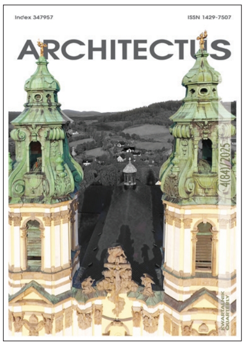

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Industrial building façades as a showcase of changes in building-integrated photovoltaics (BIPV) aesthetics

Abstract

The article analyzes the evolution of the aesthetics of opaque Building-Integrated Photovoltaic (BIPV) systems in industrial architecture. Photovoltaics (PV), as a key element in the energy transformation of buildings, are gaining significance – particularly due to their potential for façade integration. However, BIPV solutions remain a niche, mainly due to high costs, technical complexity, and limited awareness among designers.

The aim of the study is to show how the technological evolution of opaque PV modules has influenced changes in the aesthetics of industrial building façades. The research is based on an analysis of academic literature, technical documentation, and field observations of selected buildings in Germany and Poland. Four case studies were examined, representing key stages in the development of BIPV: from early silicon-based modules, through glass thin-film technologies, flexible laminates, to advanced aesthetic solutions with interference coatings.

The results indicate a clear shift in BIPV design approach – from emphasizing PV technology as a feature of futuristic design, to seeking visual harmony and "aesthetic camouflage" of PV modules. BIPV aesthetics are becoming increasingly customized thanks to growing possibilities for personalizing the color, format, and texture of modules. Despite technological advancements, BIPV-integrated façades remain rarely used in industrial buildings, where rooftop-mounted Building-Applied Photovoltaics (BAPV) systems still dominate.

Further development of BIPV in industrial architecture requires greater awareness among designers and the promotion of successful implementations that combine energy generation with high architectural quality.

Key words: industrial architecture, building-integrated photovoltaics (BIPV), photovoltaic aesthetics, BIPV façades, opaque photovoltaics

Introduction

Photovoltaics (PV) play an important role in the building sector's transition to clean and sustainable energy (Constantinou et al. 2024; Van Noord et al. 2025). Specifically, PV systems have become integral to redefining the function of building envelopes (Bonomo, Frontini 2024). This shift is driven by the EU's Energy Performance of Buildings Directive (EPBD), reinforced by the Green Deal and "Fit for 55" package, aiming for a 55% reduction in greenhouse gas emissions by 2030. The industrial sector poses unique challenges (Neuwirth, Fleiter and Hofmann 2024); however, PV is still regarded as having potential to support the transition of less energy-intensive industries towards a carbon-neutral future.

Among all renewable energy options, PV are unique in their capacity to be integrated into the building envelope. Since the first rooftop installations on industrial buildings in the 1980s, PV technologies have evolved to enable façade integration. Building-Applied Photovoltaics (BAPV) – standard panels mounted onto existing structures – have become the mainstream solution for industrial buildings due to their cost-effectiveness and ease of installation. However, while effective in terms of energy generation, such solutions proved insufficient in terms of aesthetic expectations (Van Noord et al. 2025). To address these concerns, Building-Integrated Photovoltaics (BIPV) have gained prominence by replacing traditional construction materials and transforming building envelopes into active, multifunctional skins that not only generate energy and provide weather protection, but also contribute meaningfully to architectural design.

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This article examines the evolution of opaque photovoltaic technologies applied to industrial building façades, with particular emphasis on their aesthetic transformation. Drawing on selected case studies, it demonstrates how key technological milestones have influenced design strategies in this field. Although the main focus is on BIPV systems, the study also considers hybrid BAPV/BIPV applications that reflect broader trends in the visual and material integration of photovoltaics within industrial contexts. For the purpose of this research, the term *industrial buildings* refers to production, research, and environmental infrastructure facilities characterized by large façades, modular structures, and high potential for photovoltaic integration. Such buildings, offering good solar exposure, extensive surfaces, design flexibility, and strong association with technological innovation, provide particularly suitable conditions for exploring the aesthetic evolution of BIPV.

The adoption of BIPV façades in industrial contexts remains limited. Key barriers to broader uptake across building typologies include higher costs, technical complexity, and a lack of awareness or knowledge among stakeholders (Bonomo et al. 2024; Smith et al. 2024; Parolini et al. 2024). Studies on architects' attitudes toward PV have shown that aesthetic considerations are the primary factor for over 85% of respondents when selecting BIPV – ranking higher than cost or performance (Basher et al. 2023). Nonetheless, awareness of available design options remains low, underscoring the need for reliable databases, accessible references, and broader dissemination of technical and design information. Early academic studies on BIPV mentioned industrial buildings among other typologies (Hagemann 2002; Marchwiński 2005). Later research that focused more specifically on this field (Muszyńska-Łanowy 2009) did not yet capture the broader aesthetic development of BIPV, as the technology was then at an early stage of its architectural implementation. Contemporary literature still discusses mostly isolated cases of BIPV façade applications in industrial settings without tracing their evolution. This article seeks to address that gap by providing insight into how the changing properties of opaque PV have transformed the aesthetics of industrial facilities.

Methods

This study employs a multi-source research approach, integrating both primary and secondary data. A comprehensive literature review was undertaken, drawing on published books related to BIPV and peer-reviewed articles accessed through Google Scholar and ResearchGate databases. Due to research focus on industry standards and specific products also grey literature was considered. Reports published by the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS) were examined to provide up-to-date insights and an overview of the current state of BIPV technologies and their international deployment. Technical data sheets and handbooks from manufacturers of construction materials and PV modules were reviewed to assess the physical characteristics of BIPV systems. First-hand knowledge on state-of-the-art of technology was obtained during the Intersolar trade fair in Munich, where direct engagement with industry professionals, product demonstrations, and expert lectures provided insight into current trends and market innovations.

Following the in-depth understanding of the technology development stages, the case studies were selected as representative examples of significant BIPV applications and design solutions in industrial buildings. The selected sites include two manufacturing plants, one research and laboratory facility and a waste treatment plant. The geographic scope is limited to projects located in Germany and Poland, reflecting the spatial dissemination of the technology. Site visits were conducted to allow for direct observation and photographic documentation of the façade systems and the architectural integration of BIPV. The photographic documentation was collected over several years: 2007 (Gelsenkirchen); 2014, 2025 (Berlin Adlershof).

BIPV: Definition and challenges of opaque façade integration

Integrating PV into the building envelope creates a multifunctional system that serves both as an energy generator and a construction element (Kuhn et al. 2021). This dual role requires an interdisciplinary approach – combining architectural design, structural engineering, and solar technology. According to IEC 63092 and EN 50583, BIPV systems must comply with both electrical and construction standards. A PV module qualifies as "building-integrated" when it replaces conventional materials and contributes structurally to the envelope; its removal necessitates a substitute construction element. Beyond electricity generation, it must ensure, e.g., structural integrity, fire and noise protection, environmental separation, and safety – thus becoming an integral part of the façade (Berger et al. 2018; Bonomo et al. 2021).

Various industrial building façade systems are suitable for opaque BIPV integration; yet each presents challenges. Achieving a balance between energy performance and aesthetic quality is particularly important (Smith et al. 2024; Parolini et al. 2024).

Façades often face suboptimal solar exposure due to their 90° tilt, shading, and variable irradiance, requiring careful material selection and system configuration to ensure sufficient energy yield. PV modules integrated into façades are exposed to elevated temperatures, leading to thermal stress, reduced energy efficiency and durability. Cold façades – with layered construction and ventilation cavities – are well-suited for BIPV, enabling passive cooling and concealed wiring without compromising structural integrity. In such systems, standard or customized BIPV modules can replace opaque cladding. Their modular nature simplifies installation and maintenance. Warm façades without ventilation require specific PV material solutions capable of withstanding higher operating temperatures.

A wide range of PV module types, typically with a 30-year service life, is suitable for both new and retrofit projects. Over 200 commercial BIPV products are currently available in the European Union (Bonomo, Frontini 2024; Basher et al. 2023).

Façade-integrated PV systems must meet high aesthetic standards (Li et al. 2025; Borja Block et al. 2024). To ensure architectural coherence, opaque BIPV often require project-specific adaptations in module colour, texture, shape, size, and cell layout (Kuhn et al. 2021). The increasing variety of materials with diverse visual and technical properties and potential for customization, supports integration in industrial architectural contexts. This design flexibility is essential to evolving the formal language of PV façades.

The evolution of BIPV in industrial architecture

Over the past 30 years, the evolution of BIPV in industrial architecture has been driven by technological progress, environmental concerns, and architects' ambitions to integrate solar energy into building envelopes. As technologies advanced, PV systems became more efficient and diversified in terms of materials and design. These improvements enabled more seamless integration of PV components into building structures. What began with the use of standard, off-the-shelf modules has gradually evolved into project-specific solutions tailored to architectural and functional requirements.

The following section presents four milestone buildings showcasing opaque BIPV (Table 1).

Early integration – from BAPV to BIPV

In the late 1980s and 1990s, façade-mounted PV modules evolved from standard BAPV to more integrated BIPV solutions. Early opaque PV solutions used crystalline silicon (c-Si) solar cells in glass–foil laminates. Glass–glass modules, heavier and more expensive, were used less frequently. Designs featured rectangular shapes, blue or black cells arranged in grids with visible busbars and aluminum frames. Frameless modules offered a more seamless look but posed delamination and mounting issues. Polycrystalline silicon (p-Si) stood out for its shimmering, textured surface, reinforcing a high-tech aesthetic of building envelopes. Colorful and geometric variations remained rare due to high costs and efficiency trade-offs (Weller et al. 2010; Borja Block et al. 2024).

A landmark project from this era is the Scheuten Solar facility in Gelsenkirchen (1999). The most advanced solar cell plant in Europe at the time combined high-performance production with striking architecture, serving as both a factory and demonstration center to showcase cutting-edge PV

Table 1. The Evolution of BIPV in Industrial Architecture – technical characteristics of opaque PV façade systems implemented in case study examples (elaborated by M. Muszyńska-Łanowy)
Tabela 1. Ewolucja BIPV w architekturze przemysłowej – charakterystyka techniczna nieprzezroczystych systemów fasad PV w analizowanych przykładach (oprac. M. Muszyńska-Łanowy)

Case study building	Scheuten Solar	Soltecture	Eco-incinerator	Helmholtz-Zentrum Berlin (HZB)
Year constr./BIPV	1999	2009	2011-2015 /2019	2016 / 2021
Adress	Am Dahlbusch 23, Gelsenkirchen	Groβ-Berliner Damm 152, Berlin-Adlershof	Giedroyc Street 23, Krakow	Albert-Einstein-Straße 15, Berlin-Adlershof
Architectural office	Hohaus & Partner	Rainer Girke	Manufaktura Nr 1, Teller Architekci, Łapiński Architekci, PROCHEM S.A.	DGI Bauwerk Gesellschaft von Architekten mbH
Building function	Solar cells manufacturing plant	PV modules manufacturing plant	Waste incineration plant	Research building
BIPV orientation	SW	SW, SE	S	N, W, S
BIPV tilt	Variable	900	Variable	900
BIPV size	264 m^2	578 m^2	116 m^2	380 m^2
Cell technology	Polycrystalline (p-Si)	Copper-Indium-Diselenide (CIS)	Monocrystalline (m-Si)	Copper-Indium-Gallium-Selenide (CIGS)
Module type	Shell S115-C	Soltecture SCG-HV-F	DAS Energy 12x2M	Avancis Skala 7003
Module construction	Glass-Tedlar®	Glass–glass	ETFE / PET	Glass–glass
Encapsulant	EVA	EVA	Patented fiberglass-reinforced plastic	Polymer
Frame	Framed	Frameless	Frameless	Frameless
Module dimensions	1220 × 850 × 25 mm	1250 × 650 × 7 mm	2035 × 377 × 2 mm	1587 × 664 × 38 mm
Module weight	14 kg	12.6 kg	2.8 kg	17 kg
Module nominal power	115 W	90 W	120 W	135 W
Module quantity	240	700	152	360/N 56, W 56, S 248
Mounting system	Mounted on Kalzip® SolarClad	Concealed Custom façade cassette	Direct bonding Kalzip® AluPlus	Concealed Metal curtain wall
Installed power	26.4 kWp	39 kWp	17.5 kWp	48.6 kWp
Annual yield	n.d.	35 MWh/a	12 MWh/a	30 MWh/a

Fig. 1. Scheuten Solar, Gelsenkirchen (1999). A pioneering example of PV integration in an industrial building façade (photo by M. Muszyńska-Łanowy)

Il. 1. Scheuten Solar, Gelsenkirchen (1999). Pionierski przykład integracji fotowoltaiki w elewacji budynku przemysłowego (fot. M. Muszyńska-Łanowy)

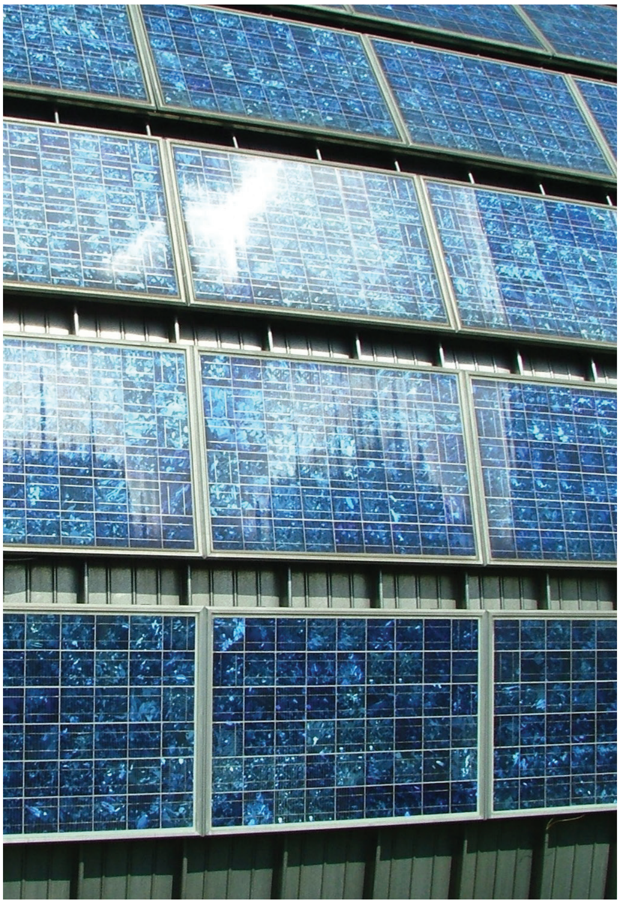


Fig. 2. Scheuten Solar, Gelsenkirchen (1999). PV modules with a visible crystalline cell structure and a regular grid pattern, mounted on standing seam aluminium cladding (photo by M. Muszyńska-Łanowy)

Il. 2. Scheuten Solar, Gelsenkirchen (1999). Moduły PV o widocznej strukturze krystalicznych ogniw i regularnym układzie siatki, zamontowane na aluminiowej blasze na rąbek stojący (fot. M. Muszyńska-Łanowy)

integration in industrial architecture (Deutsche Shell 1999). The building's iconic feature is its elliptical, south-facing office façade, which merges fluidly with the roof, with a bold yellow-red canopy marking the entrance. Its dynamic form reflects the innovative spirit of PV technology (Fig. 1).

Two BIPV systems were used: a now-decommissioned semi-transparent c-Si curtain wall and an opaque aluminum façade with surface-mounted PV modules, attached via non-penetrative clips to the standing seams of Kalzip® aluminum sheets (Corus Bausysteme 2001). Framed modules were arranged in rhythmic horizontal bands – five per segment – symmetrically flanking the central glazed strip across sections. The modules feature a visible cell grid, with irregular crystalline structure of the p-Si creating a shimmering effect (Fig. 2). The interplay between the blue-silver tones of the PV modules and the aluminum cladding reinforces the industrial aesthetic. The Kalzip®'s flexibility enabled curved profiles, concealed electrical integration, and allowed modules to be elevated for rear ventilation. This produced a cohesive, expressive façade, reflecting the era's technological ambition.

Thin-Film technologies

In the early 2000s, second-generation thin-film technologies – amorphous silicon (a-Si), copper indium selenide (CIS), copper indium gallium selenide (CIGS), and cadmium telluride (CdTe) – significantly advanced PV integration into industrial building façades. In addition to environmental benefits – such as reduced semiconductor use and lower-energy production –thin-film offered notable architectural advantages. Their slim profiles and compatibility with glass, metal and polymer substrates have enabled seamless integration into diverse façade systems, supporting both constructability and aesthetic flexibility. Better performance under shading, high temperatures, and diffuse light compared to c-Si made them particularly suitable for façade applications (Weller et al. 2010).

Thin-film PV expanded the color palette: brownish a-Si; graphite-black CIS and CIGS; greenish-black CdTe. Smooth, monochromatic surfaces complemented the minimalist aesthetic typical of industrial architecture. Notably, black CIS modules with subtle pinstripes attracted architectural interest (Sulfurcell Solartechnik n.d. c). Refined visual strategies – including tinted or patterned glass – have enabled BIPV façades to convey visual patterns, inscriptions, or branding. These approaches have proven especially relevant in showcase buildings, where technological demonstration plays a central role, as well as in retrofitted projects that require visual harmony with the existing architectural context (Peharz et al. 2019). A combination of declining costs, material adaptability, and aesthetic versatility has contributed to the growing implementation of thin-film BIPV in industrial architecture.

The Soltecture facility in Berlin-Adlershof represents one of the most notable early applications of CIS in industrial architecture, awarded a German Solar Prize in 2010 for its "exemplary combination of an ecologically sound building concept and aesthetically appealing design" (Krehl Girke Architekten, n.d.). The project marked a strategic shift from PV manufacturing to BIPV solutions, emphasizing architectural collaboration. To reflect this design focus, the company rebranded from Sulfurcell to Soltecture.

Alongside a rooftop PV array, the building featured a fully integrated façade system: CIS modules formed seamless cladding across the southwest and southeast elevations of the administrative and production buildings (Sulfurcell Solartechnik n.d. c). The frameless glass modules were mounted horizontally in rhythmic bands – some inactive to maintain visual consistency – creating a refined, monolithic appearance (Sulfurcell Solartechnik n.d. b). The panels resembled plain black glass, their glossy surface and deep color contrasting sharply with the adjacent matte, wood-toned HPL cladding (Fig. 3). On the production hall, the modules were arranged in irregular horizontal stripes, positioned alongside anthracite-colored profiled metal panels (Fig. 4).

For seamless integration, a custom cassette system based on ventilated metal façade principles was developed. The modules were bonded to anodized aluminum frames using silicone adhesive and mounted with concealed clips, stabilized by hooks at the lower edge. Prefabricated units allowed for efficient on-site installation, and the ventilated cavity provided passive cooling, controlled water drainage, and protected the underlying insulation. As a pilot project, the façade required special permits. Since silicone bonding lacked general approval in Germany, additional windload tests were carried out (Sulfurcell Solartechnik n.d. a; DETAIL Architecture 2010).

Following company's insolvency, the building was dismantled, yet its minimalist black façade remains a landmark in thin-film BIPV design, renowned for its refined aesthetic and material clarity.

Flexible and lightweight BIPV

The development of glass-free PV laminates has expanded the architectural potential of BIPV. Thin-film solar cells

Fig. 3. Soltecture facility, Berlin-Adlershof (2009). Black thin-film CIS modules form a sleek, monolithic surface with strong architectural coherence (photo by M. Muszyńska-Łanowy)

Il. 3. Zakład Soltecture, Berlin-Adlershof (2009). Czarne, cienkowarstwowe moduły CIS tworzą gładką, monolityczną powierzchnię o wysokiej spójności architektonicznej (fot. M. Muszyńska-Łanowy)

Fig. 4. Soltecture, Berlin-Adlershof (2009). BIPV CIS modules with a reflective surface, seamlessly aligned with the corrugated metal cladding; the dark, mirror-like finish visually conceals the solar function (photo by M. Muszyńska-Łanowy)

Il. 4. Soltecture, Berlin-Adlershof (2009). Moduły BIPV typu CIS o refleksyjnej powierzchni, płynnie zintegrowane z falistą okładziną metalową; ciemne, lustrzane wykończenie wizualnie maskuje funkcję solarną (fot. M. Muszyńska-Łanowy)

Fig. 5. Eco-incinerator, Kraków (2019). Flexible m-Si PV modules following the curved geometry of the green metal façade; the exposed and rhythmically repeated layout emphasizes the expressive character of the industrial building (source: courtesy of KHK SA Archives)

Il. 5. Spalarnia odpadów, Kraków (2019). Elastyczne moduły fotowoltaiczne m-Si dopasowane do zakrzywionej geometrii zielonej metalowej elewacji; wyeksponowany i rytmicznie powtarzalny układ podkreśla ekspresyjny charakter budynku przemysłowego (źródło: fot. z archiwum KHK SA)

Fig. 6. Eco-incinerator, Kraków (2019). Two different PV technologies on the building façades. The vivid blue of the rigid glass BAPV creates a striking visual effect against the original envelope (source: courtesy of KHK SA Archives)

Il. 6. Eco-incinerator, Kraków (2019). Dwie różne technologie PV na elewacjach budynku. Intensywny niebieski kolor sztywnych modułów szklanych BAPV tworzy wyrazisty efekt wizualny na tle oryginalnej powłoki (fot. z archiwum KHK SA)

embedded on lightweight metallic or polymer substrates – stainless steel, ETFE (ethylene tetrafluoroethylene), or TPE (thermoplastic elastomers) – are encapsulated in multi-layer polymers. Their reduced weight, mechanical flexibility, and adaptability to complex surfaces enable direct application onto flat, concave, or convex geometries without the need for secondary substructures.

Early implementations in the 2000s explored triple-junction a-Si cells laminated onto stainless steel foils, optimized for high performance under diffuse light and elevated temperatures. Although these systems faced long-term durability issues – such as delamination, corrosion, and environmental degradation – they laid the foundation for the credibility of flexible BIPV in architectural practice (Call et al. 2008).

Contemporary flexible modules are based on CIGS or thin-film silicon technologies. Textured ETFE front sheets enhance light trapping, UV stability, hydrophobicity, and weather resistance, while EVA encapsulants ensure optical clarity and structural cohesion. The modules are available in graphite, dark-blue or other hues, depending on absorber material and surface finish. They feature smooth, matte or semi-gloss textures and a ribbon-like format, cut from rolls for customizable widths, lengths, and shapes to suit specific design needs (DAS Energy 2021; Call et al. 2008).

With a weight up to ten times lower than conventional glass-based PV panels, flexible laminates are particularly suited for industrial façades, where load-bearing constraints, simplified installation, and aesthetic cohesion with metal cladding systems are key considerations.

The Eco-Incinerator in Kraków is the first facility in Poland to incorporate flexible modules. Characterized by expressive architecture with flowing forms and vivid colors, the building resembles a multicolored ribbon inspired by local landscapes and folk motifs (Czernek 2024). Clad in green and red aluminum panels, the structure exemplifies contemporary industrial design merging function, symbolism, and environmental responsibility (Fundació Mies van der Rohe 2025).

The facility features an educational path showcasing key technologies, with PV emphasizing its environmental and educational roles as a model of sustainable industrial infrastructure. Following a rooftop array, a flexible PV system was added in 2019 on the southern elevation of the main hall (Krakowski Holding Komunalny 2020). Two façade sections were clad with flexible modules, featuring monocrystalline (m-Si) cells embedded in fiberglass-reinforced polymer with non-reflective ETFE front sheet (Kalzip 2019; DAS Energy 2021). The modules were directly glued to Kalzip® standing seam aluminum cladding, eliminating the need for substructures and allowing seamless integration with the curvilinear façade (Fig. 5). Their ribbon-like format follows the envelope's sinuous lines, aligning with vertical seams to preserve visual rhythm and reinforce the building's identity. Though visually seamless, the laminates are added to an existing façade and therefore do not meet the true definition of BIPV.

Initially, an extension with green-tinted modules was considered to better match the façade's colors, however, due to cost and energy performance considerations, glass m-Si panels were applied as BAPV in 2024 (Krakowski Holding Komunalny 2020). Mounted on subframes aligned with the wall's angle, the rigid, reflective surfaces contrast sharply with the earlier, more sculptural system, disrupting its chromatic and volumetric coherence (Fig. 6).

Aesthetic camouflage

As Peharz et al. (2019, 12) observe, "the main value of BIPV products is now becoming invisibility". The seamless integration both visually and constructively reflects a fundamental shift in how PV is perceived within contemporary architectural practice: from a visible symbol of energy generation to a discreet, integrated part of the façade. This reflects trends identified by Chivelet, Kapsis and Frontini (2025), highlighting two key directions for future BIPV façades: personalized PV modules adapted to specific geometries and grids, and visual camouflage through color modulation or masking patterns.

Colour remains a key factor in enhancing architectural expression and ensuring visual coherence with surrounding materials and building identities (Bonomo et al. 2021). However, such aesthetic customization often reduces energy efficiency, increases production complexity and cost (Peharz et al. 2019; Basher et al. 2023). These trade-offs are particularly significant in the context of industrial building façades, which must balance technical performance and durability with corporate branding, visual consistency, and economic feasibility.

To address these challenges, non-pigmented optical technologies like interference coatings have emerged as promising alternatives. Based on the principle of selective light reflection in nanometric multilayer structures with alternating refractive indices, these coatings applied to the inner surface of the front glass generate durable, uniform colours through optical interference, without affecting the performance of the active layer. A wide range of colours is achievable – including light grey and white – while concealing the underlying cells and ensuring a smooth, homogeneous appearance (Basher et al. 2023; Borja Block et al. 2024).

The Helmholtz-Zentrum Berlin (HZB) Living Lab Façade in Berlin-Adlershof (2021) exemplifies this approach, serving as both a research platform and architectural showcase that demonstrates the technical feasibility of façade-integrated PV and its potential for architectural aesthetics (Albinius et al. 2025).

The building features ventilated curtain wall façades clad with frameless CIGS thin-film modules, installed across three elevations (Fig. 7). Special attention was paid to the design of the BIPV façade to ensure both technical and visual integration (Energie n.d.). Homogeneously coloured modules were precisely matched in size, shape, and finish to the adjacent aluminium cladding. A concealed rear-rail system enabled seamless integration without visible clamps, preserving visual continuity and ensuring compatibility with various substructures.

The blue front glass, free of visible cells or interconnections, creates a surface akin to continuous tinted glazing. Depending on light and viewing angle, the hue shifts from light blue to violet to dark blue (Fig. 8), enhancing chromat-

Fig. 7. Helmholtz-Zentrum Berlin (HZB), Berlin-Adlershof (2021). The Living Lab BIPV façades serve as a testing platform and showcase the aesthetic potential of innovative thin-film materials in architectural integration (photo by M. Muszyńska-Łanowy)

Il. 7. Helmholtz-Zentrum Berlin (HZB), Berlin-Adlershof (2021). Elewacje BIPV Living Lab pełnią funkcję platformy badawczej, jednocześnie prezentując estetyczny potencjał innowacyjnych materiałów cienkowarstwowych w integracji architektonicznej (fot. M. Muszyńska-Łanowy)

Fig. 8. Helmholtz-Zentrum Berlin (HZB), Berlin-Adlershof (2021). Blue CIGS modules seamlessly integrated into the curtain wall using concealed brackets and flexible profiles. The interference coating masks the cell structure, creating intense colour and light-dependent gradients, while the matte glass finish adds an elegant appearance (photo by M. Muszyńska-Łanowy)

Il. 8. Helmholtz-Zentrum Berlin (HZB), Berlin-Adlershof (2021). Niebieskie moduły CIGS płynnie zintegrowane ze ścianą osłonową przy użyciu ukrytych uchwytów i elastycznych profili. Powłoka interferencyjna maskuje strukturę ogniw, tworząc intensywny kolor i zależne od światła przejścia tonalne, matowe szkło nadaje elewacji elegancki wygląd (fot. M. Muszyńska-Łanowy) ic modulation while preserving visual harmony. The matte finish further reduces reflectivity, reinforcing the façade's aesthetic.

The Living Lab provides long-term, real-world performance data on the behaviour of BIPV under varying weather and seasonal conditions. A dense sensor network monitors electrical and building physics parameters. Disseminating data via a dedicated platform supports knowledge transfer. Tests showed that deeper ventilation cavities improved rear-side cooling, with limited impact on energy yield, and confirmed the energy potential of non-optimal orientations to produce energy under diffuse and reflected light (Albinius et al. 2025; Energie n.d.).

Although twice as costly as a conventional façade (Albinius et al. 2025), the BIPV Living Lab façade demonstrates how innovative PV can be effectively integrated into industrial buildings – supporting sustainability goals, serving as a research and demonstration platform, and reinforcing architectural identity without compromising design integrity.

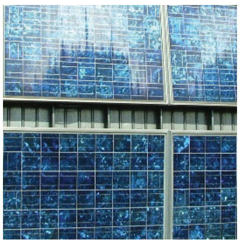
Conclusions

The analysis of the evolution of opaque BIPV façades in industrial buildings – based on four case study examples – highlights how technological advances have directly influenced both the materiality and visual language of industrial architecture. The comparative approach revealed a gradual transition from functional, technically driven applications toward increasingly expressive and design-conscious solutions. This confirms the study's main assumption that the aesthetic transformation of industrial building façades is closely linked to the technological maturation and diversification of BIPV materials.

Over the past three decades, design strategies for PV integration have evolved from emphasizing the visibility of solar modules to approaches prioritizing visual coherence and material continuity (Table 2). This transformation has been driven by significant technological progress, enabling BIPV materials to mimic or complement conventional cladding systems in form, texture, and colour. Early crystalline silicon systems, with their clearly visible cell grids, reflective surfaces, and metallic frames, expressed the technological essence of solar architecture and conveyed an explicitly "high-tech" aesthetic. The subsequent development of thin-film and flexible technologies enabled a more seamless façade integration, offering homogeneous surfaces, dark tones, and customizable formats aligned with the minimalist logic of industrial architecture. The latest generation of BIPV moves beyond mere surface treatment toward a deeper architectural synthesis – where PV elements merge optically and materially with the building envelope itself. Through interference coatings, selective light reflection, and advanced laminates, the energy-active façade blurs the boundaries between construction, technology and architectural expression.

Industrial buildings have proven particularly relevant for the implementation of BIPV, as their large, expressive façades not only accommodate energy generation but also serve as communicative surfaces for technology branding and corporate identity. In some cases, they operate as "living laboratories", where pilot systems are tested and monitored under real-world conditions, reinforcing the educational and promotional roles of such facilities within the broader discourse on sustainable architecture. Furthermore, full-scale demonstrators are essential for validating both the technical and visual performance of innovative technologies, accelerating their adoption in the industrial building sector.

Table 2. The visual properties of BIPV technologies in selected case studies (elaborated by M. Muszyńska-Łanowy)
Tabela. 2. Właściwości wizualne technologii BIPV w wybranych studiach przypadków (oprac. M. Muszyńska-Łanowy)

				
	p-Si glass-foil	CIS glass-glass	m-Si polymer	CIGS glass-glass
Cell visibility	High	Very low	Medium	None
Surface texture	Crystalline pattern (p-Si properties)	Smooth, uniform, stripped (visible close up)	Textured (front ETFE properties)	Smooth, uniform (refined front glass quality)
Color tone	Light to dark blue + silver	Graphite/black	Graphite	Gradient blue-violet-dark blue (tonal shifts)
Gloss level	Semi-gloss (front glass properties)	Gloss (front glass properties)	Low-gloss (front ETFE properties)	Semi-matte, satin (treated glass surface)
Visual uniformity	Low – grain boundaries, cell pattern	High – homogeneous appearance	Medium – subtle cell outlines	Very high – no visible cell or contact pattern
Light interaction	Non-uniform reflection Shimmering effect	Diffuse reflection, low-chromatic tonal shifts	Minimal reflectivity Low tone variation	Light-dependent chromatic shifts

However, despite advances in both technical and visual integration, BIPV remains a niche segment, and rooftop-mounted BAPV systems continue to dominate. Expanding the knowledge base and design literacy among architects, engineers, and investors is crucial for unlocking the architectural potential of BIPV façades. The current moment represents a critical phase in the wider adoption of the technology – one that requires aligning architectural ambition, technical capability, and economic feasibility. Real progress will depend not only on continued material innovation but also on the dissemination of practical knowledge, interdisciplinary collaboration, and policy support that recognizes the aesthetic dimension of solar architecture.

Future research should continue to explore how emerging BIPV technologies – such as coloured coatings, flexible laminates, and novel photovoltaic materials – can further enhance the expressive and communicative capacities of industrial envelopes, strengthening their role within sustainable architectural practice.

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Streszczenie

Elewacje budynków przemysłowych jako wyraz zmian w estetyce fotowoltaiki zintegrowanej z budynkiem (BIPV)

Tematem artykułu jest ewolucja estetyki nieprzezroczystych systemów fotowoltaicznych zintegrowanych z budynkiem (BIPV) w architekturze przemysłowej. Fotowoltaika, jako kluczowy element transformacji energetycznej budynków, zyskuje na znaczeniu – szczególnie dzięki możliwości integracji z elewacjami. Rozwiązania BIPV nadal pozostają jednak niszowe, głównie z powodu wysokich kosztów, złożoności technicznej oraz ograniczonej świadomości wśród projektantów.

Celem badania było ukazanie, w jaki sposób ewolucja technologiczna nieprzezroczystych modułów fotowoltaicznych wpłynęła na zmiany w estetyce elewacji przemysłowych. Analiza została oparta na literaturze naukowej i specjalistycznej, dokumentacji technicznej oraz obserwacjach terenowych wybranych obiektów w Niemczech i Polsce. Przeanalizowano cztery przykłady reprezentujące kluczowe etapy rozwoju technologii BIPV: od wczesnych modułów krzemowych, przez cienkowarstwowe technologie na szkle, elastyczne laminaty, aż po zaawansowane rozwiązania estetyczne z zastosowaniem powłok interferencyjnych.

Uzyskane wyniki wskazują na wyraźną zmianę podejścia do projektowania systemów BIPV – od akcentowania technologii fotowoltaicznej jako elementu futurystycznego designu, w kierunku poszukiwania wizualnej harmonii i „estetycznego kamuflażu" modułów PV. Estetyka BIPV staje się coraz bardziej zindywidualizowana dzięki rosnącym możliwościom personalizacji koloru, formatu i faktury modułów. Pomimo postępu technologicznego elewacje zintegrowane z BIPV wciąż rzadko są stosowane w budynkach przemysłowych, gdzie dominują systemy fotowoltaiki aplikowanej na budynku (BAPV) montowane na dachach. Dalszy rozwój BIPV w architekturze przemysłowej wymaga zwiększenia świadomości projektantów oraz promowania udanych realizacji, które łączą efektywne wytwarzanie energii z wysoką jakością architektoniczną.

Słowa kluczowe: architektura przemysłowa, fotowoltaika zintegrowana z budynkiem (BIPV), estetyka fotowoltaiki, fasady BIPV, nieprzezroczysta fotowoltaika