Optimisation of Photovoltaic Systems for Different Applications

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Executive Summary

Photovoltaic (PV) deployment is entering a new phase of diversification. Ground-mounted systems have driven the rapid global expansion of solar power, but future growth will also increasingly rely on solutions that integrate electricity generation into existing infrastructure and land use. These include building-integrated photovoltaics (BIPV), floating photovoltaics (FPV), and agrivoltaics (AV), which address land competition while also supporting urban decarbonization, enabling water–energy synergies, and advancing sustainable agricultural production. However, these applications differ fundamentally from conventional PV installations. They operate in complex environments, perform multiple functions, and involve a broader range of stakeholders, including architects, farmers, water authorities, and local communities. Consequently, traditional PV design approaches developed primarily for ground-mounted systems are no longer sufficient.

A previous IEA PVPS Task 13 report assessed the influence of climate on PV performance and reliability. The present report expands this perspective by showing that the application context has become an equally important design driver. Integrated PV systems must simultaneously ensure reliable electricity generation, compatibility with buildings, water bodies or agricultural activities, long service lifetimes with predictable financial performance, and environmental and social acceptance. Meeting these requirements necessitates a shift from single-metric optimisation, primarily focused on energy yield and cost, to a multidimensional performance framework.

In this context, integrated PV systems should be understood as multifunctional infrastructure rather than stand-alone energy assets. Their evaluation, therefore, extends, as shown in Table 1, beyond traditional indicators such as performance ratio or levelised cost of electricity. Key performance indicators for these applications can include, for example, energy yield per avail-able area, self-consumption and dual-use value creation. Furthermore, environmental interactions with surrounding systems, as well as durability, safety and public acceptance should also be considered depending on the type of integration.

Table 1: Application-specific key performance indicators (KPI) compared to ground-mounted PV (GPV)

KPI Layer	GPV	BIPV	FPV	AV
Energy	Energy yield/ Performance ratio	Area-specific yield	Floating-condition yield	Land-use efficiency
Economic	LCOE/ CAPEX-OPEX optimisation	Self-consumption	Mooring and anchoring costs	Dual-use revenue
Environmental	GHG emission/ land impact	Building decarbonisation	Water/fauna interaction	Land productivity
Social	Public acceptance/ land-use	Architectural acceptance	Visual acceptance	Farmer acceptance

Furthermore, this report shows that applying conventional PV design assumptions to integrated systems can lead to significant inaccuracies. Compared with ground-mounted installations, integrated PV systems experience modified thermal behaviour and heat transfer, heterogeneous and dynamic irradiance conditions, additional mechanical and environmental stressors, and distinct degradation pathways and performance loss rates. Without adapting components, design and modelling approaches, these differences can result in higher degradation rates, inaccurate energy yield predictions, underestimated risks, and sub-optimal component selections.

In particular, the report examines the specific technical challenges associated with three main applications. BIPV systems must fulfil the dual function of electricity generator and building component, requiring compliance with structural and fire-safety requirements while addressing restricted ventilation and frequent partial shading. FPV systems operate in water-based environments characterised by high humidity, corrosion risk, biofouling, and dynamic mechanical loads from wind and waves, with thermal behaviour strongly influenced by platform design and environmental exposure. AV systems must balance electricity production with agricultural productivity, requiring system geometries and operating strategies that accommodate crop requirements while addressing shading, soiling, and interactions with farming activities. Across all applications, configuration-specific design choices are shown to strongly influence performance and degradation behaviour.

Table 2 provides an overview of the main climate-specific and integration-induced stressors affecting PV systems, the associated failure modes, and corresponding mitigation strategies discussed in this and the previous report. The table highlights how traditional climate risks, such as low temperatures, thermal cycling, high operating temperatures, UV exposure, humidity and soiling, interact with additional stressors introduced by BIPV, FPV, and AV applications. By mapping each stressor across climate zones and application types, the table illustrates that integrated PV systems face a broader and more complex risk landscape than conventional ground-mounted installations. It also summarises key mitigation measures, emphasising the need for application-specific material selection, system design, and operational strategies to ensure long-term reliability and performance.
A key contribution of the report is also the evaluation of existing standards, including IEC 61853 energy-rating methodologies, in the context of integrated PV. Limitations of current testing and modelling approaches are identified, highlighting the need for representative mounting conditions, improved thermal modelling, enhanced understanding of application-specific degradation, and expanded field data from dedicated benchmarking facilities. These findings provide a foundation for future research and standardisation.

The report translates these insights into practical guidance covering site assessment, component and material selection, system design and layout optimisation, and monitoring and operational strategies. Integrating application-specific considerations from the earliest stages of project development can reduce technical and financial risks while improving long-term performance and reliability.

Table 2: Application-specific stressors, failures and mitigation measures.

Stressors	Failures	Climate-specific risk level			Integration-induced risk level			Mitigation Measures
		Cold & Snow	Hot & Arid	Hot & Humid	BIPV	FPV	AV	
Low temperatures	Embrittlement of materials, cracking of encapsulant and solder joints	high	-	-	-	-	-	Use of flexible encapsulants and back sheets
Extreme temperature fluctuations	Thermal cycling cracks (solder joints, inter-connections, cells)	low-medium	low-medium	low-medium	medium	-	-	Use thermally stable materials, reinforced interconnections
High Operating Temperatures	Encapsulant degradation, delamination, discolouration	-	high	medium	medium (facades)-high (roofs)	low	-	Optimised ventilation, high-temperature-resistant encapsulants BIPV: rear ventilation, FPV: passive cooling
Mechanical Stress	Glass breakage, frame deformation, cell cracks, (severe) power loss	high (snow load)	high	-	high (roof maintenance)	igh (waves, anchoring, ice, maintenance)	medium-high (wind)	Strengthened module frames, thicker or reinforced glass, special coatings, smart tracking (for wind or snow) FPV: reinforced mounting and anchoring systems AV: intelligent tracking
Salt Mist /Chemical exposure	Corrosion, electrical insulation failure	-	high (coastal)	high (coastal)	-	High (salt water)	medium-high (fertilizers and pesticides)	Anti-corrosion coatings, PID-resistant materials, sealed junction boxes FPV: Anti-corrosion materials and coatings
UV Exposure	Backsheet cracking, encapsulant yellowing, loss of adhesion	low-medium (high altitude)	high	low-medium	medium	-	-	UV-resistant backsheet and encapsulant materials
Moisture Ingress & Humidity	Corrosion (junction box, interconnections), delamination	low-medium (frost)	-	high	-	High	medium-high (agricultural environment)	Edge sealants, high-barrier backsheet, improved lamination techniques FPV: hydrophobic encapsulants
Soiling	Power loss, surface degradation, hot spots	high (snow load)	high (dust, sand)	high (biofilm, animal dirt)	low (facade)-medium (roofs)	High (mainly bird dropping)	high	Frameless modules, self-cleaning coatings, scheduled cleaning, tilted installation to minimise accumulation of snow or dust FPV: anti-biofouling surface treatments, AV: vertical modules, robots, tractor implements, and irrigation systems
Light transmission or quality	BIPV: reduced indoor daylight, visual discomfort, overheating of indoor spaces; AV: insufficient/inadequate light for plants; FPV: reduced light penetration in water	-	-	-	high (opaque facades or glazing)	High (opaque floating structures)	high	Semi-transparent or spectrally selective modules light modelling during design FPV/AV: Optimised spacing and layout optimisation, BIPV: solar heat gain optimisation, seasonal optimisation studies
Stone impact stress	Glass breakage, cell cracks	-	-	-	-	-	medium-high (machineries)	Reinforced PV modules with thicker glass for enhanced durability, longevity and structural strength
Shading by surrounding	Power loss, hot-spots, bypass diode failure, glass breakage	-	-	-	high	Low	high (vegetation)	Bypass segmentation or back-contact cells, module-level power electronics AV: optimised layouts and mounting heights, adaptive tracking strategies
Animals	cable/connector damage, shading	-	-	-		medium	high	AV: Fencing mechanisms such as electric fencing to prevent large animals from approaching too close to the system
Fire	Catastrophic failure of system	-	-	-	high	-	-	BIPV: Fire resistant/retardant materials
Noise	Noise transmission, low acoustic comfort in building	-	-	-	medium	-	-	BIPV: acoustic insulation layer

Key Takeaways

- New integrated PV applications such as BIPV, FPV and AV are becoming new drivers for future PV growth, enabling energy generation within buildings, water bodies, and agricultural land while addressing land-use and sustainability challenges;
- The application context requires a shift from conventional optimisation based only on energy yield and cost toward a multidimensional framework including reliability, durability, environmental impact, and social acceptance;
- Integrated PV systems experience new operating conditions and stressors — including modified thermal behaviour, partial shading, humidity, corrosion, biofouling, and mechanical loads — making conventional ground-mounted PV design assumptions insufficient;
- Application-specific design, modelling, materials, standards, and operational strategies are essential to improve long-term performance, reliability, and risk assessment for BIPV, FPV, and AV systems.