POREĐENJE FOTONAPONSKIH TEHNOLOGIJA ZA PRIMENU U INTEGRISANIM SOLARNIM SISTEMIMA NA OBJEKTIMA (BIPV)

COMPARISON OF PHOTOVOLTAIC TECHNOLOGIES FOR BUILDING-INTEGRATED APPLICATIONS (BIPV)

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Rastuća potreba za zgradama gotovo nulte potrošnje energije (nZEB) pozicionirala je fotonaponske sisteme integrisane u građevinske elemente (BIPV) kao ključno rešenje za ugradnju obnovljivih izvora energije direktno u samu strukturu objekata. Ovaj rad daje komparativni pregled fotonaponskih (PV) tehnologija pogodnih za BIPV – sa fokusom na kristalni silicijum (c-Si), tankoslojne tehnologije kao što su kadmijum-telurid (CdTe) i bakar-indijum-galijum-selenid (CIGS), kao i nove tehnologije uključujući organske i perovskitne solarne ćelije. Tehnologije se procenjuju prema ključnim kriterijumima kao što su električna efikasnost, vizuelna integracija, mehanička fleksibilnost, troškovi, dugotrajnost i primenljivost na različite građevinske elemente kao što su fasade, krovovi i providne površine. Posebna pažnja posvećena je tome kako svaka tehnologija ispunjava zahteve energetske efikasnosti i arhitektonske integracije neophodne za BIPV sisteme. Rad takođe razmatra kompromise između tehničkih performansi i estetskih zahteva, nudeći praktične smernice za izbor odgovarajućih PV tehnologija u kontekstu integrisane primene. Referisani su i primeri postojećih BIPV implementacija radi ilustrovanja praktične upotrebe i raznovrsnosti ovih tehnologija. Rezultati ovog rada doprinose unapređenju održivih i energetski efikasnih praksi u projektovanju objekata, pružajući podršku arhitektama, inženjerima i donosiocima odluka u ostvarivanju ciljeva nZEB kroz efikasnu primenu BIPV rešenja.

Ključne reči: *fotonaponske tehnologije; solarni sistemi integrisani u objekte (BIPV); zgrade gotovo nulte potrošnje energije (nZEB); obnovljivi izvori energije; energetska efikasnost*

The growing demand for nearly Zero-Energy Buildings (nZEBs) has positioned Building-Integrated Photovoltaics (BIPV) as a crucial solution for embedding renewable energy generation into the fabric of buildings. This paper provides a comparative overview of photovoltaic (PV) technologies suitable for BIPV—focusing on crystalline silicon (c-Si), thin-film technologies such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), as well as emerging solutions including organic and perovskite solar cells. These technologies are evaluated based on key criteria including electrical efficiency, visual integration, mechanical flexibility, cost, durability, and applicability to various building components such as façades, roofs, and transparent surfaces. Special attention is given to how each technology meets both energy performance and architectural integration requirements essential for BIPV systems. The paper also discusses trade-offs between technical performance and aesthetic considerations, providing practical guidance for selecting appropriate PV technologies in building-integrated contexts. Several examples of existing BIPV implementations are referenced to

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illustrate the practical application and diversity of these technologies. The results of this study contribute to the advancement of sustainable and energy-efficient building design practices, providing support to architects, engineers, and decision-makers in achieving nZEB goals through the effective implementation of BIPV solutions.

Key words: *photovoltaic technologies; building-integrated photovoltaics (BIPV); nearly zero-energy buildings (nZEB); renewable energy sources; energy efficiency*

1 Introduction

In recent years, the concept of Zero Energy Buildings (ZEBs)—and particularly *nearly Zero-Energy Buildings* (nZEBs)—has gained significant global attention, evolving from a research interest into a central component of energy and climate policy. An nZEB is typically defined as a highly energy-efficient building that covers its very low energy demand largely by energy from renewable sources, preferably produced on-site or nearby [1]. As nZEB standards emphasize both minimization of energy demand and integration of renewable energy locally, Building-Integrated Photovoltaics (BIPV) have emerged as a pivotal solution. BIPV refers to photovoltaic materials that replace conventional building materials in parts of the building envelope—such as roofs, skylights, façades, or shading systems—serving a dual function as both construction elements and energy generators [2].

2 Photovoltaic Technologies for BIPV Applications

2.1 Crystalline Silicon (c-Si)

Crystalline silicon (c-Si) remains the foundation of modern photovoltaic technology and continues to dominate the BIPV market, accounting for over 95% of global PV installations as of 2022 [3, 4]. Its continued supremacy is grounded in the abundance and affordability of raw silicon, favorable semiconductor properties—such as an ideal bandgap (~1.1 eV) and high carrier mobility—and a mature, low-risk industrial supply chain [4, 5]. Early laboratory efficiencies hovered around 6–10 % in the 1960s, but improvements in wafer quality, surface passivation, and cell architecture have driven efficiencies above 22 % for commercial modules, with research-grade cells reaching over 26 % [5].

Commercially, most silicon solar cells are fabricated using boron-doped monocrystalline wafers—typically around 180–200 μm in thickness—produced via the Czochralski (CZ) method. The CZ process, originally developed for microelectronics, provides nearly defect-free silicon crystals, yet introduces trace levels of impurities such as oxygen, carbon, and metallic ions. Oxygen, while beneficial in microelectronics for enhancing mechanical strength and aiding defect gettering, can form boron–oxygen complexes under illumination [6].

For BIPV applications, crystalline silicon offers key advantages such as mechanical robustness, high efficiency per unit area, and compatibility with architectural elements like glass–glass modules and custom-colored laminates, enhancing aesthetic flexibility [7, 8]. However, its rigidity, weight, and inherent opacity limit its applicability in areas requiring flexibility, semi-transparency, or curved surfaces [8, 9]. The two predominant forms of crystalline silicon used in BIPV—monocrystalline and polycrystalline—differ in crystal structure, manufacturing cost, and typical efficiencies, each with unique tradeoffs for integrated applications [6, 9].

2.1.1 Monocrystalline Silicon

Monocrystalline silicon solar cells are manufactured using highly purified, semiconductor-grade silicon, typically processed via the CZ method. In this process, silicon is melted in a quartz crucible under an inert atmosphere, often argon, to prevent contamination. Controlled amounts of dopants, such as boron for p-type or phosphorus for n-type conductivity, are introduced into the melt to tailor the semiconductor's electrical properties [6, 10].

A small, precisely oriented seed crystal is dipped into the molten silicon and slowly withdrawn while being rotated. Careful control of thermal gradients, pulling rates, and rotation speeds allows the formation of a single-crystal cylindrical ingot with minimal structural defects [6, 10, 11]. Maintaining stable temperature and flow fields during crystal growth is essential to suppress instabilities that could degrade crystal quality [11].

Monocrystalline wafers cut from these ingots serve as the base for high-efficiency photovoltaic cells. Their uniform crystal structure enables superior carrier mobility and longer diffusion lengths compared to polycrystalline silicon, resulting in higher power conversion efficiencies. While research cells have surpassed 26 % efficiency, commercial monocrystalline modules commonly achieve efficiencies between 20 % and 23 % under standard test conditions [12]. Recent developments, such as passivated emitter and rear contact (PERC) architectures and heterojunction technologies, have further enhanced performance [12].

Despite their high efficiency and favorable long-term stability, monocrystalline silicon modules tend to be more expensive to produce due to energy-intensive fabrication and material waste during wafer cutting. However, their superior power density makes them particularly suitable for space-constrained BIPV applications, such as building facades and rooftops where maximizing output per area is essential [8, 13].

2.1.2 Polycrystalline Silicon

Polycrystalline silicon, also referred to as multicrystalline silicon, is widely used in photovoltaic manufacturing due to its lower production cost compared to monocrystalline alternatives [13]. It is produced by casting molten silicon into square or rectangular molds, which are slowly cooled to allow solidification. This results in a block-shaped ingot composed of multiple crystal grains, which is then sliced into wafers using wire saw techniques.

While polycrystalline silicon generally exhibits lower carrier mobility and higher recombination losses due to the presence of grain boundaries, its simpler fabrication process and higher material utilization make it an economically attractive option for utility-scale installations and certain BIPV applications where aesthetics and module efficiency are less critical [12, 13].

Typical commercial module efficiencies for polycrystalline silicon range from 17 % to 20 %, which is slightly lower than monocrystalline modules, but the cost–performance ratio remains favorable in many contexts [12, 13]. Early ribbon-based growth techniques enabled wafer production without traditional ingot slicing, but these methods are largely obsolete in today's PV industry [6].

Despite the rise of monocrystalline modules in recent years, polycrystalline silicon remains relevant due to its balance of cost, availability, and proven performance in large-scale and integrated solar systems.

2.2 Thin-Film Technologies

Thin-film photovoltaics offer a lower-cost and more flexible alternative to crystalline silicon, using significantly less material and enabling deposition on larger or curved substrates. Unlike wafer-based cells, thin-films can be manufactured as large-area modules and in integrally interconnected formats [14, 15].

Silicon-based thin-films, like crystalline silicon-on-glass (CSG), drastically reduce silicon usage by depositing micrometer-thick layers (~50 μm) on glass substrates. CSG mini-modules typically reach around 8–11 % efficiency, demonstrating proof-of-concept for silicon thin-films [16].

Non-silicon thin-films dominate commercial thin-film markets today:

- Amorphous silicon (a-Si) offers low toxicity and flexibility but remains limited by modest efficiency and light-induced/stress degradation, though modern mini-modules can retain more than 80 % power after 5000 h accelerated testing [17].
- Cadmium telluride (CdTe) is a leading commercial technology with about 22 % efficiency. It offers a shorter energy payback time (≈1–1.5 years) and lower lifecycle greenhouse gas emissions compared to crystalline silicon modules, although its cadmium content requires careful environmental control [18].
- Copper indium gallium selenide (CIGS) provides conversion efficiencies up to ~22 % at the cell level, with high absorption and thin typical layers. CIGS can be deposited on flexible substrates, supporting semi-transparent and curved BIPV applications [19].

2.2.1 Amorphous Silicon

Hydrogenated amorphous silicon (a-Si:H or a-Si) remains an important thin-film photovoltaic material due to its low manufacturing costs, reduced material usage, and compatibility with large-area and flexible substrates. Unlike crystalline silicon, a-Si lacks a long-range ordered structure, which allows for low-temperature deposition on various substrates, including glass and flexible polymers. This makes it especially appealing for BIPV, where lightweight and mechanically adaptable solutions are often required.

While its initial power conversion efficiency may appear promising, a-Si:H suffers from light-induced degradation known as the Staebler–Wronski Effect (SWE). This phenomenon leads to a drop in performance during the early stages of operation. However, continued research into deposition techniques and post-treatment methods has shown that much of this degradation can be mitigated. In particular, optimized plasma-enhanced chemical vapor deposition (PECVD) processes have led to improved material quality, reducing defect density and improving carrier lifetimes. As a result, modern single-junction a-Si:H solar cells can reach stabilized efficiencies exceeding 10 %, depending on cell structure and processing conditions [20].

Although its efficiency is modest compared to crystalline or other advanced thin-film technologies, the unique combination of environmental friendliness, mechanical flexibility, and ease of large-scale manufacturing ensures that a-Si:H still occupies a relevant niche—especially in applications where form factor, cost, and integration potential take precedence over peak performance.

2.2.2 CdTe

Cadmium telluride (CdTe) remains one of the most mature and commercially successful thin-film photovoltaic technologies. With a direct bandgap of approximately 1.45 eV and a high absorption coefficient, CdTe can absorb most of the solar spectrum with just a few micrometers of active material. This property significantly reduces material usage and manufacturing cost compared to traditional crystalline silicon, making CdTe especially attractive for large-scale terrestrial deployment [21].

Recent advancements in back contact engineering, bandgap tuning, and grain boundary passivation have enabled laboratory-scale efficiencies exceeding 22.1 %, with commercial modules now regularly surpassing 19 % [22]. These achievements are largely the result of optimized deposition techniques such as close-spaced sublimation (CSS), vapor transport deposition (VTD), and sputtering, all of which support scalable and high-throughput manufacturing [21, 22].

From a sustainability perspective, CdTe modules exhibit a short energy payback time and favorable life cycle metrics. They outperform many other PV technologies in terms of greenhouse gas emissions per unit of electricity generated [23]. Moreover, the closed-loop recycling of CdTe modules is well-established, contributing to their environmental appeal despite concerns about cadmium toxicity. Proper encapsulation and end-of-life recovery mitigate these risks, while tellurium supply constraints remain an active area of research and strategic resource planning [23].

2.2.3 CIGS

Copper indium gallium diselenide (CIGS) thin-film solar cells are among the most efficient and versatile technologies within the thin-film family. They combine a direct and tunable bandgap (1.0–1.7 eV) with a high absorption coefficient ($>10^5$ cm^{-1}), enabling strong light absorption in layers as thin as 1–2 μm [24]. This allows for lightweight and compact modules that maintain excellent performance even at reduced material usage.

Efficiency improvements in CIGS devices have been largely driven by alkali post-deposition treatments (PDTs) involving Na, K, or Rb, which improve grain boundary passivation, increase carrier lifetime, and enhance open-circuit voltage [24]. Laboratory-scale cells have achieved power conversion efficiencies exceeding 23 %, while commercial modules typically range between 16 % and 19 % [24, 25]. Further advances include optimization of buffer layers and bandgap engineering through controlled gallium incorporation.

One of the major advantages of CIGS technology lies in its mechanical flexibility. Recent studies demonstrate flexible modules on polyimide substrates achieving efficiencies above 22 %, comparable to rigid glass-based devices [26]. Such properties enable the use of CIGS in curved, lightweight, or BIPV systems, where traditional rigid silicon panels are unsuitable.

CIGS films are typically deposited using vacuum-based processes such as co-evaporation or sputtering, but emerging solution-based and roll-to-roll manufacturing techniques show promise for scalable, low-cost production [25]. Nevertheless, the technology still faces challenges related to long-term stability**,** indium and gallium resource limitations, and the environmental impact of cadmium-based buffer layers. Current research focuses on material substitution, recycling, and process optimization to ensure sustainable large-scale adoption [24, 25].

2.3 Emerging PV Technologies

Emerging photovoltaic technologies—notably perovskite solar cells, organic photovoltaics (OPV) and quantum-dot (QD) solar cells—are attracting strong interest for BIPV applications because they address the practical and aesthetic limitations of conventional silicon and established thin-film modules. Compared with bulk crystalline and conventional thin-film options, these new approaches offer low-temperature, solution-based fabrication routes that enable lightweight, flexible and conformable modules; tunable optical properties (including semi-transparency and color control) that facilitate façade and daylighting integration; and adjustable bandgaps or layer stacking strategies that open the door to higher tandem efficiencies and spectral matching to building needs [27]. Reviews of PV construction technologies and thin-film innovations also highlight manufacturability and form-factor advantages (which reduce mounting and structural requirements) as key drivers for BIPV adoption of these materials [28, 29].

Beyond aesthetic and mechanical benefits, sustainability and eco-design considerations are increasingly important for building projects. The literature notes that life-cycle, material availability and end-of-life impacts must be assessed in parallel with performance gains; these considerations are central to comparing emerging PV options for real BIPV deployments and to guiding research toward lower-impact formulations and recycling pathways [30].

2.3.1 Perovskite Solar Cells

Perovskite solar cells combine high optoelectronic quality with low-temperature, solution processing, which has driven rapid lab-scale gains in power conversion efficiency. The soft, hybrid lead-halide absorbers used in most high-performance devices are defect-tolerant and support long carrier diffusion lengths, and they can be deployed in planar, mesoscopic, or tandem architectures that suit lightweight, semi-transparent, or flexible modules. Efficiency advances came from compositional tuning, interface passivation, and improved charge-selective contacts; tandem stacks (e.g., perovskite/silicon) are a practical route to exceed single-junction limits [27, 31].

Stability remains the main barrier: moisture, oxygen, heat, UV and ion migration drive degradation. Mitigation strategies include mixed-cation/halide formulations, surface passivation, and robust encapsulation or device designs that limit reactive contacts [31, 32].

Perovskites lend themselves to scalable, low-temperature deposition (slot-die, printing, blade coating), but transferring sensitive lab passivation recipes into wide-area, robust processes is an ongoing challenge [27, 29]. Lead content raises environmental concerns; practical responses include minimizing lead per module, reliable encapsulation, and planned recovery/recycling. Lead-free alternatives are being explored but generally lag in performance and durability [30, 32].

Their tunable absorption and thin form factor make perovskites especially promising for BIPV applications such as semi-transparent windows and façade elements, provided module lifetime, encapsulation, and safety certification are demonstrated. Near-term priorities are scalable encapsulation, large-area passivation, recycling pathways, and further work on tandems to reach high-efficiency, durable BIPV products [28, 31].

2.3.2 Organic PV

Organic photovoltaics (OPV) rely on carbon-based semiconductors—conjugated polymers and small molecules—that absorb light and transport charges in ultrathin active layers. This chemistry enables very lightweight, bendable devices that can be manufactured at low temperatures and printed onto flexible substrates, which is especially useful for architectural surfaces where form and weight matter [15, 33].

Recent gains in OPV performance stem from tailored donor–acceptor couples, control of phase separation in bulk-heterojunction films, and improved interlayers that reduce energy losses at contacts. While peak laboratory efficiencies remain modest compared with inorganic cells, OPV shows practical advantages under diffuse or indoor lighting and where semi-transparent or decorative PV is required [33]. Lifetime and operational robustness limit wider deployment: organic absorbers and electrodes are vulnerable to photo-oxidation, moisture, and repeated mechanical strain. Effective responses include intrinsically more stable molecules, photostable additives, and barrier encapsulation tailored for flexible modules. Adapting these protections for continuous, roll-to-roll processing without prohibitive cost is a central engineering task [29, 33].

From a manufacturing viewpoint, coating and printing techniques (slot-die, gravure, inkjet) are the natural production routes for OPV and allow coating onto curved or lightweight elements. For building integration this opens possibilities—laminated window films, lightweight façade membranes, or conformable shading devices—but integration must account for optical appearance, fire codes, and expected module life [15, 28].

2.3.3 Quantum Dot PV

Quantum dot (QD) photovoltaics exploit nanoscale semiconductor particles to tune optical absorption and electronic properties through size and surface chemistry rather than by changing bulk composition. Colloidal QDs (e.g., lead sulfide, lead selenide) and QD-sensitized architectures enable strong, size-dependent absorption across visible and near-infrared wavelengths, offering flexible bandgap engineering for both single-junction and tandem designs [34, 35].

Device strategies fall into a few families: QD-sensitized electrodes that couple QDs to wide-bandgap oxide scaffolds, colloidal QD thin films employing ligand exchange to improve transport, and hybrid heterojunctions that combine QDs with organic or metal-oxide charge-transport layers. Progress has concentrated on balancing light absorption with efficient charge separation and extraction — improvements in surface passivation, ligand chemistry, and contact engineering have raised photogenerated current while reducing trap-mediated recombination [34]. Unique opportunities for QDs include multiple exciton generation (MEG) and strong absorption per unit thickness, which could push theoretical efficiency limits if practical MEG harvesting and low-loss extraction can be realized. However, stability, trap states, and toxic heavy-metal content (notably lead) remain key hurdles; encapsulation, compositional tuning, and low-temperature solution processing are active mitigation paths under study [35].

For integration into buildings and other applications needing lightweight or flexible form factors, QD devices' solution processability and tunable appearance are attractive. Still, long-term durability, standardized manufacturing routes, and end-of-life considerations need resolution before broad deployment—issues also discussed in building-integration reviews where QD approaches are compared with other thin-film options [15].

3 Comparative Analysis of PV Technologies for BIPV

The integration of photovoltaics into building components has shifted focus beyond mere energy generation, incorporating broader goals of architectural harmony, cost-effectiveness, and material versatility. Consequently, selecting an appropriate PV technology for BIPV applications requires a multidimensional analysis that evaluates not only electrical performance but also aesthetic, mechanical, and economic considerations. As outlined in the preceding sections, each photovoltaic technology—spanning established crystalline silicon, diverse thin-film variants, and emerging materials—presents a distinct set of characteristics. Variations in efficiency, flexibility, visual integration, durability, and cost shape their respective suitability for integration into different building elements such as façades, roofs, and transparent surfaces.

Crystalline silicon modules, particularly monocrystalline types, continue to outperform most alternatives in terms of power conversion efficiency (PCE), often exceeding 20 % under standard test conditions. However, their rigid structure and opaque nature limit their integration into architecturally demanding applications such as semi-transparent façades or curved surfaces [36, 37]. Thin-film technologies offer lower efficiency (typically 10–15 %) but benefit from superior performance under diffuse light and high temperatures, making them more suitable for certain BIPV scenarios. These materials also provide better possibilities for aesthetic and flexible integration due to their reduced thickness and lighter weight [36, 38]. Emerging PV technologies promise further advances in efficiency-to-cost ratio, particularly through low-temperature manufacturing on flexible substrates. However, their limited long-term stability remains a barrier for widespread architectural deployment [38].

From an architectural standpoint, flexibility, transparency, and customizability are critical. Thin-film and emerging technologies are better positioned than c-Si in this regard. CIGS modules can be produced on flexible substrates and exhibit colors compatible with architectural norms, while organic and perovskite technologies allow for semi-transparent or tinted layers that can be used in windows or skylights [38, 39]. Crystalline silicon modules, while highly efficient, impose visual constraints due to their dark, uniform appearance and rigidity. Though efforts are underway to improve the aesthetics of c-Si modules through surface texturing or color treatment, these modifications often come at the expense of electrical performance [37].

Considering mechanical flexibility and substrate compatibility, the use of flexible substrates significantly expands the range of BIPV applications, particularly for curved or non-traditional surfaces. Technologies such as CIGS and organic solar cells have shown strong promise in this context. For example, CIGS modules can be fabricated on lightweight, pliable materials, offering moderate power conversion efficiencies along with enhanced mechanical robustness [36, 39]. In contrast, rigid crystalline silicon modules, despite their structural durability, are typically confined to flat surfaces or support frames, limiting their applicability to complex building geometries.

Cost considerations remain paramount in BIPV, where the dual functionality of materials (as both building envelope and energy generator) must justify higher upfront investments. While c-Si modules have benefitted from decades of scaling and are now relatively cost-competitive, thin-film technologies—especially CIGS—present favorable economics due to lower material use and simplified deposition processes [36, 37]. Emerging technologies currently face higher costs per watt due to manufacturing immaturity, limited lifetime, and encapsulation challenges. However, their potential for low-cost, roll-to-roll fabrication and integration into construction materials offers promising pathways for future economic viability [38].

Durability under environmental stressors is another critical factor for BIPV. Crystalline silicon modules offer proven long-term performance with lifespans exceeding 25 years. CdTe and CIGS thin films also exhibit strong durability, though slightly less so under extreme conditions [36, 37]. In contrast, perovskite and organic PVs suffer from degradation due to moisture, UV exposure, and thermal cycling. Despite ongoing research into encapsulation and stabilization strategies, these technologies are not yet ready for long-term, outdoor architectural use without protective layers or hybrid structures [38].

No single PV technology simultaneously maximizes all performance criteria for BIPV. For instance, while c-Si excels in efficiency and durability, it is less adaptable in form and appearance. Thin films strike a balance between performance, aesthetics, and integration versatility. Emerging technologies, though still experimental, offer exciting potential for achieving seamless integration with building materials, especially when visual and form-factor flexibility are prioritized over long-term performance [36, 37, 39]. Thus, the choice of PV technology in BIPV should reflect the specific goals of the architectural project, balancing energy yield, visual quality, structural constraints, and lifecycle costs.

4 Case Examples of BIPV Implementations

Several real-world implementations of BIPV showcase how photovoltaic technologies can be harmoniously embedded into building envelopes, fulfilling both energy generation and architectural roles. These examples span across different climates, structural types, and design objectives, underlining the flexibility and potential of BIPV systems.

A comprehensive full-scale case study was conducted on a laboratory building in Germany, where CIGS thin-film modules were integrated into a ventilated double-skin façade, *Figure 1*. The BIPV system replaced conventional cladding elements with glass-glass modules, combining architectural functionality with renewable energy generation. Continuous monitoring of electrical output, façade surface temperature, and irradiance demonstrated stable performance even under diffuse light conditions. The study emphasized that proper façade design—particularly ventilation gap configuration and real-time performance tracking—can significantly enhance both the thermal behavior and energy yield of CIGS-based BIPV façades [40].

Figure 1. Laboratory building with blue PV façade located in Berlin, Germany [40]

In the case of the San Antón Market in Madrid, Spain, the skylight BIPV system incorporates semi-transparent PV glass laminates, *Figure 2 (a)*. These glazing units are typically based on a-Si thin-film photovoltaic technology. Thin-film modules are favored in skylight and curtain wall applications due to their more uniform light transmittance, which enhances visual comfort and aesthetic integration in architectural spaces. The double-glazed configuration of these BIPV elements also contributes to thermal insulation, aligning with both energy and building envelope performance requirements [41].

In Gothenburg, Sweden, a multi-storey car-park façade was fitted with colored semi-transparent CdTe thin-film glazing modules, *Figure 2 (b)*. These modules operate not only as decorative wall cladding but also as energy-producing elements, offering a blend of aesthetic expression and functional solar power generation. The colorization is achieved by customizing interlayer or patterning to yield various hues while maintaining partial transparency. This example demonstrates that CdTe technology can be leveraged for façade integration beyond conventional black panels, making it suitable for visually expressive architectural settings [41].

(a) (b)

Figure 2. (a) The skylight of the San Antón Market located in Madrid, Spain [41]*; (b) Car-park façade located in Gothenburg, Sweden* [41]

5 Conclusions

The comparative analysis presented in this paper highlights how different photovoltaic technologies can be effectively adapted for BIPV, depending on their physical, electrical, and aesthetic characteristics. Crystalline silicon remains the most efficient and durable solution but is limited by its rigidity and visual uniformity. Thin-film technologies such as CdTe and CIGS provide greater design flexibility, lower material consumption, and improved integration potential, making them particularly suitable for façades and curved surfaces. Emerging PV technologies—including perovskite, organic, and quantum-dot cells—introduce new possibilities for lightweight, semi-transparent, and color-tunable designs, though their long-term stability still requires further development. Continued progress in material research, manufacturing processes, and regulatory support will further strengthen the role of BIPV as a key enabler of nZEBs and sustainable urban environments.

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