analyze the current status and development prospects of BIPV technologies, identifying key deployment barriers such as high investment costs, limited availability of real-world performance data, and coordination challenges between stakeholders involved in façade, HVAC, and building design. Broader review studies on building-applied and building-integrated PV systems [20–22] further confirm that façade-mounted photovoltaics are increasingly recognized as an important component of low-energy and urban buildings; however, they are most often examined from a technological, architectural, or conceptual perspective, with comparatively limited emphasis on detailed techno-economic assessment under real operating conditions. Complementing the academic literature, design-oriented guidance is provided by the IEA-PVPS technical guidebook [23], which consolidates best practices for BIPV system selection, façade integration strategies, and decision-making processes across different building typologies. Other contributions explore façade and balcony PV from a techno-economic and operational perspective. Polański et al. [24] analyze the potential of balcony and loggia PV installations in large-panel prefabricated residential buildings, which are characteristic of urban housing stock in Central and Eastern Europe, including Poland. Their study addresses legal frameworks, installation feasibility, module technologies, and performance under varying tilt and azimuth angles, demonstrating that balcony-mounted PV can constitute a meaningful source of on-site renewable energy for apartment residents under local climatic and regulatory conditions.

A study focusing on non-optimal PV orientations [25] further demonstrates that vertical or near-vertical installations can deliver advantageous self-consumption and economic outcomes, despite lower or redistributed annual energy yields. Taking into account Spanish climatic and market conditions, hourly electricity prices and building consumption patterns, it was shown that façade-mounted PV systems improve self-consumption ratios and reduce payback time compared to traditionally optimised installations. This highlights the importance of temporal generation profiles over annual yield maximisation alone. Similarly, Schram and Shirazi [26] conducted a comprehensive, multi-year evaluation of façade-integrated PV systems across different configurations, incorporating financial, technical, and environmental indicators in the context of the Dutch and German electricity markets. Their results show that façade-mounted PV systems—especially those installed on east- and west-facing façades—can maintain stable economic value over time, even as the value factors of optimally oriented rooftop PV systems decline. These findings highlight the potential of façade PV to enhance self-consumption, reduce grid interaction stress, and improve overall system value in urban energy systems. Pyltsov et al. [11] revisited the techno-economic viability of façade-mounted PV systems in dense urban environments facing increasing electrification and rising distribution system upgrade costs. Focusing on a high-rise building context in New York City, the authors demonstrate that BIPV and BAPV installations on façades can effectively increase distributed energy penetration and alleviate local distribution network congestion, despite their lower capacity factors compared to rooftop PV. Their analysis shows that façade PV systems become economically viable when coupled with appropriately sized battery storage, enabling valuable grid exports. The study identifies an optimal storage capacity of approximately 1.2–1.3 times the average daily PV generation and indicates that façade PV systems can generate revenues comparable to rooftop installations, partly due to higher installable capacity and the potential reduction of soft costs in single, large-scale projects.

Despite a range of advantages, façade-mounted PV systems are commonly perceived as technically inferior to conventional rooftop installations due to their generally sub-optimal tilt and orientation. Vertical or near-vertical PV panels receive lower levels of direct solar irradiance because of unfavorable incidence angles, which typically results in reduced annual energy yields compared to optimally tilted, south-facing rooftop systems [27]. Reported empirical and simulation-based studies indicate that differences in annual yield commonly range from 20% to 40%, depending on climate, latitude, and shading conditions [25,28–30]. However, the magnitude of this yield penalty is strongly location-dependent, even within Europe. In particular, when seasonal effects such as snow accumulation on rooftop installations are taken into account, the effective performance gap may be substantially reduced. Under Central European climatic conditions (e.g., Poland), vertical façade-mounted PV systems may therefore perform more favorably than commonly assumed in standard annual yield comparisons, which often neglect winter operational constraints of rooftop PV. Consequently, the perceived geometric disadvantage of façade-mounted BAPV systems should be interpreted with caution, as it represents not a universal limitation but a context-specific techno-economic challenge.

These considerations are supported by previous research adopting a broad techno-economic perspective. Existing studies on façade PV systems have demonstrated that their value cannot be fully assessed using annual energy yield metrics alone. Recent studies indicate that the performance gap between façade-mounted and optimally inclined PV systems is neither uniform nor constant throughout the year. While vertical installations generally exhibit lower annual energy production per unit area, they can demonstrate relative advantages during specific seasonal and operational conditions. In particular, during winter and other periods characterized by low solar elevation angles, vertical PV systems may capture diffuse and low-angle solar radiation more effectively than tilted rooftop installations. Moreover, vertical façades are less susceptible to snow accumulation and associated shading losses, which can significantly impair winter performance of roof-mounted PV systems. Field measurements and simulation studies conducted in high-latitude regions have shown that south-facing vertical PV façades can achieve energy yields comparable to, or even exceeding,

those of optimally tilted systems during winter months [31]. Beyond seasonal yield characteristics, façade-mounted PV systems also offer advantages related to the temporal distribution of electricity generation. Deploying PV panels on façades with different orientations—such as east, south, and west—can extend the daily production period and flatten the power generation curve, thereby improving alignment with typical building load profiles and increasing on-site self-consumption [32]. These aspects are particularly relevant in urban buildings, where electricity demand often peaks outside the midday hours traditionally associated with rooftop PV production.

Recent literature also increasingly recognizes the importance of power electronics and control strategies in improving the performance of façade-mounted photovoltaic systems. While many early BIPV and BAPV studies implicitly assume string inverter architectures (widely used in rooftop&ground installations), several authors note that vertical façades, balconies, and urban envelopes are inherently subject to non-uniform irradiance, frequent partial shading, and heterogeneous module orientations. In this context, module-level power electronics (MLPE), such as microinverters and DC power optimizers, are identified as a key enabler for effective energy harvesting from non-ideal and fragmented PV surfaces [33–35]. Significant progress in MLPE devices (for example, in terms of their efficiency) now allows the use of individual microinverters for each PV module without significantly increasing the cost of solar energy acquisition. As a result, the traditional limitations associated with string optimization in conventional string inverter systems can be effectively mitigated, enabling the productive use of periodically shaded areas, including parts of façades and balconies. These advances are particularly relevant for façade-mounted BAPV systems, where non-optimal orientations, combined with appropriate power electronics, may unlock additional operational and economic benefits beyond annual yield metrics alone. In parallel, recent review studies on machine-learning-based power forecasting for BIPV and BAPV systems [36] highlight growing interest in the operational optimization of façade-mounted PV under complex urban conditions, including variable irradiance, partial shading, and diverse orientations. Accurate short-term power prediction is increasingly recognized as a key enabler for effective energy management, self-consumption maximization, and grid interaction in BIPV and BAPV systems.

In summary, although façade-mounted PV systems face inherent geometric limitations, growing empirical evidence suggests that their seasonal performance characteristics and techno-economic behavior merit more detailed investigation. Vertical BAPV installations may offer distinct advantages, including enhanced winter performance, improved matching between electricity generation and building demand, and competitive economic value in dense urban contexts.

While much of the existing literature has focused on architectural integration and energy performance of BIPV solutions—such as semi-transparent panels or multifunctional façade elements—comparatively fewer studies have addressed the techno-economic performance of standard, monofacial PV panels retrofitted onto façades in a BAPV configuration. This research gap is particularly important given that BAPV systems based on off-the-shelf PV panels, combined with MLPE solutions, may partially compensate for lower annual yields through reduced capital expenditure, simplified installation, and greater economic flexibility.

The study is structured around three fundamental research questions.

(1) Is electricity generation from building façades and balconies economically viable? This question further examines to what extent such installations may affect façade aesthetics and whether the resulting systems should be classified as building-integrated photovoltaics (BIPV) or building-applied photovoltaics (BAPV).

(2) Are there significant technical barriers to the installation and operation of PV systems on façades and balconies, including constraints related to mounting, shading, and electrical integration?

(3) Should façade and balcony PV be treated in the same technical categories and assessed using identical efficiency criteria?

By identifying the conditions under which BAPV systems can complement—or in specific periods outperform—optimally tilted rooftop PV installations, this work contributes to a more nuanced understanding of the role of façade photovoltaics in sustainable building design.

2. Materials and Methods

The aim of the research and analysis is to identify the advantages and disadvantages of BAPV and BIPV techniques. Given the large body of scientific literature on this topic, the authors aim to present a quantitative comparative analysis of the actual energy yields from façades and balconies, based on annual yields in four BAPV/BIPV locations in Poland, compared to the optimal tilt angle for a given geographical location, whether on a roof or on the ground. Real PV production data was obtained from the Distribution System Operator (DSO) for each location (Cases 1–4) for year 2025, and was then compared with modelled production for these conditions. Annual yields for the ideal tilt angle in each location were also modelled. Four graphs were obtained for each location (see Figs. 6–9), which illustrate the advantages through a technical analysis based on the measured and modelled operating parameters of PV systems installed on building façades in Polish climatic conditions. The second part analysed the cost-effectiveness of the system overall (SPBT) and examined the potential impact of simple BAPV installations on balconies on the budgets of prosumers, particularly those at risk of energy poverty.

This article analyses functioning BAPV/BIPV photovoltaic installations mounted on buildings in four locations in Poland (see Figure 1). The selection includes different types of BAPV/BIPV: Case 1 features a typical framed module installation that replaced a railing on a large balcony on the upper ground floor of an old residential building. Case 2 consists of three high-power PV panels attached to the façade of a building whose entire roof is already covered with PV panels. Case 3 involves covering the balcony of a renovated building with PV panels, as this is the only way to obtain energy from renewable energy sources (RES) on this plot. Case 4 features a modern PV façade that was designed alongside a low-energy office building.

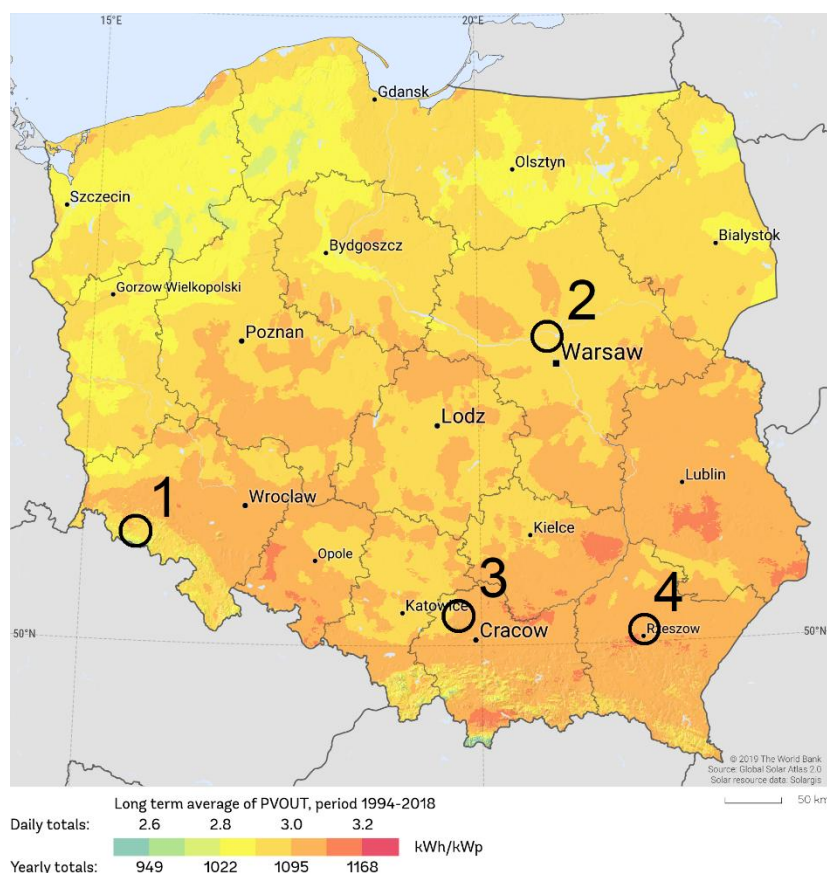


Figure 1. Location of the experimental PV case study sites in Poland, indicated on the photovoltaic power potential map. [Author's own study based on data obtained from the Global Solar Atlas 2.0, a free, web-based application developed and operated by Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data,

with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: <https://globalsolaratlas.info>.

2.1. Case Study No 1

The first case analysed involves a 5 kWp installation on the balcony railing of an old, historical building. It is not possible to use PV on the roof of this building (Szkłarska Poręba, Southwest Poland). The PV installation has been operating there for three years, producing less energy than the modelling results predicted due to periodic (summer) shading by deciduous trees on the south side. The best energy yields (even better than the simulation results) turn out to be in winter (see Figure 2), when the house requires (due to the climate zone) the most energy. Twelve PV panels arranged at an angle of 55 degrees tilt cause the snow that accumulates there from November to March to slide off. The system is operated by one string inverter (Deye 1 kW – Ningbo Deye Inverter Technology Co., Ltd., Ningbo, China) and three microinverters (Envertech 500 W – Envertech, Shanghai, China).



Figure 2. Case 1 - balcony PV installation – shading caused by nearby trees (only the 12 leftmost PV panels are considered, as the one rightmost operate in off-grid mode) [Own source].

2.2. Case Study No2

Case 2 is a building in a city that has an extensive rooftop and façade PV system (Legionowo, Central Poland). Over three consecutive years, the system was expanded from 5 kWp to 20.5 kWp, including 1.5 kWp on the façade. The system is connected to two 8 kW Goodwe 8ET string inverters (Goodwe, Suzhou, China) and six Envertech microinverters, with capacities matched to the power of the PV panels. The system operates with a 48 kWh battery energy storage system (BESS) and two electric cars that operate as a BESS via vehicle-to-grid (V2G) technology, providing a periodic self-consumption rate of 95% in spring and autumn [37]. The panels on one side of the roof are arranged at a 45-degree angle and those on the other side at a 55-degree angle.

During winter, as can be seen in Figure 3b, part of the rooftop is covered in snow and therefore not operational. In winter 2025/26, this part of the PV system was completely out of action for seven weeks. At this time, the façade part works perfectly (see Figures 3a and 3b).

For this Case, the output from the panels located above (to the right on Figure 3a,b) the façade on which the three PV panels constituting Case 2 are installed - was also compared.



Figure 3. Case 2 balcony PV installation – detached building with roof-top and facade PV, comparison of panel operating conditions during: (a) autumn; (b) winter, where the roof panels are almost completely covered with snow, while the vertical panels on the façade remain exposed to sunlight and produce energy [Own source].

2.3. Case Study No 3

The case concerns a detached building in the countryside with a photovoltaic system installed on its east- and south-facing balconies (Jerzmanowice, South Poland). Consisting of 5 kWp PV, the system is connected to two Goodwe 8ET string inverters with a maximum capacity of 3 kW each. Operating without a battery energy storage system (BESS), the system allows energy to be “stored in the grid” for 12 months, (net metering at a ratio of 1:0.8), providing a regular self-consumption rate of up to 98%.

The panels are mounted at a tilt of 85 degrees on the balcony railing. As shown in Figure 4, five panels face east and five face south. In winter, as can be seen in Figure 4b, the surrounding roofs are covered in snow, which slides off the PV panels at the same angle. This installation provides almost 120% of the annual energy demand, with 20% being left into the grid to cover the cost of annual energy storage.



Figure 4. Balcony PV installation – detached building with roof-top with two PV fasades: (a) Southfacing and (b) East-facing (one PV module is temporarily taken off for maintenance during the photo session) in winter [Own source].

2.4. Case Study No 4

This case concerns an office building located in Rzeszow-Zaczernie (southern Poland), where ventilated façade cladding composed of brown-colored photovoltaic (PhotonWall, “PV Decor Rust” series by ML System SA, Zaczernie, Poland) panels was installed on an elevation with a significant

proportion of glazing. The total installed capacity of the PV system is 22.7 kWp (see Figure 5), inverted by Fronius Symo3 inverters (Fronius International GmbH, Wels, Austria).



Figure 5. Façade with 22,7 kWp ventilated PV panels (the brown area) – glazed office building façade [Source: ML System S.A.; reproduced with owner permission].

Table 1 summarizes the technical parameters of the PV systems for the analyzed case studies.

Table 1. Comparison of the analysed PV systems in four “CASE” locations.

Description	CASE 1	CASE 2	CASE 3	CASE 4
Location	Szklarska Poręba S-W Poland (50°50'35.2"N 15°33'16.2"E)	Legionowo, Central Poland (52°23'40.9"N 20°56'31.6"E)	Jerzmanowice, South Poland (50°13'19.2"N 19°44'36.2"E)	Zaczerwie, South Poland (50°06'26.7"N 22°00'41.9"E)
Orientation	E+S	SWW	E+W	S
Tilt [°]	55	90	85	90
Capacity [kWp]	5	1,5	7	22,7

2.4. Simulations

The simulations were performed using the PVGIS 5.3 (Photovoltaic Geographical Information System) tool [38,39], which has been extensively used in the literature for estimating photovoltaic energy production across different climatic zones in Europe and system configurations [40–42]. Input parameters were selected to reflect the technical characteristics of the real PV installations at each analyzed location.

3. Results

First, authors used the PVGIS software to simulate the theoretical yields on facades and balconies. Then, the data was compared with the actual data obtained between 01/01/2025 and 31/12/2025 in locations related to CASE 1, 2, 3 and 4, divided into winter and summer periods. Finally, where possible, the authors calculated and compared the production data from 1 kWp of panels installed on the façade and on the roof or ground.

A comparison of simulated and measured monthly energy yields for the analyzed cases is shown in Figures 6–9, while Table 2 summarizes the results.

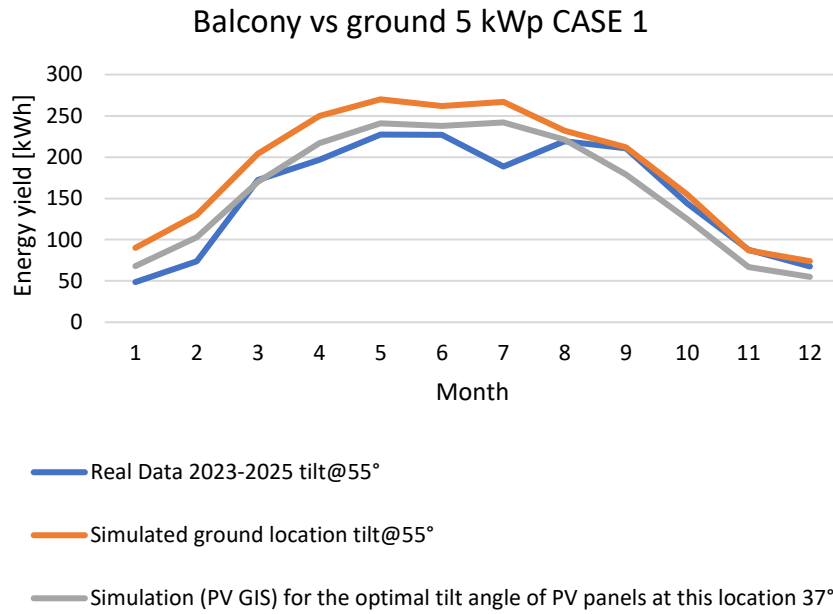


Figure 6. Simulation vs real data of monthly energy for the Case 1 installation (yield from 2x2,5 kWp balcony PV).

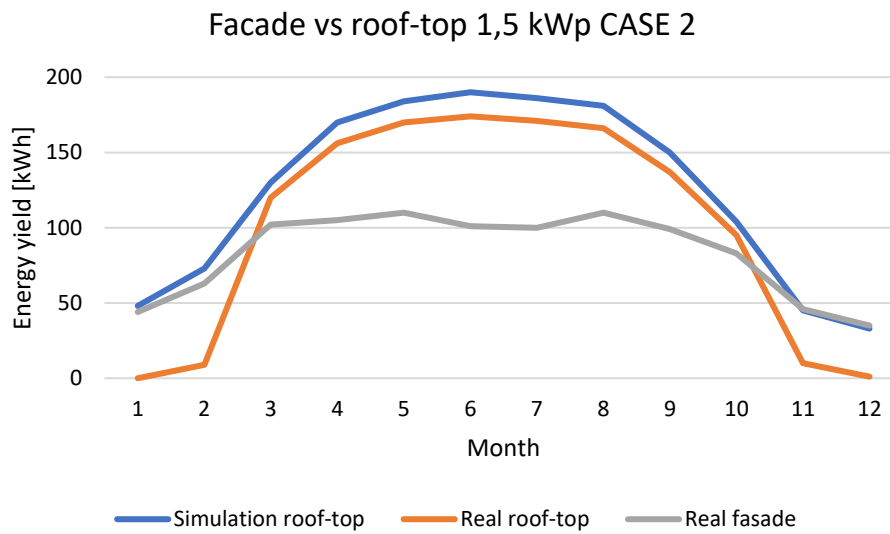


Figure 7. Simulation vs real data of monthly energy for the Case 2 installation.

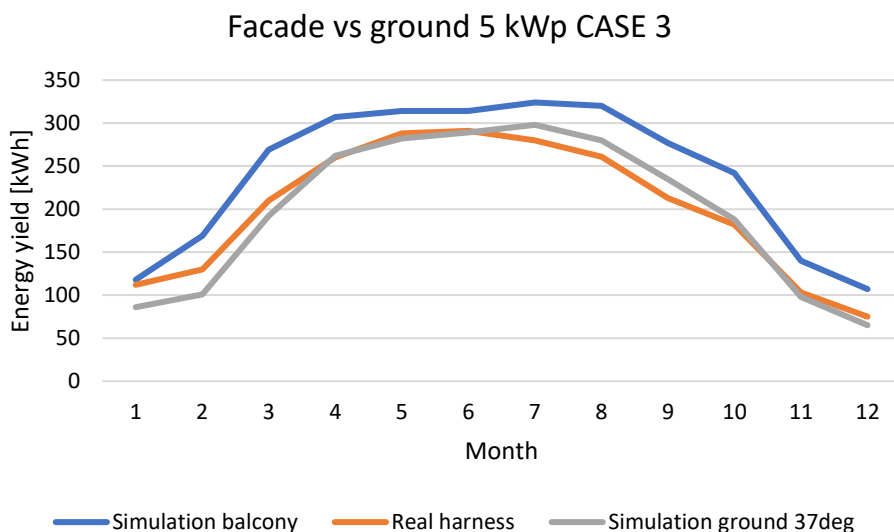


Figure 8. Simulation vs real data of monthly energy for the Case 3 installation.

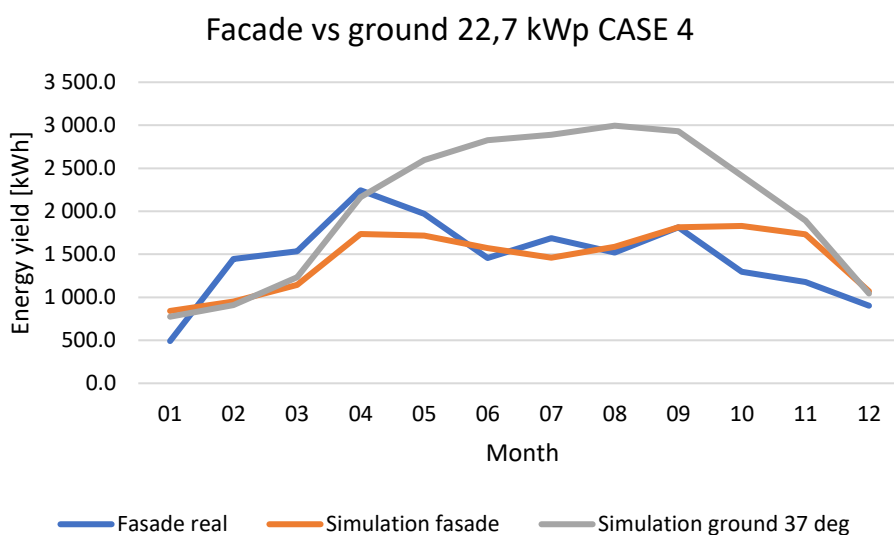


Figure 9. Simulation vs real data of monthly energy for the Case 4 installation.

Table 2. Comparison of simulated and actual yields for the CASES 1-4.

Case / Description	Season and PV System Type	Real Balcony/ façade generation [%]	Ground or Roof-top Sim. (PVGis) generation [%]	Comment	
CASE 1 balcony vs roof-top, tilt 55°, South Faced South West Poland, LF=14%**	Winter ground	293	15,20%	Usually snowed	
	Winter balcony	391	17,60%	Some snow	
	Summer ground	1852	84,80%	Optimal tilt	
	Summer balcony	1633	82,40%	Shade + not optimal tilt	
	Total ground sim. (Recalculated for 1 kWp)			100%	
	Total balcony real (Recalculated for 1 kWp)		97%		
CASE 2		92%	93%	No snow shade	

Recalculated for 1 kWp)	Winter façade			
façade 90 °vs roof-top, tilt 37 deg,	Winter roof-top	10%	93%	~ 60 days of snow
South_West Faced	Summer façade	93%	93%	Not optimal tilt
Central Poland, LF=14%**	Summer roof-top	100%	93%	Two fasades East+South
	Total roof-top sim. (Recalculated for 1 kWp)		100%	
	Total façade real (Recalculated for 1 kWp)	83%		
	Winter balcony	180%	72%	Partly snowed
	Winter roof-top	20-100%	98%	Depends on snow
CASE 3 (Recalculated for 1kWp)	Summer balcony	88%	72%	Shading by a tree
balcony 85 °vs roof-top 37 deg, tilt	Summer roof-top	100%	98%	“Optimal”*** tilt
South Faced	Total ground sim. (Recalculated for 1 kWp)	100%		
Central Poland, LF=14%**	Total balcony real (Recalculated for 1 kWp)		141%	
	Winter	32%		No snow, less energy
	Winter		24%	More energy, snow shading
CASE 4 , (glased fasade) 90 °vs ground 37°tilt	Summer	68%		~ 35-41% less yield
South Faced	Summer		76%	Summer ground
South East Poland, LF=14%**	Total ground sim. (Recalculated for 1 kWp)	100%		Optimal ground tilt/ no shades
GroundPV@37 deg****, LF=14%	Total fasade (Recalculated for 1 kWp)		71%	

* Yield comparison kWh/kWp for roof-top/ground mounted PV and fasade/balcony PV. ** LF= loss factor 14 % (realistic loss factor due to tech. limitations of the whole set) by PVGiS. *** - “optimal tilt” suggested by PVGiS as “optimal tilt” for the given location. **** data for comparison only (maximum realistic yield at certain location without shades).

4. Discussion

4.1. Is Generating Energy from Building Facades and Balconies Becoming a Necessity or a Trend? Does PV Disrupt the Aesthetics of a Building’s Facade, and Should It Be Designed as BIPV or BAPV?

Until now, façade or elevation PV installations have been relatively rare in the PV industry in Europe. In the case of the former, the use of standard PV panels with frames forced designers to accept divisions between the panels and clear outlines of the frames. This was particularly the case because installing standard framed PV panels requires a gap of approximately 1 cm to be created between them, both vertically and horizontally. This usually disrupted the coherence of the façade, especially since there are currently no “standard-dimensioned” panels on the market, although this is changing quickly. Matching the symmetrical width of the panels always resulted in some undeveloped area at the ends of the façade. A breakthrough came with the use of glass façade panels with active PV coatings (Case 4, Photon Wall). These also have installation limitations, but departing from frame division has opened up new possibilities for constructing active façades and even entire roofs [43]. However, this is only possible in new buildings where the glass-covered façade/roof has been structurally designed. If the PV design is created simultaneously with the façade or roof design

in such a case, there should be no disruption to its aesthetics. The same may be true of the design of PV coverage for external building balconies. If they form part of the architectural design's aesthetic convention, they can be an interesting architectural element; however, they can be difficult to use from a technical point of view (e.g. fixing, inverters). In both cases, the PV generator is a single device, designed from the outset for a given façade. Even if its power and energy yield are insignificant for the building's energy balance, it can still be an important source of 'stable' renewable energy throughout the year. This could be of fundamental importance for designing nZEB or Plus Energy buildings. However, the situation is completely different in the case of individual PV balconies, which are becoming increasingly popular in Europe, including Poland. These micro-installations, created by prosumers, will be spontaneous and lack a unified design, so they will never bring aesthetic consistency to the façade. Therefore, they are likely to disrupt the architectural order of the façade. However, their high degree of individualization will lead to greater energy efficiency, as they will power individual household needs. Each household will seek to maximize energy consumption and adjust its consumption profile to the generation of electricity from the sun. As we have shown, an individual balcony installation will be able to obtain more energy with a higher utility value for the prosumer than a large building façade with a PV façade. This is one of the important points the authors intend to prove. In summary, the authors believe that, in the near future, facades and balconies will be as important as roofs for energy harvesting. This will be particularly important in urban buildings, where energy demand is set to increase while space for energy harvesting remains limited. As aesthetic issues may become less important over time, it is worth starting work today on defining what is and isn't aesthetically acceptable.

4.2. Are There Significant Technical Barriers to Installing PV Systems on Façades or Balconies, Particularly PV Panels in Standard Frames with String Inverters?

In terms of technical barriers, which will all have to be gleaned from the literature, there is a clear division between the significant challenges of creating glass façades with an active PV coating and the challenges of creating professional solutions designed as BAPV. An equally significant challenge will be matching the electrical connections of the panes or panels to the inputs of the PV inverters to efficiently manage the solar lighting of the façade, both for generating electricity and reducing temperature (important for the building's thermal performance). Conversely, the multitude of balcony PV solutions available on the market indicates that this sector is already becoming popular without waiting for scientific opinion or government subsidies. Unlike PV coatings designed together with the glass façade, these solutions are inexpensive, but unfortunately may affect the aesthetics, as discussed in the first research question. Despite the significantly higher cost of installing PV glass façades, more and more investors are opting for this solution; the only barrier seems to be the cost of such a solution rather than any technical barriers. In the case of individual balcony and façade developments, all technical barriers have already been overcome (as demonstrated by CASE 1–3), so technology is no longer an issue.

Although reviews on BIPV and BAPV systems acknowledge shading and mismatch losses as critical performance limitations [15,19,20], a growing body of literature addresses how advances in MLPE technologies mitigate these effects in façade applications. The increasing maturity of microinverter-based architectures—combined with declining hardware costs—has substantially reduced the energy yield penalties traditionally associated with partial shading and orientation diversity, particularly in urban environments with balconies, recesses, and façade protrusions. This technological shift challenges earlier techno-economic assumptions that vertical and façade-mounted PV systems are inherently inferior to optimally tilted rooftop installations.

4.3. Should Façade and Balcony PV Be Treated in the Same Technical Categories and Assessed Using Identical Efficiency Criteria?

The authors believe that BIPV installations on façades and individual BAPV installations (e.g. on balconies) should be treated differently. The former are always created as part of the architectural design of new (or renovated) buildings, involving large one-off financial outlays for implementation. This results in a large PV system with large inverters and an appropriate connection to the building's energy system. Conversely, as demonstrated by CASE 1, 2 and 3, balcony and façade systems are typically installed by individual owners of balconies or parts of façades as small, gradually expandable systems. While this poses a risk of introducing aesthetic disorder to the building's façade, it can also be a joint initiative of all residents, as demonstrated by practice in Poland, resulting in an aesthetically pleasing outcome. According to the authors, this is a topic that requires separate studies.

However, the most important thing is that introducing façade or balcony PV systems leads to individual residents reducing their demand for 'black energy'. In countries with a significant number of collective residential buildings, such as Scandinavia and Eastern Europe, these installations may be more inclusive. They provide an opportunity for those who do not have their own home (and therefore no roof for rooftop PV) to have their own micro-source of electricity, and they have so far been excluded from the energy transition towards prosumerism.

Therefore, according to the authors, although these two techniques (PV facades and PV balconies) seem very similar, they should not be compared. There are two main differences. The first is technical: installing small panels with a capacity of 150–600 Wp and individual energy harvesting control via microinverters (MLPE) allows more energy to be obtained throughout the year than from façades (comparing to string inverters). It is very difficult to select the appropriate set of connections (strings) for standard string inverters, which are designed to work with ground- or roof-mounted PV. As long as these are individual installations for each household, the usefulness of this energy obtained individually may be much higher than that obtained from a large façade. Experience shows that prosumers in countries where electricity is expensive tend to shift their consumption to periods when energy is being produced by the sun. Secondly, glazed elevations or facades can only be used in newly designed buildings of a high standard, where people do not live 24/7, whereas balcony PV can be installed wherever there are balconies. This could be practically anything from 19th-century tenement buildings in Western European cities to 20th-century large-panel construction. The most important difference remains the issue of aesthetics, as adding small panels to existing balconies may be much less aesthetically pleasing than creating a uniform glass façade that also acts as a PV generator.

However, the energy yield from façades, (even if it is 40% lower than that from roofs), can be invaluable for implementing a policy of universal public participation in the energy transition within the framework of the Citizen Energy Community (CEC) and Renewable Energy Community (REC) concepts, in accordance with European Directives (e.g. 2019/944 IEMD [4], and RED [5]).

This would give balcony owners a sense of contributing, albeit in a small way, to the universal transformation programme from which they have been excluded until now. In Poland, less than 0.3% of the 1.7 million individual roof PV installations are façade and balcony installations, representing significant potential, as shown in the Cases 1, 2 and 3

4.4. Economic Aspects

4.4.1. The Current Market for Balcony BAPV Systems

Preliminary market research conducted by the authors on 'ready-made do-it-yourself (DIY) PV installation kits' with flexible PV panels indicates that these are significantly more expensive than the standard framed panels connected to microinverters used in Cases 1–3. The price difference is probably due to the high margins on niche products such as 'specialised balcony PV kits'. Research shows that trading companies justify this with 'safety considerations', suggesting that specialised, thinner, lighter flex panels cause less damage when detached from the façade. They also claim that

flex panels significantly reduce installation costs, which has not been confirmed in CASE 1-3. However, it is difficult to find confirmation of this thesis in scientific and industry-related literature on the topic. Popularizing such a solution is likely to result in a significant reduction in the price of flexible panels while simultaneously leading to the wider use of framed panels in these applications.

4.4.2. Payback Periods

Simple SPBTs for 1 kWp kit purchases (based on prices in Poland – see Table 3) demonstrate the significant potential of inexpensive DIY kits built using microinverters, which are already sold by online retailers. A major advantage is the ability to expand such systems successively (by adding further panels and MLPE), which significantly reduces the entry barrier for prosumers with balconies in apartment blocks.

Table 3. Cost comparison of PV systems considered in Case 1-4.

Case	PV System Type	Total Cost of Installation EUR/kWp	Time of warranted operation (years)	SPBT (years)	Comments:
CASE 1 (Recalculated for 1kWp) (Framed PV panels special mounting system, microinverters, connection and commissioning), Min. installation power 1-2 kWp	balcony @tilt 55°	770	10-15	< 9,6	Providing energy value of 0,29 Eur/kWh
CASE 2 (Recalculated for 1kWp) (Framed PV panels, microinverters, connection and commissioning), Min. installation power 0,5 kWp	façade @90° BAPV	630	10-15	3	Providing energy value of 0,29 Eur/kWh
CASE 3 (Recalculated for 1kWp) (Framed PV panels, regular mounting, microinverters, connection and commissioning), Min. installation power 0,5 kWp	balcony @40-85°	790	10-15	7	Providing energy value of 0,29 Eur/kWh
CASE 4 (Recalculated for 1kWp) (Frameless PV panels, string inverters, connection and commissioning), Min. installation power 10 kWp	façade @90° BIPV	NA	min. 15	10	According to manufacturer declaration

4.4.3. Energy Value

Shifting the generated energy profile from summer to winter (while reducing it in summer) creates a better match of prosumer's production profile than rooftop systems. This is also better suited to the DSO grid, which is overloaded with PV summer production (23 GWp in Poland).

4.4.4. Self-Consumption Potential

Potentially increasing self-consumption is very important for small balcony systems due to the fact that they are single-phase. MLPEs feed energy into the local distribution network, where all devices are connected to the same circuit (phase). In Poland, systems above 4–5 kW DC are typically three-phase, and it is common for flats to have one phase only.

4.4.5. Energy Storage Potential

Using even a small (3–5 kWh) battery energy storage system (BESS) in a household with balcony PV can significantly increase daily self-consumption by shifting the load to after sunset, which can significantly impact the annual energy balance.

4.4.6. Energy Self-Consumption Issue

Due to the fact that they are single-phase, it is very important to potentially increase self-consumption for small balcony systems. Micro-inverters (MLPEs) feed energy into the local distribution network, where all devices are connected to the same circuit (phase). In Poland, PV systems > 5 kW DC are typically three-phase, and it is common for one phase to be used for consumption and another for feeding energy into the grid. This is not being balanced at the meter level. This situation will not occur with a single-phase installation, which is financially more advantageous for prosumers with smaller systems, as described here.

5. Conclusions

1. The main result of the research is that BIPV and BAPV solutions cannot easily be compared in technical (e.g. feasibility) or economic (e.g. CAPEX and OPEX costs, or repowering) categories. They should therefore be treated as completely different products for different target groups. While large, expensive façades will be used for modern, newly built buildings, BAPV enables the creation of micro-installations with significantly smaller energy yields that are also valuable to owners. While the former will have to function for as long as the building exists (or until the first major renovation of the façade), the latter can be repowered every few years in a simple manner (as it was already done in Case 2). At a time when energy independence and resilience are becoming important values, every part of the building envelope that can be used for efficient energy harvesting should be utilised.
2. Balconies and BAPV facades, which are not widely recognised as a cheap source of energy with a very short payback period (3-7 years), should form the 'second wave' of prosumerism where most roofs and unused land is already being used for PV installations. The important issue of the aesthetics, should be treated as a major contemporary architectural challenge.
3. In the context of ever-increasing energy costs for end users and the growing threat of energy poverty, aesthetic considerations should take a back seat to the ability to generate cheap energy at the times when it is most expensive. This is particularly important in countries with a high proportion of black energy in the energy mix (such as Poland), where black, high-emission energy is expensive in relation to earnings and only becomes cheaper when large-scale sources of renewable energy sources (PV and wind turbines) are in operation.
4. In both BIPV and BAPV cases, adding an extra layer to the façade affects its thermal properties. Users commented that this works well for balconies, as PV panels provide additional protection from direct sunlight.
5. BIPV façades are undoubtedly aesthetically pleasing, and thanks to their natural ventilation system, they can be more efficient than traditional PV modules integrated into the façade (Case 4). A clear disadvantage is that they cannot be added to an existing façade at will, but must be designed simultaneously with the building's façade. They are also significantly more expensive than the BAPV systems analysed in Cases 1–3.

Author Contributions: Conceptualization, J.B. and M.D.; methodology, J.B. and M.D.; software, J.B.; validation, J.B. and M.D.; formal analysis, J.B. and M.D.; investigation, J.B. and M.D.; resources, J.B.; data curation, J.B.; writing—original draft preparation, J.B. and M.D.; writing—review and editing, J.B. and M.D.; visualization, J.B. and M.D.; supervision, J.B. and M.D.; project administration, J.B. and M.D.; funding acquisition, J.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The datasets presented in this article are not readily available because they are part of a broader ongoing study. Requests to access the datasets should be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

PV	photovoltaics / photovoltaic
BIPV	building-integrated photovoltaics
BIPV-T	building-integrated photovoltaic–thermal system
BAPV	building-applied photovoltaics
PV/T	photovoltaic–thermal
MLPE	module-level power electronics
BESS	battery energy storage system
V2G	vehicle-to-grid
RES	renewable energy sources
DSO	Distribution System Operator
DIY	do-it-yourself
CEC	Citizen Energy Community
REC	Renewable Energy Community

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