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A REVIEW OF INNOVATIVE WIND TURBINES AND PHOTOVOLTAIC ARCHITECTURES

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Abstract: This study is framed by the accelerating displacement of fossil energy carriers, driven by depletion and externalities (GHG emissions and ecosystem impacts), and by the global shift toward converter-interfaced variable renewable energy (VRE). The objective is to justify, using recent deployment evidence, why next-generation photovoltaic (PV) and wind energy conversion system (WECS) technologies constitute the highest-leverage innovation targets for near-term capacity scale-up and grid-compatible decarbonization. Methodologically, the work combines (i) macro-trend interrogation of IRENA renewable capacity statistics (2015–2024) with (ii) a structured technology review of emerging wind concepts (vortex-induced vibration bladeless harvesters, passive/ducted building-integrated turbines, and modular multi-rotor architectures) and advanced PV architectures (bifacial modules and transparent PV/TLSC devices), focusing on dominant physical mechanisms, conversion chains, and deployment constraints. Results show that 2024 delivered a record +585 GW (+15.1%) renewable capacity expansion, with PV (+452 GW; +32.2%) and wind (+113 GW; +11.1%) contributing 96.6% of net additions, whereas hydro, bioenergy, and geothermal exhibited marginal growth. Key technology bottlenecks are identified: resonance-bandwidth limits in VIV harvesters (addressable via adaptive stiffness tuning), aerodynamic losses and siting dependence in passive systems, and load/wake management in multi-rotor arrays; bifacial PV bankability remains coupled to rear-irradiance modelling and mismatch control, while TPV is constrained by the transparency-efficiency trade-off. The findings indicate that accelerating PV/WECS innovation is pivotal for sustained renewable expansion under realistic environmental variability.

Key words: Energy conversion, bladeless wind turbine, photovoltaic systems, renewable energy, wind energy conversion systems.

1. INTRODUCTION

The progressive depletion of conventional fossil-based energy carriers, most notably petroleum and natural gas, together with their well-documented externalities (greenhouse-gas emissions, criteria air pollutants, and broader ecosystem impacts), has reached a level that is increasingly viewed as a systemic constraint for long-term industrial development. This convergence of resource scarcity, climate forcing, and environmental degradation has intensified scientific and engineering efforts toward scalable, low-carbon energy conversion pathways and has accelerated innovation across the renewable energy landscape [1], [2], [3], [4], [5].

Within this framework, renewable resources have acquired strategic relevance because they are intrinsically replenished on human time scales, exhibit favorable life-cycle environmental profiles, and are broadly available across diverse geographies. Among the main renewable options: solar, wind, hydropower, and marine/tidal systems, solar photovoltaics (PV) and wind energy conversion systems (WECS) have emerged as the fastest-growing technologies worldwide, driven by rapid cost declines, modular deploy ability, and maturity of manufacturing and grid-integration ecosystems. From a physical standpoint, these technologies directly transduce naturally occurring energy fluxes into electrical power: PV modules convert incident solar irradiance into direct current via semiconductor junction processes (photogeneration, charge separation, and carrier collection), whereas wind turbines extract kinetic energy from atmospheric flow and convert it to electricity through aerodynamic torque production coupled to electromechanical generators. Importantly, during operation both pathways provide electricity generation with negligible direct atmospheric emissions, enabling decarbonized power supply when appropriately integrated with power electronics, control strategies, and grid-support functionalities [6], [7], [8], [9], [10].

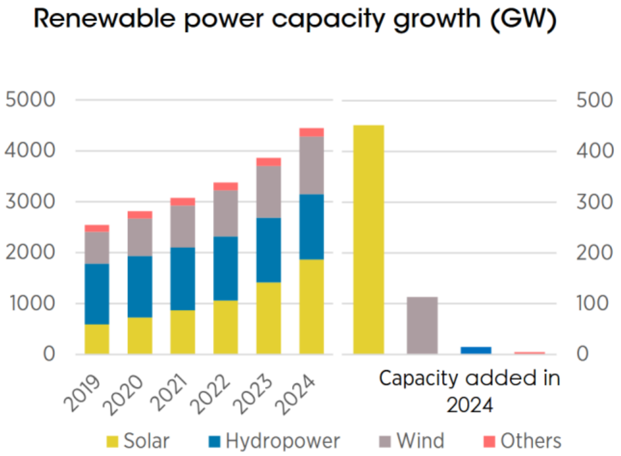

Figure 1 Global cumulative installed renewable power capacity by energy source, 2015–2024 (IRENA data) [11]

Based on IRENA (International Renewable Energy Agency) statistics, global renewable installed power capacity registered an unprecedented expansion in 2024, increasing by 585 GW, which corresponds to a +15.1% year-on-year growth rate. The decomposition of net additions by technology indicates a highly concentrated growth pattern dominated by variable renewable energy (VRE) sources: solar photovoltaics (PV) contributed +452 GW (+32.2%), accounting for more than three quarters of the total capacity increment, while wind power added +113 GW (+11.1%). In contrast, dispatchable and legacy renewable technologies exhibited markedly lower marginal growth: renewable hydropower increased by +15.0 GW (+1.2%), bioenergy by +4.6 GW (+3.2%), and geothermal by +0.4 GW (+2.5%) [11].

From a system-level perspective, the 2024 capacity build-out is characterized by an intensified reliance on PV–wind deployment, with solar and wind jointly representing 96.6% of all net renewable additions. This technological skew underscores the continued acceleration of converter-interfaced generation within the global portfolio, driven by the scalability and modularity of PV and the mature supply-chain dynamics of onshore/offshore wind [11].

Motivated by these highly consequential IRENA-derived capacity expansion trends, where solar PV and wind exhibit a markedly accelerated, near-exponential growth trajectory relative to other renewable technologies, this study strategically concentrates on the most recent technological advancements in photovoltaic module architectures and wind turbine systems, as these rapidly evolving, high-deployment-rate domains presently constitute the dominant vectors of global renewable capacity growth and, consequently, offer the greatest leverage for performance gains, cost reduction, and grid-integration scalability.

2. INNOVATIVE WIND TURBINE TECH CONCEPTS

2.1 Bladeless turbine

In recent years, a growing body of research has focused on enhancing the energy-conversion efficiency of wind harvesting devices that rely on vortex-induced vibration (VIV) as the primary transduction mechanism, rather than conventional aerodynamic torque production [12], [13], [14], [15]. Within this class, hybrid bladeless turbines have emerged as a promising architecture, integrating electromagnetic induction (EMI) and piezoelectric transduction in a single system to broaden the conversion pathways and increase net electrical output. The hybridization strategy is motivated by the complementary characteristics of the two mechanisms, namely, the comparatively high current capability and robustness of EMI-based generators versus the high voltage density and compact form factor of piezoelectric elements, thereby enabling improved electromechanical coupling and potentially higher overall conversion efficiency under suitable operating conditions [16]. Nevertheless, the performance of VIV-based harvesters remains strongly governed by frequency matching: peak energy extraction occurs only when the excitation (vortex-shedding) frequency is synchronized with the structure’s natural frequency, i.e., within the resonant lock-in regime, which constrains efficiency under highly variable wind fields [12], [13], [14], [15], [16].

A canonical bladeless wind turbine typically comprises a slender mast (often approximated as a circular cylinder) elastically mounted to a rigid foundation via a compliant element (flexible rod or spring–damper assembly), as schematically indicated in Fig. 2. Unlike classical horizontal-axis or vertical-axis turbines, this configuration does not employ rotating blades to generate shaft power; instead, it converts the wind’s kinetic energy into transverse structural oscillations driven by vortex shedding. As uniform flow impinges on the cylindrical body, separation occurs and a periodic wake develops, producing alternating low-pressure regions on either side of the cylinder and thereby generating an oscillatory lift force approximately normal to the mean flow direction. For appropriate Reynolds-number intervals, the wake organizes into a von Karman vortex street, and the corresponding unsteady aerodynamic loading can excite the structure into sustained vibrations. Under lock-in conditions, the vortex-shedding frequency adapts toward the structure’s natural frequency, substantially amplifying vibration amplitude and, consequently, the available mechanical power for conversion. The harvested energy thus follows a two-stage pathway: wind kinetic energy → mechanical vibration energy → electrical energy via coupled transducers [12], [17], [18], [19].

From an electromechanical integration perspective, the compliant support is coupled to an energy conversion module consisting of a coil-magnet assembly and/or piezoelectric elements, depending on the hybrid topology. In the electromagnetic branch, relative motion between the coil and the magnetic field induces an electromotive force according to Faraday's law, with the output strongly dependent on flux density, coil geometry, and the relative velocity of the moving component. For analytical tractability, the magnetic field is frequently modeled as quasi-uniform in the active region, a reasonable approximation when the flux is generated by axially symmetric permanent magnets and the air-gap is designed to minimize spatial non-uniformity. This assumption simplifies the derivation of the electromechanical coupling coefficient and the equivalent circuit representation used for coupled aeroelastic–electrical simulations [12], [17], [18], [19].

Figure 2 Wind energy system with bladeless turbines [20]

Peak vibration amplitudes in vortex-induced vibration (VIV) harvesters are attained when the vortex-shedding frequency, f_s, coincides with the dominant structural natural frequency, f_n, i.e., $f_s \approx f_n$. This operating condition is typically described as aeroelastic resonance and is frequently associated with the lock-in regime, in which wake dynamics synchronize with the structural response, resulting in a marked increase in oscillation amplitude and mechanical power availability. Within this regime, the unsteady aerodynamic loading-primarily the lift component induced by alternating vortex shedding, is commonly represented in reduced-order formulations as a quasi-harmonic (approximately sinusoidal) excitation acting transverse to the mean flow. The electromechanical conversion stage is then implemented via electromagnetic induction, whereby relative motion between a coil and a magnetic flux field induces an electromotive force in accordance with Faraday's law, consistent with the fundamental operating principle of conventional electromagnetic generators [19].

From a system-level perspective, bladeless VIV-based wind harvesters exhibit several practical advantages relative to bladed turbines. The most prominent benefit is the absence of rotating drivetrain components, which reduces mechanical complexity, mitigates failure modes associated with bearings/gearboxes, and lowers both manufacturing and life-cycle maintenance costs. Additionally, these devices can offer comparatively high power density per occupied area when deployed in arrays, due to reduced spacing constraints and the potential for closer packing without wake-interaction penalties typical of large-rotor systems. They are also generally associated with lower acoustic emissions and reduced ecological disturbance, particularly with respect to avian interactions, since they eliminate high-tip-speed blades that drive tonal noise and collision risk [12], [13], [14], [16], [19], [21]. A further operational advantage is their capability to sustain energy conversion at low mean wind speeds, provided that the aeroelastic system is tuned such that lock-in can occur within the prevalent wind-speed distribution, thereby improving the continuity of energy supply in weak-wind environments [18].

Notwithstanding these merits, the dominant performance constraint of VIV harvesters remains their strong dependence on resonant conditions. In realistic atmospheric boundary-layer flows, wind velocity is intrinsically non-stationary; thus, deviations from the resonant band ($f_s \neq f_n$) cause reduced oscillation amplitudes, weaker electromechanical coupling utilization, and a measurable decline in harvested power and conversion efficiency [19]. To alleviate this limitation, recent studies have proposed strategies to broaden the effective resonance bandwidth (or to shift resonance in real time), including the implementation of magnetorheological elastomers (MREs) with field-dependent stiffness. By modulating the shear modulus and effective stiffness through an applied magnetic field, MRE-based elements enable adaptive tuning of $f_n$and, consequently, improve frequency tracking relative to the variable excitation spectrum imposed by fluctuating wind conditions [14].

Experimental and modeling investigations indicate that magnetic-field-controlled stiffness variation can enhance energy capture by maintaining operation closer to the lock-in region over a wider range of wind speeds, thereby increasing average power output and reducing yield volatility. Beyond purely energetic metrics, such adaptive systems support decarbonization objectives by enabling distributed, low-maintenance renewable generation suitable for applications with stringent reliability constraints and limited servicing access, such as remote environmental sensing platforms and industrial automation nodes. Accordingly, VIV-based bladeless architectures-particularly when combined with adaptive tuning, are increasingly positioned as enabling technologies within broader renewable energy transition pathways [12], [14], [18].

Reported performance figures in the literature further underscore the potential of the concept under optimized conditions. For example, an overall conversion efficiency of 82.7% has been documented for a specific operating point, corresponding to 1.438 W electrical output from 1.739 W extracted mechanical power. Such performance is typically attributed to the simplified mechanical architecture, characterized by the elimination of rotating gear trains and reduced parasitic drivetrain losses, suggesting that, with appropriate scaling and array-level design, bladeless VIV systems may offer a viable route toward higher-capacity implementations in future wind energy deployments [19].

2.2 *Passive wind turbine system*

Passive wind turbine technology has recently attracted increased attention as a non-conventional wind-harvesting paradigm, primarily because it is engineered to exploit built-in aerodynamic guidance rather than active yaw control or large-scale rotor orientation. In these architectures, the energy conversion unit is typically embedded within a stationary housing, and the system's ability to intercept and process the incoming flow is governed by the geometry of the intake, diffuser, and flow-acceleration features. The elimination of externally exposed rotating components substantially reduces tonal aerodynamic noise, mitigates vibration transmission to supporting structures, and decreases susceptibility to wear mechanisms associated with bearings, pitch systems, and yaw drives. As a result, passive wind concepts are frequently positioned as low-maintenance, low-disturbance solutions with reduced environmental footprint and limited wildlife interaction risk relative to open-rotor configurations [22], [23], [24], [25].

A defining aerodynamic mechanism enabling these devices is the Venturi effect, which arises when a fluid is forced through a locally constricted cross-section. In practical passive wind designs, the contraction is realized by two optimally contoured aerodynamic profiles (or guide-vanes/airfoils) that shape a converging passage. Under quasi-steady conditions, conservation of mass and Bernoulli-type arguments imply that the mean flow velocity increases in the throat region while the static pressure decreases, thereby establishing a pressure-driven entrainment that draws additional air from the lateral boundaries of the channel. This induced suction effectively increases the volumetric flow rate through the energy conversion core beyond what would be captured by the rotor's frontal area alone, thereby raising the available aerodynamic power flux delivered to the generator stage. The conversion unit typically consists of a small-diameter rotor placed within a duct connected to (or coincident with) the throat region, where the accelerated flow produces higher local dynamic pressure and improved rotor loading. Consequently, the wind's kinetic energy is converted into mechanical shaft power and subsequently into electrical power via an integrated generator, with overall performance strongly dependent on contraction ratio, loss coefficients, inlet turbulence intensity, and duct/rotor matching (i.e., the coupling between accelerated flow conditions and rotor aerodynamic characteristics) [22], [23], [24], [25], [26].

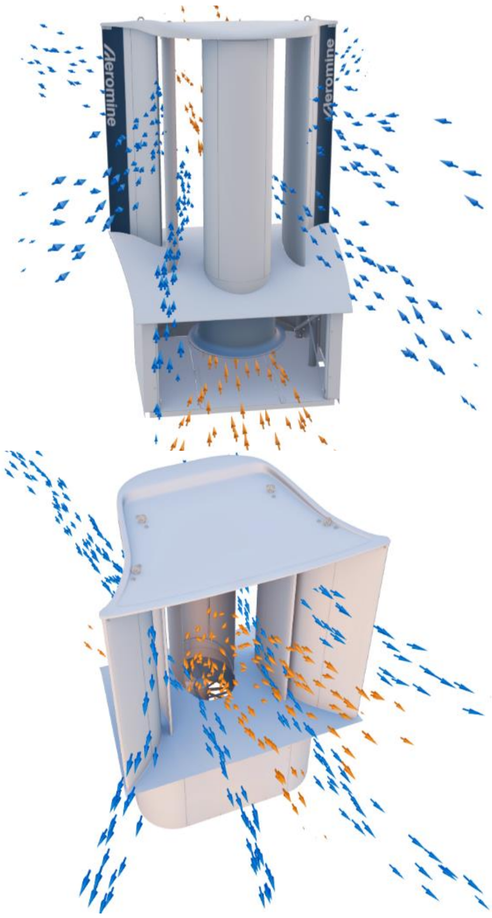

Figure 3 Concept of the Aeromine passive wind turbine system [24]

The Aeromine concept leverages a building-integrated aerodynamic flow-conditioning architecture intended to intensify and redirect the near-building wind field toward a compact power take-off unit. The system employs contoured airfoil-like fins and guide elements that impose a controlled redistribution of static pressure around the device, thereby establishing a sustained pressure gradient between the intake and the discharge region. This pressure differential drives an accelerated through-flow along a defined intake pathway and delivers conditioned airflow to an internally enclosed energy conversion stage. From an aerodynamic standpoint, the device functions as a localized flow concentrator in which geometric contraction, guided turning, and pressure recovery are exploited to increase the effective mass flow rate through the conversion core relative to the ambient free-stream, with system performance governed by local boundary-layer behavior, turbulence intensity, and rooftop/edge flow separation phenomena [22], [23], [24], [25].

The electromechanical module typically incorporates a permanent-magnet generator (PMG) integrated within a sealed enclosure. Hermetic sealing reduces ingress of particulates, moisture, and saline aerosols (relevant for coastal installations), while passive thermal management (conduction to the housing and natural/forced convection to ambient air) supports long-duration operation without active cooling hardware. These design choices reduce failure susceptibility and extend service intervals by minimizing exposure of critical components to weathering and contamination. In certain implementations, the system is engineered to provide an AC output compatible with direct coupling to the building's electrical distribution architecture, thereby reducing balance-of-system complexity. Specifically, inverter-less operation can be achieved when the generator topology and power-conditioning strategy (e.g., grid-synchronous generation or integrated conversion within the machine electronics) are configured to meet voltage/frequency requirements, which can lower conversion losses and decrease installation and operational expenditures [22], [23], [24], [25].

Figure 4 Installation of the Aeromine passive wind turbine system on a building [24]

From an integration perspective, the device's vertically oriented, compact form factor is advantageous for deployment in urban and peri-urban environments where strict spatial constraints, setback requirements, and acoustic/environmental regulations often limit the feasibility of conventional open-rotor turbines. By concentrating the energy conversion components within a building-mounted enclosure and avoiding large exposed rotors, such systems can reduce visual impact, mitigate noise concerns, and simplify permitting pathways, thereby expanding the addressable application space for wind-derived generation in densely built settings [22], [23], [24], [25].

Aeromine-type systems are also well suited for hybrid renewable configurations, particularly in combination with rooftop photovoltaic (PV) arrays. The complementarity between wind and solar resource availability, driven by diurnal thermal gradients, seasonal weather patterns, and synoptic variability, can improve aggregate generation smoothness and increase the effective utilization of on-site electrical infrastructure. In practice, co-located wind–PV architectures can reduce reliance on grid imports during non-overlapping resource periods, improve self-consumption ratios, and support peak-shaving strategies, thereby enhancing both techno-economic performance and operational resilience [22], [23], [24], [25].

More broadly, the Aeromine approach aligns with sustainability-driven energy strategies by enabling distributed renewable generation that can be retrofitted into existing building stock and integrated into established electrical infrastructures with comparatively low additional balance-of-system burden. As regulatory and environmental constraints become increasingly stringent, building-integrated passive wind solutions provide a pragmatic pathway toward cleaner electricity supply, reduced operational carbon intensity, and improved energy autonomy at the building or campus scale [22], [23], [24], [25].

2.3 Modular multi-rotor wind energy system

Modular multi-rotor wind energy systems constitute an emerging alternative to conventional single-rotor, utility-scale turbines by adopting a distributed-rotor architecture in which multiple small or medium turbines are integrated into a coordinated array mounted on a common, typically vertical, support structure. The underlying design rationale is to increase the effective rotor-swept capture through modularity while mitigating well-known constraints of large-rotor platforms, including high yaw-system duty cycles under veering winds, elevated installation complexity, and the pronounced maintenance burden associated with large drive-train components and offshore logistics [27], [28], [29], [30], [31].

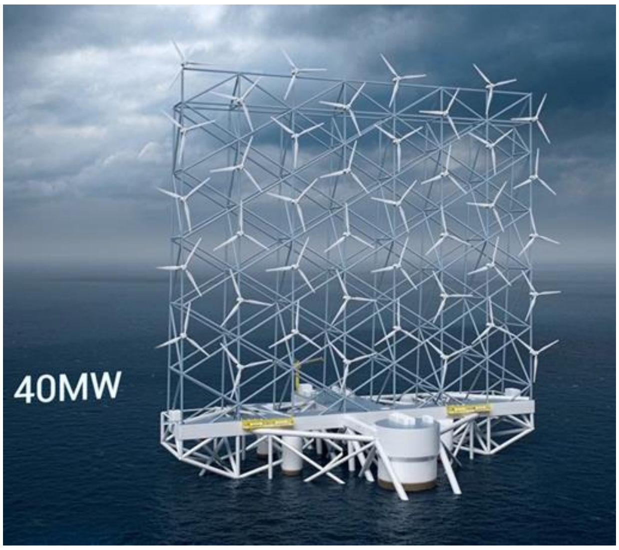

Figure 5 Modular multi-rotor wind system [30]

A principal technological advantage of this concept is its improved directional robustness. By distributing several rotors across a fixed frame and exploiting spatially varying inflow conditions, the system reduces dependence on continuous active yawing and can maintain energy extraction over a broader range of wind directions. In effect, the array behaves as a multi-aperture collector whose aggregate performance is less sensitive to instantaneous wind-direction fluctuations, thereby improving operational stability and resilience under non-stationary meteorological forcing (gusts, shear, turbulence intensity variations, and mesoscale directional shifts) [27], [28], [29], [30], [31].

From a structural–aerodynamic standpoint, modular multi-rotor configurations also enable a more favorable load partitioning relative to a single large rotor. Mechanical and aerodynamic loads are distributed among multiple units and transferred through the support structure as a superposition of smaller contributions, potentially reducing peak bending moments and allowing refined control of fatigue damage accumulation through redundancy and modular operation. Additionally, the distributed layout can improve wind-resource utilization by enabling design strategies that manage wake interactions at smaller spatial scales, with the possibility of tailoring rotor spacing and vertical placement to local shear profiles and turbulence structures. These attributes can support energy yields comparable to-or, in certain deployments, exceeding, those of a single large turbine, while reducing the overall environmental footprint through lower visual impact, potentially reduced wildlife interaction risk, and improved siting flexibility [27], [28], [29], [30], [31].

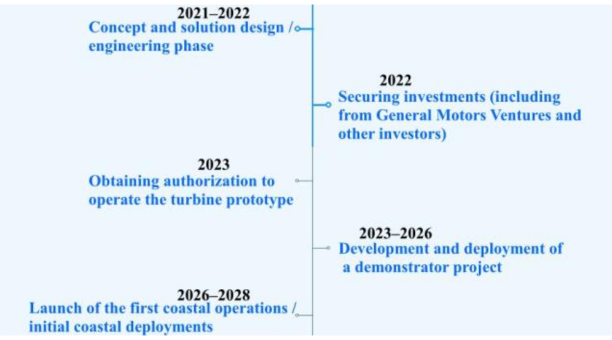

Figure 6 Project stages for the development of modular multi-rotor wind systems [30]

A further differentiator is the potential reduction in operations and maintenance (O&M) costs. Since aerodynamic loading and drivetrain torque are shared across multiple rotors, individual components experience lower extreme load events and may exhibit reduced wear rates, thereby extending service life and improving reliability. The modularity of the system can also enhance maintainability by enabling unit-level replacement (swap-out of a turbine module rather than major on-site overhaul), reducing downtime and limiting the scope of unplanned interventions-an especially relevant advantage for offshore/coastal installations where access windows are constrained and maintenance costs dominate life-cycle expenditure [27], [28], [29], [30], [31]. Over the project horizon, these effects translate into improved availability, reduced corrective maintenance frequency, and lower total operating costs.

Overall, modular multi-rotor systems represent a meaningful step in the evolution of wind-energy conversion technology by introducing a flexible, scalable design space that can reshape wind-farm engineering-particularly for offshore and coastal deployments where logistics, reliability, and structural scaling constraints are critical. By combining potential gains in annual energy production with reduced O&M intensity and improved environmental compatibility, this approach aligns with the broader objective of accelerating the transition toward cost-effective, low-carbon electricity generation [27], [28], [29], [30], [31].

3. INNOVATIVE PV TECH CONCEPTS

3.1 *Bifacial photovoltaic systems*

Bifacial photovoltaic (PV) modules differ fundamentally from monofacial architectures through the incorporation of optically transmissive rear encapsulation (e.g., glass–glass or transparent backsheet configurations), which enables photoactive conversion on both the front (direct-facing) and rear (ground-facing) surfaces. By activating the rear-side junctions, bifacial devices can convert not only the plane-of-array (POA) direct component but also a significant fraction of the

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diffuse sky irradiance and the albedo-driven reflected component originating from the surrounding environment (ground cover, roof membranes, façade elements, and adjacent structures). Consequently, the energy yield of bifacial modules typically exceeds that of monofacial counterparts under identical front-side irradiance conditions, with the incremental gain governed by the rear irradiance ratio, spectral distribution, view factors, and array geometry. When deployed on single- or dual-axis trackers, bifacial configurations can exhibit substantial yield enhancements, commonly reported in the range of ~35–40% relative to fixed-tilt monofacial baselines, owing to increased POA irradiance capture and improved rear-side exposure over the diurnal cycle [32], [33], [34], [35], [36], [37], [38], [39].

Figure 7 Bifacial photovoltaic systems

The performance advantage of bifacial PV is further amplified in high-albedo settings (e.g., snow-covered terrain, bright sand, light-colored gravel) or when engineered reflective surfaces are introduced to increase effective ground reflectance. Under such boundary conditions, rear-side irradiance can become a non-negligible contributor to the total collected photon flux, thereby improving specific yield (kWh/kWp) and enhancing project-level economics in large-scale plants. These attributes render bifacial technology particularly attractive for utility-scale installations, where small percentage improvements in annual energy production translate into meaningful reductions in levelized cost of electricity (LCOE) and accelerated payback periods [32], [33], [34], [36], [40]

Beyond yield improvements, bifacial systems introduce additional degrees of freedom in site design and layout optimization. Parameters such as module elevation, row spacing, tilt, and the selection of ground treatment (e.g., reflective coatings, membranes, or optimized ballast layouts) can be tuned to manage the rear irradiance field and mitigate self-shading. This flexibility is especially relevant for commercial and industrial rooftop deployments, where geometric constraints and shading from parapets or rooftop equipment can be addressed through optimized placement and structural integration. As a result, bifacial configurations provide a credible pathway to maximize energy harvest within a limited footprint while improving the sustainability metrics and techno-economic viability of PV projects [32], [33], [35], [37]

Despite these advantages, bifacial PV systems still face non-trivial technical challenges. Key issues include (i) minimizing electrical mismatch and power losses induced by partial shading (row-to-row shading, structural shading from mounts and clamp zones, and transient shading from nearby objects), (ii) accurately quantifying rear-side irradiance under complex, time-varying boundary conditions, and (iii) developing reliable energy-yield models that capture anisotropic diffuse irradiance, spectral effects, and geometry-dependent view factors. In practice, uncertainty in rear irradiance modeling can propagate into yield prediction errors, affecting bankability and system sizing. Nevertheless, continuous progress in bifacial performance characterization, standardized measurement protocols, advanced ray-tracing/thermal-electrical co-simulation frameworks, and field validation campaigns is consolidating bifacial modules as a cornerstone technology for next-generation PV deployment and the broader transition toward low-carbon energy systems [32], [40], [41].

3.2 Transparent photovoltaic panels (TPV)

Transparent photovoltaic (TPV) panels show substantial potential across multiple application domains, particularly in the built environment and in agricultural systems. In agricultural settings, TPV modules can deliver low-emission electricity generation while simultaneously providing partial shelter for crops against adverse weather (e.g., heavy rainfall) and certain pest pressures, and they may also support covered areas intended for post-harvest handling or grain storage. As urban agriculture expands, the development and deployment of advanced technologies have become increasingly important; however, technology integration can also increase on-site energy demand. In this context, agrivoltaic systems, which co-locate crop cultivation and photovoltaic power generation on the same land footprint, have demonstrated the capability to improve both plant biomass productivity and electrical energy yield when appropriately designed and managed [42], [43], [44], [45].

A promising TPV approach employs transparent luminescent solar concentrator (TLSC) technology, in which the device selectively absorbs ultraviolet and infrared components of the solar spectrum and converts them into electricity while maintaining visible-light transmission. Using an indium–tin oxide (ITO) functional layer together with silver electrodes, such devices have been reported to achieve power conversion efficiencies up to 10.8% with an average optical transmittance of 45.8%, indicating a practical trade-off between energy harvesting and transparency for integrated applications [46].

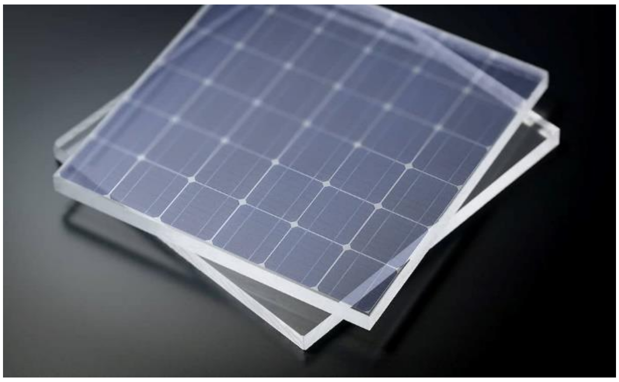

Figure 8 Transparent photovoltaic (TPV) panel

Transparent solar panel technology constitutes a notable advance in renewable energy engineering, providing an efficient and architecturally appealing pathway for solar harvesting in urban environments. These devices can be integrated into window assemblies and other glazed building envelopes, enabling high transmission of visible light while selectively absorbing portions of the solar spectrum to generate electricity, thereby maintaining indoor daylighting performance while delivering on-site power generation [43], [45], [46].

A further critical contribution of transparent PV systems lies in their potential to improve building energy performance. By modulating solar radiation entering the interior space, such glazing-integrated devices can reduce cooling loads and, consequently, lower operational energy costs and associated carbon emissions. In addition, the technology expands design flexibility for sustainable infrastructure, as it can be adapted to a wide range of architectural typologies and urban design constraints [43], [46].

4. CONCLUSIONS

IRENA capacity statistics confirm a structural shift in global renewable deployment toward converter-interfaced variable renewable energy (VRE), with solar PV and wind jointly dominating net additions in 2024; consequently, future decarbonization trajectories will be disproportionately governed by the performance, cost, and grid-integration capabilities of PV and WECS, centric technology pathways.

The examined non-conventional wind-harvesting architectures, vortex-induced vibration (VIV) bladeless systems, passive/ducted building-integrated concepts, and modular multi-rotor arrays, collectively target the principal limitations of conventional large-rotor turbines (O&M intensity, noise, wildlife impact, siting constraints, and directional sensitivity) through simplification of drivetrain topology, flow-conditioning-driven capture, and distributed load partitioning.

For VIV-based bladeless harvesters, the fundamental bottleneck remains resonance dependence (lock-in bandwidth), implying that practical scalability under non-stationary atmospheric forcing is contingent upon adaptive tuning strategies (e.g., magnetorheological elastomers) capable of real-time natural-frequency modulation and sustained electromechanical coupling under variable inflow spectra.

Passive wind systems leveraging Venturi-driven flow acceleration and pressure-gradient entrainment indicate a viable route for urban/peri-urban wind utilization, where compact form factors and enclosed power take-off modules can reduce acoustic emissions and mechanical wear while enabling integration into existing building electrical infrastructures and hybrid rooftop PV-wind configurations.

Distributed multi-rotor wind architectures introduce a scalable design space in which rotor modularity and redundancy can enhance availability and maintainability, while structural load redistribution and reduced yaw dependency can improve robustness to veering winds and turbulence, attributes that are particularly relevant for offshore/coastal deployments with constrained maintenance access windows.

On the PV side, bifacial module technology provides a high-leverage pathway for increasing specific yield (kWh/kWp) by harvesting rear-side irradiance components (diffuse and albedo-reflected), but bankable performance gains remain tightly coupled to accurate rear-irradiance modeling, mismatch-loss mitigation under partial shading, and geometry-dependent view-factor characterization.

Transparent photovoltaic (TPV) and TLSC-based devices extend PV functionality beyond conventional energy-only modules by enabling envelope-integrated generation and agrivoltaic co-utilization, where the key techno-physical trade-off is governed by the coupled optimization of spectral selectivity, optical transmittance, and power conversion efficiency under application-specific constraints.

Overall, the combined evidence supports the conclusion that near-term renewable scale-up will be maximized by accelerating innovation in PV module architectures and wind-conversion topologies that simultaneously improve energy yield, reduce life-cycle cost, and enhance deployment feasibility under spatial, environmental, and grid-operational constraints, thereby aligning technology development priorities with observed global capacity-growth dynamics.

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