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Task 13 Reliability and Performance of Photovoltaic Systems

PVPS

Optimisation of Photovoltaic Systems for Different Applications

2026

Report IEA-PVPS T13-39:2026

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The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCPs within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." To achieve this, the Programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas.

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What is IEA PVPS Task 13?

The objective of Task 13 of the IEA Photovoltaic Power Systems Programme is to provide support to market actors working to improve the operation, the reliability and the quality of PV components and systems. Operational data from PV systems in different climate zones compiled within the project will help provide the basis for estimates of the current situation regarding PV reliability and performance.

The general setting of Task 13 provides a common platform to summarise and report on technical aspects affecting the quality, performance, reliability and lifetime of PV systems in a wide variety of environments and applications. By working together across national boundaries, we can all take advantage of research and experience from each member country and combine and integrate this knowledge into valuable summaries of best practices and methods for ensuring PV systems perform at their optimum and continue to provide competitive return on investment.

Task 13 has so far managed to create the right framework for the calculations of various parameters that can give an indication of the quality of PV components and systems. The framework is now there and can be used by the industry who has expressed appreciation towards the results included in the high-quality reports.

The IEA PVPS countries participating in Task 13 are Australia, Austria, Belgium, Canada, Chile, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, the Netherlands, Norway, Spain, Sweden, Switzerland, Thailand, and the United States of America, and the Solar Energy Research Institute of Singapore.

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COVER PICTURE

(top-left) Agrivoltaic system with tractor between module rows, source: Aarhus University, Department of Agroecology, and European Energy A/S, (top-right) BIPV Façade, underground station Floridsdorf, Vienna, Austria; Project by Wiener Linien GmbH & Co KG Wien Energie GmbH, source: OFI/Gabriele Eder, (bottom-left) Ground mounted PV system located in Albuquerque US, source: Sandia/Laurie Burnham, (bottom right) Floating PV system in Leimersheim Gravellake, Germany; Project by Erdgas Südwest GmbH, source: Sapienza/Leonardo Micheli.

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PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

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IEA PVPS
Task 13
Reliability and Performance
of Photovoltaic Systems

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LIST OF ABBREVIATIONS

AC	Alternating Current
AV	Agrivoltaics
BAPV	Building-Applied Photovoltaics
BEPI	Baseline Energy Performance Index
BIPV	Building-Integrated Photovoltaics
BOM	Bill of Materials
CAPEX	Capital Expenditure
CSER	Climate-Specific Energy Rating
DC	Direct Current
DNI	Direct Normal Irradiance
EEI	Energy Efficiency Index
EEIM	Energy Efficiency Index of Module
EPI	Energy Performance Index
ER	Energy Rating
FPV	Floating Photovoltaics
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiance
G_{POA}	Global Plane of Array Irradiance
GPV	Ground-mounted Photovoltaics
H_{DH}	Diffuse Irradiance
H_{HZ}	Diffuse Horizontal Irradiance
IAM	Incidence Angle Modifier
IEC	International Electrotechnical Commission
IEA	International Energy Agency
KPI	Key Performance Indicator
LCOE	Levelised Cost of Electricity
NMOT	Nominal Module Operating Temperature
OECD	Organisation for Economic Co-operation and Development
OPEX	Operational Expenditure
PAR	Photosynthetically Active Radiation
PID	Potential-Induced Degradation
PLR	Performance Loss Rate
PR	Performance Ratio
PVPS	Photovoltaic Power Systems Programme
Rd	Degradation Rate
SAM	System Advisor Model

SEPA	Smart Electric Power Alliance
STC	Standard Test Conditions
TMY	Typical Meteorological Year
U_0 / U_1	Heat transfer coefficients used in PV thermal modelling

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 available 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 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 (façades)-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)	high (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 (façade)-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;	-	-	-	high (opaque façades 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

	FPV: reduced light penetration in water								
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

1 INTRODUCTION

Over the past decade, the rapid global deployment of photovoltaic (PV) systems has continued to diversify, combining electricity generation with other essential functions. **Building integrated PV (BIPV)** elements act simultaneously as structural, weatherproofing, insulation layers, and/or façade and roofing materials. **Floating PV (FPV)** installations, mounted on or above water surfaces, alleviate land-use pressure and can also help reduce water evaporation. In **agrivoltaic (AV) systems**, PV structures provide shading and microclimate regulation for crops, allowing a combined production of electricity and agricultural products. This multifunctionality is a defining characteristic of integrated PV and a key reason behind its growing relevance, not only in spatially constrained or sustainability-focused environments.

While BIPV is technologically mature and commercially established in European countries such as Italy, France and Switzerland, it still represents a small share of total PV capacity, primarily concentrated in high-value building projects. FPV and AV, by contrast, remain early commercial segments, with Europe contributing mainly pilot-to-early-scale projects, whereas Asia leads global deployment in both fields. Overall, these three application areas are rapidly evolving but still account each for less than 1% of global PV capacity.

As the technological scope of PV systems broadens, understanding the interactions between application-specific stressors and system performance becomes essential. Factors such as restricted rear ventilation in BIPV façades, wave-induced motion and humidity in FPV installations, or heterogeneous irradiance and microclimates in AV systems can substantially influence energy yield, module lifetime, and operational risks. Tailoring system design to these conditions is therefore critical to ensuring reliable, safe, and cost-effective operation throughout a PV system's lifetime. The need for such application-specific optimisation is further reinforced by growing evidence of distinct performance loss rates and degradation pathways associated with integrated PV solutions.

For this reason, building on the findings of the preceding report *Optimisation of Photovoltaic Systems for Different Climates* [1], this document expands the focus from climate-driven to application-specific integration challenges. The former report examined how climatic stressors influence PV performance, while the present one addresses how environmental and functional requirements shape module and system design, and how the performance and reliability of integrated PV systems can be optimised. These two reports complement the previously published IEA PVPS reports on BIPV [2], FPV [3] and AV [4].

In conclusion, this report aims to provide comprehensive guidance and a structured overview of current strategies for optimising PV module and system design across three key PV integration examples: BIPV, FPV, and AV.

Chapter 2 introduces the concept of application-specific module energy yield and discusses methodologies for evaluating module performance under different integration contexts. It also highlights the relevance of **application-specific energy ratings and performance loss rates** when selecting the most suitable module technologies.

Chapters 3 to 5 form the core of this report. Each chapter focuses on a specific application area and begins with an overview of typical operating conditions and stressors, outlining how they can influence long-term performance and reliability. Mitigation measures and optimisation strategies are then presented, covering all phases of a project, from site assessment to component selection, system layout, and operational practices. Effective site assessment and component selection are fundamental to reducing operational risks. Understanding the magnitude and impact of **climate and application-specific stressors** enables designers and investors to implement appropriate **mitigation measures** early in the development process. These strategies include the careful choice of module architecture, consideration of thermal and mechanical behaviour, selection of appropriate mounting solutions, and the implementation of application-tailored monitoring approaches. Integrating such measures from the outset ensures more reliable performance, extended module lifetimes, and improved financial predictability.

Each chapter concludes with two **case studies** illustrating how system design can be successfully adapted to the characteristics of the local environment and application-specific needs.

2 APPLICATION-SPECIFIC MODULE ENERGY YIELD

As outlined in the "Optimisation of Photovoltaic Systems for Different Climates" report [1], a key step in the design phase of a photovoltaic (PV) system is the selection of the PV module technology in relation to the expected energy yield. The previous report provided guidance on identifying the module type or technology with the highest theoretical annual and lifetime energy yields for a given climate. Several approaches were discussed, including the standardised IEC 61853 energy rating methodology, energy yield simulations, and the use of field performance data.

In the present report, the focus shifts to integrated PV applications - specifically building-integrated photovoltaics (BIPV), floating photovoltaics (FPV), and agrivoltaic (AV) systems. The applicability of the yield assessment approaches to integrated PV modules is therefore examined, and the current state of the art is presented. At the end of this chapter, an overview of existing test facilities performing technology benchmarking of integrated PV technologies is reported.

2.1 Application-Specific Module Energy Rating (ER)

2.1.1 Introduction to IEC 61853 Energy Rating

The current energy rating standard IEC 61853, originally developed for field-mounted PV systems and applicable to monofacial PV cell and module technologies, provides a robust methodology for evaluating module performance across different climates. An extension of the standard is planned in a forthcoming revision to include bifacial modules and is expected to further enhance its applicability and relevance [5].

The standard defines a **climatic specific energy rating (CSER)**, a theoretical KPI corresponding to the module performance ratio, which compares the annual energy yield of different modules:

$$CSER = \frac{EY_{M(DC)Y1} \cdot G_{ref}}{P_{max,stc} \cdot H_p} \qquad (1)$$

where $EY_{M(DC)Y1}$ is the estimated energy yield for one module over the first year of operation (kWh), G_{ref} is the irradiance under Standard Test Conditions (STC) corresponding to 1000 W/m^2, $P_{max,STC}$ is the module's power output under STC in W and H_p is the total yearly in-plane irradiation provided in Part 4 of the standard series (kWh/m^2).

The energy yield $EY_{M(DC)Y1}$ estimation is based on: (1) a set of well-defined laboratory measurements [6,7], (2) a set of six climatic profiles (i.e., tropical humid, subtropical arid, subtropical coastal, temperate coastal, temperate continental, and high elevation) [8] and (3) a set of standardised equations to be used for the calculation of the yield [9]. The ratio between the calculated annual energy yield and the module area is defined as the **energy efficiency index (EEI_M in kWh/m^2)**, a metric proposed as a KPI for a new European Energy Label for PV modules [10].

The energy rating standard, according to IEC 61215 (Clause 5), does not account for degradation or transient behaviour that occurs in the field after stabilisation. More details about the energy rating standard and its implementation into a European Energy Label can be found in the previous report [1].

2.1.2 Applicability of IEC 61853 to Integrated PV Modules

For integrated PV solutions, where available space is limited by building or land constraints, or where mounting costs represent a significant share of the total system investment, the Energy Efficiency Index (*EEI*) becomes the most relevant KPI. This indicator is particularly important when comparing products that must meet specific requirements, such as aesthetic considerations (e.g., colour constraints) or light transmission properties (e.g., for agricultural applications or daylighting needs in buildings).

Despite the inherent complexity of integrated PV systems, the proposed IEC 61853 standard can, with appropriate considerations, support the selection of the most suitable module technology for integrated PV applications. Its comprehensive evaluation framework enables comparative assessments within the same family, guides adaptations in product development, and enhances the reliability of performance predictions.

In general, the translation of real operating conditions into standard reference conditions for energy rating purposes must balance two key aspects: on one hand, the conditions should be specific enough to distinguish between different product families; on the other hand, they must remain sufficiently simple and accurate to ensure high reproducibility of measurements at a reasonable cost for customers. Consequently, it is essential to focus on the conditions that have the greatest impact on the relative energy yield. In integrated PV systems, factors such as non-optimal module orientation, varying thermal operating conditions, and differences in spectral distribution can significantly influence the benchmarking.

The following sections outline the specific considerations for each application, along with ongoing efforts and additional measures required to further adapt and enhance the standard to meet the distinct needs of BIPV, FPV, and AV systems.

Building-Integrated/Applied Photovoltaics (BIPV/BAPV)

Among the three integrated PV solutions discussed in this report, BIPV is the only one explicitly addressed in both the current and revised versions of the IEC 61853 standard.

PV modules installed on buildings, either as BIPV or BAPV, may exhibit distinct visual, spectral/optical, mechanical, and thermal properties compared to conventional glass/backsheet or glass/glass modules. Some of these characteristics can result in significantly greater variations in energy rating even within a single product family (e.g., roof tiles, façade elements). Such differences become even more pronounced when modules are evaluated under mounting conditions other than the standard field configuration (20° tilt, equator-facing, free-standing) defined in the IEC standard.

To extend the applicability of the standard to BAPV and BIPV modules, the working group responsible for the revision of the IEC 61853 standard proposes multiple mounting configuration scenarios, including new equator-facing rooftop (20°) and façade (90°) setups [5]. In particular, the 90° configuration enhances the assessment of BIPV products, allowing a more accurate evaluation of modules with improved angular response. Furthermore, this revision also captures the influence of annual temperature and irradiance profiles. An informative Annex dedicated to BIPV is also foreseen in the revised version, describing adaptations to the testing procedures, especially regarding the measurement of spectral response and angle of incidence for coloured modules, which often exhibit high variability in colour technologies and designs [11], as well as for modules with special front coatings such as antiglare treatments.

The standard includes recommendations on how to address the higher and more variable temperatures, due to reduced convective cooling, thermal contact with building substrates, and different wind exposure compared to field-mounted modules [12]. Indeed, a range of additional physical parameters beyond incident irradiance and wind speed, not considered in the Nominal Module Operating Temperature (NMOT), can influence the thermal behaviour of BAPV and BIPV modules. Martín-Chivelet et al. [13] review these influencing factors, along with alternative models that can be used instead of the one proposed in the IEC 61853 standard.

Despite these limitations, the static thermal model described in the IEC 61853 standard can still be employed during the initial design phase for comparative energy rating purposes, provided that only products within a single BIPV product family (e.g., roof tiles, façade elements) are compared and that the NMOT tests are conducted under the same or comparable conditions.

It is evident that, as currently defined, the thermal parameters U_0 and U_1 determined through the NMOT test, performed at a fixed tilt and under open-rack conditions, do not accurately represent the in-service operating temperatures of most BIPV installations. Consequently, these parameters cannot be reliably used to predict the energy yield of BAPV or BIPV systems. To address this limitation, testing under representative mounting conditions should be carried out, with detailed reporting of mounting configurations (e.g., façade versus roof, substrate thermal resistance) and backside ventilation characteristics (e.g., natural ventilation gaps, sealed integrations). Examples of potential BIPV reference mounting conditions, compared with the current standard reference environment (SRE) used for NMOT testing, are illustrated in Figure 1.

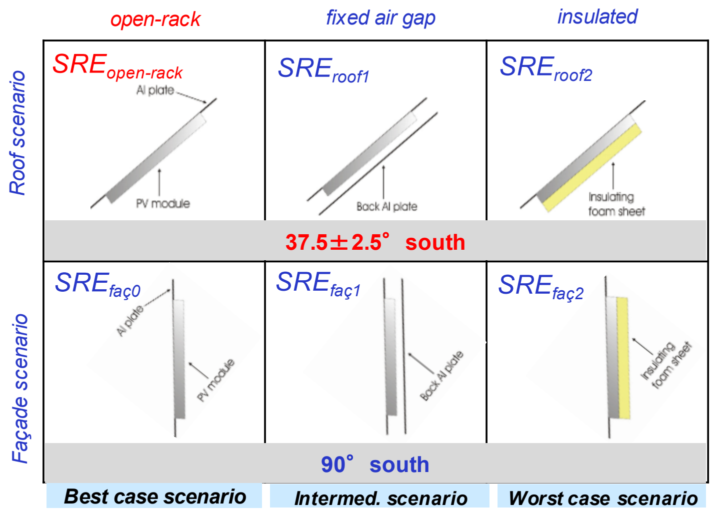


Figure 1: Standard reference environments for BIPV/BAPV modules [14]

The IEC TS 61724-2:2016 introduces a heat transfer model that depends on similar variables to those used in the NMOT procedure described in the IEC 61853-2 standard but additionally provides recommended values for the two fitting parameters corresponding to representative mounting configurations, distinguishing between open-rack, closed-roof, and insulated-back installations. An alternative testing approach for determining the NMOT of BIPV modules has been proposed by C.G. Wei et al. [15].

Moreover, under real operating conditions, BIPV modules are frequently exposed to partial or persistent shading, which adversely affects their electrical and thermal performance and long-term reliability. Consequently, the development of a rating system for shading resilience is particularly important for BIPV applications, where such effects are considerably more prevalent than in field-mounted systems.

Floating PV (FPV)

Compared to field-mounted PV systems, FPV modules are affected by several distinctive environmental and operational factors: (1) Potentially lower operating temperatures, particularly in water-cooled configurations, where heat transfer to the water surface enhances module cooling, (2) variable tilt and orientation angles caused by waves and platform movements, leading to fluctuating irradiance incidence, (3) higher humidity and condensation exposure due to proximity to the water surface, which may affect optical and electrical properties, and (4) unique albedo and diffuse irradiance contributions, originating from water reflections and enhanced sky-diffuse components.

Similar to BIPV systems, the high variability in FPV configurations leads to a wide range of thermal behaviours. The IEA PVPS Task 13 report, Floating Photovoltaic Power Plants: A Review of Energy Yield, Reliability, and Maintenance, highlights these differences by comparing operating temperatures and heat-transfer coefficients across various FPV designs.

Most FPV systems currently in operation are air-cooled, meaning that the PV modules are not in direct contact with water, and their thermal environment is primarily governed by air convection. In such systems, water temperature influences module temperature only indirectly, by moderating the ambient air temperature above the water surface. Consequently, parameters such as the mounting structure, module clearance from the water, and local wind conditions play a dominant role in determining cooling efficiency. The typically higher wind speeds over open water surfaces further enhance convective cooling, resulting in lower module temperatures.

Conversely, in water-cooled FPV systems, where modules are in direct contact with the water, thermal coupling with the water body becomes the primary heat-dissipation mechanism. The high heat transfer coefficient of water, combined with its limited diurnal temperature variation, results in lower, more stable module temperatures. In these systems, water temperature becomes the dominant factor influencing cell temperature, while water circulation (velocity and mixing) plays a role analogous to wind speed in enhancing heat exchange efficiency.

Due to these differences, the direct application of the IEC 61853 standard - particularly regarding the thermal parameters defined in Part 2 and the reference conditions in Part 4 - can misrepresent the actual energy yield of FPV modules. Nevertheless, it can provide an initial baseline for the benchmarking of FPV products against one another.

Agrivoltaic (AV)

Agrivoltaic (AV) systems are characterised by unique shading and microclimatic conditions arising from the coexistence of photovoltaic modules and agricultural crops beneath them. These factors can influence the actual energy yield in ways that differ significantly from those of standard field-mounted or BIPV systems.

The IEC 61853 standard - particularly Parts 3 and 4 - provides a general framework for the energy rating of PV systems, but further adaptations are required to adequately address bifacial modules, which are increasingly adopted in AV systems due to their ability to capture solar radiation from both sides [16]. The revised version of the IEC 61853 standard, extending its application to bifacial modules, will include 4 new mounting configurations, applicable to vertical AV systems with bifacial modules or single-axis tracking, as well as greenhouses, better represented by the rooftop mounting configuration added to cover typical BAPV configurations.

Energy rating methodologies can substantially support AV system design by quantifying how module properties - such as transparency, spectral response, and tilt configuration - influence both energy yield and light availability for crops. It is possible to balance PV electricity production with plant physiological requirements, ensuring sufficient photosynthetically active radiation (PAR) while maintaining high conversion efficiency.

Typical heat transfer coefficients for BIPV/FPV/AV

The comparison of the typical heat-transfer coefficients across different PV system types in Table 3 offers an overview of their thermal performances and operational efficiencies. The table summarises the range of typical thermal coefficients (expressed as U-values) for field-mounted PV modules, BIPV, AV and FPV. In accordance with the Faiman/IEC 61853 nomenclature [17], U_0 represents the contribution of natural convection and irradiation, whereas U_1 accounts for forced convection driven by wind. Due to the scarcity of literature values and field data, the values for water-cooled FPV and AV systems represent expected values.

Table 3: Typical and estimated thermal coefficients in various conventional and integrated PV configurations.

PV system type	U_0 [W/m²·K]	U_1 [W/m²·K /m/s]	Description / conditions	Ref
Open-rack/Field-mounted PV	25–30	3–6	Freely ventilated modules; strong convective cooling on both sides.	[17,18]
BAPV Rooftop / Close-roof mount	15–20	0–2	Limited air circulation between the module and the roof; reduced wind effect.	[14,18]
BIPV (fully integrated façade or roof)	10–15	0–1	Minimal back ventilation; nearly stagnant air layer; high operating temperature.	[14,18]
Floating PV (air-cooled)	20–35	3–6	Like open-rack but influenced by humidity and reflected radiation from the water surface.	[3]
Floating PV (water-contact / semi-immersed cooling)	30–40	4–8	Direct conduction to water and high humidity; enhanced effective heat loss.	
AV (interspace or overhead)	28–34	4–7	Modules raised 2–5 m above the field; open air circulation from below and above; enhanced convective exchange, but variable microclimate due to vegetation evapotranspiration.	

Field-mounted and AV systems exhibit relatively high heat-transfer coefficients due to open, well-ventilated mounting, with AV additionally benefiting from vegetation-induced cooling, whereas BIPV and BAPV systems experience reduced heat transfer because of restricted rear airflow, leading to higher operating temperatures. In contrast, FPV systems' thermal performance changes depending on the design. Air-cooled configurations, for instance, behave similarly to open-rack arrays, whereas water-contact configurations provide the most effective cooling through direct heat exchange with the water surface.

2.2 Application-Specific Performance Loss Rates (PLR)

2.2.1 Introduction

It is important to note that module selection based solely on energy rating indicators provides no insight into the long-term energy yield and reliability of a PV module, which is influenced by numerous factors such as the bill of materials (BOM), manufacturing processes, and the environmental stressors the module experiences over its operational lifetime. The module degradation rate (Rd), typically expressed as the percentage of power loss per year, is commonly used for warranty declarations, whereas the performance loss rate (PLR), which reflects the degradation of overall system performance, is used to estimate the payback period and lifetime energy production of a PV project. The variability in the definitions and usage of these two terms in the literature, and their consequent impact on reported degradation rates, are discussed in greater detail by K. Chen et al. [19].

Field-mounted PV modules operating in moderate climates typically exhibit mean degradation rates ranging from –0.5%/year to –1.0%/year, depending on the applied assessment methodology [20]. A negative correlation between degradation rate and hot and humid climates, and a positive correlation for cold climates, have been consistently reported in the literature [21–26]. Outliers are generally associated with extreme mechanical stress (e.g., heavy snow loads or windstorms) or low-quality modules and installations. Despite the widespread global deployment of bifacial PV modules, the literature still lacks comprehensive long-term field data on the degradation rates of bifacial modules, which are also frequently deployed in AV installations. A recent study of 189 bifacial PERC modules installed in northern Europe over 4.5 years, conducted by Bartholomäus et al. [27], reported moderate degradation rates (0.36%–0.75% per year) for most module types, and severe losses for one type, primarily attributed to potential-induced degradation (PID) and UV-induced faults. Overall, bifacial modules exhibited slightly higher early-life degradation than monofacial modules, with failures mainly linked to contact issues and rear-side degradation mechanisms rather than to typical encapsulant defects.

2.2.2 Degradation/Performance Loss Rates of Integrated PV Systems

As discussed in Sections 3.2, 4.2 and 5.2, compared to field-mounted PV modules, integrated PV modules are exposed to a broader range of increased or additional stressors, which may result in higher degradation rates. However, due to the limited operational experience and the smaller installed capacity relative to conventional ground-mounted PV systems – particularly in the case of FPV and AV applications – long-term field data remain scarce. BIPV installations have a comparatively longer track record, although the majority of deployed systems are BAPV rather than fully integrated BIPV configurations.

Building-Integrated/Applied Photovoltaics (BIPV/BAPV)
As shown by Jordan et al. [28] and further supported by Özkalay et al. [29], elevated operating temperatures typical of BIPV installations can accelerate module degradation, particularly when standard glass/backsheet (G/B) modules with rear insulation or insufficient ventilation are used [29–31]. In contrast, several large-scale studies report lower degradation rates for rooftop systems, comparable to those of ground-mounted modules. This is likely because most datasets predominantly refer to BAPV systems with adequate rear ventilation [26], or are limited to specific BIPV products - often glass/glass modules engineered to withstand increased mechanical and thermal stress [32].

Floating PV (FPV)
Despite the growing number of floating photovoltaic (FPV) systems in operation for several years, long-term performance studies remain scarce. Reported degradation rates vary depending on climatic conditions and specific floating system designs. A long-term assessment of a 2 MW_p FPV plant operating in a humid subtropical climate reported annual performance loss rates (PLRs) of approximately –0.7% [33]. Similarly, a study conducted by SERIS, based on three years of data from a large FPV testbed, found PLRs ranging from –0.5% to –0.7%

per year, values comparable to those observed in nearby rooftop systems [34]. These results are comparable to or slightly higher than the typical degradation rates of standard crystalline silicon modules in field-mounted installations. Although FPV systems are subject to distinct stress profiles in their water-based environments, emerging long-term field data indicate encouraging overall performance stability.

Agrivoltaic (AV)
Performance loss rates (PLRs) or degradation rates for AV systems are expected to be within the typical range reported for conventional ground-mounted PV systems. These values are strongly influenced by climatic conditions, mounting configurations, and the specific PV cell technologies employed. However, factors such as partial shading, soiling, and the dual land-use operational environment can contribute to increased system degradation and energy losses. In greenhouse-integrated PV applications, however, annual degradation rates tend to be lower, owing to the more controlled environmental conditions that reduce moisture exposure and other stress factors. Nevertheless, the degradation behaviour of AV systems remains highly dependent on system design, material selection, and operational context.

2.3 Research and Development Benchmarking Facilities

PV performance assessment under representative operating conditions is becoming increasingly complex due to the increasing diversification of PV applications. For this reason, dedicated R&D benchmarking facilities play a critical role in advancing integrated PV technologies. These facilities bridge the gap between controlled laboratory characterisation and real-world deployment.

In particular, for BIPV, international efforts over the past decade have led to the development of specialised façade and rooftop testbeds, where modules are installed under realistic building-integration conditions and monitored for temperature, irradiance, ventilation characteristics, and electrical output. These facilities often combine performance testing with durability assessment and fire, mechanical, and safety compliance verification [35,36].

Similarly, FPV testbeds have been established to investigate the influence of humidity, wind regimes over water surfaces, platform motion, and water–module thermal coupling. These facilities are particularly important for validating assumptions regarding enhanced cooling effects and long-term reliability in high-moisture environments.

In the AV sector, emerging benchmarking platforms allow simultaneous monitoring of PV performance and agricultural parameters (e.g., crop yield, PAR, soil moisture, and microclimate). Such infrastructures are essential for quantifying trade-offs between energy generation and agricultural productivity and for optimising module transparency, row spacing, height, and tracking strategies.

Despite these advances, the global network of dedicated benchmarking infrastructure for integrated PV, particularly for FPV and AV, remains limited compared to the extensive experience base for conventional field-mounted systems. The following table provides an overview of international test facilities dedicated to the benchmarking and performance evaluation of BIPV, FPV and AV systems in different countries.

Table 4: Overview of R&D test facilities for the benchmarking of BIPV, FPV, and AV modules and systems.

n°	R&D Institutes	Link to test infrastructure	Country	BIPV	AV	FPV
1	Austrian Institute of Technology GmbH (AIT)	https://www.ait.ac.at/en/solutions/photovoltaic	Austria	x		
2	EnergyVille	https://www.openthor.be/en https://set.kuleuven.be/over-ons/groepsdiensten-en-faciliteiten/trans-farm	Belgium	x	x	
3	Universidade Federal de Santa Catarina (UFSC)	https://canalsolar.com.br/en/UFSC-agrivoltaic-system-field-research/	Brazil		x	
4	Technical University of Denmark (DTU)	https://electro.dtu.dk/research/research-facilities/solar-power-plant	Denmark	x		
5	Aarhus University	https://projekter.au.dk/agrivolt	Denmark		x	
6	Fraunhofer Institute for Solar Energy Systems (ISE)	https://www.ise.fraunhofer.de/de/fue-infrastruktur/center/zentrum-fuer-materialcharakterisierung-und-gebrauchsdaueranalyse/outdoor-performance-lab.html https://www.ise.fraunhofer.de/en/research-projects/pv2float.html	Germany	x	x	x
7	Helmholtz-Zentrum Berlin (HZB)	https://www.baip-bipv.de/en/our-offer/research/	Germany	x		
8	Institute for Solar Energy Research Hameln (ISFH)	https://isfh.de/en/aussenteststaende	Germany	x		
9	Eurac Research (EURAC)	https://www.eurac.edu/en/institutes-centers/institute-for-renewable-energy/pages/laboratories-facilities	Italy	x	x	
10	Netherlands Organisation for Applied Scientific Research (TNO)	https://www.tno.nl/en/technology-science/facilities/solarbeat-out-door-test-facility-bipv	Netherlands	x		
11	Institute for Energy Technology (IFE)	https://ife.no/en/laboratory/ife-pv-module-characterization-and-test-ing-laboratory-2/	Norway	x	x	x
12	Solar Energy Research Institute of Singapore (SERIS)	https://www.seris.nus.edu.sg/services/floating-pv-rd-and-testbed/	Singapore			x
13	National University of Singapore (NUS)	https://www.seris.nus.edu.sg/wp-content/uploads/2024/01/BIPV-Bro-chure_2024-V4.pdf	Singapore	x		

n°	R&D Institutes	Link to test infrastructure	Country	BIPV	AV	FPV
14	TECNALIA Research & Innovation	https://www.tecnalia.com/en/infrastructure/kubik-experimental-building https://www.tecnalia.com/en/news/testing-photovoltaic-modules-in-a-real-offshore-environment	Spain	x		X
15	Center of Energy, Environmental and Techn. Research (CIEMAT)	https://rings-bipv.com/index.php/testing-facilities-cabins/	Spain	x		
16	Mälardalen University	https://www.mdu.se/en/malardalen-university/research/research-projects/matrix---evaluation-of-the-first-agrivoltaic-systems-facility-in-sweden	Sweden		x	
17	Research Institutes of Sweden (RISE)	https://www.ri.se/en/expertise-areas/test-demo/solar-testbed	Sweden	x		
18	Univ. of Appl. Sciences and Arts of Southern Switzerland (SUPSI)	https://www.supsi.ch/en/outdoor-testing-of-photovoltaic-modules-and-systems	Switzerland	x		
19	Bern University of Applied Sciences (BFH)	www.bfh.ch/pvlab	Switzerland	x	x	
20	École Polytechnique Fédérale de Lausanne (EPFL)	https:/www.epfl.ch/labs/pvlab/	Switzerland	x		
22	University of Arizona (UA)	https://biosphere2.org/research/research-initiatives/agrivoltaics	USA		x	
23	National Laboratory of the Rockies (NLR)	https://openei.org/wiki/InSPIRE	USA		x	

3 OPTIMISATION OF MODULE/SYSTEM DESIGN FOR BUILDING INTEGRATED PHOTOVOLTAICS

The integration of PV modules into buildings is being driven in some countries by limited available land, regional sustainability goals, the increasing energy demand of urban areas and evolving building regulations. In 2020, SolarPower Europe reported that 44% of the global installed PV power was mounted on buildings. While building applied PV (BAPV) dominates the installed capacity with the use of standard PV modules, building integrated PV (BIPV) remains a small but fast-growing niche, accounting for approximately 3% of total PV capacity in 2022, with Europe leading the market.

The IEA PVPS Task 15 expert group developed a streamlined hierarchical approach as a reference for classifying BIPV building skin technologies [37]. By taking into account the main technical subsystems of the multifunctional building skin, the main features in terms of function, performance, morphological, structural and energy-related aspects are organised into five levels: (1) application, (2) system (see Figure 2), (3) module, (4) component, and (5) material.

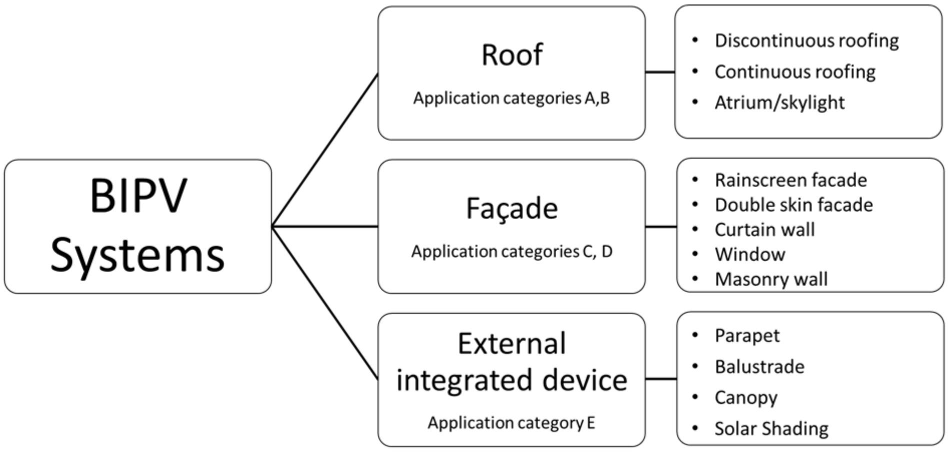


Figure 2: BIPV system classification as described in [37]. The application categories A, B, C, D and E are those used by the BIPV standards, EN 50583 and IEC 63092.

3.1 Application-Specific Needs and Key Performance Indicators (BIPV)

BIPV products - serving as roofing, façades, or structural elements - must fulfil both energy generation and construction product roles in accordance with existing international standards [38,39]. A guidebook recently published by IEA PVPS Task 15 [2], aims to support informed decision-making and promote efficient, resilient BIPV projects through case studies across various applications and climates. The authors give a broad overview of the relevant BIPV specific requirements.

At the module level, efficiency - primarily determined by the underlying cell technology - is the key electrical characteristic. This is especially important in building-integrated applications, where available surface area is often limited and maximising energy yield per square meter is required. However, aesthetic considerations can significantly influence the final product choice. Design features such as specific colours, patterned surfaces, or varying degrees of transparency - often required for architectural integration - typically result in reduced module efficiencies. As a result, the selection process frequently involves balancing electrical performance with visual and architectural requirements.

At the system level, appropriate planning can improve the electrical and overall performance of BIPV systems and optimise the direct self-consumption of locally generated PV electricity. Thermal properties, solar heat gains, daylight management, as well as acoustic properties, are among the further requirements for the planning of BIPV systems. Durability, reliability, and safety aspects, including electrical, mechanical, and fire protection requirements, are also key factors for PV modules in/on buildings or infrastructure. For widespread adoption of BIPV the typically assumed lifetime (equated to the power warranty of 30 years) might be insufficient since lifetimes as construction products ideally should be comparable to standard cladding products, with common roofing materials having lifetimes exceeding 50 years. In addition, there are aesthetic requirements and recommendations that must be considered to realize visually appealing BIPV projects.

To support architects, system developers, and other stakeholders involved in the planning of new BIPV projects, the experts of IEA-PVPS Task 15 have developed a multi-dimensional assessment tool based on the experiences and learnings of already installed BIPV projects [40]. The creation of a comprehensive, interdisciplinary evaluation methodology makes it possible to compare the multi-dimensional performance of existing BIPV systems, to derive strengths and weaknesses and to use this knowledge to plan application-optimised new BIPV systems.

Four performance categories were defined: energy-related, economic, environmental and optical/visual (see Figure 3). After defining the relevant performance indicators per category, a numerical rating system was established by the experts [41].

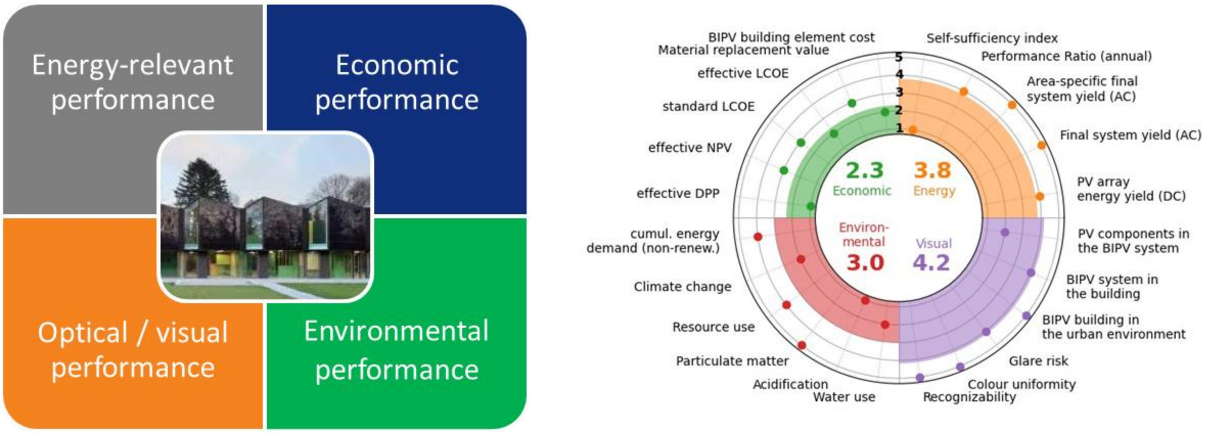


Figure 3: Multidimensional performance indicators for BIPV as developed by IEA PVPS Task 15 [41].

It must be mentioned that the focus is set in this approach to the as-designed system and does not consider the long-term performance and reliability of the BIPV components and system.

While minor efficiency losses due to aesthetic or structural constraints may be acceptable, BIPV components and system designs must be carefully optimised to minimise the risk of unexpected degradation, catastrophic failures, or safety hazards. This report therefore focuses on mitigation strategies to reduce some of these risks.

3.2 Stressors and Typical Problems (BIPV)

The stress factors and combinations of stresses to which BIPV systems are exposed, along with the adverse effects, failures, and degradation they can cause in the modules, are summarised in Figure 4. The stressors can be divided into two groups: (i) main stressors which are generally present with all BIPV installations and (ii) site-specific stressors which depend on the application type (e.g. integrated or attached roof systems, PV-façades, external devices), as well as the environmental and climatic conditions the PV-system is installed in.

Adverse effects, failures and degradation modes which have direct impact on (i) the performance of a PV-system, (ii) the lifetime of the modules or one specific component, (iii) the aesthetics and visual performance or (iv) the safety of BIPV/BAPV systems are considered.

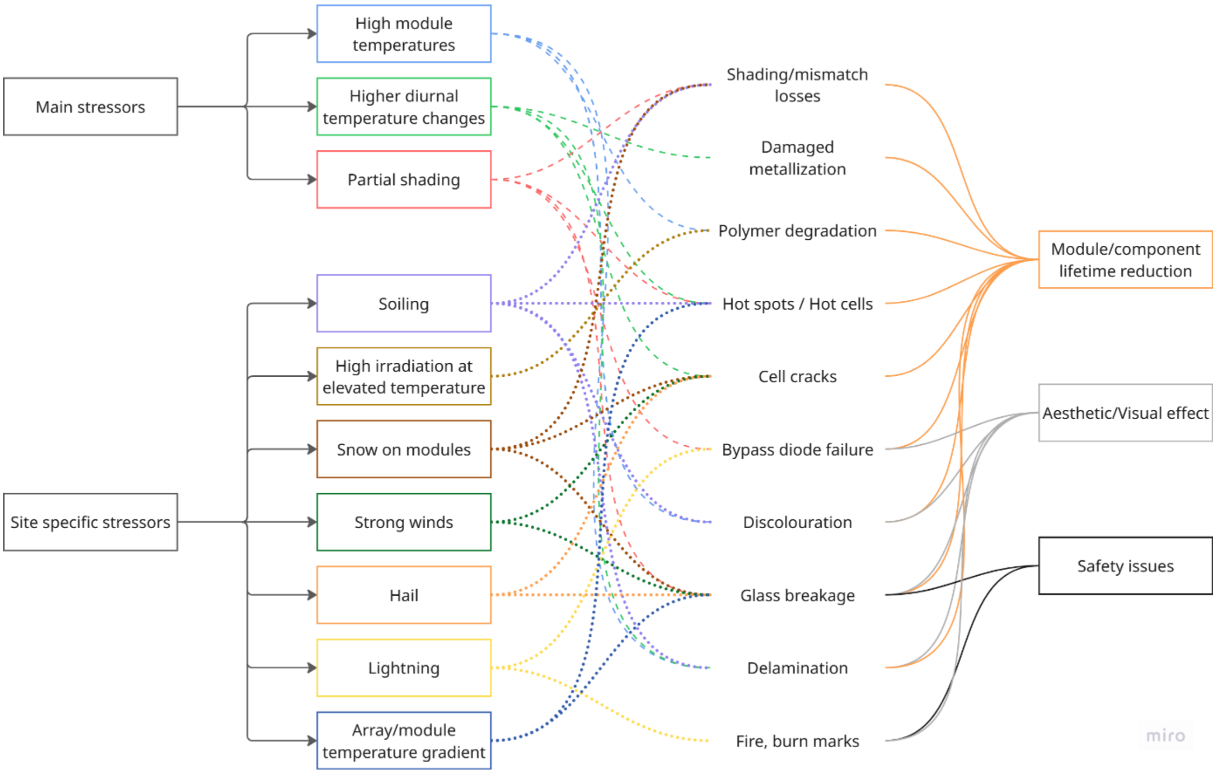


Figure 4: Stress factors and stress combinations acting on BIPV systems, along with the associated adverse effects, degradation modes, and potential module failures

BIPV modules must maintain energy performance and electrical safety throughout their lifetime while fulfilling core building functions like waterproofing, insulation, and durability. Unlike free-standing PV systems, BIPV modules face harsher environmental and operating conditions, such as (i) higher operating temperatures (due to restricted or limited rear side air ventilation), (ii) greater temperature fluctuations (due to high diurnal temperature changes), and (iii) frequent partial shading (due to sub-optimal orientations compared to conventional PV modules as well as the greater frequency of obstructing objects, such as chimneys), which can stress components and cause hot spots. These factors may exceed the tolerance of cells and materials, accelerating degradation (leading to e.g. delamination, cell cracks, discolouration, or glass breakage). Such degradation can not only raise safety concerns but also affect aesthetics, which are more critical in visible, built-up environments [29].

3.2.1 High Module Operating Temperatures

BIPV modules may operate at elevated temperatures compared to identical modules installed under open-rack conditions, mainly due to reduced or restricted rear-side ventilation [42–44]. Temperature-induced degradation of PV module components, especially polymer components, through thermal or photothermal degradation modes has been extensively investigated in numerous studies [32,45]. The IEC has considered the fact that modules reach higher temperatures in some climates or installation situations (e.g. BIPV) and published the IEC TS 63126:2020 "Guidelines for the qualification of PV modules, components, and materials for operation at high temperatures". It proposes modifications to standard module qualification and safety tests (e.g., IEC 61215-2:2021 and IEC 61730-2:2023) for modules operating at high temperatures.

This has been investigated to some extent in Task 15 [38] with the conclusion that the thresholds for applying the elevated temperature testing are not really reached in most ventilated BIPV systems in moderate climates. This is not to say that high module temperatures do not occur - they do - but it is highly dependent on the system configuration, and maybe less common than expected.

A recent study of modules installed at SUPSI (Canobbio, Switzerland – Köppen-Geiger climate zone Cfb) [46] also shows that only BIPV modules in insulated roof configurations (without rear ventilation) reached sufficiently high operating temperatures to justify the application of the high-temperature testing requirements specified in IEC TS 63126:2020 (results summarised in Table 5). However, these results also show that not all BIPV modules necessarily reach such high operating temperatures and that, therefore, not all modules to be installed in BIPV systems need to be tested under these stricter conditions.

Table 5: Summary of the analysis of open-rack, BIPV insulated roof, BIPV partially ventilated roof, and BIPV partially ventilated façade modules' operating conditions at SUPSI (Switzerland; KGCZ Cfb) according to IEC TS 63126:2020 and IEC 62892:2019. Only full-year datasets were considered to avoid potential biases caused by seasonal variations in module temperature. The numbers shown represent the number of modules that satisfy the corresponding condition [47].

Mounting Configuration	IEC TS 63126:2020		IEC 62892:2019	
	Standard T_{98}≤ 70°C	Level-1 (70°C T_{98}≤ 80°C	Extended Thermal cycling is not necessary	Extended Thermal cycling is advised
Open-rack Roof	12	-	9	3
BIPV Insulated Roof	-	5	-	5
BIPV P. Ventilated Roof	1	1	-	2
BIPV P. Ventilated Façade	6	-	-	6

3.2.2 Larger Thermomechanical Stress

Modules integrated into BIPV roof and façade applications may be exposed to higher thermo-mechanical stress compared to standard open-rack mounted modules.

For roof-integrated PV modules, this is primarily due to the higher operating temperatures resulting from the limited ventilation of the rear side compared to the same modules installed in the same orientation on open mounting systems.

The situation is more complex for façade-integrated modules. Over the course of the year, the operating temperature range of façade-mounted modules is similar to that of inclined, open-rack modules. However, the seasonal patterns of their operating temperatures differ due to variations in the tilt angle and the resulting solar irradiance.

During clear-sky winter days, façade modules tend to operate at higher temperatures than standard tilted open-rack modules because the façade surface receives sunlight at a more perpendicular angle, leading to higher irradiance (Figure 5). Since façade modules reach their highest operating temperatures during this period – when nighttime temperatures remain low – they experience larger diurnal temperature variations [46].

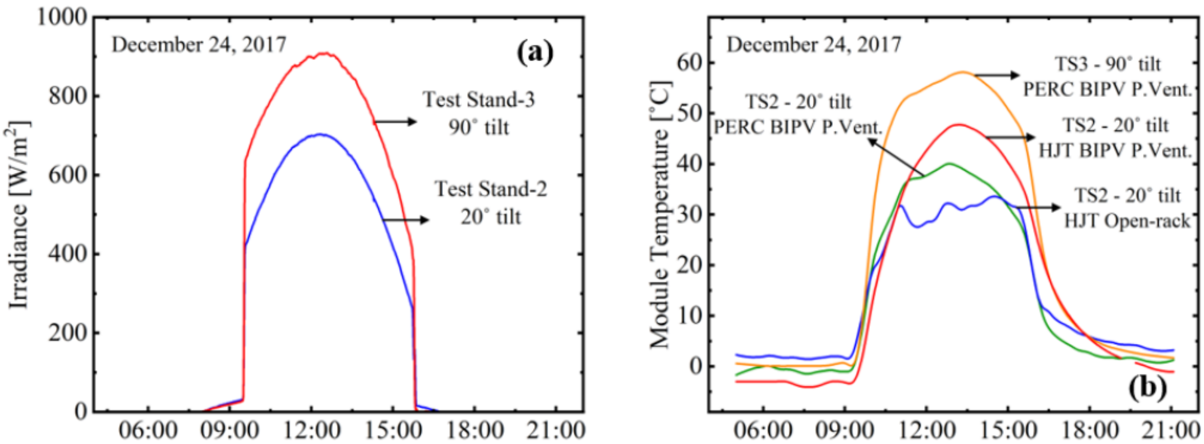


Figure 5: Daily (a) plane of array irradiance and (b) module temperature profiles from Test Stand-2 (TS2 - 20° tilt) and Test Stand-3 (TS3 - 90° tilt) on 24 December 2017, the closest clear sky day to the winter solstice. All times are local time (UTC+1) [46].

The standard IEC 62892:2019 "Extended Thermal Cycling of PV Modules" provides a methodology to determine whether extended thermal cycling (TC) test is recommended depending on the operating conditions of the modules. Following this methodology, all BIPV modules in the work of [47], whether installed in roof or façade applications, with at least limited rear-side ventilation are advised to undergo extended thermal cycling testing (Table 5). Furthermore, for BIPV modules installed in insulated roofs (no rear side ventilation) where T_{98} is between 70°C and 80°C, the maximum temperature during the TC test is recommended to be 85°C instead of 75°C.

3.2.3 Partial Shading

In contrast to large-scale PV fields, whose large areas generally ensure optimal operating conditions without obstructions, the built environment introduces challenges to maximising PV module performance and reliability due to the potential presence of persistent shading from surrounding structures such as chimneys, nearby buildings, or trees (see Figure 6). Partial shading is a common and often critical issue in BIPV when architecturally integrating PV modules (i) into an existing building (retrofitting) or (ii) into a building constructed within an existing built environment or neighbourhood.

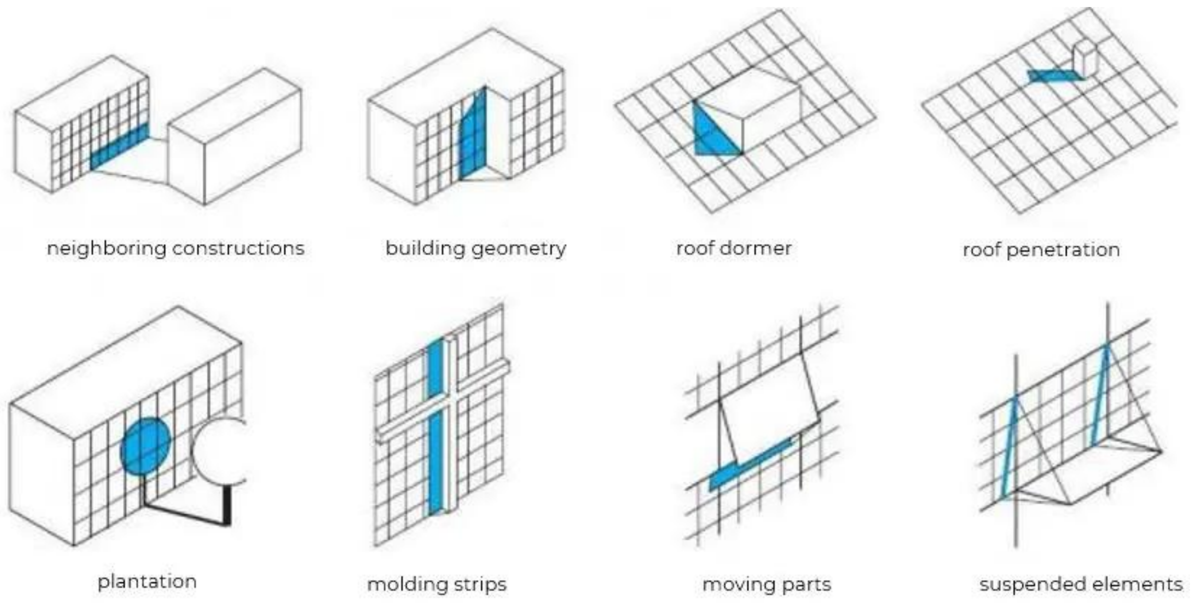


Figure 6: Schematic depiction of different shading situations [48].

Shading in BIPV systems is generally more frequent and less predictable than in conventional PV installations. Since modules are integrated into façades, roofs, canopies, or external shading components, their exposure to sunlight varies with building geometry, surrounding structures, and seasonal sun angles. As a result, shading patterns change throughout the day and across different times of the year, often leading to non-uniform irradiance across module surfaces or even across individual cell strings.

Partial shading can lead to several effects on BIPV system performance and reliability. Even a small, shaded area can result in disproportionately large power losses at the module and system level, reducing the overall performance ratio (PR). When cells in a shaded region are forced into reverse bias, they may dissipate excessive power and form a hot spot or hot cell [49], which can accelerate material degradation and in severe cases pose a safety risk. Bypass diodes can temporarily protect shaded cells by diverting current flow, but frequent activation reduces energy yield and, over time, increases the likelihood of diode fatigue or failure. Additionally, non-uniform irradiance creates electrical mismatch between strings and modules, further decreasing system efficiency [50].

3.2.4 Other Site/Application-Specific Stressors

Focusing on the application, the physical/mechanical impact of hailstones, wind load and snow varies depending on orientation, structure, and exposure. The application-dependent level of stress exposure and the expected severity of the effects are summarised in Table 6.

Table 6: Application-dependent stressors with expected severity

Exposure ***Impact***	**Façade**	**Roof**	**External devices (roofings or balcony railings)**
Soiling	low	moderate	moderate
High irradiation	variable (orientation-dependent)	high	
Snow load	low	high (cold & snowy climates)	high on roofings
Strong winds	moderate	high for BAPV, low for BIPV	moderate
Hail	low to moderate (vertical/inclined surfaces) *Hail strikes at an angle → lower force*	high (horizontal or inclined, full exposure) *Direct vertical impact → high kinetic energy*	high (horizontal or vertical, unprotected systems) *Direct vertical impact*
Lightning	low	moderate	low
Array/module T-gradients	high (in ventilated façades due to the vertical buoyancy driven convection)	moderate	low

3.3 Best Practice and Mitigation Strategies (BIPV)

3.3.1 Site Assessment

The site assessment for PV systems that are to be integrated into/on buildings or infrastructure is significantly more complex than for freestanding systems, as the limitations of the (already constructed) building and the built environment must be taken into account. However, several aspects and guidance on how to assess them are summarised in the following.

Main assessment aspects

1. Site visit: evaluate local conditions, surrounding obstacles, and the condition, geometry, and load-bearing capacity of roofs and/or façades (statics). Confirm watertightness and identify structural limitations
2. Orientation and tilt: record the orientation and inclination of roofs and façades to estimate their solar potential and expected energy yield
3. Sunlight and shading: identify shading from buildings, vegetation, and architectural elements throughout the year. Conduct 3D shading analyses to optimise the placement and layout of PV modules
4. Solar radiation and climatic conditions: assess solar resource availability, temperature variations, soiling or pollution levels, and snow accumulation as all these factors influence the expected performance, the cleaning needs, and system durability
5. Grid and utility conditions: review grid connection options, metering schemes, feed-in limitations, and capacity constraints to ensure the system can be integrated effectively
6. Regulatory and visual requirements: check building codes, fire safety rules, zoning and

heritage restrictions, and visual or glare-related limitations; ensure BIPV elements are aesthetically compatible with the building and its surroundings

7. Energy demand profile: analyse annual and hourly consumption profiles to align BIPV generation with on-site demand and maximise self-consumption

Additional Considerations

8. Structural and spatial integration: a site survey confirms whether existing structures can accommodate integrated PV components. For new buildings, structural and spatial needs should be addressed early in architectural and engineering design
9. Orientation constraints: retrofits and dense urban environments may limit ideal solar orientation; new construction offers greater flexibility to balance aesthetics and performance
10. Visual integration: material selection, colour, transparency, and module layout should support architectural quality and minimise visual impact or glare

A concise yet comprehensive site assessment enables effective integration of BIPV, ensuring structural compatibility, regulatory compliance, architectural quality, and optimal energy performance.

3.3.2 Component Selection

The selection of components for BIPV systems must address not only standard PV requirements but also the additional stressors associated with building integration and the functional and architectural role of BIPV elements as part of the building envelope. Because BIPV modules replace conventional construction materials, their durability, appearance, fire performance, and structural behaviour must be evaluated alongside electrical performance to ensure both long-term energy production and compliance with building safety and design requirements.

Visual appearance and aesthetic integration

The visual appearance and aesthetic integration of BIPV installations are particularly important because BIPV is not only an energy system but also a functional component of the building's architecture. Its appearance influences the perception of building users, public acceptance, and the building's architectural value [51]. Thus, colouring the modules or modifying the surface appearance by matting, satinising, structuring or sandblasting (reducing the potentially disturbing glare of highly reflecting PV-façades) can improve the visual integration in the built environment.

Figure 7: BIPV buildings with coloured and surface optimised modules; a) Kopenhagen international school (Photo credit: Gabriele Eder/OFI), b) V-ZUG (Photo credit: © ertex solar/Dieter Moor).

PV panels can be coloured by adding a colouration material in front of the cell. Task 15 has previously described how to quantify colours via the CIELAB colour space, where the spectrum of light reaching an observer is converted into human colour perception metrics [52].

The colouring material reflects part of the incident light spectrum which results in a reduced light irradiation on the solar cell compared to an uncoloured reference. When comparing colour losses, it is important to compare colours with the same colour intensity and saturation.

Two main types of colouration technologies exist:

- Structural colours: the colours are created via constructive interference coatings based on dielectric materials. This method is providing colours with low colouration loss; however, these colours are iridescent, such that the colour changes with incident and view angles. Optical diffusors scattering the light or flake structures with random orientation reduce this effect. Advanced optical modelling designing these structures are needed to generate especially the red hue colours [53]. In most seen implementations the colouration loss is in the range of 5%-20%.
- Absorbing pigments: these absorb part of the light spectrum and thereby creating subtractive colours. This type of colouration has though no iridescence but typically high colouration losses of 20%-50%.

Independent of the colouration technology, the colours can be applied anywhere in front of the cell as either (i) a glass coating, (ii) a coloured interlayer foil embedded between encapsulant layers or (iii) a coloured encapsulant (see Figure 8). Aesthetic requirements of the modules may necessitate reducing visible metallization, for example through back-contact solar cells, metallization masking, or coloured interconnect coatings. However, the long-term reliability and interaction of these additional materials with other established module materials and the lamination process should be carefully evaluated, as some coatings may degrade under UV, heat, or moisture exposure [54].

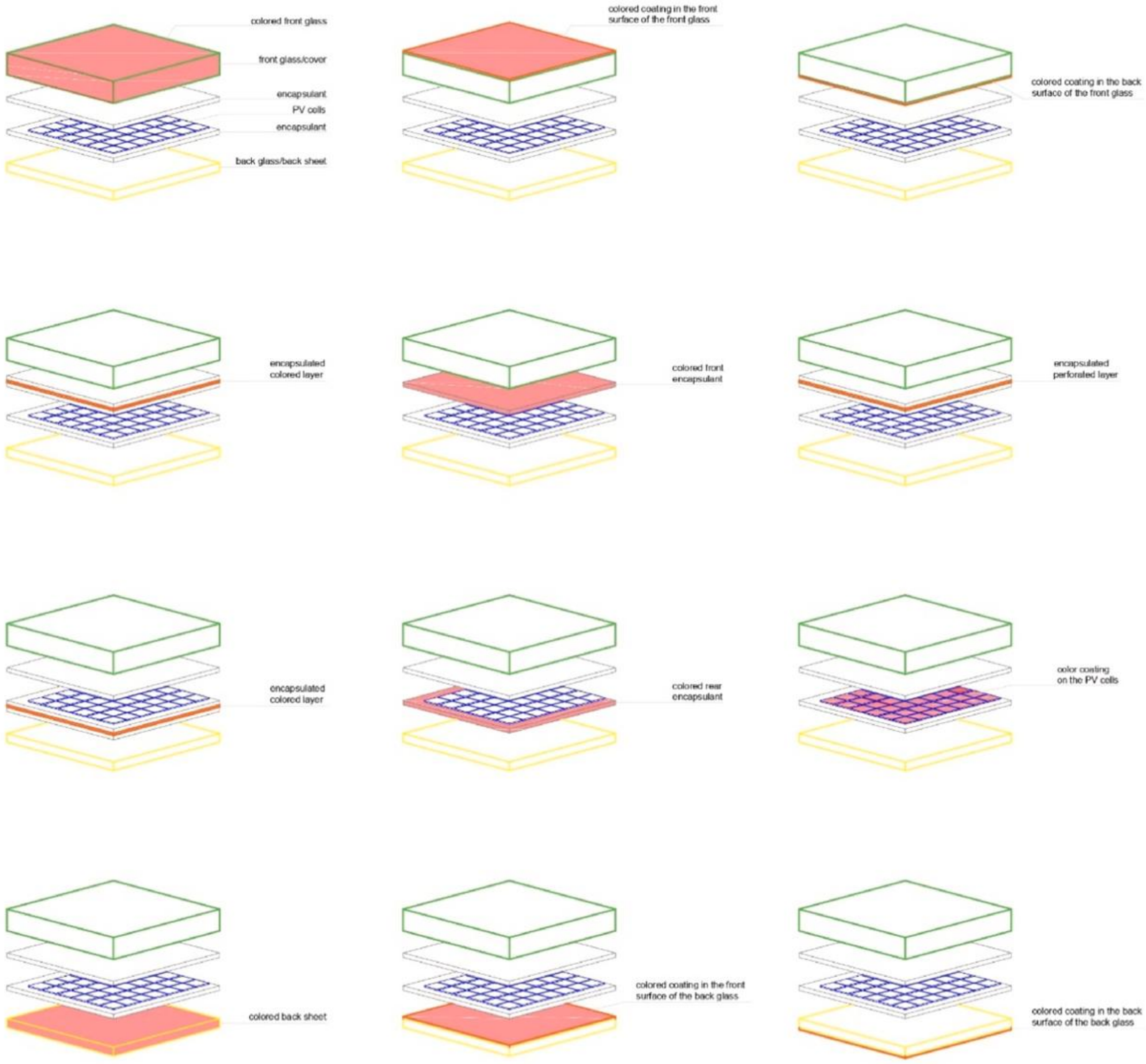


Figure 8: Colouration types – possible module stacks [53]

In visually sensitive contexts such as urban centres, transport corridors, or heritage environments, anti-glare or low-reflective surface treatments may be required to reduce visual disturbance and ensure architectural acceptance [55]. However, in dense or polluted regions, particulate soiling may reduce transmittance and increase cleaning demand. Therefore, anti-soiling, anti-static, or easy-clean surface coatings can help maintain visual and electrical performance while reducing maintenance frequency [56].

Shade tolerance

Solar module selection for BIPV systems must consider efficiency, aesthetics, and possible shading tolerance simultaneously. Because the available area for BIPV on building façades and roofs is often limited, high-efficiency solar cell types are chosen to maximise energy yield.

Many façade-integrated and some roof-integrated BIPV systems are exposed to non-uniform irradiance due to shadows cast by neighbouring buildings, chimneys, façade geometry, trees or seasonal sun angles. Therefore, system design, module design and cell selection that consider instantaneous power loss and minimise hot spot risk under partial shading are essential.

One strategy to improve module performance under partial shading is to reduce the number of cells connected per bypass diode, thus increasing the number of independently protected subsections within the module through optimised cell stringing and interconnection layouts [50,57]. This approach has led to the use of four or more bypass diodes – sometimes integrated at sub-module or even cell level – to selectively bypass smaller shaded or less-efficient areas. Although this increases the complexity of module layout, it helps reduce instantaneous power loss and possible high hot spot temperatures under certain shading conditions.

Another approach involves using back-contact (BC) solar cells, which can exhibit lower breakdown voltages and reduced hot spot temperatures under partial shading [49]. However, comparative studies across BC, PERC, TOPCon, and HJT solar cell architectures remain limited, and the shading tolerance of any module also depends on the module layout and the number and placement of bypass diodes. Further research is required to systematically evaluate shading robustness under realistic BIPV conditions.

It is important to note that there is no universally accepted definition of a shade-tolerant PV module. Manufacturers use a wide range of definitions and criteria, which creates confusion rather than clarity for users.

Durability

Material durability must be assessed with respect to both macro- and micro-climate (module-level) exposure at the installation site. BIPV modules may operate at elevated temperatures, which can accelerate UV-induced degradation of polymer components and increase thermal cycling stresses on solder bonds, interconnect ribbons, and cell metallization [47]. Materials with high UV and thermal stability should therefore be prioritised. Ensuring robust solder bonds and interconnection schemes helps reduce fatigue-related cracking caused by repeated thermal expansion and contraction. The selection of materials such as encapsulation and adhesives should be based on the specific environmental stressors identified during the site assessment to support long-term performance and reliability. Testing for material compatibility of the various components is very important.

Mechanical and safety requirements depend on the specific building envelope function. As part of the external wall or roof layer, BIPV elements must withstand both positive and negative wind pressures, including peak suction effects near edges and corners. Wind resistance should be verified in accordance with IEC 63092-2 and local building codes [2].

BIPV modules in façades, roofs, canopies, or overhead applications must satisfy impact resistance requirements as defined in the relevant PV and building glass standards. In regions with frequent severe hail events, enhanced hail impact testing beyond the standard IEC protocol may be required. For such conditions, the use of full-tempered glass and increased glass thickness may improve resistance. When lightweight modules are required, the supporting structure has limited load-bearing capacity, the selected front materials and bonding systems must still provide adequate mechanical rigidity and safety, validated through appropriate testing.

Fire resistance

Fire performance is critical when BIPV modules replace conventional façade or roofing materials. Regulatory requirements vary by country [58] and depend on the module's role in the building envelope. While good installation practices and shading-resilient module designs can reduce the likelihood of PV-initiated fires, external fire exposure from other building-related sources cannot be eliminated. Mitigation strategies include system-level design approaches, selection of G/G module designs, materials with lower combustibility, the reduction of combustible materials and the use of flame retardants to reduce flame spread and allow sufficient time for fire response [59].

3.3.3 System Design

Mitigation of shading losses
To address and mitigate these challenges, several approaches can be adopted, including more shading-resistant PV module configurations (i.e. multi-string, shingling, active diodes, cells with lower breakdown voltages), the use of module-level power electronics (power optimisers or micro-inverters) and strategic PV string design. Each of these solutions comes with its own advantages and disadvantages, with differences in active and passive power losses, reliability, and safety concerns [50].

The use of power optimisers or microinverters allows for maximum power point tracking at the individual module level, preventing shaded modules from negatively impacting overall system performance. At the system level, PV strings can be strategically designed and configured to minimise shading effects, thereby reducing instantaneous power losses due to partial shading. For more details, see the report T13-27-2024 on *Performance of Partially Shaded PV Generators Operated by Optimised Power Electronics* [50].

Figure 9: Plus-energy residential building in Seewadelstrasse – Affoltern am Albis (ZH–CH). Through careful wiring it is possible to control the shading of the modules from the building itself https://solarchitecture.ch/shading/. (Photo credit: Viridén + Partner AG).

Snow loads, snow guards
Partial shading of PV roofs, for example, can also be caused by an uneven snow cover (see Figure 10). Furthermore, a dense layer of snow on the modules prevents electricity production, thus leading to significant energy losses in winter. However, snow on a BIPV or BAPV roof usually causes an additional problem: high mechanical stress, especially when the snow becomes wet during the thawing phase in spring. The mechanical stability of the module is the most important requirement, especially in cold and snowy regions. Module size, glass thickness, frame selection, and mounting structures all have a strong influence on this [60]. An effective design choice can be the use of frameless modules, as the down sliding snow then is not hindered by the module frame and have been proven to shed snow 50% faster than

framed modules [61]. For details see report T13-32-2025 on *Optimisation of Photovoltaic Systems for Different Climates,* Chapter cold and snowy climate [1]. The mechanical stability against high loads, however, is much higher with framed modules [60], so a compromise has to be found depending on the requirement profile at a given site.

Figure 10: a) uneven snow load on a BIPV-installation, b) BAPV-system with broken modules and frames after a winter with heavy snow loads (Photo credit: Gabriele Eder/OFI).

Cable management

Effective cable management and labelling ensure BIPV roof longevity. The use of cable trays, clips, and ties can help secure the wiring, prevent mechanical stress, and avoid abrasion from sharp corners and movement due to wind or other vibrations that could damage wiring or connectors. On the one hand, when using an edge junction box with BIPV insulation glass units, DC wiring can be routed along the posts and beams. On the other hand, when a conventional rear junction box is used, wiring can run indoors, concealed within trays, for cable management and aesthetic reasons [2].

Monitoring

Monitoring of the electricity output of BIPV installations is essential for several technical, economic, and safety-related reasons. Unlike conventional PV systems, BIPV modules are embedded into the building envelope, making accessibility and fault detection more challenging. Monitoring ensures the system is operating according to design specifications and helps identify performance losses due to shading, soiling (dirt, bird droppings, pollution) and degradation over time. But also, early detection of technical issues, such as module failures or string-level faults, inverter errors or disconnections, hot spots from partial shading or defective cells and cable or connector degradation/malfunction is possible through proper monitoring.

Well-designed ventilation chamber

BIPV modules can be installed in either partially limited or fully limited rear-side ventilation configurations. In cases of partially limited ventilation, a well-designed ventilation chamber that allows sufficient airflow can help reduce thermal and thermomechanical stresses. This, in turn, can prevent potential issues such as overheating and temperature-induced material fatigue and aging especially in BIPV roof applications related to partially limited rear side ventilation and consequently high module temperatures [47].

Accessibility for maintenance

Accessibility for O&M must be integrated into the mounting concept, ensuring that modules can be removed individually without compromising the building envelope or adjacent elements.

Mounting systems should provide defined service gaps, safe access points, and load-compatible fixing interfaces. Module designs should include standardised connectors and rear-side access to junction boxes to enable rapid replacement. The overall system layout must ensure maintainability of both electrical and waterproofing components throughout the system's lifetime.

3.4 Case Studies (BIPV)

3.4.1 Case Study 1: Coloured BIPV Façade

Introduction

Integrating PV into buildings enables renewable energy generation without additional land use and contributes to reducing the operational carbon emissions of the building. In dense cities, façades offer a large and largely unused surface for solar electricity generation, particularly when rooftop space is limited. This case study demonstrates how BIPV can combine energy generation, architectural expression and building-envelope functionality within urban environments.

The 368 kWp project in Amsterdam, developed by Kondor Wessels Vastgoed, features 1735 coloured PV modules integrated across the entire building façade. These modules function as part of the building envelope, delivering weather protection, solar shading, and a cohesive architectural appearance.

System Details and Environmental Context

Figure 11. View of the BIPV system. (Photo credit: Kondor)

System data	Site data
Typology: BIPV	Climate: temperate maritime (Cfb)
Category: Façade	Location: Amsterdam
Year of installation: 2025/2026	Altitude: ~2 m a.s.l.
Surface: 3013 m²	Irradiance: up to 1,000 W/m^2
Size: 368 kWp	Temperature: −5°C to 32°C
Module n°: 1,735	Wind: frequent strong coastal winds, gusts up to ~30–35 m/s
Module type: coloured frameless glass/glass (flat and curved)	Snow: negligible / rare accumulation
Tilt: 90° (vertical façade)	Ice: occasional frost events
Azimuth: multi-orientation (all directions)	

Located in a dense urban and maritime environment, the building is exposed to high humidity and frequent wind loads. These conditions require façade systems with high durability and robust anchoring solutions. At the same time, the urban surroundings impose strict architectural integration constraints, making this project a representative example of how BIPV can be deployed in cities where aesthetic and functional requirements are equally important.

Performance and Reliability of Integrated Solution: Challenges and Mitigation

Operating a vertical BIPV façade in a coastal urban climate introduces challenges that differ significantly from those of conventional PV systems. The primary constraints are aesthetic integration, wind loads, module customization and maintaining a good level of electrical performance despite vertical orientation and colouration.

To fulfil the architectural and aesthetic requirements, the façade had to blend harmoniously with the surrounding urban context while maintaining uniform colouration across thousands of uniquely shaped panels. Achieving colour consistency across flat PV modules and curved glass surfaces was a major challenge. MorphoColor® technology was selected because it generates colour through light interference rather than pigments, minimising absorption losses.

This solution allows the façade to achieve a homogeneous appearance while preserving high photovoltaic efficiency. In addition, the choice of frameless and custom-sized modules, including curved modules, contributed to achieving a clean and continuous surface, eliminating visible borders and enhancing the seamless visual integration of the PV façade. Figure 12 shows how the module dimensions and colours were matched to the building geometry. Digital modelling was used to design the alignment between PV modules and façade elements.

Figure 12. Close view of the parapets with customised modules in multiple orientations. (Photo credit: Kondor)

Special attention was then given to the mounting concept in order to simplify installation while ensuring long-term reliability and maintainability. A standardised mounting system compatible with all module sizes and shapes - including curved modules - was developed, featuring reinforced anchoring and optimised load distribution to safely transfer loads to the building structure. A ventilated façade cavity contributes to improving the thermal behaviour of the modules and the building envelope.

As façade-integrated systems function as part of the building envelope, they must comply with strict construction and safety requirements. The modules and mounting system were therefore designed and tested to withstand wind pressure and suction loads, accommodate thermal expansion of the façade structure, and ensure long-term durability as cladding material. Compliance with fire-safety and curtain-wall standards was an essential part of the certification process.

Although vertical PV systems typically yield less annual energy than optimally tilted rooftop installations due to reduced irradiance, urban shading and multiple orientations, multi-oriented façades provide a complementary generation profile. They tend to produce more electricity during winter months and at low sun angles, which aligns well with building energy demand. To mitigate performance losses, high-efficiency cells were selected, and the electrical layout was optimised to maximise energy yield across the different façade orientations and to reduce mismatch losses from different orientations and module sizes.

Key lessons learned from the BIPV system:

- Interference-based colouration can successfully balance aesthetics and performance.
- Standardisation of mounting systems is critical when dealing with high module variability.
- Early collaboration between architects, façade engineers and PV specialists is essential.

3.4.2 Case Study 2: Solutions for Partially Shaded BIPV Façade Areas

Introduction

In Vienna, Austria, photovoltaic G/G modules integrated into the glass façade of the U6 building at Floridsdorf station generate electricity and provide shade at the same time. Vienna Lines, in cooperation with Vienna Energy, realised their first façade-integrated PV system as well as on the roofs (BAPV) of the U6 Floridsdorf station and the adjacent signal box. On sunny days, this system can produce more electricity than is needed on-site for lighting, elevators, and escalators in the station. Excess electricity is fed into the grid at neighbouring subway stations. With this BIPV power plant, Wiener Linien (Vienna's public transport operator) can cover one-third of the U6 station's total annual electricity demand.

System Details and Environmental Context

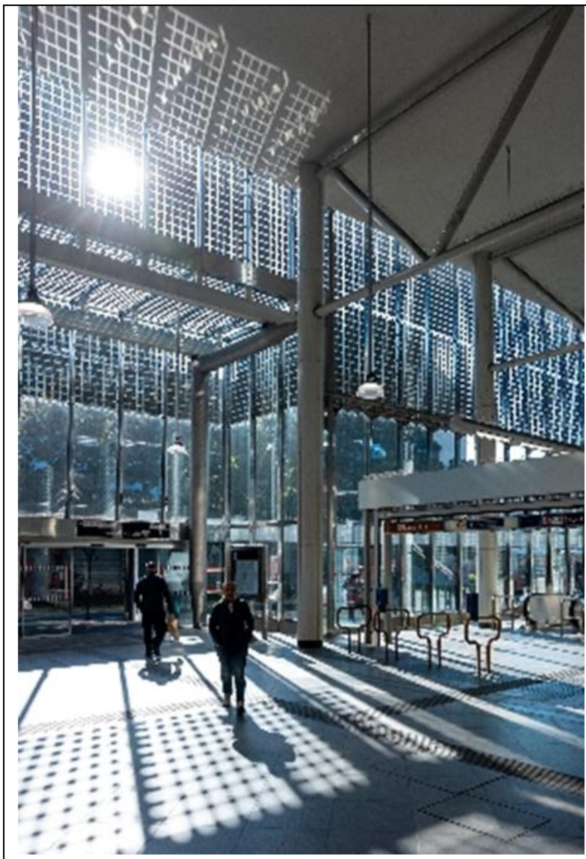


Figure 13. First Façade-Integrated PV System at the underground station in Floridsdorf, Vienna. (Photo Credit: Vienna Lines / Max Döringer)

System data I

Typology: BIPV

Category: Façade

Surface: 762 m²

Size: 87.8 kWp; 775 kWh/kWp

Module type: frameless semi-transparent (60% Si-cells, 40% transparent glass) glass/glass modules;

Tilt: 90°

Azimuth: east

Year of installation: 2025

System data II

Typology: BAPV

Category: roof

Size: 75.88 kWp; 997 kWh/kWp

Tilt: 10°

Azimuth: south-west

Year of installation: 2025

Site data

Climate: moderate continental (Cfb)

Location: Vienna, Austria

Altitude: ~170 m a.s.l.

Irradiance: up to 1000 W/m²

Temperature: −5°C to 32°C

Average annual precipitation: ~620 mm.

Ice: occasional frost events

BIPV Façade

The 1,300 m² east-facing glass façade at the eastern entrance of the station required renovation. As part of the modernization work, semi-transparent PV modules were integrated into the façade. Approximately 60% of the façade area (approx. 762 m²) is used for electricity generation and shading via semi-transparent PV glass elements, while the remaining area remains transparent (glass) and allows daylight to pass through.

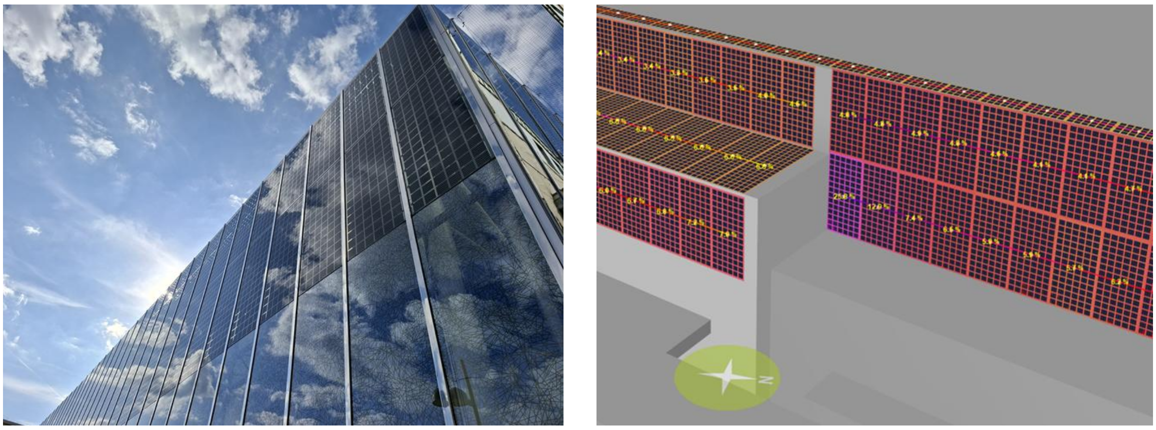


Figure 14: Façade-Integrated Photovoltaic System @ the underground station in Floridsdorf, Vienna of the Vienna Lines; Operational since 06.2025. (Photo credit: Gabriele Eder/OFI)

The individual semi-transparent PV modules also have a ratio of ~60% solar cells to 40% transparent glass surface. This allows the implementation of an innovation while simultaneously ensuring that the architectural character of the glass façade is preserved. Furthermore, this contributes to climate change adaptation, as the subway station building will heat up less.

No module optimisers were used. The small, partially shaded areas were not used for PV-module installation (see **Figure 14**).

Key Lessons Learned for Shaded BIPV Modules

There are no ready-made solutions for (shaded) BIPV systems; each project must be considered and optimised individually. Possible solutions:

- Connect modules individually and use optimisers in cases of very irregular shading.
- Connect them in strings and use different MPPT inputs on the inverter.
- Do not connect modules in shaded areas because, for example, there is no space for optimisers.
- The entire process should be considered and planned from the outset using simulation tools.

Note: In addition to the advantages of optimisers, the disadvantages must also be considered, such as the failure of the power electronics. This can be very problematic in a high-rise building if access is restricted. Lesson learned: use optimisers only for very irregular shading and consider accessibility and fire safety.

4 OPTIMISATION OF MODULE/SYSTEM DESIGN FOR FLOATING PV

Floating PV (FPV) systems are an increasingly attractive solution to alleviate the land competition arising from the massive deployment of PV. They refer to mounting solar PV systems on structures that float on water [3]. As of 2024, global installed FPV capacity exceeded 9.1 GW [62] (Figure 15) and estimates suggest that covering just 1% of the global reservoirs' surface area could host over 4 TW of installed FPV capacity [63]. However, FPV systems also require new performance and environmental considerations.

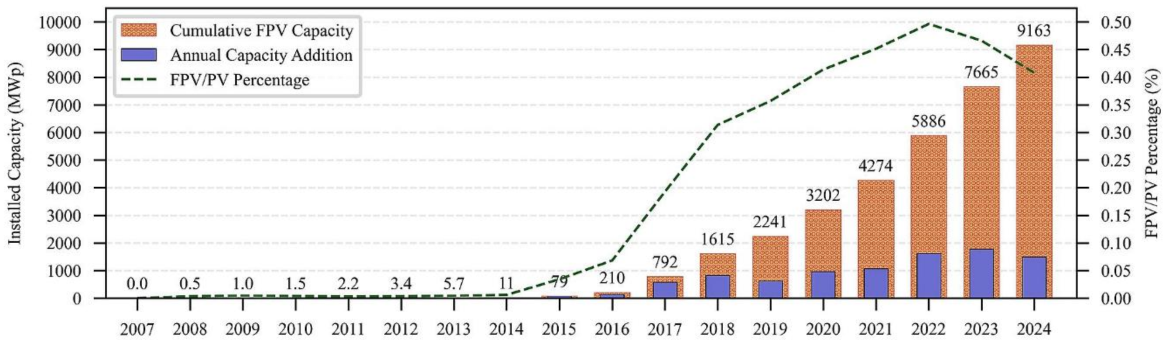


Figure 15: Growth of Global Installed Capacity of Floating Photovoltaics from 2007 to 2024 [64].

This chapter presents a set of key performance indicators (KPIs) to address the unique behaviour, risks and opportunities associated with FPV systems. In addition, it discusses the application-specific stressors and some mitigation strategies that can be put in place to maximise the performance, durability and reliability of this technology. Lastly, two case studies are presented to highlight how the design of FPV systems can be adapted to the specific characteristics of each location.

4.1 Application-Specific Needs and Key Performance Indicators (FPV)

Most KPIs for PV systems focus on energy output and economic viability, such as the Performance Ratio (PR) and the LCOE. The PR of FPV systems may benefit from lower operating temperatures compared to traditional land-based systems, which would improve efficiency [65]. However, PR in FPV installations may also be negatively affected by floating-specific challenges, such as biofouling and module movement caused by wind and wave action [66]. To date, the LCOE of FPV is still found to be higher than GPV, mainly because of the higher CAPEX (mainly due to floats and anchoring systems) and the still-limited economy of scale [67]. However, this gap could be reduced in the future, thanks to the increasing FPV capacity and the rising costs of land [67]. Moreover, most LCOE comparisons do not typically account for dual-use synergies, such as the potential for shared infrastructure with hydropower or wind energy, or additional revenues from reduced water evaporation, which could further increase the cost-competitiveness of FPV [68]. Furthermore, LCOE computation is not only affected by average annual yields, but also by the magnitude of uncertainty in forecasting these averages

[69]. This uncertainty arises through the site- and technology-specific intermittent character of generated annual yields and should consequently be factored into a faithful comparison of FPV and GPV LCOEs.

In addition to energy and economic indicators, FPV systems require additional attention to environmental metrics to understand and mitigate the potential ecological impacts on aquatic ecosystems. The evaluation of these metrics is increasingly required by permitting authorities and is thus becoming growingly important for the overall performance evaluation of FPV projects. Some of the most relevant environmental metrics are described in Table 7.

Table 7. Typical Environmental KPIs for FPV installations.

Metric	Definition
Coverage Ratio (%)	The proportion of the waterbody's surface area covered by the FPV system.
Water Temperature Profile	The variation in water temperature with water depth.
Photosynthetically Active Radiation (PAR)	The amount of sunlight (400–700 nm) available for photosynthesis in the water column.
Dissolved Oxygen (DO)	The concentration of oxygen dissolved in water, essential for the respiration of fish and other aquatic organisms.
Turbidity	A measure of water haziness.
Chlorophyll-a	A pigment found in photosynthetic organisms, used as a proxy for phytoplankton biomass and primary productivity in aquatic ecosystems.
Water Level Fluctuation	Describes the changes in the surface elevation of the waterbody over time, due to seasonal variation, reservoir operations, rainfall, or evaporation.

In addition to the abovementioned metrics, social acceptance could also play an important role in the successful deployment of FPV. Preliminary studies [70,71] show that concerns about visual impact and effects on local fauna can lower public acceptance of this technology, as floating structures are often perceived as artificial elements within a natural landscape. Thus, specific metrics must be used as indicators of potential opposition as they can help guide site selection, design adaptations, and community engagement strategies.

4.2 Stressors and Typical Problems (FPV)

The need for additional KPIs becomes evident when considering the unique environmental and mechanical stressors affecting FPV systems. The water environment introduces conditions that differ significantly from those encountered by land-based installations, including high humidity, salt exposure (in some locations), biofouling, wave-induced motion and complex anchoring loads.

These stresses can impact the performance, durability, and reliability of FPV modules and are shown in **Figure** 16, together with the anticipated failure modes they may cause.

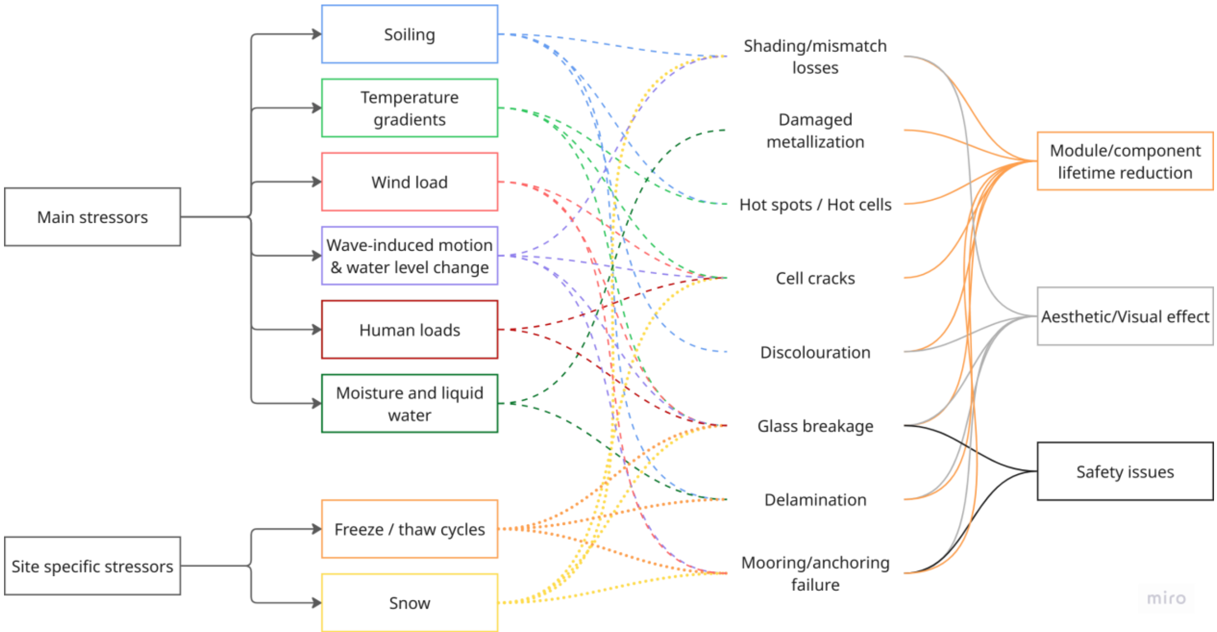


Figure 16. Stressors, induced degradation mechanisms and failure modes in FPV modules.

4.2.1 Soiling

FPV arrays are known to be particularly exposed to localised soiling from bird droppings, which create strong shading and increase the risk of hot-spot formation [3]. The accumulation of soiling can be worsened by high humidity and water or salt spray, which increase particle adhesion. In tropical areas, biofouling and organic residues (e.g., algae, pollen) may further accelerate soiling-induced losses.

4.2.2 Temperature

Thermally induced stress in PV systems is due to extreme temperatures and diurnal and seasonal temperature fluctuations. This is a significant reliability concern for PV modules [72]. Rapid and repeated temperature swings can cause cyclic mechanical stress in module components due to the mismatch in coefficients of thermal expansion among materials. Over time, this stress can lead to microcracks in the cells, solder joint fatigue and delamination of encapsulants.

FPV systems are generally expected to operate at lower temperatures than land-based systems due to proximity to water. However, recent studies show that this cooling effect is not guaranteed and is highly dependent on system design and environmental exposure [73]. Also, the characteristics of the site can influence the thermal behaviour of the modules. FPV systems installed in a water basin surrounded by buildings or vegetation, for example, may experience reduced wind exposure, potentially leading to higher module temperatures during peak irradiance hours [74]. Therefore, reduced thermally induced stress in FPV systems cannot be generalised across installations.

Furthermore, FPV modules may experience higher temperature spatial variance compared to land-based systems, due, for example, to bird droppings causing non-uniform shadings and, thus, hot-spot formation [72].

4.2.3 Mechanical Stressors

FPV systems face mechanical stresses that can differ significantly from those encountered in land-based PV, especially due to dynamic interactions with the water environment. These can impact system durability, component integrity and long-term energy performance.

Wind and Waves

Mechanical stress conditions that FPV modules experience are highly dependent on the technology, mounting configuration and site characteristics. These stresses tend to increase when moving from smaller to larger freshwater inland water bodies and to nearshore and offshore water bodies. Two of the most critical mechanical stressors in FPV applications are wind loads, which exert pressure and suction on floating structures, and wave loads, which introduce torsion, vibration, impacts, and other dynamic mechanical forces.

In [75], the distribution of aerodynamic forces acting on PV modules, including sink and drag components is discussed. The analysis highlights how tilt angle and pitch influence not only the global forces on the FPV system and mooring/anchoring components, but also the distribution of wind pressure. Wind tunnel tests on FPV arrays show that inner rows of PV panels are progressively shielded by the outer ones, significantly reducing the wind load on interior sections. However, the exact wind force distribution is complex and varies with wind direction and array geometry.

As the requirements for FPV systems have progressively increased, ensuring their safety has become an essential concern. Consequently, comprehensive safety analyses are required, based on numerical simulations, such as Computational Fluid Dynamics (CFD), hydrodynamic analysis and Finite Element Analysis (FEA), whose results must be validated through experimental testing. In [76] and [77], such simulations were employed to simulate the combined impact of wind and wave loads on an east–west FPV system. The results confirmed the non-uniform distribution of wind loads, with front rows exposed to the highest stress and downstream rows benefiting from shielding, in line with findings from [75]. Additionally, the system's aerodynamic behaviour was shown to be highly sensitive to wind direction: perpendicular winds (0° and 180°) generated the highest drag and lift forces, requiring more robust structural reinforcement in the most exposed areas. In contrast, oblique wind angles resulted in reduced aerodynamic loads but introduced more complex and potentially turbulent flow patterns.

Wave-induced motions can lead to torsional stress, vibrations and slamming forces that impact both the PV modules and the structural components. Waves can cause dynamic loads that vary with wave height, direction, and period, potentially leading to mechanical wear and tear [78,79]. Additionally, waves can lift modules above their design height, affecting electrical components and leading to water ingress, and dynamically change the tilt angle and the orientation of the modules [80].

While results from field studies are still relatively scarce, laboratory methods are now being developed to mimic wave-induced torsion, vibration and wave impact, investigating mechanical stress behaviour until failure [81]. Recently, a consortium of three partners (TNO, Deltares, and Oceans of Energy) conducted a unique full-scale experimental test in a wave flume [82]. One experiment focused on the impact of wave slamming on PV modules installed on a fixed test rig in a controlled environment. This type of loading is especially relevant to offshore systems based on flat pontoon concepts, such as those implemented by Oceans of Energy. These pontoon systems face a unique risk of localised mechanical damage on the edges due to the proximity of the PV panels to the water surface.

In the experimental setup, crystalline silicon PV modules were exposed to breaking waves up to 2.5 meters in height. Because of the limited water depth in the flume, wave steepness exceeded typical values found in open sea conditions, intensifying the mechanical stress. Results showed a clear positive correlation between wave height and both the pressure and force exerted on the modules. The highest pressures reached 16 kPa, with total loads per module peaking at 25 kN, equivalent to the weight of 30 to 35 adults standing on a single module.

Strain measurements indicated a positive correlation between strain and wave heights with maximum deformations up to around 200 microstrain (µm/m) at maximum wave heights of 2.5 meters. It is important to note that the specific way the module is attached to the underlying structure has affected the measured strains, making the results unique to the tested Oceans of Energy platforms. Despite these substantial mechanical loads, the tested modules exhibited no signs of damage such as glass breakage.

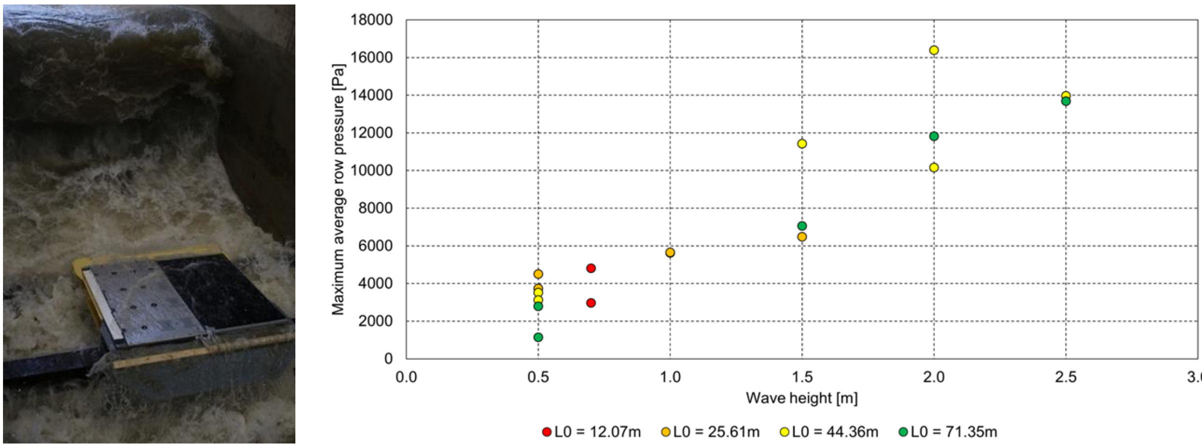


Figure 17. Left: Experimental set-up employed in [82]**, showing the wave slamming tests on a PV module mock-up. Right: Maximum average row pressures plotted against wave height. Each data point corresponds to a regular wave train, with the colour indicating the associated deep-water wavelength (L0).**

Ice and Snow

Frozen conditions on floating structures introduce unique mechanical loads that are rarely encountered in conventional land-based PV or temperate FPV installations [83]. Among the most critical issues is the formation of ice layers, which can induce significant squeezing and uplifting forces on the FPV array, particularly where the ice is thicker. As the array becomes partially or fully embedded in the frozen surface, it is subject to dynamic mechanical stresses, especially if the ice thickness varies significantly over time. The anchoring system plays a fundamental role in the system's resilience to such conditions. When underwater anchoring materials such as concrete piles or gravity anchors are used, the frost heave resistance of the concrete must be evaluated carefully. Similarly, shore-based anchors face lateral forces and floating effects due to freezing, which markedly differ from the mechanical stresses experienced in non-freezing environments. In these cases, temporary anchoring measures may be required during the freezing season to safeguard the structural integrity of the system and prevent dislodgement or damage due to the impact of floating ice.

Extremely cold regions often bring the additional challenge of heavy snow loads, which, combined with ice-related stresses, require specialised structural solutions. These include the use of reinforced anchoring components and materials with proven resistance to low-temperature embrittlement, which inevitably slows down construction timelines and increases installation costs relative to standard FPV projects.

Water level fluctuations
Variations in water height, driven by seasonal changes, reservoir management, hydropower operations or weather events can vary the load on mooring lines and possibly modify the geometry of the array, increasing risks of bending and fatigue.

Maintenance
Maintenance activities, particularly when involving direct human interaction with the PV array, can introduce mechanical stress that may compromise the integrity of the FPV modules. One concern for FPV is to enable easy access for cleaning and maintenance of the modules. In many system configurations, this is enabled through dedicated walkways or even by designing specific vessels. For FPV system designs where the modules are fully supported by the water body, a study shows that it is feasible to walk on the modules during inspection or cleaning, without inducing damage to the modules.

A Finite Element Method (FEM) analysis conducted on modules fully supported by the water body underneath showed that mechanical stress induced by stepping on a module is significantly less compared to land-based installations. A recent report [84] indeed found that a 121 kg person stepping on a glass-glass module with 2.0 mm glass thickness will not induce damage to glass or cells in PV modules positioned on a floating membrane, i.e. in a mounting structure where the module is fully supported by the water body (Figure 18 and Figure 19).

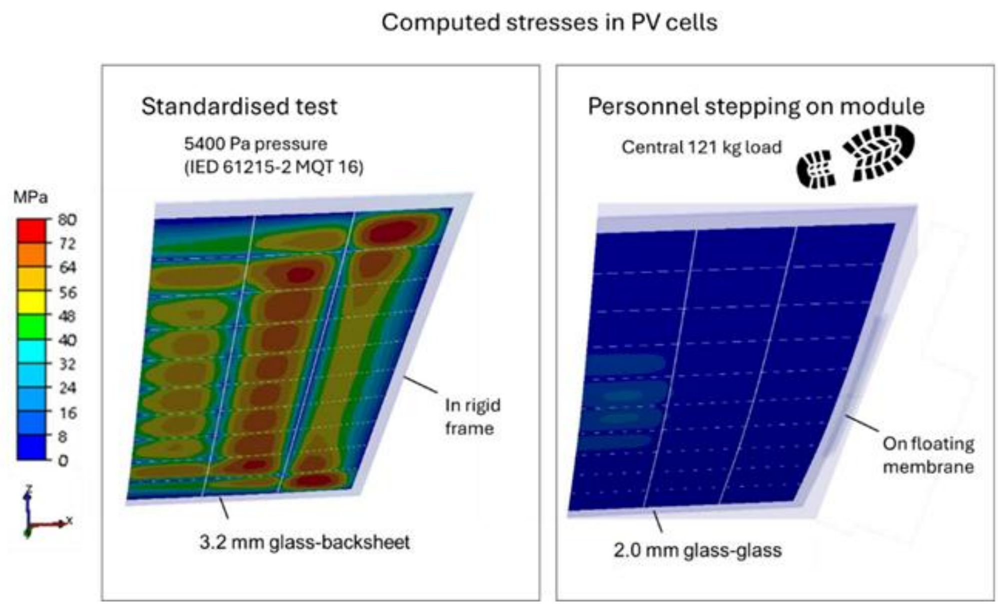


Figure 18. Two simulations of stress in PV modules. To the left is a simulation of the stress (expressed as a pressure in MPa) induced by the extended IEC standard (IEC 61215-2, MQT 16) and to the right is the simulation of stress induced by a person stepping on the module. Source: IFE report Walkability of PV modules: stresses induced by personnel stepping on PV modules on a floating membrane. IFE/F-2024/047.

However, even if these results highlight a considerable safety margin, caution is still required. Loads applied near structural discontinuities, such as close to aluminium reinforcements, can lead to localised bending and increased stress. Moreover, dynamic actions such as jumping can still create high transient loads that may exceed the module's mechanical tolerance and potentially lead to fractures or internal cell damage.

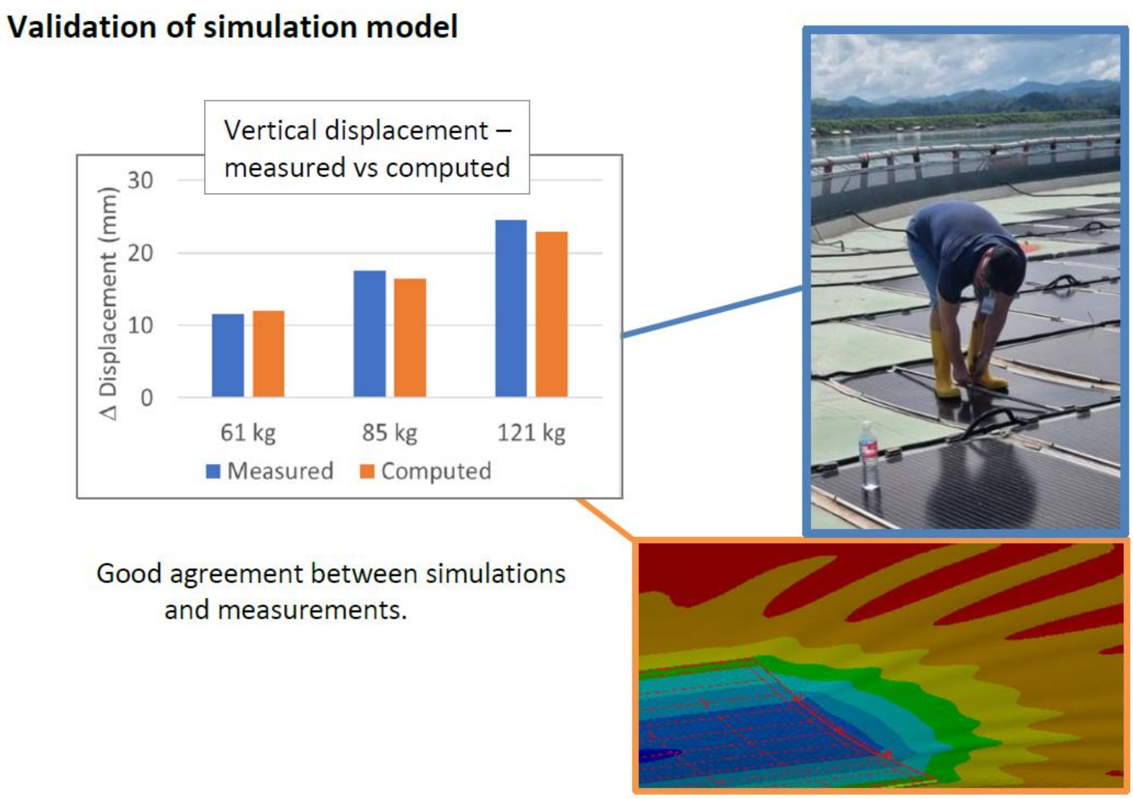


Figure 19. The simulations in Figure 18 are validated against displacement measurements. The module displacement calculated by the simulation is in good correspondence with the displacement measured by a person standing on the module on site. Source: IFE report Walkability of PV modules: stresses induced by personnel stepping on PV modules on a floating membrane [84,85]**.**

4.2.4 Moisture

Moisture ingress in PV modules is known to be one of the main contributors to mid-to-end-of-life module degradation or failure via, for example, delamination or corrosion [86–90]. Due to the presence of FPV modules on top of water bodies, there are concerns that ingress is even more severe than in land-based modules.

While the expectation of higher humidity levels above water than land seems logical, the module temperature also plays a critical role. If lower module temperatures are realised, this will slow down both the ingress rate and the amount of moisture that can diffuse into a PV module, as well as the reaction rates of several moisture-induced degradation mechanisms, such as hydrolysis and corrosion [91,92]. To understand how moisture ingress differs between FPV and land-based modules, both RH and module temperature should thus be evaluated.

There are only a few studies [34,93–95] that have compared time-series data of both temperature and humidity around FPV and land-based systems. The first three studies [34,93,94], which each investigated a single site, all focused on performance. The latter study [95] compared multi-year time series of measured temperature and humidity at different lakes and nearby land locations spread across the world and modelled the resulting moisture ingress. It showed that humidity levels are not necessarily higher over water than over land, while module temperatures could also be greater in either direction. Modelled moisture concentrations inside the modules were typically higher over land than over water. However, changes in the degree of FPV module cooling and the module position above water caused dissolved moisture content changes that were generally higher than the differences between FPV and land-based PV. One drawback of this study was that the sites did not have actual PV systems on them, thus missing the effect of the systems themselves on humidity and temperature. Further comparisons of humidity and temperature at operating FPV and land-based systems are therefore required.

Lastly, it is important to note that both liquid water and salt can affect rates of moisture ingress and/or worsen the resulting degradation. For example, both stressors can reduce adhesion [96–98], which can lead to faster moisture ingress through delaminated areas. In fact, edge sealant debonding has been observed after exposure to salt water in the field [99] or lab [100], resulting in a loss of function. Once able to reach the PV cells or metallization, liquid water can accelerate corrosion [101], while ions in salt can contribute to degradation as well in mechanisms akin to PID [102].

4.3 Best Practice and Mitigation Strategies (FPV)

Despite the early stage of development, some sources already provide guidelines and best practices to support the planning, design, and deployment of FPV systems.

4.3.1 Site Assessment

The successful deployment of FPV systems starts with a comprehensive site assessment, which must integrate solar resource analysis with detailed evaluations of water body characteristics, environmental risks, mechanical loads, and infrastructure access.

As with traditional ground-mounted systems, solar irradiance is a fundamental factor in estimating FPV energy yield. Knowledge of typical and extreme wind and wave conditions is critical for selection of FPV technology, as well as planning and designing the FPV mooring and anchoring systems [78]. Knowledge about the water depth and water level fluctuations is also a key input to the design. Wave and current conditions also influence structural loads, and wave-induced tilt changes can move the modules away from the designed inclination and orientation which can reduce energy yield via increased mismatch losses and increase mechanical stress on the system [103]. In addition, the risk of a dry water basin and/or flooding should be taken into account, to prevent damages to the structure [78].

In cold climates, the formation of ice can pose a serious risk to the FPV system, further exacerbated by the additional mechanical load that can be induced by snow. Mitigation strategies may include ice-protection structures (similar to a wave-breaker), seasonal removal, reinforced structures, or anti-icing technologies. However, in very cold regions, the risks associated with ice floes, frequent freeze/thaw cycling, and snow accumulation create operational conditions that are not yet compatible with the reliable deployment of floating solar systems. For this reason, current research suggests that waterbodies with average monthly low air temperatures below −15 °C are generally unsuitable for FPV applications [104].

Ease of access to the site and the FPV system is crucial for both installation and operation and maintenance, as it can influence system design, including the need for boat access or dedicated floating platforms, and deployment. Furthermore, proximity to existing electrical infrastructure and grid interconnection points should be assessed early, as these can significantly influence project costs and feasibility [78].

Additionally, site assessment could provide information on the potential environmental and water quality impacts of FPV installations, including possible effects on aquatic ecosystems, thermal stratification, and dissolved oxygen levels [103]. Furthermore, water quality parameters such as salinity can help assess the risk of corrosion and biofouling, both of which can affect the durability and performance of FPV components [78]. Potential conflicts with local human activities such as fishing, recreation or navigation should also be assessed as these would influence both system layout and community acceptance.

4.3.2 Component Selection

The selection of components for FPV systems must address not only standard PV performance requirements but also the specific challenges of water-based environments such as corrosion or movement-induced stresses.

Modules installed in FPV systems should be designed to resist moisture/water ingress and mechanical stress. Specifically, it has been suggested that FPV modules should consist of materials with low moisture transmission properties [79,105,106], and that the humidity-related accelerated stress tests go beyond what is currently described in IEC 61215 [78,106–108], for example by performing damp heat testing for up to 3000 hours instead of 1000, or carrying the test out at higher temperature and/or humidity. Concerns of increased moisture ingress seem to be shared by industry, with several Chinese Tier 1 companies having launched specialised FPV modules, preferably glass/glass with alternative BOMs that, amongst other things, aim to slow down moisture ingress, for example via the use of hydrophobic encapsulants and edge sealants, reduce the effect of mechanical stress by using reinforced frames and reduce the effect of fouling by using specialised coatings [100,109–114]. However, due to the early age and heavy competition in the FPV market, there is generally little open data on FPV module reliability that can substantiate the concerns of increased moisture ingress, fouling and mechanical impact. Furthermore, for near-shore or offshore applications, salt mist corrosion resistance, as tested under IEC 61701, is highly recommended [78].

In general, to design meaningful testing protocols specific to FPV module qualification, much more knowledge is required on the quantification of stressors and potential failure modes in the field. This knowledge is essential for making proper correlations with modelling studies and laboratory testing. Currently, an IEC TC 82 project group is working on defining accelerated test protocols aimed at providing guidelines for the further qualification of solar PV modules for operation in floating environments. These protocols will specifically address three different environments: inland water bodies, coastal waters, and seas and oceans.

Even when not submerged, all cables must be robust, waterproof, and resistant to elevated temperatures to prevent current leakage or electric shock. Properly rated marine-grade cables, sealed connectors, and IP67 or higher-rated junction boxes are recommended for FPV installations [103]. Factors such as cable cross-section, material type, connection layout, and ambient temperature all influence the magnitude of the resistive heating losses. Optimising cable lengths, selecting suitable conductor sizes, and minimising voltage drops are essential steps in reducing energy losses and improving economic performance [115].

The selection of mooring and anchoring components should account for site-specific factors such as water depth, varying water levels, exposure to ice, and mechanical loads. The mooring mechanism typically employs nautical-grade nylon or polyester ropes, with the lines secured at multiple corners of the floating platform [103]. A summary of different types of anchoring and mooring is reported in [116].

In cold climates, the technical requirements for FPV systems are further heightened. Product materials must be capable of resisting extremely low temperatures to prevent brittle cracking or fracture. The overall array structure requires sufficient strength to resist frost heaving, which must be verified through extensive freezing and thermal-cycling tests [116]. Additionally, the buoyancy-to-weight ratio (ratio of the buoyant force to the weight of an object) must be increased to accommodate the extra weight imposed by snow accumulation. This is typically achieved by adjusting the number or the volume of floating elements to provide greater buoyant force per unit area, ensuring both safety and structural stability [116].

4.3.3 System Design

For a classical shed-based PV design, the geometrical parameters optimised to maximise energy yield are illustrated in **Figure** 20. These parameters include the distance between two consecutive rows, referred to as pitch (dr) and the tilt angle (γ). For bifacial PV modules, the distance from the water surface (h_w) must also be considered. While the combination of pitch and tilt has a similar effect on energy production in FPVs as in GPVs, h_w has additional implications in floating systems. Specifically, h_w influences the thermal behaviour of the PV modules.

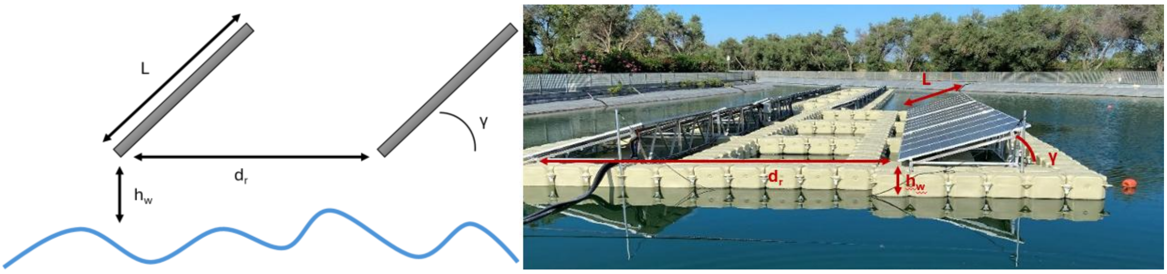


Figure 20. Relevant geometrical parameters of a shed-based FPV system design. Left: Schematic adapted from [117]**. Right: picture of a FPV installation in Catania, Italy** [118] **(Photo credit: Giuseppe Marco Tina, University of Catania).**

Evaporative cooling affects the air temperature around the modules, and evaporation also influences longwave radiation from the sky. Although this is only slightly impacted by the module's distance from the water, studies like [118] indicate that h_w primarily affects the module temperature by altering the wind speed to which the modules are exposed: greater heights generally allow better cooling.

Compared to ground-mounted systems, FPVs generally operate at lower temperatures, which can lead to improved module efficiency. The cooling mechanisms depend on the geometry of the system [119]. If modules are suspended above the water surface, cooling takes place thanks to convection and evaporation. The magnitude of the cooling depends on environmental factors (e.g., wind speed, relative humidity, and ambient temperature) as well as design parameters. For example, the effectiveness of convective cooling can be significantly reduced by obstructions that hinder air circulation beneath the PV modules, such as closed floater geometries or dense structural layouts [120]. In contrast, water-cooled FPV systems, in which modules rest directly on floating membranes in contact with the water body, allow for conductive heat transfer between the module structure and the water and can significantly enhance thermal dissipation [121,122]. However, horizontally mounted modules suffer from reduced POA irradiance at higher latitudes, which also decreases the yield [123]. Additionally, the absence of tilt hinders the effect of natural cleaning mechanisms such as rainfall, potentially increasing the impact of soiling.

Given the pitch and tilt of an FPV system, the orientation of PV modules (portrait versus landscape) also impacts energy yields, especially in bifacial systems [118]. In landscape configuration, a larger portion of the module area is closer to the water surface. In contrast, portrait configuration allows for better ventilation and greater capture of back-reflected radiation. Experimental results show that landscape bifacial configurations produced 1.23% more energy than portrait bifacial configurations. Similarly, monofacial modules in landscape orientation outperformed portrait by 1.9% [118]. However, the employment of bifacial modules in FPV applications has been slowed down by the relatively low albedo of water, which has typical values lower than 10%, limiting the bifacial gain [91]. To enhance rear-side irradiance, some FPV systems have experimented with adding dedicated reflective surfaces beneath the modules [72]. These solutions may significantly improve bifacial performance, but can be prone to biofouling, dust accumulation and other debris (Figure 21), which reduce reflectivity and increase maintenance requirements.

Figure 21. Biofouling and organic soiling observed on a reflective surface beneath a FPV system in [72].

Mechanical considerations are fundamental in FPV design, especially as wind stresses increase with larger inland water bodies. To reduce wind-induced mechanical stress on the supporting structure, FPV systems are commonly deployed at relatively low tilt angles [124], typically below 15°. Nevertheless, some commercial solutions can accommodate steeper tilts. In some cases, FPV installations have also adopted tracking systems or east–west orientations [125]. Both vertical-axis tracking (VAT) and horizontal-axis tracking (HAT) have been field-tested at sites such as Suvereto and Colignola in Italy [126]. However, despite the potential for significant yield gains, their widespread adoption remains limited due to high capital investment and maintenance costs. East-west configurations typically consist of fixed-tilt modules arranged in alternating rows with opposite azimuths to capture morning and afternoon sunlight more evenly throughout the day. This layout results in a flatter generation curve, reduces module-to-module shading and increases the installed capacity per unit area.

Wind tunnel and simulation studies have shown that the leading rows of an FPV installation are subjected to the highest aerodynamic forces, while central columns and downstream rows benefit from a shielding effect, resulting in significantly lower mechanical stress [77]. By concentrating structural reinforcement only where necessary, such optimisation strategies reduce material costs and overall system weight without compromising safety or durability.

Beyond mechanical and performance considerations, system design choices may also influence the environmental footprint of FPV installations, with important implications for permitting, monitoring, and long-term sustainability. Specifically, the key quantity linking FPV's ecological impact to its energy yield is the coverage ratio, which is the percentage of waterbody surface covered by the FPV installation.

The coverage ratio directly affects the FPV energy yield by limiting the installed capacity but may also indirectly alter the FPV energy yield by impacting the waterbody's hydrological and ecological setup. Since the coverage ratio influences light penetration into the waterbody and wind shear on its surface, it also affects the waterbody's hydrological and ecological conditions [127–130]. An example is the water surface temperature [129,131] that influences heat transfer from and to PV modules, affecting PV module temperatures and thus also module efficiency in the process. Further research is needed to assess the microclimate arising from such an interaction loop between meteorological conditions above water, the waterbody and the FPV installation.

Yet research results on the optimal coverage ratio are still tentative and dependent on the waterbody type. Therefore, permitting authorities in some countries (for instance Germany, Spain, or Italy at the time of writing) have capped permissible coverage ratios as a precautionary measure to preserve lake biodiversity. In other countries, developers must show that the desired coverage ratio is not impacting threshold values for key hydrological and ecological markers. In this case, we advise forecasting the impact of a range of coverage ratios through modelling. After installation, permitting authorities may impose monitoring of the hydrological and ecological conditions. To comply, it is advised to monitor at minimum the variables in **Table 8**, whose relevance may depend on the waterbody type. While data evaluation usually does not entail direct consequences for the site where data were collected, it may tilt local authorities' favours for subsequent FPV projects or even influence relevant legislation.

Table 8: Recommended measurements and devices for hydrological monitoring (adapted from [132]**).**

Indicators	**Measured variable**	**Measuring Device**
Hydrodynamics	Water movement	Wave Buoy
Wind	Wind speed and direction	Anemometer
Light in water column	Amount of available light	PAR sensor for continuous measurements
		Secchi disk for one-time measurements
Oxygen in water column	Concentration of oxygen	Optical (Luminescent) DO Sensor Chain (continuous at various depths)
		Exo YSI optical dissolved smart sensor. (continuous at fixed depth)
Primary production	Chlorophyll-a	Optical Fluorescence Sensor (Exo YSI Sensor)

Temperature in water column	Water temperature	Thermistor Chain (continuous at various depths)
		Exo YSI sensor (continuous at fixed depth)
Turbidity	Number of particles in water column	Exo YSI sensor (continuous at fixed depth)
Multiprobe	light, temperature, pH, redox potential, dissolved oxygen, oxygen saturation, salinity, turbidity, conductivity, and chlorophyll-a	A fixed position multiparameter probe (Aquaread 'AP7000)

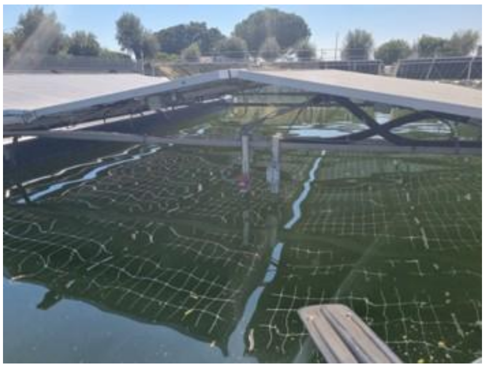
4.4 Case Studies (FPV)

4.4.1 Case Study 1: East–West-oriented FPV

Introduction

This case study presents a 16.2 kWp bifacial East–West-oriented floating PV (EW-FPV) system located at the Enel Green Power Innovation Hub & Lab in Catania, Italy (37.41°N, 15.04°E). The system is installed on an artificial lake with an area of approximately 3,000 m² and an average depth of 3.5 m. Five FPV systems are hosted on the water surface, including the EW-FPV array presented here. This system consists of 36 bifacial PV modules mounted in an East–West configuration at a tilt of 10°, with a lower-edge clearance of approximately 0.52 m above the water surface (Figure 22).

System Details and Environmental Context

	System Data	Site Data
 **Figure 22. Side view of the East-West floating PV system (EW-FPV). (Photo credit: Giuseppe Marco Tina, University of Catania)**	Category: Artificial lake Installed capacity: 16.2 kWp Number of modules: 36 Module type: Bifacial Tilt: 10° (East–West configuration) Azimuth: East / West Lowest module height above water: ~0.52 m Number of strings: 4 Rated string power: 450 W × 9 modules String open-circuit voltage: 49.55 V × 9 String voltage at MPP: 41.35 V × 9 String current at MPP: 10.88 A Number of inverters: 2 Inverter type: Three-phase with 2 DC MPPT circuits Rated DC power per inverter: 8700 W Max DC power per MPPT: 4800 W	Ref. climate: hot-summer mediterranean climate (Csa) Site type: Artificial Lake Lake surface: ~3,000 m² Average water depth: 3.5 m

The installation, previously analysed in [133], is an example of FPV systems operating in Mediterranean climates. The east–west bifacial configuration allows higher installed capacity per unit area than traditional monofacial south-facing layouts. Additionally, the EW geometry provides a flatter power profile across the day, reducing generation peaks.

The system's energy performance was monitored over a one-year period. The system is equipped with front-facing reference PV cells on each string to measure irradiance on the module plane. Furthermore, environmental data like direct normal irradiance (*DNI*), global horizontal irradiance (*GHI*), wind speed and ambient temperature as well as system data like global plane of array irradiance (G_{POA}) module temperature and DC power were collected, along with historical climate data from PVGIS for long-term comparison.

Performance and Reliability of Integrated Solution: Challenges and Mitigation

The estimation of any PV system's energy yield depends on both system's characteristics as well as local conditions. However, modelling tools and approaches differ in their assumptions and default loss factors. A breakdown of the main loss assumptions for two of the most common solutions, PVsyst and SAM, is provided in **Table 9**. As can be seen, discrepancies include higher soiling loss assumptions in SAM (5%) compared to PVsyst (3%), and differing values for incidence angle modifiers, module mismatch, and wiring losses. These modelling differences can significantly influence the simulated energy yield.

Table 9. Comparison of loss assumptions used in the simulations performed with SAM and PVsyst. *Default* indicates parameters set to the software's predefined values but modifiable by the user, whereas *auto-defined* refers to values internally calculated by the software model and not directly specified by the user.

Loss categories	SAM	PVsyst
Radiation losses	Average soiling losses =5%	Yearly soiling loss factor=3%
	Reflection (IAM) (auto-defined): o For the East system=1.9% o For the West system=2.2%	Incidence Angle Modifier (IAM) model: Fresnel, normal glass (Default), (auto defined): o For the East orientation = 3.3% o For the West orientation = 3.6%
DC side	Module temperature deviation from STC (auto-defined) = 5.35% Module mismatch = 0.5% DC wiring = 2% DC power optimiser losses= 1%	PV loss due to temperature = 5.3% Ohmic loss = 1.5% (Default) Module mismatch = 2.0% String voltage mismatch = 0.1%
AC side	AC wiring = 1% Inverter loss = 2.5%	Inverter losses = 3.8%

This case study presents an experimental and numerical analysis of the energy yield estimation using PVsyst and SAM, following the methodology illustrated in **Figure 23**.

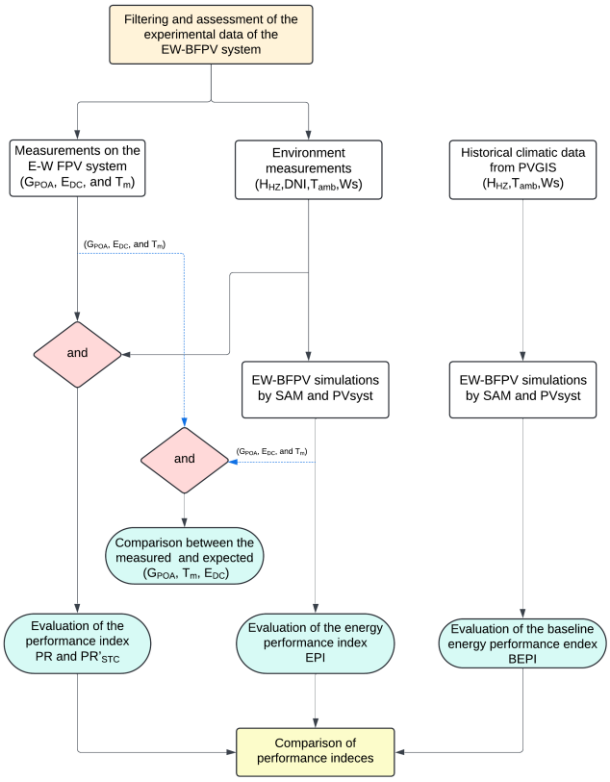


Figure 23. Flowchart of the performance evaluation methodology for the East–West bifacial floating PV (EW-BFPV) system in Catania, Italy [133]**. H_{HZ} is the Horizonal Irradiance.**

The monitoring campaign lasted one year to compare measured environmental variables and long-term historical climate data. Figure 24 presents this comparison, showing monthly averages as well as the percentage deviation between measured and historical values for key parameters such as irradiance, ambient temperature, and wind speed.

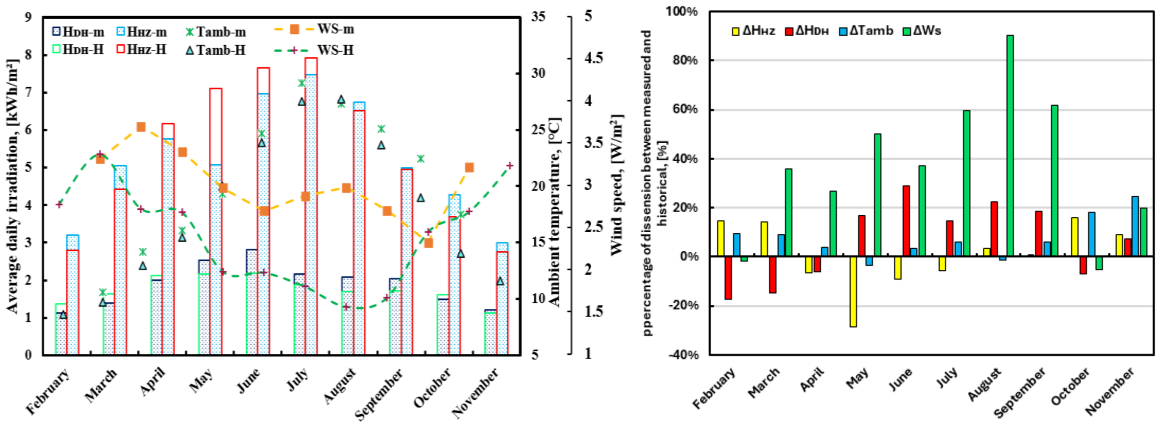


Figure 24. Comparison between historical (H) and measured (m) monthly environmental variables for the EW-BFPV system [133]**: (a) Average daily values of irradiance (Diffuse Horizontal Irradiance, H_{DH} and Horizontal Irradiance, H_{HZ}), ambient temperature (Tamb),**

and wind speed (WS); (b) Relative monthly deviation (%) between measured and historical data.

Two IEC 61724 indicators were evaluated for the EW-BFPV system using SAM and PVsyst to quantify software-related uncertainty [134]. The Energy Performance Index (EPI) expresses the ratio of the measured yield to the expected yield, calculated using actual weather data and the Baseline Energy Performance Index (BEPI) is defined as the ratio of measured output to predicted output, calculated using representative conditions for the location [133].

Figure 25Figure 25Figure 25A side-by-side comparison of the monthly EPI and BEPI indicators (Figure 25) highlights the consistency between the two modelling tools and also reveals seasonal variations driven by both irradiance conditions and model assumptions. As shown in the left plot of Figure 25, monthly EPI values from the two tools generally converge, with average differences of 0.020–0.025 (east: 0.97 vs. 0.967; west: 0.96 vs. 0.94). Summer results remain within 0.83–0.98, with inter-tool differences limited to a few percentage points.

The BEPI, computed from long-term historical weather data, spans 0.7182–1.1408 (right plot of Figure 25). Average differences between SAM and PVsyst are 0.02. Overall, SAM and PVsyst exhibit strong convergence but imply an inherent 2%–4% uncertainty in EPI/BEPI estimation, which should be considered when interpreting deviations within the IEC 61724 framework and in long-term performance monitoring.

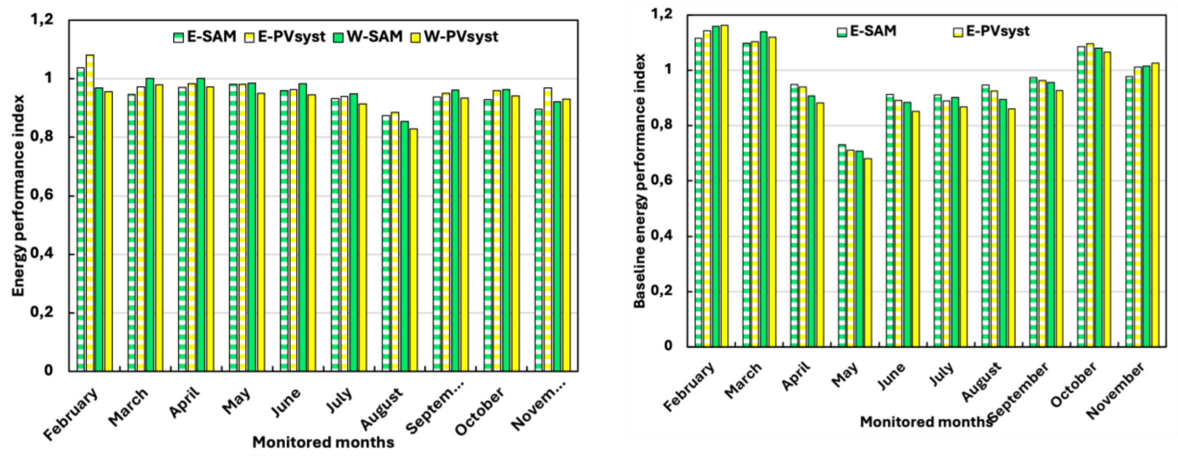


Figure 25. Monthly IEC 61724 performance indices of the EW-BFPV system; (left) EPI (SAM vs. PVsyst) and (right) BEPI (SAM vs. PVsyst) for east and west orientations [133]**.**

Despite the similar qualitative results, the quantitative analysis confirmed that model-based performance assessments are still sensitive to the choice of simulation tool and embedded assumptions. This is due to the dissimilar models, assumptions and input data. Given the high humidity observed at the Catania site, this may partially explain the divergence in module temperature predictions between the two tools. Overall, the use of fixed loss factors could simplify year-over-year comparisons but may obscure real degradation trends or seasonal variability. The study demonstrates that while both used tools can provide reasonably accurate results, one consistently showed a slight superiority in its predictive capabilities. This is mainly related to the thermal models used.

4.4.2 Case study 2: Alpine FPV

Introduction

There is growing interest in assessing the PV (and FPV) performance and resilience in high-altitude environments. An example of FPV operating under extreme environmental conditions is the installation at Lake Les Toules, a high-altitude reservoir in the Swiss Alps. This demonstration project, developed by Romande Energie SA, was conceived as a pilot to evaluate the technical and economic feasibility of FPV systems in alpine regions [135].

Lake Les Toules is an artificial lake located 1,810 meters above sea level. The site experiences a broad range of environmental stressors, including snowfalls of up to 2 meters within 24 hours, ice thickness reaching 60 cm, and wind speeds up to 42.8 m/s. Ambient temperatures range from −25°C to 30°C. These are far from being the typical climatic conditions for conventional FPV systems and pose significant challenges to structural integrity, energy yield predictability and year-round operability. Therefore, maintenance costs are largely affected by these conditions.

The system, installed in 2019, spans 2,240 m² and is made of 1,400 frameless bifacial PV modules (Figure 26), for a total capacity of 448 kWp. It features a south-oriented dual-tilt configuration: during the mid-June to mid-December period, the array floats on the lake at a tilt of 37°. During the remainder of the year, the system rests on the reservoir bed with a winter tilt angle of 32°.

System Details and Environmental Context

Figure 26. Aerial view of the system [136]**.**

System data	Site data
Category: artificial lake	Ref. climate: subarctic/ alpine climate (Dfc)
Year of installation: 2019	Altitude: 1,810 m
Surface: 2,240 m²	Irradiance: up to 1,300 W/m²
Size: 448 kWp	Temperature: -25 to 30 °C
Module n°: 1,400	Wind: up to 42.8 m/s *
Module type: frameless bifacial	Snow: up to 2 m in 24 h
Tilt: 37° (32°) *	Ice: up to 60 cm ice layer
Azimuth: south	
** two tilt angles, as the structure floats from mid-June to mid-December and remains on a platform at the bottom of the reservoir for the other half of the year with its own tilt angle*	** corresponding to a 50-year return period*

Installing FPV on dammed alpine lakes makes it possible to produce renewable energy without consuming additional land or altering the natural landscape. Reservoirs that are periodically emptied provide an opportunity for FPV systems to alternate between floating and grounded states, combining seasonal storage with solar production. High-altitude conditions offer further advantages for winter performance due to enhanced ground-reflected irradiance from snow albedo and lower operating temperatures. These benefits are counterbalanced by higher mechanical loads and limited accessibility.

Performance and Reliability of Integrated Solution: Challenges and Mitigation

Operating at high altitude on an artificial reservoir introduces several site-specific challenges. Seasonal conditions lead to cyclical transitions between floating and grounded configurations, which induce vertical displacement and the risk of structural deformation. Heavy snowfall and drifting can generate asymmetric loads and prolonged accumulation. The formation of ice up to 60 cm thick introduces dynamic forces acting on both anchoring and grounding components. Winds can reach speeds of 42.8 m/s, requiring aerodynamic optimisation and reinforced structures. The winter conditions also complicate maintenance operations and prolong downtime.

During the site assessment phase, a land-based pilot plant was deployed near the reservoir. This preliminary installation was used to characterise the environmental conditions, especially snow accumulation and wind exposure, and to test different PV module types and mounting strategies under controlled but representative conditions. Additionally, particular attention was given to the ground configuration of the lakebed, which needed to be sufficiently flat and stable to accommodate seasonal grounding of the system. Uneven terrain would indeed result in localised stress points during the transition from floating to grounded state, increasing the risk of structural deformation and platform instability. While artificial levelling of the lakebed could mitigate these issues, it was deemed potentially cost-prohibitive and environmentally sensitive.

In terms of component selection, bifacial PV modules were chosen to capitalise on the high winter albedo effect and to facilitate snow melting. A frameless design was preferred to minimise snow accumulation and to enhance passive snow shedding. From an economic perspective, PV modules represented only 5 to 10% of the total costs of the system. For this reason, higher-performance modules were adopted. Given the harsher-than-usual operating environment, the procurement plan also accounted for a larger stock of spare parts, to minimise downtime in case of component failures.

The system design phase focused on developing a platform capable of withstanding both buoyant and grounded configurations. Reinforced floaters were used to handle partial support and asymmetrical loads. Additionally, row spacing was compacted to minimise wind exposure, and structural streamlining was applied to enhance the aerodynamic performance of the array.

Field experience has highlighted that steep tilt angles alone are not sufficient to ensure effective snow shedding, because snow compaction beneath the modules can hinder gravitational release. The height above ground is a main parameter, allowing to store accumulated snow. Furthermore, snowdrift simulations must be conducted to assess redesign options and site-specific mitigation strategies. Among the solutions under evaluation are the use of upstream physical barriers, such as hedgerows or snow nets, aimed at limiting wind-driven accumulation. On the actual array, this snow accumulation provoked multiple damages.

Another key area of ongoing refinement is related to the mechanical decoupling of system functions. The initial platform design, capable of transitioning between floating and grounded configurations, has to be further optimised by separating the flotation elements from the structural support and anchoring components. Anchoring must be reengineered to operate independently of grounding loads, reducing the risk of stress concentrations during seasonal transitions. In parallel, adaptive foundation solutions have to be considered to accommodate uneven terrain without compromising stability.

Ice interaction has proven to be one of the most critical challenges in this environment. Direct contact between metallic grounding elements and seasonal ice cover has led to design adjustments, including repositioning and insulating the affected components. To better anticipate potential risks, structural modelling efforts are underway to simulate extreme ice scenarios, such as entrainment and adhesion events. Building on this work, future iterations of the system should incorporate flexible joints and sacrificial components designed to absorb and mitigate ice-induced mechanical stress, ensuring that localised damage does not compromise the overall integrity of the array.

Simulation results initially estimated a FPV annual yield of 1,469 kWh/kWp, which already included near shading-, low-water albedo- and tilt-related losses (Figure 27). However, the measured performance reached 1,418 kWh/kWp, a difference mainly due to snow coverage. Nonetheless, this represented an overall gain of 29.1% compared to a non-alpine plant.

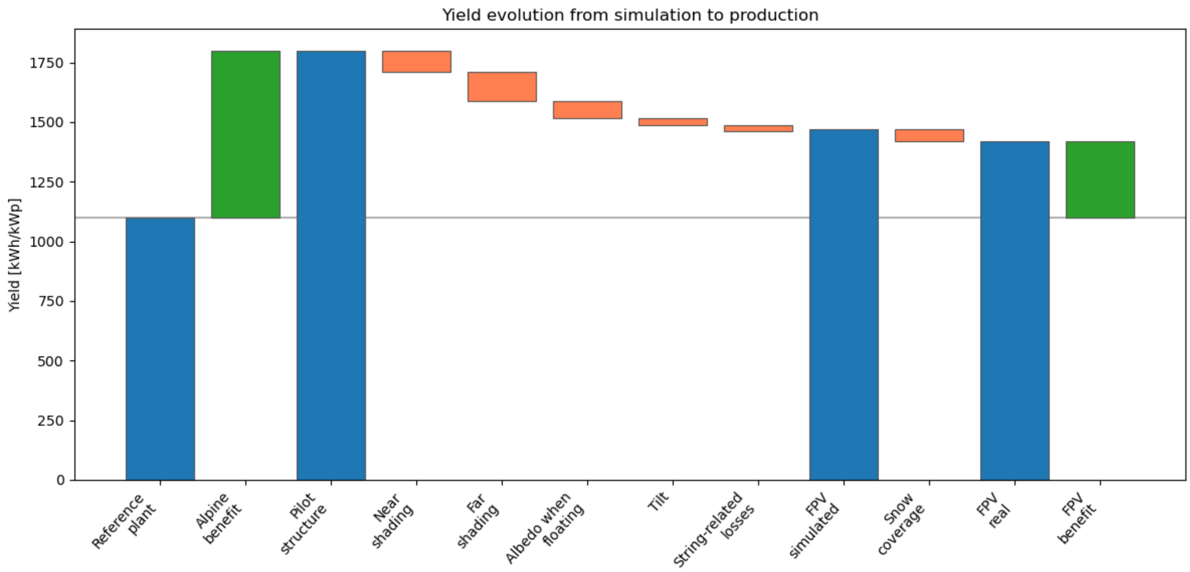


Figure 27. Simulated versus actual energy yield at Lake Les Toules FPV installation. Adapted from [137]**.**

The demonstration project on lake Les Toules proved the technical feasibility of alpine FPV and especially the production increase. Yet, the return of experience highlighted several issues that must be addressed before being able to expand this solution to a larger scale. One of the main issues is the integrity of the PV modules under wind and snow coverage. The operating costs of such an array must as well be optimized. Finally, national and international legal frameworks for such installations are not yet available.

5 OPTIMISATION OF MODULE/SYSTEM DESIGN FOR AGRIVOLTAICS

Agrivoltaic (AV) systems co-locate agricultural activities or land management practices (e.g., livestock grazing or biodiversity enhancement measures) with PV electricity production, reducing land-use competition between food and electricity production.

A clear definition of AV systems is essential, as they represent a novel technology or system integration involving multiple stakeholders, often with conflicting objectives. Such a definition is also crucial for establishing legal frameworks to overcome regulatory barriers, ensure flexibility for both farmers and PV developers, and unlock the full potential benefits of AV systems [4]. The previous report by IEA PVPS Task 13 [4] classifies the various definitions of AV systems based on four main criteria: the increase of the land use efficiency, the share of light between photosynthesis and PV modules, the intensity of agricultural activities, and the synergies and interaction between agriculture and electricity production [4]. Depending upon the degree of fulfilment of those criteria, the definition of AV systems can be narrow (i.e., high degree of fulfilment) or broad (e.g., low or no degree of fulfilment), as depicted in Figure 28. For instance, in a narrow definition of AV systems, only overhead AV systems combined with crop production can be considered as AV systems because they guarantee high land use efficiency, clear sharing of light between the agricultural and energy activities, high intensity of agricultural practices, and measurable synergies (e.g., benefits of shading from PV modules to crops).

Although the definition of AV systems varies across national laws, regulations, and standards, this chapter adopts a broader definition that includes AV systems beyond cropping systems. This incorporates AV systems integrated with animal husbandry, enabling further examination of potential stressors associated with combining PV systems with livestock.

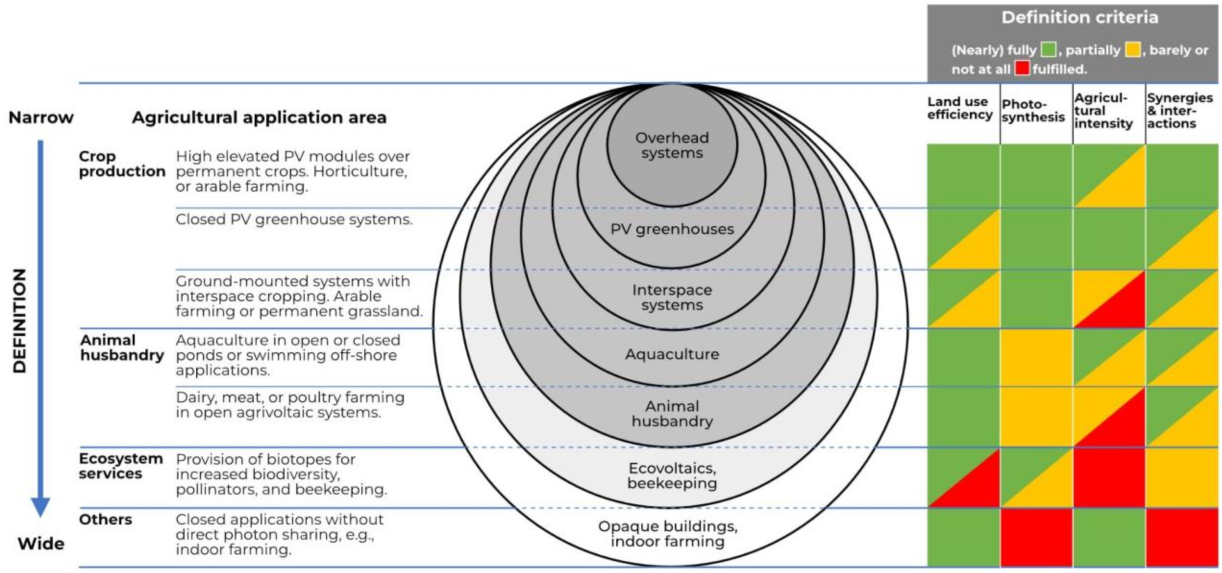


Figure 28: Classification of the AV systems definitions based on four principles, including land use efficiency, light sharing, agricultural intensity, and synergies and interactions [4].

The co-location of agricultural activities and PV production is achieved in most configurations by using specialised PV system designs or operation for the systems equipped with trackers. These arrangements allow traditional agricultural practices, such as crop cultivation and livestock grazing, with minimal adjustments (e.g., standard agricultural machinery can still be used). This ensures high compatibility between agriculture and PV systems. A classification of AV systems based on their layout and application is illustrated in Figure 29. Additionally, further classifications have been discussed in the literature, particularly regarding the transparency of PV modules, which is a crucial design element for ensuring optimal crop performance [138].

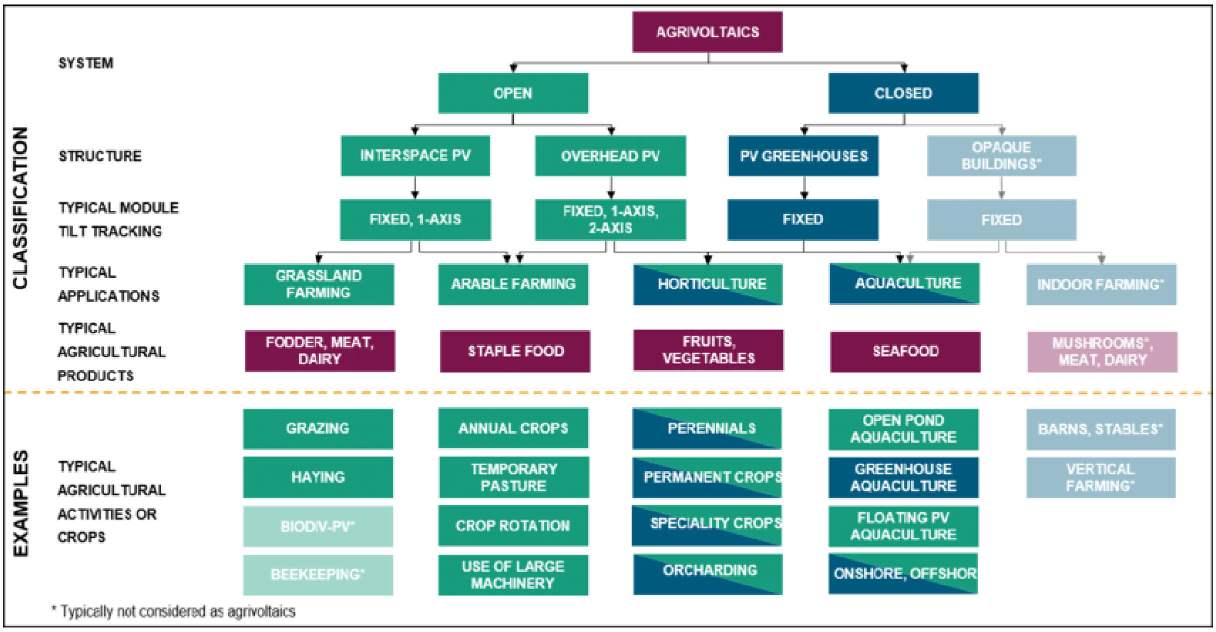


Figure 29: Classification of AV systems layouts [139,140]**.**

This chapter first introduces the key performance indicators (KPIs) for AV systems, which differ from those of conventional PV systems, which focus solely on solar energy conversion. Subsequently, it provides an overview of application-specific stressors, which include factors related to agriculture, weather, biodiversity, and system design. The chapter then discusses potential mitigation strategies from the perspectives of site assessment, component selection, and system design. Finally, two case studies from the Nordic region are presented, highlighting the challenges faced and the strategies implemented to overcome them.

5.1 Application-Specific Needs and Key Performance Indicators (AV)

As compared to conventional PV systems, AV systems' KPIs span from crop production to electricity production, including microclimate, land use efficiency, aesthetics, and water conservation KPIs.

From an agronomic perspective, typical KPIs include the absolute crop yield (t/ha) and the relative crop yield, defined as the ratio of yield under the AV system to yield under non-shading reference conditions. The relative crop yield is an important KPI adopted in several legal frameworks to guarantee the continuity of agricultural activities [141]. Another important agronomic KPI is the yield coefficient of variation (CV), which measures and compares crop yield stability under AV systems versus open-field conditions. For instance, Amaducci et al. [142] performed simulations of maize yield under AV systems for the period 1976–2014 and found that the CV of maize under AV systems was significantly lower than that under open-field conditions, highlighting the substantial potential of AV systems for yield stabilisation. The agronomic performance depends on the microclimate generated by the PV modules' shading; thus, several microclimatic KPIs are important to consider, among them, the irradiation reduction [143], the ambient temperature variation [144], and the precipitation distribution [145] represent some of the most important. Another important KPI, given the co-location of PV and crop production, is water use. The shading from the PV modules alters the ground irradiation budget, reducing evapotranspiration and, in turn, water consumption [144]. A commonly used KPI is the land equivalent ratio, defined as the summation of the relative crop yield and relative electricity yield [146]. Connected to the LER, another important KPI for land-use is the buffer zone and the corresponding land losses, defined as the land not used under an AV system to ensure the safe coexistence of agricultural and energy activities [147].

From an electricity production perspective, KPIs used for conventional PV systems also apply to AV systems. These include the specific energy yield (kWh/kW$_p$/year), the performance ratio, the capacity factor, and the degradation rate. Important aspects and related KPIs to consider in AV settings include soiling losses and PV module operating temperature. The presence of agricultural activities inevitably leads to soiling events on PV systems and thus losses, yet the literature on the topic is extremely limited [141,148–150]. On the other hand, the crop evapotranspiration in AV systems can reduce the operating temperature of PV modules through evaporative cooling effects, leading to electricity yield gains [151].

A preliminary overview of KPIs for AV systems was provided in the IEA PVPS Task 13 report titled “Dual Land Use for Agriculture and Solar Power Production: Overview and Performance of Agrivoltaic Systems” [4], which includes both agricultural and energy performance KPIs. A more in-depth overview of KPIs for AV systems, including aesthetic or integrated KPIs has been provided in the IEA-PVPS report “PV Project Decisions: Quality, Performance, and Economic Value” [152].

5.2 Stressors and Typical Problems (AV)

Due to their dual-use configuration, AV systems are exposed to a unique combination of stressors that emerge from the interaction between PV infrastructure and agricultural operations. Nevertheless, the typical stressors affecting GPV systems still apply and may, in certain instances, be intensified. These stressors can be broadly classified as: (i) main stressors and (ii) site-specific stressors. Main stressors are the common, recurring challenges inherent in the dual-use nature of AV systems. Site-specific stressors, by contrast, are highly dependent on the local geography, climate, soil type, and agricultural practices. This category also includes low-probability but high-impact stressors, such as rare, extreme events that, although infrequent, can cause severe damage to both the agricultural and energy components of the system.

An overview of stressors in AV systems, along with the adverse effects, failures, and degradation they can cause to agricultural activities and PV electricity production, is summarised in Figure 30.

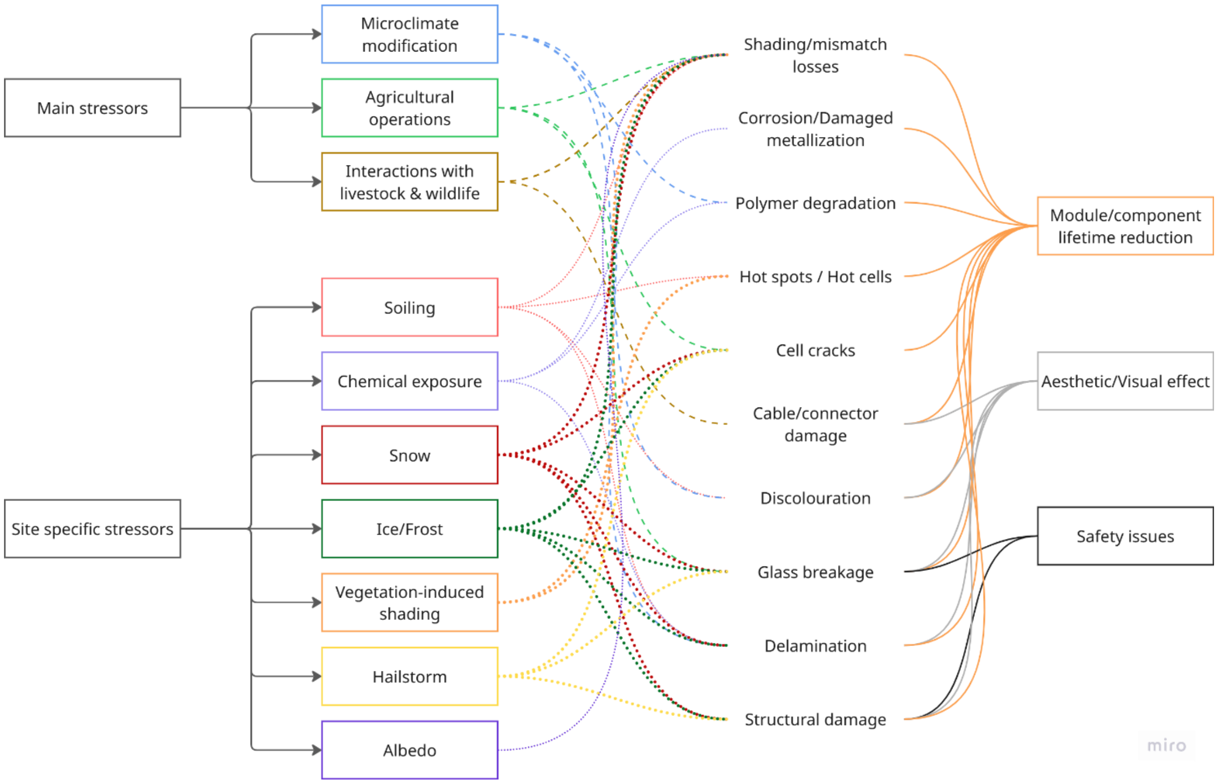


Figure 30: Stress factors acting on AV systems, along with the associated adverse effects, degradation, and failures on both agricultural activities and PV electricity production.

A parallel classification of AV-related stressors can be carried out based on the origin/source of these stressors: agricultural-related stressors (e.g., increased soiling due to agricultural practices, damage from agricultural machinery, use of chemicals fertilisers and herbicides, livestock interaction with PV modules and structures, shading from crops on PV modules due to variation in crop canopy, high humidity because of crop evapotranspiration), weather-related stressors (e.g., wind speed, hail and snow load, extreme weather events), biodiversity related stressors (e.g., wild-animal interaction with PV modules and structures), and system-design-related stressors (e.g., non-uniform light, temperature and rain distribution on crops and ground due to the PV module density and system configuration, integration with parallel infrastructures such as irrigation systems).

5.2.1 Microclimate

A key agronomic challenge in AV systems is the alteration of the microclimate beneath and around PV structures [153]. Microclimate is defined as the variation in specific environmental conditions, such as irradiation, temperature, relative humidity, wind speed, precipitation, and soil moisture, within AV systems compared to the surrounding area [141]. Shading can protect crops from heat and water stress, a major benefit of AV systems in warming climates or during periods of heat stress [151]. However, AV systems can simultaneously decrease ground and crop temperatures, alter light, wind, and precipitation distributions, and raise local humidity, with negative effects on crop yield [141,143,154,155]. Poorly designed PV modules, high PV module density, incorrect row spacing, or improper orientation can cause excessive or uneven shading, reducing photosynthetic activity [141]. Closely tied to these dynamics is the altered water distribution [145]. Since PV panels intercept rainfall, they can create uneven moisture patches in the field. Areas closer to the modules may receive little to no rainfall, while runoff from the edges of the PV modules can cause erosion, puddling, or irregular watering patterns, ultimately affecting soil health and fertility. These patterns influence crop water availability, potentially creating zones of both excessive moisture and localised drought. Without appropriate solutions and adaptation strategies, this can lead to significant variability in crop growth, negatively affecting both yield and quality. These heterogeneous growing conditions can lead to nonuniform crop development across the field [141], which may complicate agricultural practices such as fertilizer and pesticide applications and harvest timing. For certain crop species in specific climates, this can increase susceptibility to fungal pathogens, meaning the microclimate advantage can quickly become a plant health risk unless carefully monitored and managed [156]. On the agronomic side, the altered microenvironment beneath PV arrays can influence soil fertility. Microclimatic alterations beneath PV arrays can also affect soil processes, such as soil biological activity and nutrient cycling, with possible implications for crop performance [157]. Microenvironmental changes may also affect pollinators and soil biota, including pollinator visitation, insect community composition, and the structure of microbial and invertebrate communities, all of which are fundamental to soil health [158].

5.2.2 Agricultural Operations

Operational incompatibility between PV electricity production and agricultural activities represents a main stressor for AV systems. Agricultural activities (e.g., cropping or grazing) and PV electricity production have different priorities that must be balanced. AV systems that do not consider agricultural requirements before installation and for the lifetime of the project may hinder routine field operations, leading to inefficiencies in agricultural practices and PV safety issues [141]. For example, insufficient clearance between PV module rows or bulky mounting structures can obstruct the passage of farm equipment, especially large harvesters and planters, increasing the risk of damage to PV modules, PV system components, structures and machinery. Poorly planned PV installation, operation and maintenance activities can substantially affect soil compaction, leading to lower crop performance [141]. Agricultural compatibility issues can be minimised by engaging farmers early in the AV system design stage. This would also facilitate reducing safety issues and help farmers avoid modifying established agricultural practices.

One major challenge for PV elements in AV settings concerns agricultural machinery operation, especially for AV cropping systems, as the movement of tractors, harvesters, and other equipment, such as rotary implements, around and beneath the PV structures can pose risks for accidental damage [141]. At the same time, restricted access created by mounting heights or row spacing can complicate routine maintenance of the PV components themselves. The severity of these issues depends heavily on farm-specific practices and the design choices made during system installation. The implementation of no-till practices in AV systems can lower PV system operation and maintenance costs by reducing damaging risks [159].

5.2.3 Soiling

Soiling of PV modules by dust, soil particles, and pollen lifted by wind and field activities poses a direct threat to electricity yield. As indicated in the specific IEA PVPS report on AV systems [4], soiling is likely to be one of the main stressors affecting the electrical performance of AV cropping systems. In this report, soiling is considered a site-specific stressor in AV systems because it is mostly associated with AV cropping systems, and less with other configurations (e.g., AV grazing systems). Factors such as pollen during the flowering season and certain crop management practices (e.g., ploughing, herbicide use, and chemical fertilisers application) can significantly increase soiling levels. This highlights the importance of establishing optimal cleaning schedules that align with the timing of agricultural activities to minimise losses and prevent follow-up failures, such as hot spots or mismatch effects caused by severe or non-uniform soiling within the installation. Conversely, compared with the mature state of soiling research for traditional GPV systems, research on AV remains scarce, as noted by Zainali et al. [160]. Up until now, only two studies have addressed the topic, although not in much depth. The study by Jung et al. [148] presented experimental results on the impact of soiling on the PV performance of an AV installation in Chile. Their findings showed soiling rates of 0.17%/day to 0.35%/day and a maximum soiling loss of 30.2% for a module that was never cleaned, highlighting the limited effectiveness of rain for cleaning. Gebhardt et al. [149] evaluated the impact of soiling on AV installations in Germany across configurations (i.e., overhead, tracked, and vertical AV) and crops. They found transmittance losses ranging from 0.1% to 47%, with high heterogeneity across configurations and samples. A particularity of AV systems is the greater accumulation of soiling on the rear side of the modules compared to conventional GPV systems, due to heavy machinery passing beneath them. In AV installations, soiling tends to be stickier, thus minimising the potential natural cleaning effect of rain events. Keeping modules clean, therefore, becomes an essential operational task, adding another layer of maintenance to the dual-use system.

5.2.4 Chemical Exposure

AV systems, particularly AV cropping systems, must contend with corrosion and material degradation. Agricultural environments are chemically active, and common inputs such as fertilizers and pesticides can accelerate the corrosion of metal components or degrade polymer-based materials, in conjunction with higher soil moisture rates compared to conventional GPV systems [161]. Higher moisture rates due to the combination of crops, and in some cases, with irrigation systems, pose further threats to PV modules and metallic structures. Over time, this not only increases maintenance needs but can also threaten the integrity of the PV infrastructure. Figure 31 illustrates corrosion observed at an AV research facility in Almería, Spain, likely resulting from exposure to fertilizers that increase chloride and ammonia concentrations on metallic surfaces, insufficient corrosion protection (e.g., inadequate galvanization thickness during installation), or a combination of both factors.

Figure 31: Corrosion visible on the structural elements of an elevated AV research installation after only one year of operation in Almería, Spain. (Photo credit: Álvaro Fernández Solas, DLR)

5.2.5 Animal Interaction

Another site- and application-specific stressor arises from direct animal interactions [162]. Livestock grazing combined with PV systems, as well as wildlife entering the fields (more likely in AV settings rather than conventional GPV systems due to the presence of growing crops), can increase soiling losses, disturb or damage cables, or even damage PV modules and structural components. Animals can also affect the crops grown between or beneath the arrays, adding another layer of unpredictability to the system's performance.

5.2.6 Albedo

In combination with AV cropping systems, albedo can represent both a stressor and a booster for PV performance, depending on crop type and crop management practices [141]. Albedo refers to the fraction of solar irradiance that is reflected by the ground and is influenced by factors such as ground cover and the angular and spectral properties of the irradiance [163]. It plays an important role in the energy performance of PV systems, especially with PV systems equipped with bifacial PV modules, and it plays an even more important role in AV systems because the ground cover can vary substantially over time, based on crop type and crop management strategies, such as crop rotation. This variation in albedo, in conjunction with the annual variation in solar irradiation, can cause a reduction or increase in PV electricity supply. For example, bare soil is marked out by some of the lowest albedo values. Thus, practices like tilling or especially ploughing in AV systems that can expose PV modules to some of the lowest albedo values should be performed, if possible, during months marked by lower solar irradiation values. Like soiling and chemical exposure, the effect of albedo is considered in this report a site-specific stressor because its variation is mostly associated with AV cropping systems.

5.2.7 Vegetation

Intermittent shading, especially from tall crops or vegetation near the supporting structure (see Figure 32), can introduce complex, rapidly changing shadow patterns on the PV modules. These transient shadows may cause electrical mismatch within the arrays, leading to power fluctuations and increasing the likelihood of localised hot spots that can reduce PV module lifespan if left unmanaged.

Figure 32: Ley grass not removed by the forage harvester close to the vertical AV research system in Kärrbo Prästgård, Sweden. (Photo credit: Pietro Elia Campana, Mälardalen University)

5.2.8 Low-Probability High-Impact Stressors

AV installations, both supporting structures and PV modules, must also endure local climatic loads, which vary widely from site to site, more than conventional GPV systems due to the peculiarity connected to AV system configurations. From a structural point of view, elevated structures from overhead AV systems make them particularly sensitive to high winds, storms, or heavy snowfall. Similarly, vertical AV systems can be more severely affected by high winds as compared to conventional GPV systems [164]. These conditions demand more robust engineering solutions to ensure long-term stability and operational safety [165].

Among these, severe meteorological occurrences, particularly large hailstorms, represent one of the most catastrophic/harmful risks. Because AV systems integrate PV infrastructure directly into agricultural production zones, an extreme event can simultaneously impact both systems. A single hailstorm can shatter module glass, deform mounting structures, and damage electrical connections, while also destroying or severely damaging the crops. This dual vulnerability amplifies economic losses and can undermine the installation's long-term viability. The threat is compounded by the fact that AV systems often span large surface areas, are based on novel structural configurations, and are elevated, making them more exposed to hail impacts, high winds, and other severe weather. Another important low-probability but high-impact event relates to fire risk. Fire hazard is a well-known risk for conventional GPV systems in relation to vegetation mismanagement [166]. In AV systems, especially in AV cropping systems, the risk of fire hazard is magnified by the presence of crops that, at particular growing stages (e.g., ripening and grain filling stages for wheat) and after harvesting, are highly flammable [167]. Wildfires can have direct and indirect effects on PV modules by igniting PV modules or affecting the production due to aerosols released in the atmosphere, affecting PV performances [168]. Fire hazard poses an important risk to both crops and PV systems, with PV systems incurring the greatest economic damage. The risk of fires in AV systems is not only connected with wildfires but also with PV self-ignition, mostly caused by hotspots, installation faults, and elevated temperatures [169]. It is important to note that, regardless of the cause, fires involving PV modules can result in significant releases of toxic chemicals into the atmosphere and into the ground, with subsequent impacts on soil and groundwater quality. In combination with water-based fire-extinguishing methods, these effects can substantially reduce the site's agricultural potential. As climate variability intensifies, the frequency and severity of hailstorms and other extreme weather phenomena, such as droughts, are expected to increase [165], making comprehensive risk mitigation strategies indispensable for future AV development.

5.3 Best Practice and Mitigation Strategies (AV)

5.3.1 Site Assessment

For AV installations, the site suitability assessment needs to go beyond the typical criteria used for conventional GPV systems, such as irradiation conditions, topography aspects (e.g., slope and elevation), proximity to the electricity grid, and distances from airports, settlements or water bodies [170]. In countries with specific AV regulations, such as Germany [171], site selection must also comply with legal requirements. Recent studies have specifically assessed the spatial potential and site selection for AV projects using Geographic Information Systems (GIS) and Analytic Hierarchy Process (AHP) approaches [172,173]. This subsection aims to describe the key factors to consider when evaluating site suitability for AV systems, emphasizing the main differences from conventional GPV installations.

Agronomic factors also need to be considered, including soil type, soil classification, evapotranspiration rates, and water availability [141]. Regarding soil properties and compared to conventional GPV systems, additional chemical and nutrient analyses should be performed to assess soil fertility for AV projects. Rösch and Fakharizadehshirazi [174] used as a further criterion for the site suitability of AV systems, the Soil Quality Rating [175] defined as the yield potential with respect to the most productive area. These supplementary analyses should be tailored to the crop species likely to be cultivated in specific areas. Crop characteristics and their associated management practices can also influence site selection [173]. For example, certain mandatory tillage operations that require heavy machinery may significantly increase installation costs, as they demand highly customised foundations and support structures, thus potentially making AV deployment unfeasible in some areas. In addition, other important factors, such as fire safety considerations, should be included in site assessments. Compared to conventional GPV systems, AV installations typically involve greater amounts of biomass, underscoring the need for thorough safety evaluations. These assessments may lead to costly preventive measures that could limit the suitability of certain locations for AV development.

Furthermore, social acceptance may represent an additional criterion influencing site selection, as public perceptions of AV systems can differ from those of conventional GPV installations [176]. In AV systems, site selection should consider not only the social acceptance of nearby residents but, especially, that of farmers, who can potentially benefit economically from AV systems, such as by renting out their land. A key feature of AV is its potential to enhance public support for PV installations [177]. To effectively increase acceptance rates, it is essential to gather input and feedback from stakeholders. This not only helps identify suitable areas for AV deployment but also reveals public perceptions and existing barriers, thereby enabling more tailored system designs and business models that better attract farmers.

Biodiversity, landscape aesthetics, and ecosystem conservation are other key criteria in the siting of AV systems. While several studies have examined this aspect in the context of conventional GPV, research specific to AV remains limited [178–181]. Despite AV’s potential environmental advantages over conventional GPV systems [182], the foundations and structural components still affect soil health and biodiversity, warranting evaluation [183]. Potential soil compaction during installation should be considered, as it can lead to significant changes in soil fertility and biodiversity in the first years of operation [184]. Also, PV modules and their supporting structure can contribute to habitat alteration. The potential changes should be assessed [185], especially in those areas with endangered species [186]. Key assessment aspects include species diversity and abundance, potential impacts on behavioural patterns, and changes in reproductive success and survival rates. An appropriate biodiversity assessment can also help identify measures, such as insect nets [187] and other pollinator attraction approaches [188], which can be implemented to prevent damage and ensure sustainable AV systems. Other important aspects to be considered for the siting of AV systems include the potential to guarantee food and energy security in impoverished areas and to counter rural depopulation [141]. One of the major challenges in assessing the suitability of AV systems for a site is defining the implementation purpose and the socio-environmental, technical, and economic priorities. This definition is likely to be set by national, regional, or local contexts and priorities, and thus it is likely to vary over space and time [141]. An example can be connected to the soil quality criterion. High-quality soils can be prioritised for AV system sites if the goal is to maximise land-use efficiency and protect those soils from conventional GPV systems [174]. On the other hand, AV systems can be incentivised in low-quality soil areas if the primary purpose of the installation is to revitalize marginal lands and avoid competing with food production [189,190].

When siting AV systems, it is also essential to assess the risk and likelihood of extreme weather events at the proposed location. This evaluation can help identify potential impacts and enable developers and installation companies to adapt system designs and implement preventive measures accordingly. The extent of these adaptations should be proportional to the identified risks' probability and severity, balancing the associated costs with the expected benefits to ensure long-term system resilience and performance.

5.3.2 Component Selection

In most AV system legal definitions, agriculture must remain the primary purpose, and thus, agriculture must be maintained throughout the system's entire lifetime [171,191–193]. In some standards, such as the Italian UNI/PdR 148 [194], both the relative performance of agriculture and energy compared to mono-use of land (e.g., only agriculture or only PV production) must be maintained. At the PV module level, to mitigate the negative effects of shading on crop yield, it may be beneficial to select PV modules with higher transparencies, depending on the layout of the system, the climate, and the specific crops or crop rotations involved [141]. While higher transparency in PV modules may allow for a better integration of crops and PV systems, the cost of semi-transparent PV modules is generally higher than that of conventional opaque modules [195]. Semi-transparent PV modules can also be engineered not only to control the quantity of light, but also to control the quality of light in the so-called wavelength-selective PV modules [138]. The efficiency and reliability of PV modules are essential to the long-term performance of the system's electricity production, as they are in other PV applications.

Given the co-location in proximity to agricultural activities, PV modules, as well as other key components of the system, are typically stressed more than other conventional GPV system applications due to the high risk of direct and indirect damages (e.g., stones from rotary machinery or the presence of livestock), higher moisture rates due to the greater evaporation rates, and higher chemical deterioration exposure (e.g., connected to the spray of herbicides or the spread of fertilizers) [4,141].

At a PV system level, the selection of the layout and the design of the PV system (e.g., PV module density), or the PV system operation for those equipped with trackers, must be accurately customised to guarantee agricultural compatibility and crop production performances [141].

Mechanical Damage
Agricultural PV modules are exposed to unique mechanical damage risks compared to conventional installations, arising from both farming activities and environmental conditions [196–198]. Potential damage sources include impacts from agricultural machinery, collisions with irrigation booms, contact with tall crops, and interactions with livestock or birds. As with any other conventional GPV systems, additional potential damage sources include weather-related stresses such as hail, heavy snow loads, strong winds, or abrasion from dust and sand. Additional risks stem from inadequate mounting structures, improper installation of mounting structures, poor handling during maintenance, and vandalism. Mitigation measures include raising and reinforcing module mounting structures to keep them clear of agricultural equipment and animals, using tempered or laminated glass with a higher thickness for improved hail and impact resistance [197], designing robust frames with higher load ratings, applying surface coatings for abrasion resistance, and ensuring proper spacing between modules and crop zones.

Light Management
One of the main limitations of AV systems is the uncertainty in agricultural performance due to the light reduction from conventional opaque PV modules, although this is specific to climate, crop, and system layout [141]. To meet the light requirements of crops, two main strategies are generally adopted: reducing the opaque PV module density (i.e., the number of PV modules per row and/or the number of rows) or deploying semi-transparent PV modules (i.e., PV modules with spatially segmented solar cells, either crystalline silicon or thin film, or other solar cell technologies including perovskite, organic and dye-sensitised solar cells, concentrating systems, and luminescent solar concentrators [139]).

One of the main effects of installing PV modules, both opaque and semi-transparent, on crops is to increase the proportion of diffuse light [199]. Diffuse light has been shown to improve greenhouse crop growth by enhancing canopy light penetration and distributing PAR more evenly, which increases whole-plant photosynthesis [200,201]. Studies report yield gains of 5–11% in crops like tomatoes and cucumbers, along with improved biomass in leafy greens, lower leaf temperatures (by 3–5 °C), and reduced heat stress, leading to better crop quality and efficiency [202,203].

Semi-transparent PV modules with reduced cell density can act as effective light diffusers through three main mechanisms. First, roughened glass surfaces increase scattering at the air–glass interface, redistributing incident sunlight more uniformly [204]. Second, the use of thermoplastic encapsulants with higher crystallinity, such as certain thermoplastic polyolefin (TPO) formulations, enhances internal light scattering by increasing haze [205,206]. Also, transparent backsheets can increase the light diffusivity of PV modules by exploiting both surface and volume scattering mechanisms [207].

Among semi-transparent PV technologies, wavelength-selective technologies have received special consideration in recent years. Wavelength-selective solar cell technologies are engineered to optimise the exploitation of the light spectrum by transmitting to crops only the wavelengths that drive photosynthesis (mostly blue and red, with a small fraction of green [208]) and use the remaining fraction of the light spectrum for energy conversion [208]. This light spectrum optimisation is achieved through various approaches, as described in detail by Ma Lu et al. [138], including tuning the absorption characteristics of the active layer, applying coloured semi-transparent layers, or incorporating optical filters. This spectral tailoring can improve photosynthetic efficiency, crop yield, and quality, while simultaneously reducing UV stress. Such spectral conversion approaches are already applied in greenhouse films, where they have been shown to improve both yield and crop quality [209,210]. A new approach currently under development is the use of light conversion additives for PV modules, with the Belgian company IP FAB reporting work on light-shifting back-encapsulant additives for AV applications (see Figure 33) [211]. However, no publicly available test reports on their performance have been released to date. Light conversion additives for PV modules can enhance crop growth by modifying the solar spectrum transmitted to plants, converting less useful wavelengths, such as UV or part of the green spectrum, into red or blue light that is more efficiently absorbed for photosynthesis.

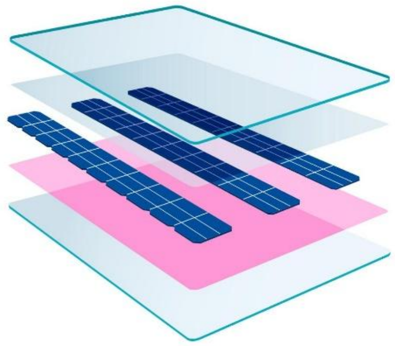


Figure 33: Back encapsulant with light conversion additives for better crop growth [211]**. (Photo credit: ©IP Fab)**

In a similar concept, Thomas et al. [212] proposed embedding a distributed Bragg reflector as an optical layer on the rear side of a glass/glass PV panel with spatially segmented crystalline-silicon bifacial solar cells. The reflector is engineered to be transparent to PAR while reflecting near-infrared light to the bifacial solar cells, as depicted in Figure 34. Further improvement of the concept proposed by Thomas et al. [212] can be the further selection of wavelengths within the PAR region, since not all of the PAR region is harnessed by crops with the same efficiency.

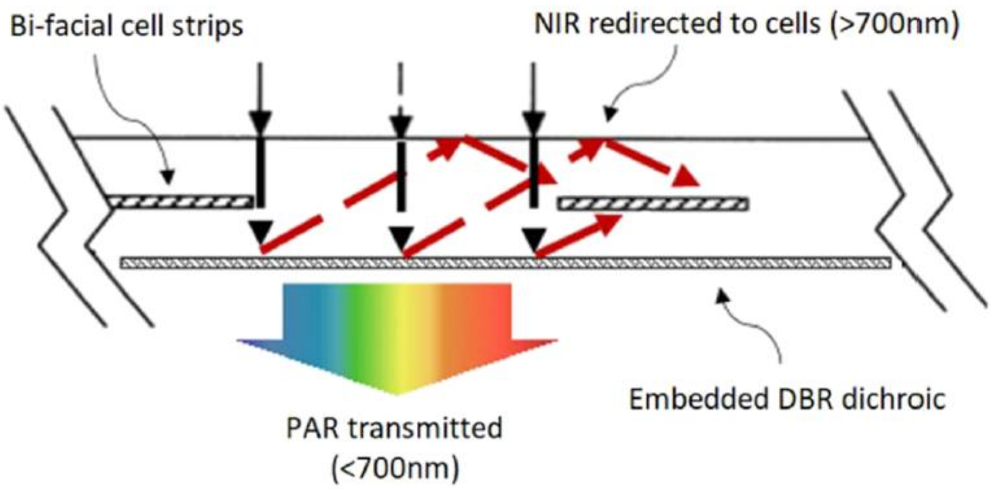


Figure 34: Spectrally selective AV system PV module concept leveraging a distributed Bragg reflector (DBR) to pass PAR and reflect near-infrared (NIR) wavelengths [212].

Resistance to Ammonia

Ammonia exposure in agricultural environments poses a significant degradation risk to PV modules through its high permeability in polymeric components and its strong interaction with moisture [213]. Studies show that ammonia diffuses rapidly through common encapsulants such as EVA and backsheets such as PET-based laminates, reaching cell edges in a short time, thereby initiating localised corrosion and polymer degradation [161,214–218]. Field and laboratory investigations revealed that adhesives, junction box materials, and cable sheathing are particularly susceptible to ammonia. Erosion of adhesives has caused junction box detachment and arcing in modules installed above livestock exhaust outlets [218]. Degradation mechanisms vary depending on the material. In polymers, saponification and the chemical degradation of additives weaken adhesion. In backsheets, ammonia exposure—particularly under humid conditions—reduces adhesive thickness and homogeneity, potentially leading to delamination. The effects of humid ammonia exposure are significantly more pronounced than those observed under dry conditions [217]. Metals such as aluminium frames and silver contacts are also corroded, while glass can suffer hydroxyl-ion-driven corrosion under accelerated wet conditions, particularly on ARC-coated surfaces [214]. Importantly, the presence of moisture greatly amplifies ammonia's corrosive potential: dry ammonia storage showed negligible impact, whereas humid ammonia led to significant adhesive thinning, pore formation in backsheets, and discolouration of sealants [214].

To mitigate ammonia-induced degradation at the module level, several strategies can be implemented. Double-glass modules offer superior resistance by minimising polymer permeability, thereby reducing ammonia ingress [214]. Using adhesives, sealants, and junction box housings made from ammonia-stable polymers, rather than sensitive materials such as polycarbonate, helps prevent premature failure. Anti-corrosive coatings on aluminium frames and the use of more inert metals for contacts can further reduce risk. At the design level, increasing the distance of solar cells from module edges, applying robust edge sealing, and avoiding installations directly above stable exhausts or other high-ammonia-emission zones are effective preventive measures.

Leaching from PV Modules

The co-location of PV modules with agricultural activities raises significant concerns about the potential leaching of hazardous substances from PV modules, which could adversely affect crop production. Research by the University of Stuttgart indicates that the risk of pollutant release from crystalline silicon (c-Si) modules is strongly dependent on the PV modules' physical state [219]. In the worst-case scenario, by using scrap panels ground to fine particles, significant leaching was observed: more than 15% of the total lead (Pb) content from solder ribbons was released into acidic water within 56 days, and tellurium (Te) traces from metallization were also detected, underscoring the environmental hazard if broken module waste is exposed in landfills [219]. Similarly, in long-term immersion of small intact module pieces (5×5 cm) for 1.5 years, degradation of the aluminium back contact and gradual Pb release occurred, particularly under acidic or humid conditions [220]. By contrast, undamaged full-size c-Si modules showed little to no detectable leaching under comparable environmental exposures, as the intact encapsulation and lamination layers act as effective barriers. Thus, it can be concluded that intact c-Si modules, whether in service or properly stored, pose minimal leaching risk. This was confirmed in another recent study on PV module waste and toxicity, which found that concerns about c-Si modules are often overstated and that this risk could slow solar deployment [221]. c-Si modules, which make up most of the market, consist mainly of glass, aluminium, polymers, and silicon, with only trace amounts of metals such as copper, silver, tin, and less than 0.1% lead in solder. Due to these low concentrations and the protective encapsulation structure, the environmental leaching risks are minimal and manageable.

5.3.3 System Design and Operation

One of the most important design aspects of AV systems is finding the optimal trade-off between electricity and crop production per area, while considering agricultural compatibility issues. This design or optimisation approach cannot rely only upon economic aspects because in most cases (e.g., except for high-income crops) revenues from electricity production are significantly higher than income from crops [222,223]. Focusing solely on economic factors might skew the design approach, leading to a system that is extremely similar to a conventional solar park. Moreover, as mentioned in the introduction, AV systems are starting to be highly regulated, especially for meeting the requirements of maintaining crop production during the lifetime of the system, and in certain regulations or standards to meet specific crop yield or light requirements on the ground [141]. In such a context, as also highlighted in a previous AV report [4], to meet those requirements, it is necessary to rely on modelling and simulation tools that can depict all the processes affecting PV and crop production. For instance, crop production is primarily affected by the shading cast by the PV modules on the ground. That shading affects the amount of solar energy received, the quality (i.e., higher diffuse irradiation), and the energy balance at the ground, thereby affecting temperature, evapotranspiration, and soil water availability. Crop performance is also affected by the redistribution of rainfall and wind speed induced by PV modules. All those changes, as depicted in Figure 35, create a specific microclimate under the PV modules that, in combination with crop production, can produce a feedback effect on the PV modules, like reducing operating temperature due to higher evapotranspiration rates and thus increasing specific electricity production.

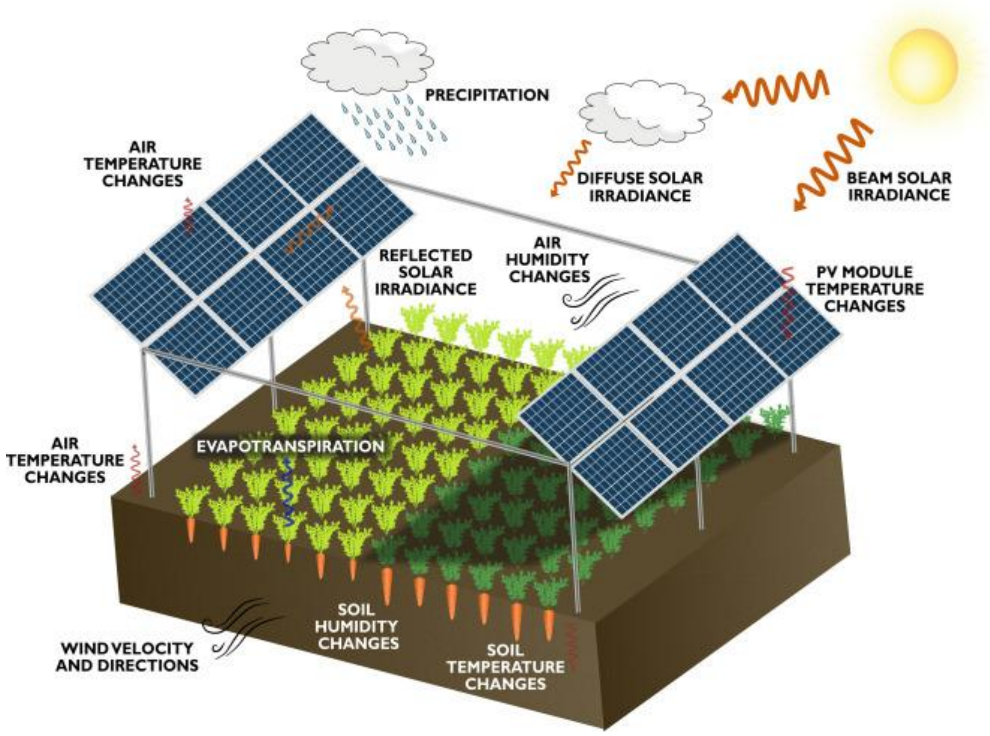


Figure 35: Microclimate under AV systems [160]**.**

To accurately design AV systems, it is thus necessary to have integrated modelling and simulation tools that combine at least those 4 key models: shading model (to simulate ground shading, inter-row shading of PV modules, and the associated irradiance incident on the ground and the PV array), microclimate model (to simulate temperature and energy balances on ground and crop), crop model, and PV model. The availability of such integrated models allows for correlating the effects of PV systems design parameters (e.g., row distance, tilt, height, PV module transparency) to crop yield and PV production, as depicted in Figure 36 where the row distance, a key design parameter for vertically mounted and east-west oriented AV systems, is correlated to agronomic and energy performances.

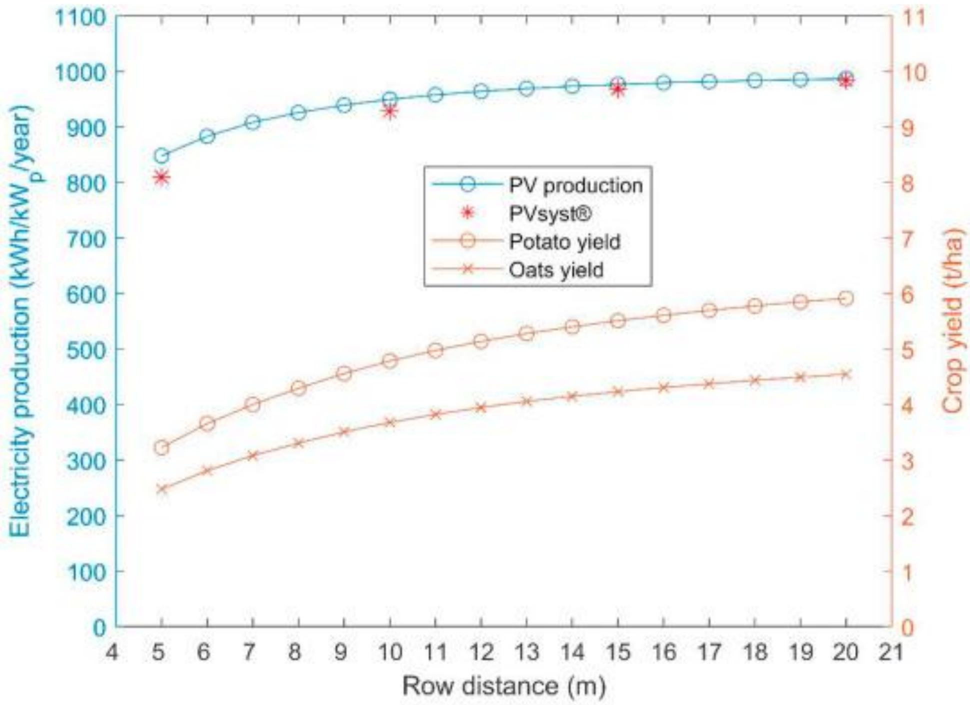


Figure 36: Correlation between row distance and crop and energy yields in a vertically mounted and east-west oriented AV system [224]**.**

Crop and energy performance, and thus the design of AV systems, depend not only on PV system design parameters but are also significantly affected by other crop- and weather-related parameters. For instance, crops are classified based on their shade tolerance [225,226]. Combining shade-tolerant crops with PV modules enables higher ground shading and higher electricity production per hectare than with less shade-tolerant crops. Typically, crops are cultivated in crop rotations, thus, considering possible crop rotations during the lifetime of the AV system should be a standard procedure for optimal system design and for assessing its performance before installation [227]. Similarly, crop and energy performances are weather-dependent, thus, accurate system design should be carried out by considering the variability of weather data on overall system performance, for instance, by performing multi-year simulations [227]. This is to say that simulations should not be limited to typical weather scenarios (e.g., using Typical Meteorological Year data), but should also address diverse possibilities, including different global climate projections [228] and extreme weather years. Plant dimensions also strongly affect the structure's clearance height, the ground coverage ratio, and, in turn, the system design and the optimal AV system configuration. The system design is also strongly influenced by ancillary services that the AV system might provide, such as uniform rainfall distribution and/or rainfall harvesting and storage [229]. In fixed AV systems, water is collected using gutters installed between modules and storage systems for later use in irrigation or PV module cleaning, ensuring that water is distributed efficiently and as needed [230]. Such systems not only mitigate the negative effects of rainfall disruption but also provide additional opportunities to optimise water use in agriculture. Nevertheless, they entail high upfront investment costs and greater system complexity due to parallel water systems, including water tanks, pipelines, and distribution systems [231]. In AV systems equipped with trackers, rainfall management can be achieved by appropriately operating the solar trackers to mitigate the uneven distribution [145].

Soil and crop types, along with their respective management strategies, influence the selection of foundations and the design and configuration of the system. Geotechnical properties affect the foundation type, as they do in conventional GPV systems. Nevertheless, the foundation type should also consider soil and crop management practices, for instance, the deployment (or interaction with existing agricultural infrastructure) of drainage and irrigation systems.

The foundation and the entire structural design should be reinforced compared to the conventional GPV system due to higher loads and greater risks in AV systems. AV system supporting structures need to withstand higher loads due to special system configurations that enable the integration of PV with agricultural activities. Higher loads are also associated with the fact that agricultural infrastructure, if not already in place, can leverage the PV module-supporting structure for implementation. This is the case for irrigation systems and for rainfall harvesting and storage systems.

Soil type and crop management strategies also affect the soiling in AV systems, and currently, there are no soiling models that account for the particularities of AV systems, highlighting the need for further research in this area [141]. Nevertheless, the presence of crop management practices is likely to affect the soiling rate in AV systems. Thus, the design process of an AV system might also consider this aspect, in conjunction with weather-related statistics (e.g., precipitation timing and crop management). In conditions where soil properties (e.g., sandy soils) or management strategies (e.g., ploughing or tilling) might cause significant soiling during high solar irradiation periods combined with low probability of rainfall events, AV systems equipped with high tilt PV modules (e.g., vertically mounted AV systems) might be preferred over other configurations to reduce soiling losses [149]. AV systems equipped with trackers might adapt their tracking strategies during agricultural practices to increase PV module tilt angles and reduce soiling losses. As for traditional PV systems, AV installations must be designed to facilitate cleaning and O&M operations [1]. However, AV systems must also ensure that such operations cause minimal disruption to agricultural practices and crop development, introducing additional constraints on layout, accessibility, and maintenance scheduling. PV module cleaning can be performed using conventional cleaning equipment commonly employed in GPV systems, such as robotic cleaners, washing systems, and cleaning arms [56]. Alternatively, cleaning can be integrated with agricultural operations by using tractor-mounted sprayers or dual-purpose irrigation systems with sprinklers oriented toward the PV modules. If detergents are used, they should be compatible with agricultural practices and comply with food safety regulations to avoid contamination of crops and soil [232].

5.4 Case Studies (AV)

5.4.1 Case Study 1: Solvallen AV project, Sweden

Introduction

The Solvallen AV project in Västlingby, near Fellingsbro (59.46 °N, 15.52 °E), is Sweden's first large-scale AV system owned by the energy company Linde Energi AB [233]. The AV project business model comprises three principal actors: the landowner, who leases the land to the AV system owner (i.e., Linde Energi AB), and the farmer, who continues to perform agricultural activities.

System Details and Environmental Context

	System data	Site data
 **Figure 37. Aerial view of the Solvallen AV project in Vässlingby, Sweden. (Photo credit: Pietro Elia Campana, Mälardalen University)**	Category: farmland Year of installation: 2023 Rated capacity: 635.58 kWp Module type: Bifacial Tilt: 90° (portrait configuration) Orientation: 50% facing east, 50% facing west (front face) Topology: 5 inverters	Ref. climate: Humid continental, warm summer (Dfb) Altitude: 32 m Irradiation: 895 kWh/m^2 (TMY) [234] Temperature: 7.2 °C (TMY) [234] Wind: 3.3 m/s (TMY) [234] Precipitation: 439 mm (TMY) [234]

The system consists of vertically mounted bifacial modules (Longi LR5-72HBD) [235] in a portrait configuration, oriented east-west. The module glass thickness is 2+2 mm, with maximum static loadings of 5,400 Pa on the front side and 2,400 Pa on the rear side [235]. The AV system's capacity is 635.58 kW_p. The system's topology comprises 5 inverters: four 110 kW units connected to a 145.8 kW_p PV array and one 40 kW unit connected to a 52.38 kW_p array. Each 110-kW inverter is connected to 18 strings of 15 PV modules, while the 40-kW inverter is connected to 5 strings of 16 PV modules and one string of 17 PV modules. The entire PV array is distributed across 20 rows, with pitches primarily of 10 m. To smooth the power production curve, half of the PV module rows are oriented with the front face of the bifacial modules facing east, while the remaining rows face west (bifaciality factor: 70±5%). Two rows have different row pitches, corresponding to 8 and 12 m (as seen in Figure 37). The motivation for the various row distances is to test, for research purposes, the effects of row distance on power production, crop production, and land-use efficiency.

Since 2023, the AV system has been connected to the research project “Optimised design of AV systems in Sweden”, funded by the Swedish Knowledge Foundation and led by Mälardalen University in collaboration with Linde Energi AB and Solkompaniet Sverige AB [236]. One of the goals of the AV project and the associated research project is to test multiple crops in parallel and to understand how different row distances and irradiation environments affect crop growth and how different crops grown in parallel affect albedo and power production. In the 2025 crop-growing season, four rows were kept as ley grass (two 10 m rows and the 8 m and 12 m rows); two rows were cultivated with wheat, two with barley, two with oats, and two with yellow peas.

The system is monitored by several permanently installed sensors, including PV system power, microclimate, albedo, PAR, and tilted broadband irradiance, in addition to a central weather station, as depicted in Figure 38. More crop-specific, but periodic, experiments include leaf area index, light-response curves, and crop yield and properties at the end of the growing season.

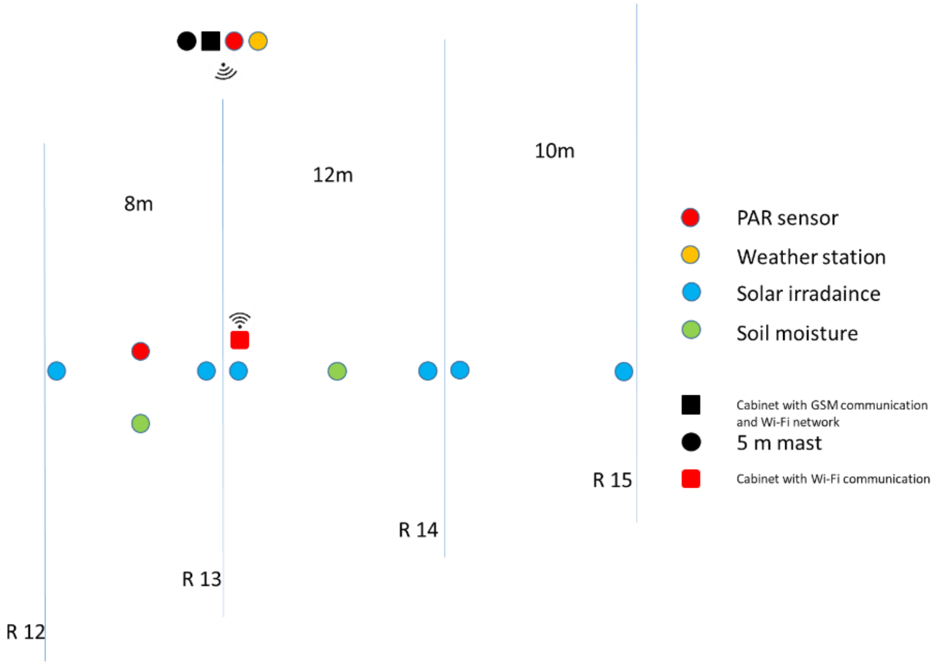


Figure 38: AV monitoring system layout established between rows 12 and 15 (i.e., R12-R15), excluding power measurements directly retrieved from the inverter.

Performance and Reliability of Integrated Solution: Challenges and Mitigation

Being the first large-scale commercial AV system has come with some challenges. These are exacerbated by the vertical configuration, which, however, minimises land loss, typically 5%-15%, and reduces soiling losses [237]. One of the first challenges concerns the cable management in relation to the supporting structure. As shown in Figure 39 (left), the return cables to the inverter provide continuous shading on the backside of the PV modules, thereby increasing energy losses. Moreover, the portrait configuration of the modules, combined with the diode location, reduces electricity yield during the first and last hours of the day compared with landscape-oriented PV modules, as also observed by Rucker and Birnie [238]. Another major challenge for the AV system is adopting a supporting structure that directly relies on the PV module aluminium frames as the primary load-bearing structure. As shown in Figure 39 (right), several modules were affected by glass fractures. Investigations are still ongoing, but here is one potential hypothesised motivation for the glass fractures. In cold regions like Sweden, frost can cause structural deflection of the supporting structure due to the continuous cycling of soil freezing and thawing [239]. When the soil freezes, an uplift force is created, and movement can be counteracted only by frictional forces generated by the piles below the frost depth. If those movements are nonuniform due to heterogeneity in soil conditions or soil moisture during the soil-freezing and thawing cycles, they might induce nonuniform movements in the two supporting piles, generating torsional forces on the PV module frame and leading to fractures. Accurate foundation design, coupled with detailed geotechnical analyses, is required for such AV mounting structures, especially in high-latitude regions. Experiments are planned for 2026-2027 to investigate potential movements of supporting structures during freeze/thaw cycles and during extreme wind events, another hypothesised factor in the glass fractures.

Figure 39. Connecting cables back to the inverter cause shading on the PV modules (left), and the PV module on the right has fractured glass, with the main fracture extending from the bottom-right corner to the top-left corner. (Photo credit: Pietro Elia Campana, Mälardalen University)

5.4.2 Case study 2: Flakkebjerg AV Test Site

Introduction

The Flakkebjerg AV site was constructed as part of the AGRIVOLT project, which is a 5-year research and demonstration project supported by Innovation Fund Denmark (IFD) [240]. The project's goals include assessing the economic viability of ground-mounted single-axis tracking (SAT) systems for AV use, demonstrating the use of agricultural robots for crop management between SATs, achieving 80% crop and PV yields compared to reference setups, and evaluating the economic and social impacts of AV systems in Denmark.

System Details and Environmental Context

	System data	**Site data**
 **Figure 40: Aerial photograph of the Flakkebjerg AV test facility at Aarhus University taken in Spring 2025. (Photo credit: European Energy A/S)**	Category: farmland Year of installation: 2023 Rated DC capacity: 998 kWp Rated AC capacity: 990 kWp Module type: bifacial PERC, mounted in 2-in-portrait (2P) on SATs Tracking system: 1-axis tracker developed by European Energy Articulation limits: ±55° Pitch: 12 m Torque Tube height: 2.6 m Torque Tube length: 20 m Ground Cover Ratio: 0.39	Ref. climate: Temperate oceanic climate (Cfb) Location: Flakkebjerg, Denmark Altitude: 55 m Irradiance: 1076 kWh/m² (TMY) [241,242] Temperature: 8.9 ºC (TMY) [241,242] Wind: 5.3 m/s (TMY) [241,242] Precipitation: 691 mm (2025) [243]

The site was established in August 2023 and features 11 rows of 2P SATs with bifacial PERC PV modules. The 2P SATs and control system were developed by European Energy A/S and enable crop cultivation in a 10 m section between rows. There is a 2 m section directly under each SAT reserved for biodiversity-supporting flowers and plants. The tracker controllers are programmable, which permits investigations of anti-tracking, diffuse stow, and other advanced tracking strategies. Other innovative features include a patented telescopic (retractable) tracker-pile design and a hydraulic system that allow the entire PV array to be lifted vertically, intended for safe and efficient installation of large-format (i.e., 660 W_p) PV modules.

The crops between the 11 rows of 2P SATs are a variety of food and forage crops commonly grown in the Danish agricultural industry. For example, the first harvest in 2024 consisted of winter wheat, a wheat variety mixture, winter rye, oats, spring barley, spring wheat, fava beans, buckwheat, and intercropped peas and barley. The intention is to introduce some new crops each year. For example, in the 2024-2025 growing season, winter rapeseed and potatoes have been introduced, and a 2.6 m tall, 80 m long polytunnel (greenhouse) has been installed for higher-value crops like melons. On the north side of the facility, there is the reference field, which has the same crops as the test field but without PV arrays (Figure 41.a).

Figure 41: a) Example of agricultural work performed between rows with trackers facing opposite directions where work is taking place, and the remaining rows left in astronomical tracking mode. b) Four inter-row sensor masts for monitoring key indicators of agricultural productivity between rows in the test field. A fifth equivalent sensor mast is in the reference field. (Photo credit: Aarhus University, Department of Agroecology, and European Energy A/S)

The site is instrumented with numerous sensors to monitor the performance of the PV system and crop yields. For PV monitoring, the site features multiple pyranometers and reference cells to measure front- and backside irradiance, multiple Resistance Temperature Detectors to monitor back-of-module temperature, and two types of dust sensors for soiling monitoring. On the agricultural side, the site features five sensor masts, which all include PAR, precipitation, soil temperature/moisture, relative humidity, ambient temperature, and leaf moisture measurements (Figure 41.b). Four of these masts are spaced equidistant between PV rows in the test field, while the fifth is in the reference field.

Performance and Reliability of Integrated Solution: Challenges and Mitigation

Fieldwork with the autonomous robot has been challenging due to unstable GPS signals received while driving directly under the steel tracker structures. The robot and its equipment are only 2.5 m wide, so one solution is to attach wider (~10 m) implements to the robot and have the robot always drive in the middle of the 12 m rows. The use of alternative GNSS satellite constellations may also remedy the issue. In terms of agricultural yield, the 2024 harvest showed several crops with lower productivity in the SAT rows than in the middle rows. However, these data are considered provisional because sowing conditions were suboptimal in the first year, and the 2P SATs did not begin sun-tracking until late summer 2024. Additional years of study are needed to draw meaningful conclusions.

The 2025 growing season has shown that adaptive sun-tracking strategies are needed for AV systems. For example, certain crops (e.g., rapeseed) are growing taller than the SAT's 70 cm ground clearance at ±55° tilt. This results in the PV array compressing the crops, potentially damaging them, and causes power losses due to the crops partially shading the PV array. A similar observation has been made for the polytunnel installed between two SAT rows: at times in the morning/afternoon, the tunnel casts shadows on the PV arrays. Therefore, adaptive backtracking strategies that can avoid partial shade while optimising electricity yield are being investigated: for example, those proposed by Casares de la Torre et al. [244].

Farmers and technicians regularly perform work between the 2P SAT rows at Flakkebjerg (i.e., sowing, pest management, measurements, and harvesting). Therefore, ground-mounted trackers in optimised AV designs require that the trackers face away from each other when such work is carried out (Figure 41.a). Developing a control system that is simple and intuitive for personnel unfamiliar with PV operation and maintenance is critical. Furthermore, control system priorities, guidelines for farmers/users, and safety protocols must be developed judiciously.

6 CONCLUSIONS

This report discusses how design and operation of PV components and systems deployed in integrated applications can be optimised. Three integrated PV applications are analysed: **Building-Integrated PV (BIPV), Floating PV (FPV), and Agrivoltaics (AV)**, each characterised by its own set of environmental stressors, design constraints, and application-specific requirements. The long-term reliability of integrated solutions depends heavily on environmental stressors, which differ significantly from those in standard ground-mounted systems. Available field data for FPV and AV are still limited, but early results indicate that properly designed systems have similar lifespans compared to conventional systems. Nevertheless, specific factors, such as high humidity, frequent partial shading, and mechanical loads, if not adequately addressed during design and system operation, can accelerate degradation.

Challenges, available mitigation measures, and further development needs for each integration type are summarised here.

- **Building-Integrated Photovoltaics (BIPV):** BIPV systems combine electricity generation with building-envelope functions, requiring modules to satisfy both energy and construction requirements. Elevated operating temperatures, restricted rear ventilation, frequent partial shading, and mechanical and fire-safety risks represent the principal challenges affecting long-term performance and reliability. Mitigation strategies include improved ventilation concepts, the use of shading-tolerant modules, robust module designs, enhanced fire-resistant materials, and application-specific monitoring and maintenance strategies.
- **Floating Photovoltaics (FPV):** FPV systems enable PV deployment on water bodies, reducing land-use conflicts, but introduce a set of new challenges. The water environment can potentially allow lower operating temperatures, but this strongly depends on platform design and local wind exposure. Wave- and wind-induced mechanical loads require specific design approaches that differ from those used for land-based systems. High humidity, potential corrosion, biofouling, and dynamic loads from wind, waves, ice, and water-level fluctuations represent the main stressors affecting long-term performance and reliability. Mitigation strategies include the use of moisture-resistant module designs, enhanced corrosion protection, reinforced mounting and anchoring systems, and dedicated monitoring and environmental assessment.
- **Agrivoltaics (AV):** AV systems combine PV electricity generation with agricultural production, requiring system design and operation to balance crop light requirements with PV electricity production. The dual-use environment introduces additional variables, including heterogeneous microclimatic conditions, high risk of mechanical damage, a chemically active environment due to the use of pesticides and fertilisers, partial shading from crops and structures, and increased soiling from agricultural activities. These factors can influence both energy yield and long-term reliability. Mitigation strategies include optimised system layouts, adaptive tracking and operation strategies, careful component selection, and dedicated monitoring of both agricultural and electrical performance.

For all three integrated PV applications, there is a clear need for application-specific testing, improved modelling, and long-term field data. BIPV requires further work on durability and realistic testing approaches, FPV still lacks standardised methods to evaluate water-related mechanical and environmental stresses, and AV needs optimised layouts and modelling tools to support deployment across different crops and climates. Overall, the report demonstrates that more representative test environments and shared reference datasets are essential to improve system design and enable more reliable performance predictions.

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