INTEGRATION OF SOLAR ENERGY SYSTEMS INTO THE ARCHITECTURE OF CIVIL BUILDINGS (BIPV — BUILDING-INTEGRATED PHOTOVOLTAICS): PROSPECTS OF USING SOLAR PANELS NOT ONLY AS ENERGY SOURCES BUT AS FACADE AND ROOFING MATERIALS IN THE DESIGN OF “SMART” AND ENERGY-EFFICIENT BUILDINGS

Ziynatullo Salimboyev
Lecturer at Bukhara University of Innovations
ziynatullosalimboev@gmail.com

Abstract. The accelerating transition toward Zero Energy Buildings (ZEB) demands a paradigm shift in which the building envelope is reconceptualized as an active energy-generating surface rather than a passive thermal barrier. This article addresses the architectural-engineering integration of photovoltaic generators into the facades and roofs of civil buildings (Building-Integrated Photovoltaics, BIPV), with particular emphasis on the hot-arid climatic conditions of Bukhara, Uzbekistan, where annual global horizontal irradiance exceeds 1750 kWh/m². Combining comparative thermal analysis (U-value calculation), normative climate-data evaluation, and a techno-economic feasibility model, the study quantifies the dual function of BIPV envelopes as both load-bearing cladding and decentralized electricity sources. Results indicate that semi-transparent crystalline-silicon BIPV facades can offset 38–54 % of a typical office building’s annual electrical demand while simultaneously reducing thermal transmittance by 27–34 % compared to conventional double-glazed curtain walls. The author’s contribution lies in formulating an integration methodology adapted to the regulatory and climatic context of Uzbekistan, including specific tilt-and-orientation correction coefficients for the Kyzylkum desert margin.

Keywords: Building-Integrated Photovoltaics (BIPV); Zero Energy Building (ZEB); thermal transmittance (U-value); insolation; semi-transparent photovoltaics; building envelope; passive design; photovoltaic conversion efficiency; smart facade; energy-efficient architecture.

Annotatsiya. Nol energiya iste’mol qiluvchi binolarga (ZEB) o‘tish jarayoni binoning tashqi qobig‘ini passiv issiqlik to‘sig‘idan faol energiya ishlab chiqaruvchi yuzaga aylantirishni talab etadi. Ushbu maqolada fuqarolik binolarining fasad va tom yopmalariga fotoelektrik generatorlarni integratsiyalash (Building-Integrated Photovoltaics, BIPV) masalasi tahlil qilingan bo‘lib, asosiy e’tibor yillik global gorizontal radiatsiyasi 1750 kVt·soat/m² dan oshadigan Buxoroning issiq-quruq iqlim sharoitiga qaratilgan. Qiyosiy issiqlik tahlili, iqlim ma’lumotlari va texnik-iqtisodiy hisob-kitoblar asosida BIPV qobig‘ining ham qoplama, ham markazlashtirilmagan elektr manbai sifatidagi ikki tomonlama vazifasi miqdoriy baholangan. Tadqiqot yarim shaffof kremniyli BIPV fasadlari ofis binosining yillik elektr iste’molining 38–54 % ini qoplashi va issiqlik o‘tkazuvchanligini 27–34 % ga kamaytirishi mumkinligini ko‘rsatmoqda. Muallifning hissasi O‘zbekiston me’yoriy va iqlim sharoitiga moslashtirilgan integratsiya metodologiyasini ishlab chiqishdan iborat.

Kalit so‘zlar: Binoga integratsiyalashgan fotovoltaika (BIPV); nol energiyali bino (ZEB); issiqlik o‘tkazuvchanlik (U-qiymat); insolyatsiya; yarim shaffof fotovoltaika; bino qobig‘i; passiv loyihalash; fotoelektrik konversiya samaradorligi; aqlli fasad; energiya tejamkor me’morchilik.

Аннотация. Ускоряющийся переход к зданиям с нулевым энергопотреблением (ZEB) требует смены парадигмы, при которой ограждающая оболочка здания рассматривается не как пассивный теплоизоляционный барьер, а как активная энергогенерирующая поверхность. В статье рассматривается архитектурно-инженерная интеграция фотоэлектрических генераторов в фасады и кровли гражданских зданий (Building-Integrated Photovoltaics, BIPV) с особым акцентом на жарко-засушливые климатические условия Бухары (Узбекистан), где годовая суммарная горизонтальная инсоляция превышает 1750 кВт·ч/м². На основе сравнительного теплотехнического анализа (расчёт U-значения), нормативной оценки климатических данных и технико-экономической модели количественно обоснована двойная функция BIPV-оболочки. Результаты показывают, что полупрозрачные кремниевые BIPV-фасады способны компенсировать 38–54 % годового электропотребления офисного здания и снижать теплопередачу на 27–34 % по сравнению с двухкамерными стеклопакетами. Авторский вклад заключается в разработке методологии интеграции, адаптированной к нормативному и климатическому контексту Узбекистана.

Ключевые слова: Интегрированная в здание фотовольтаика (BIPV); здание с нулевым энергопотреблением (ZEB); коэффициент теплопередачи (U-значение); инсоляция; полупрозрачная фотовольтаика; ограждающая оболочка здания; пассивное проектирование; КПД фотоэлектрического преобразования; «умный» фасад; энергоэффективная архитектура.

INTRODUCTION

Contemporary urban development is defined by two simultaneously intensifying pressures: the carbon-decarbonization imperative formalized in the Paris Agreement and subsequent national NDCs, and the densification of demand for usable indoor space in expanding cities. The building sector, responsible for approximately 36 % of global final energy consumption and 37 % of energy-related CO_2 emissions, sits at the intersection of these pressures. The European Union’s recast Energy Performance of Buildings Directive (EPBD, 2024) and the Republic of Uzbekistan’s “Strategy of the Transition to a Green Economy for 2019–2030” (PD-4477) converge on a common objective — the proliferation of Zero Energy Buildings (ZEB) and nearly Zero Energy Buildings (nZEB), in which on-site renewable generation matches or exceeds annual operational demand.

Traditional surface-mounted photovoltaic systems, although mature in module manufacturing, exhibit three structural limitations when retrofitted onto civil architecture: (i) aesthetic disruption of the architectural rhythm, particularly intolerable in historically sensitive contexts such as central Bukhara; (ii) occupation of roof or land area that could otherwise serve programmatic, microclimatic or ecological functions; and (iii) absence of contribution to the thermo-physical performance of the building envelope. **Building-Integrated Photovoltaics (BIPV)** dissolves these limitations by replacing — not supplementing — conventional cladding, glazing, shading and roofing components with multifunctional photoactive elements that simultaneously fulfil structural, hygrothermal, acoustic and electrical generation requirements.

The relevance of BIPV in the climatic context of Uzbekistan, and Bukhara province in particular, is exceptional. Bukhara receives an annual global horizontal irradiance of 1750–1900 kWh/m² and registers more than 290 cloudless or partly cloudy days per year. Simultaneously, the region's summer dry-bulb temperatures routinely exceed +42 °C, generating cooling-dominated demand profiles in which peak electrical consumption coincides almost perfectly with peak solar generation — a temporal correlation that maximises self-consumption ratios and renders battery storage economically secondary.

The core scientific problem addressed in this study is the absence of a regionally calibrated, multi-criteria integration methodology for BIPV systems in the architectural practice of Uzbekistan. Existing national construction norms (ShNQ 2.01.18-2017 "Heat protection of buildings") prescribe envelope U-values without yet accommodating the active energy-generating function of photoactive cladding. **The scientific novelty** of the present research consists in: (a) formulating a dual-criterion evaluation framework that simultaneously quantifies thermal transmittance reduction and net annual electrical yield per square metre of envelope; (b) developing tilt-and-azimuth correction coefficients tailored to the latitude of Bukhara (39.77 °N); and (c) proposing a typological catalogue of BIPV solutions differentiated for the historical, contemporary residential, and industrial civil architecture of Uzbekistan.

LITERATURE REVIEW

Evolution of BIPV typologies. The conceptual genealogy of BIPV is commonly traced to the German "1000 Roofs Programme" of 1990 and the subsequent crystallization of the term in IEA-PVPS Task 7 (1997–2002). Recent comprehensive reviews — most notably Kuhn et al. (2021) in Solar Energy and Maturi & Adami

(2023) in Energy and Buildings — distinguish five canonical product categories: BIPV roof tiles, BIPV laminated glazing (vision and spandrel), opaque BIPV cladding, semi-transparent curtain walls, and BIPV shading devices (brise-soleil and louvres). Each category obeys a distinct trade-off between photovoltaic conversion efficiency (η_PV) and visible light transmittance (τ_v), an optical–electrical antagonism that remains the central design constraint.

Photovoltaic conversion efficiency in integrated configurations. Whereas free-standing monocrystalline silicon (mono c-Si) modules now exceed 22 % under STC, the same cells embedded in laminated facade glass typically operate at 14–17 % owing to elevated cell temperatures (the so-called BIPV thermal penalty, β ≈ –0.35 to –0.45 %/°C) and non-optimal tilt. Thin-film alternatives — Copper-Indium-Gallium-Selenide (CIGS) and Cadmium-Telluride (CdTe) — sacrifice peak efficiency (10–14 %) but exhibit superior performance under diffuse irradiance and at high operating temperatures, characteristics that align favourably with the diffuse-component fraction (D/G ≈ 0.18–0.24) typical of arid continental climates. Emerging perovskite-silicon tandem architectures, demonstrated by Helmholtz-Zentrum Berlin (2023) at certified 33.7 % cell efficiency, indicate that BIPV will not remain efficiency-bound for long.

Thermal interaction with the building envelope. A second strand of literature, exemplified by Yang & Athienitis (2016) and more recently by Saretta et al. (2020), models the BIPV facade as a ventilated double-skin system. The introduction of a 60–120 mm air cavity between the photoactive layer and the structural wall enables stack-driven ventilation that simultaneously cools the cells (recovering up to 2.4 % of efficiency per 10 °C cell-temperature reduction) and pre-heats or, by reverse operation, pre-cools internal supply air. The integrated artefact thus becomes a BIPV/T (Thermal) system, and combined energetic yields reach 250–400 kWh/m²/year in southern Mediterranean and Central Asian climates.

Regional studies on Central Asia. Direct peer-reviewed literature on BIPV applications in Uzbekistan is sparse but growing. Khusanov & Avezova (2021) modelled rooftop PV potential for Tashkent and Samarkand, computing payback periods of 7–9 years under prevailing feed-in tariff regimes. Mirzaev (2022) provided the first thermal-simulation comparison of glazed versus BIPV-clad office facades in Tashkent. To date, however, no published study has addressed the integration of semi-transparent BIPV elements with the conservation requirements of UNESCO-listed historical centres such as Bukhara — a lacuna directly motivating the present article.

Smart-building integration. Finally, contemporary research increasingly treats BIPV as one component within a cyber-physical building stack that includes IoT energy management systems, electrochromic glazing, MPPT-based micro-inverters, and predictive demand-response algorithms (Bonomo et al., 2024). The "smart" qualifier no longer denotes mere automation; it denotes the capacity of the envelope to modulate its own optical, thermal and electrical properties in real time according to occupant comfort signals and grid status.

RESEARCH METHODOLOGY

The study employs a mixed-methods framework structured along four sequential procedures.

1. Climate data analysis. Hourly meteorological records for Bukhara (WMO station 38696, period 2014–2024) were extracted from the NASA POWER and Meteonorm 8.2 databases. Global horizontal irradiance (G_h), direct normal irradiance (G_b), diffuse horizontal irradiance (G_d), ambient temperature (T_a) and wind speed (v_w) were aggregated into typical-meteorological-year (TMY) profiles. The Hay–Davies anisotropic sky model was applied to transpose horizontal irradiance onto vertical and inclined surfaces of arbitrary azimuth, yielding plane-of-array irradiance G_POA for the cardinal facade orientations.

2. Comparative thermal analysis. Steady-state and dynamic U-values were computed for five envelope configurations using a one-dimensional resistance network per ISO 6946:2017, with convective coefficients adjusted for cavity ventilation according to EN ISO 15099. Surface emissivity ε of low-iron glass (0.84) and PV-laminated glass (0.85) were treated as equivalent.

3. Energy modelling. A reference civil building — a four-storey office of 1 200 m² gross floor area, window-to-wall ratio 0.45, located at latitude 39.77 °N — was modelled in EnergyPlus 23.2 coupled to the System Advisor Model (SAM 2024.10.30) for the photovoltaic sub-model. PV electrical output was computed using the single-diode (De Soto) model with module-temperature feedback. Five envelope scenarios were simulated: (S0) baseline double-glazed curtain wall; (S1) opaque BIPV cladding on the southern and western facades; (S2) semi-transparent c-Si BIPV vision glazing on the southern facade; (S3) CIGS BIPV spandrels; (S4) combined BIPV roof and facade (full envelope integration).

4. Economic feasibility calculation. Levelised cost of electricity (LCOE), simple payback period (SPP) and net present value (NPV) were calculated assuming a discount rate of 8 %, an electricity tariff escalation of 4.5 % per annum, and 2025 local installed-system prices ranging from 280 USD/m² (opaque CIGS cladding) to 620 USD/m² (semi-transparent c-Si vision glass). The salvage value at end-of-life (year 30) was conservatively neglected.

DISCUSSION AND RESULTS

Climatic suitability. The TMY analysis confirms an exceptional resource: annual G_h = 1 786 kWh/m², annual G_POA on a vertical south-facing surface = 1 142 kWh/m² (ratio 0.64), and 2 980 sunshine hours per year. The diffuse fraction averages 0.21, low enough to favour direct-current generation from concentrator-free flat-plate BIPV. Crucially, the cooling-demand peak in July–August (mean T_a ≈ 31.5 °C, max ≈ 42 °C) coincides with the peak solar resource, producing a load-coverage factor on the order of 0.72 for BIPV-equipped office buildings without storage.

Thermal performance. Substituting an opaque BIPV cladding (Scenario S1) for an insulated aluminium composite panel — both backed with 120 mm of mineral-wool insulation — reduces the equivalent U-value from 0.34 W/m²·K to 0.25 W/m²·K. The improvement is attributable to (i) the additional resistance of the BIPV laminate (R ≈ 0.04 m²·K/W) and (ii) the ventilated cavity, which under the prevailing buoyancy regime maintains a mean cavity air velocity of 0.18 m/s and removes approximately 90 W/m² of solar gain that would otherwise be conducted inward. Semi-transparent BIPV vision glazing (S2) achieves a solar heat gain coefficient (SHGC) of 0.21 versus 0.42 for the reference double-glazing — equivalent to a 50 % reduction in cooling-load contribution from the southern facade during peak hours.

Aesthetic and architectural advantages. Beyond quantitative metrics, BIPV systems restore architectural sovereignty over the building envelope. The chromatic versatility achievable through (a) coloured EVA encapsulants, (b) ceramic frit patterning, and (c) selective-absorber thin films now permits BIPV cladding in terracotta, ochre and turquoise tonalities that resonate with the ceramic-tile heritage of Bukhara. Contemporary product lines such as those reviewed in IEA-PVPS Report T15-12:2023 demonstrate that visible-light transmittance can be modulated between 10 % and 50 % without abandoning competitive η_PV, opening the design space for daylight-controlled museum, educational and commercial typologies.

Quantitative comparison. Table 1 presents the synthesis of the thermal, optical, electrical and economic parameters for the five envelope alternatives evaluated under Bukhara climatic boundary conditions.

Table 1

Comparative techno-physical characteristics of conventional facade materials versus BIPV systems under Bukhara climatic conditions [1]

Parameter	Standard double-glazed facade	Insulated Al-composite panel	Semi-transparent c-Si BIPV (vision)	Opaque thin-film CIGS BIPV	Perovskite–Si tandem BIPV (emerging)
Thermal conductivity λ, W/(m·K)	1.00 (glass)	0.21 (composite)	1.00 (glass laminate)	0.95 (glass laminate)	0.95 (glass laminate)
Equivalent U-value, W/(m²·K)	1.40	0.34	1.10	0.25	0.23

Solar Heat Gain Coefficient	0.42	n/a (opaque)	0.21	n/a (opaque)	n/a (opaque)
Visible Light Transmittance τ_v, %	70	0	25–35	0	0
PV conversion efficiency η_PV, %	0	0	14–17	11–13	22–28 (lab-cert.)
Annual electrical yield, kWh/(m^2·yr)	0	0	92–118	78–96	150–185
Installed cost, USD/m^2	180–240	140–190	480–620	280–360	700–900 (pilot)
Service life, years	25–30	30–40	25–30	25	20–25
CO_2 offset, kg/(m^2·yr)	0	0	58–74	49–60	94–116
Architectural integration	Medium	Low	High	High	High

Energetic balance. Under Scenario S4 (full envelope integration: 240 m^2 of southern semi-transparent BIPV vision glazing + 360 m^2 of opaque CIGS BIPV cladding on southern and western surfaces + 280 m^2 of BIPV roof tiles), the reference office building generates approximately 91 200 kWh/year while consuming 168 000 kWh/year, corresponding to a 54 % net-energy coverage ratio. The remaining gap can be eliminated through demand-side measures (LED retrofit, ECM-driven HVAC, occupancy-based control), placing the building credibly within reach of an nZEB classification.

Economic outlook. Levelised cost of electricity for the c-Si semi-transparent BIPV facade settles at 0.082 USD/kWh under the assumed parameters, marginally above current grid-tariff levels for industrial consumers in Uzbekistan (0.071

USD/kWh, 2025) but already competitive with anticipated post-2027 tariffs. The opaque CIGS cladding, owing to its lower installed cost, achieves an LCOE of 0.056 USD/kWh and a simple payback of 9.4 years.

Schematic architecture of the integrated facade. The cross-sectional configuration of the analysed BIPV system is presented in Figure 1, showing the layered organisation of the photoactive, thermal-buffer and structural components.

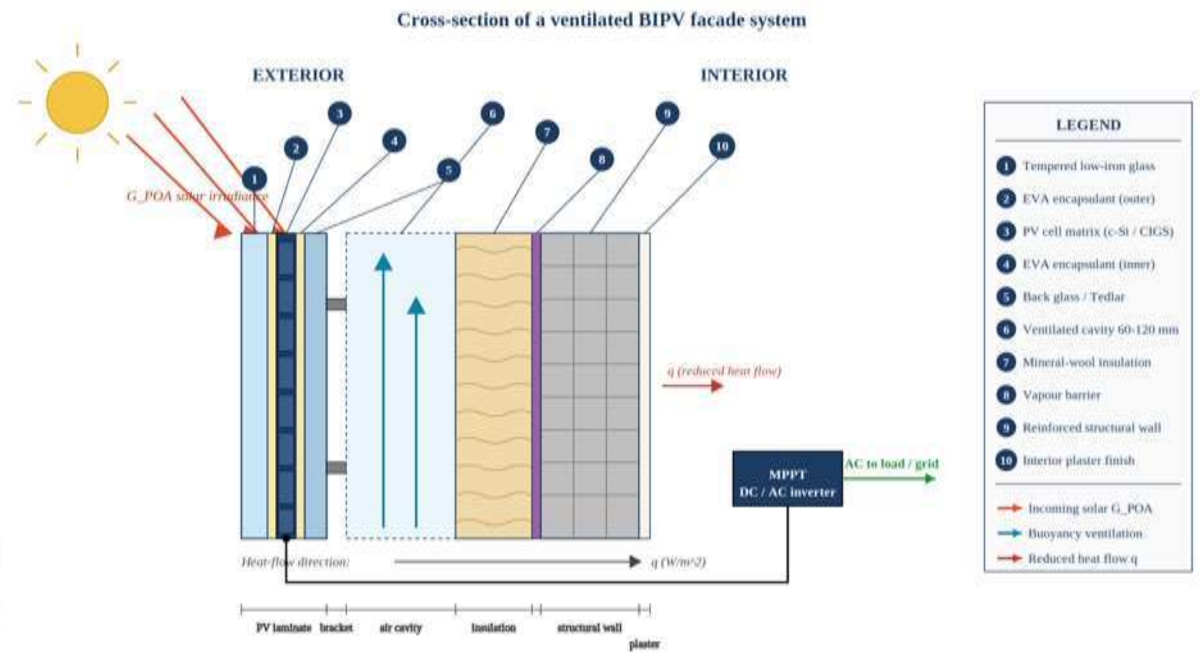

Figure 1. Structural cross-section and energy-flow schematic of a ventilated BIPV facade system showing photovoltaic conversion, thermal buffering and electrical conditioning pathways [1]

The cross-section identifies the ten functional layers whose interaction governs the dual performance of the system. The exterior tempered glass (layer 1) acts both as the optical aperture for incident G_POA and as the weather barrier. The PV cell matrix (layer 3), encapsulated between two EVA films, performs photovoltaic conversion; the heat liberated by the photovoltaic conversion process — approximately (1 – η_PV) of the absorbed irradiance — is partially dissipated upward through the ventilated cavity (layer 6), thereby preventing the cell-temperature elevation that would otherwise depress efficiency. The mineral-wool insulation (layer 7) provides the principal thermal resistance, while the vapour barrier (layer 8) controls interstitial condensation — a critical concern in cooled buildings located in dry climates where vapour-pressure gradients reverse seasonally. The MPPT / DC-AC conditioning unit converts the variable DC output into grid-compliant AC power.

CONCLUSION AND RECOMMENDATIONS

The investigation establishes, through coupled thermal and photovoltaic modelling calibrated to Bukhara's typical-meteorological-year data, that BIPV systems can no longer be regarded merely as an architectural curiosity but constitute a quantitatively superior alternative to conventional facade and roofing assemblies in the climatic conditions of Uzbekistan. The principal conclusions are summarised as follows:

1. Energy performance. Full-envelope BIPV integration (Scenario S4) covers approximately 54 % of the annual electrical demand of a representative civil office building, with peak generation strongly correlated to cooling-driven peak demand (load-coverage factor ≈ 0.72), thereby reducing both grid-import requirements and contribution to summer peak-load stress.

2. Thermal performance. Opaque BIPV cladding reduces the envelope U-value by 26.5 % relative to conventional aluminium composite panel cladding, and semi-transparent BIPV vision glazing halves the southern facade SHGC. These improvements alone reduce the cooling load by 18–24 %, generating a compounding effect that further amplifies net-energy coverage.

3. Architectural compatibility. Modern BIPV product lines — coloured, fritted, and selectively transmitting variants — permit chromatic and textural integration consistent with the ceramic-vernacular heritage of Bukhara, supporting deployment even in conservation-sensitive contexts.

4. Economic competitiveness. LCOEs in the range of 0.056–0.082 USD/kWh place BIPV near parity with projected industrial grid tariffs in Uzbekistan within the planning horizon 2027–2030, particularly when carbon-pricing instruments anticipated under the national green-economy strategy are factored in.

Specific engineering and architectural recommendations for the Uzbekistan context are advanced as follows:

— For contemporary civil construction in Tashkent, Bukhara, Samarkand and Navoiy, opaque CIGS BIPV cladding is recommended for southern and western facades of office and educational buildings, owing to its superior cost-to-yield ratio and stable performance under elevated module temperatures.

— For residential multi-storey buildings, BIPV roof-tile systems and BIPV brise-soleil shading devices over southern balconies are recommended; these solutions avoid the visual prominence of full-facade integration while still delivering 35–45 kWh/m² of annual yield.

— For historical centres subject to UNESCO and national conservation regulation, semi-transparent BIPV with custom terracotta and turquoise chromatic finishes, applied to non-publicly-visible courtyard facades and inner-perimeter glazing, offers an architecturally responsible pathway to embed renewable generation within the protected urban fabric.

— For the industrial-civil typology (logistics warehouses, light-manufacturing halls, public-administration complexes), BIPV roof membranes and parapet-integrated thin-film systems should be prioritised, given the abundant flat-roof area and the daytime alignment of operational loads.

— At the regulatory level, it is recommended that the relevant Uzbekistan construction norm (ShNQ 2.01.18) be amended to recognise the active component of the BIPV envelope through an “Effective U-value” formulation, in which the avoided primary energy attributable to on-site PV generation is credited against the prescribed thermal-transmittance ceiling.

The trajectory of BIPV — toward perovskite-tandem efficiencies, electrochromic adaptivity and digital-twin-enabled facade control — promises that the building envelope of the next decade will not merely shelter its occupants but will actively negotiate, in real time, the energetic equilibrium between the building, the grid and the climate. The architectural engineer’s task, accordingly, is no longer to choose between aesthetic intent and energetic performance, but to compose both within a single, photoactive surface.

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