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METHOD ARTICLE

Introducing a novel approach to certifying integrated photovoltaic product families using semi-fabricates

[version 1; peer review: 1 approved with reservations]

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Abstract

Background

The building-integrated photovoltaics (BIPV) market is expanding, but adoption remains constrained by high costs and complex certification. These issues arise from highly customised designs, varying in shape, size, colour, and materials, driven by regulations, construction needs, and aesthetics, often requiring costly manual production. The Horizon Europe project Mass-Customisation 2.0 (MC2.0) addresses this by introducing PV "semi-fabricates" (SFs): automated, partially finished components tailored to specific BIPV applications. SFs enable flexible design while allowing manufacturers to complete final products through automated processes. The project also tackles certification gaps, as current schemes are not suited to mass-customised BIPV

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solutions.

Methods

To address this, we propose a workflow beginning with a review of PV standards, BIPV guidelines, construction norms, and national construction regulations, supported by IEA-PVPS Task 15 insights and input from standardisation experts and insurers. In the proposed methodology, product requirements are analysed to define SF and product families, followed by Failure Mode and Effects Analysis (FMEA) at SF, product, and interface levels. Based on identified risks, relevant norms are selected and, when relevant, new test sequences are designed.

Results

SFs often lack junction boxes or mechanical supports, making full PV certification impossible. Certification at the SF level is feasible only with representative attachment scenarios; otherwise, it must occur at the end-product level. Applying complete PV certification to niche BIPV products, where volumes are relatively small, can be unnecessarily costly, especially where PV and construction regulations overlap.

Conclusions

The proposed approach enables identification of appropriate certification pathways and targeted testing strategies, reducing unnecessary burden. Further work should harmonise PV and construction standards, develop modular test sequences, and engage insurers and regulators.

Plain Language summary

Building-integrated solar panels (BIPV) are growing in use, but high costs and complex certification still slow down their adoption. This is mainly because BIPV products are highly customised, varying in size, shape, colour, and materials, which often leads to manual and expensive production.

The MC2.0 project proposes a new approach using “semi-fabricates” (SFs), which are partially finished solar components made with automated processes. These can then be adapted into different final products, keeping design flexibility while reducing costs.

Certification is also a challenge because current systems are designed for standard solar panels, not customised BIPV. SFs often cannot be certified on their own, and certifying each custom product can be costly.

The project suggests a new method: analyse product requirements, assess risks, and apply only the necessary standards and tests.

Certification may happen at the SF level when possible, or otherwise at the final product level.

This approach maintains safety while reducing unnecessary testing, helping new BIPV solutions reach the market more easily.

Keywords
Photovoltaics, building, certification, standards, façade, tile, window



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Introduction

The certification of photovoltaic (PV) products is traditionally built around mainstream, standardised modules and high-volume product families. As a result, current certification frameworks are poorly suited to the emerging field of integrated photovoltaics (IPV), where mass-customisation introduces variability in the bill of materials, dimensions, shapes, and power output. Certifying every possible configuration is too costly and time-consuming; for example, IEA PVPS Task 15[1] notes that achieving full PV certification according to IEC standards requires four to six months for a single product, assuming no testing issues, and this timeline does not include country-specific BIPV requirements. Semi-fabricates (SFs), partially processed PV components central to the Mass-Customisation 2.0 (MC2.0) concept,[2] further complicate certification, as they often lack junction boxes, mechanical supports, or other elements required for complete PV qualification. Conversely, applying full PV certification to finished IPV products can be excessive, particularly for applications with limited exposure to stressors (e.g., SFs inside insulating glass units). Overlapping PV and construction regulations frequently lead to duplicated testing, increasing costs without improving safety. These challenges highlight the need for a less expensive, more flexible, targeted certification pathway that can accommodate variability without compromising reliability.

In this article, we propose an alternative certification framework in which testing responsibilities are distributed between the SF and the IPV end-product manufacturers: SFs undergo pre-testing for aspects relevant to their level of completion, while tests that cannot be meaningfully performed at the SF stage are carried out on the final IPV product. Developing such an approach requires consideration of multiple layers of normative and regulatory requirements. We therefore reviewed conventional PV standards, BIPV-specific guidelines, and construction regulations at both the European and national levels for key MC2.0 markets (Italy, The Netherlands and Switzerland), complemented by insights from IEA-PVPS Task 15. The Task 15 report "Advancing BIPV Standardization: Addressing Regulatory Gaps and Performance Challenges"[1] highlights the current fragmentation of certification requirements and calls for harmonisation across the construction sector to support BIPV adoption. One of the conclusions of the report is that helping manufacturers identify suitable test schemes can significantly reduce the burden of safely bringing products to market. This also underpins the rationale for our approach.

Reducing unnecessary retesting is a central objective. The IEA-PVPS Task 15 report[1] provides a very inspiring example in the context of aging tests for BIPV applications, where a consolidated procedure reduced the required number of test modules from sixteen to twelve by combining overlapping stress sequences. This demonstrates that a thorough analysis of failure modes and associated stressors can yield more efficient qualification strategies while preserving safety. Similar questions arise when attempting to certify IPV products simultaneously as building components and PV modules:

- Which tests or test sequences are essential for each product family?
- Can some sequences be merged or applied at the SF level?
- Which tests are optional but provide extra quality or reliability guaranties to the stakeholders?

To ensure that the proposed certification pathway aligns with real-world needs, we conducted a broad stakeholder analysis. The stakeholders relevant to the BIPV sector were grouped into four key domains (Figure 1): (1) the certification industry, including European, national, and regional regulatory bodies working within IEC and EN frameworks; (2) IPV manufacturers, including cell, module, and end-product developers; (3) the research sector, comprising PV institutes and IEA Task 15 experts; and (4) the construction sector, including architects, façade manufacturers, developers, and insurers whose acceptance is essential for market integration. Their feedback helped us identify the current challenges and opportunities for combined testing schemes bridging construction and PV standards.

Finally, to define both SF and product families, we revisited the requirements and design guidelines established at the onset of MC2.0. This formed the basis for a workflow that harmonises certification strategies, technical constraints, regulatory demands and market needs. The resulting framework supports a vision where specialised manufacturers produce large volumes of customisable SFs that feed into diverse IPV product families. Such flexibility is particularly critical for building-integrated PV (BIPV) applications, where tailored solutions are essential to wider adoption.

Methodology

In this article we propose an alternative certification framework that distributes PV testing between SFs (where possible) prior to integration, and the IPV end-product for tests that require components, attachments or integration into elements not present in the SFs. Additionally, this framework helps define and certify product families (groups of products with limited variations) instead of certifying each possible variation.

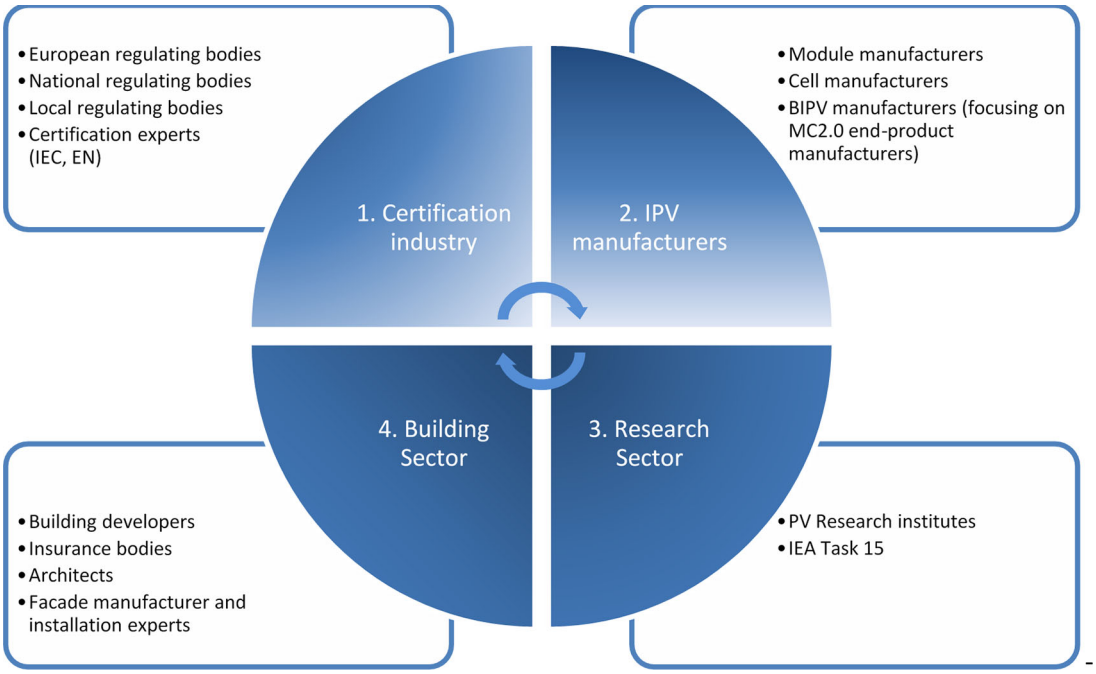


Figure 1. Mapping of relevant stakeholders.

The process begins with defining the final product or product family, establishing its core requirements, design specifications, intended market, and overall functional application. Once the product vision is clear, the next step is to select the relevant product standards that apply to its category and use-case. Building on this, the process proceeds with identifying specific standard requirements across different regions and industries to ensure full regulatory and commercial compliance. In parallel, an end-product Failure Mode and Effects Analysis (FMEA)[3] is drafted to map out potential risks and determine the relevant tests and standards, ultimately ensuring a robust and compliant product. The FMEA addresses critical risks across three levels: the SF, the complete product, and the interfaces between them. This step can also help product manufacturers that want to provide extra guarantees on reliability. Finally, boundary conditions, such as environmental stress levels (e.g., based on climate), are established, and certification pathways for different product families are outlined. The workflow is presented in Figure 2.

Identification of IPV product families based on semi-fabricate and application type

IPV products were grouped into distinct "families" based on their associated semi-fabricates (SFs) and their intended application. The key terms used for this classification are defined below:

- **Semi-fabricate (SF):** A PV cell system configuration in its intermediate stage, before integration into the final IPV product.
- **End-product:** The completed IPV system designed for a specific application and incorporating a defined SF configuration.
- **Product family:** A group of end-products intended for the same application and built using similar types (e.g. similar bill of materials) of SFs.

An overview of this multi-level classification is shown in Figure 3. To reflect the differing functional and regulatory demands of various applications, IPV product families were separated into two main categories: **Insulating Glass Unit (IGU) BIPV products** and **façade or roof-tile BIPV products** used as building cladding. Each category faces distinct performance, safety, and market requirements.

Based on these definitions, we analysed the requirements applicable to each product family within the European context, focusing specifically on the Swiss, Italian, and Dutch markets. These requirements encompass CE-marking obligations, insurance expectations, and market-specific conditions that must be met for successful commercial deployment.

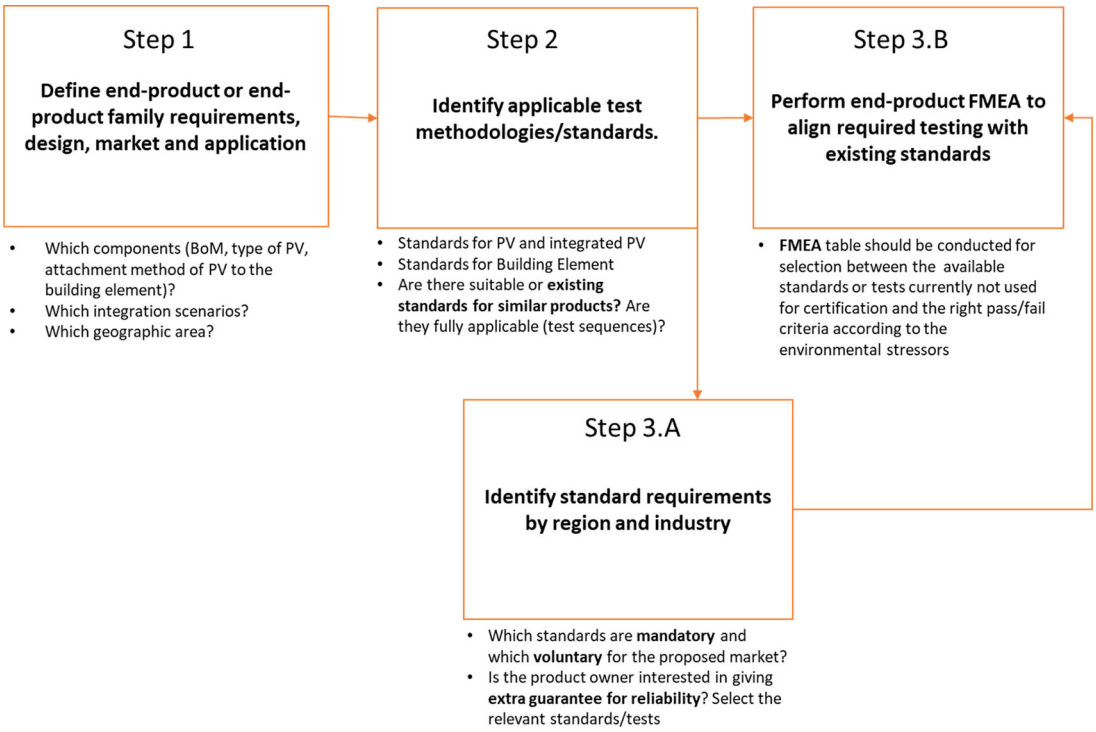


Figure 2. Workflow for certification identification process.

Current status of BIPV related standards

In the domain of photovoltaic and building-integrated glazing technologies, a coordinated group of international standards defines the optical characterisation, performance requirements, and lifecycle conformity of both conventional glazing and laminated photovoltaic glass. ISO 9050:2003[4] establishes the foundational methodology for quantifying light transmittance, solar direct transmittance, total solar energy transmittance, ultraviolet transmittance, and related glazing factors, forming the basis for thermal, daylighting, and energy modelling of building envelopes. Its forthcoming replacement, ISO/DIS 9050,[5] modernises this framework by redefining the scope to focus on the luminous and solar characteristics of glazing, and updating terminology and calculation procedures to better reflect current glazing technologies and performance evaluation practices in the built environment. Complementing these optical/energetic standards, ISO/TS 18178:2018[6] provides comprehensive requirements for appearance, durability, mechanical and electrical safety, test methods, and designation of laminated solar photovoltaic glass intended for construction applications, offering a unified approach for BIPV products that must simultaneously meet architectural glazing and PV-module performance criteria. To support long-term reliability and ensure continued compliance following design modifications, ISO/TS 21486:2022[7] specifies the retesting requirements for laminated solar PV glass, outlining mandatory verification procedures when changes occur in glass composition, interlayers, solar cell technologies (crystalline or thin-film), interconnectors, or terminations, thereby safeguarding performance consistency and safety throughout the product lifecycle. Structural safety of BIPV products in project conditions (final dimensions, supporting system, wind zone, snow zone, height of the building, air temperatures and solar irradiance, etc.) is assessed according to EN 16612,[8] FprEN 19100 series (currently in the stage of the Formal Vote) or according to national guidance documents and standards, e.g. NF DTU 39,[9] NEN 2608[10] and DIN 18008 series.[11]

EN 50583–1:2016[12] is a European standard that defines the requirements for BIPV modules when they are used as construction products. It focuses on the properties of PV modules relevant to essential construction requirements under the Construction Products Regulation (CPR 305/2011)[13] and the applicable electro-technical requirements under the Low Voltage Directive[14] and relevant CENELEC standards. In particular, it specifies how BIPV modules must meet building-related performance expectations, such as mechanical resistance, fire safety, weather protection, and durability, while also addressing their electrical safety and functionality as photovoltaic generators. The standard applies only to BIPV modules (not concentrating PV or building-attached PV) and covers modules that are designed to be integrated into the building envelope (façades, roofs, shading elements, etc.), but it does not address the mounting structures, which are included in EN 50583–2.[15] It is intended for manufacturers, system designers, planners, installers, testing bodies, and

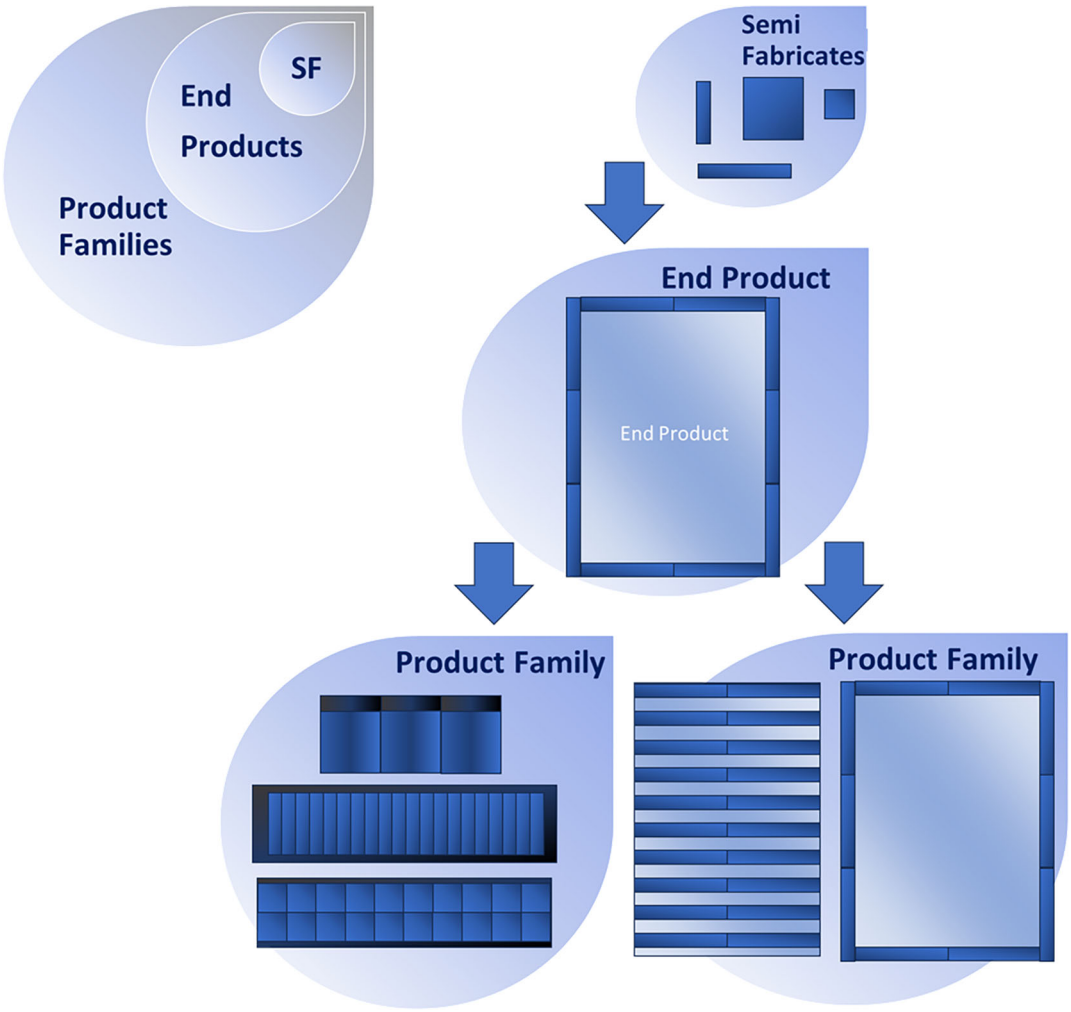


Figure 3. Multi-level classification of the Semi-Fabricates (SFs), end-products and product families.

construction authorities, and references a broad range of international standards, technical reports, and guidelines relevant to glazing and PV applications. A newer version of this standard is under development, where harmonisation for multiple EU countries was attempted. However, harmonisation is challenging, since the standard refers to the Low Voltage Directive, which is not a regulation, but a directive, meaning that BIPV must comply with the national regulations for construction products. Considering IEC standards, the respective standard is IEC 63092 (−1 and − 2)[16,17] (based on EN-50583 and adapted for international application), which mainly describes the requirements for BIPV, however, it mainly includes guidelines, it is not a testing standard, and also refers to the IEC PV related standards, IEC 61730[18,19] and IEC 61215,[20,21] and the CPR.[13]

Retesting of BIPV

BIPV requires flexibility in terms of sizes and material choices, and when such design or material modifications occur, IEC TS 62915[22] provides the formal framework for determining how PV modules must be retested to maintain type approval, design qualification, and safety certification. The standard establishes a uniform approach for evaluating any change from the originally assessed PV module design, covering both wafer-based crystalline silicon technologies and thin-film modules, and lists typical modifications along with the corresponding retest requirements derived from relevant test standards. In its 2023 second edition, IEC TS 62915[22] updates its references to IEC 61215[20,21] and IEC 61730,[18,19] introduces retesting requirements for new tests such as dynamic mechanical load (MQT 20) and potential-induced degradation (MQT 21), integrates component-level standards (IEC 62788–1[23–28] and IEC 62788–2 series[29]), and includes a comprehensive matrix summarising retesting needs for each type of design or material change, ensuring that evolving BIPV designs remain compliant with safety and reliability expectations. A PV module manufacturer who targets BIPV markets should consider certifying their largest possible product size for the most failure-prone material

combination and attachment scenarios. In case the largest product is too large to be certified, due to technical difficulties, a representative sample should be considered.

Fire safety

Fire safety for BIPV follows three regulatory levels. At Level 1, the EU CPR[13] and national construction regulations in EU Member States and Switzerland define the fundamental legal obligations for construction products. At Level 2, harmonised EN standards for construction products and IEC/EN standards for PV components ensure that BIPV elements meet structural and electrical requirements. At Level 3, products undergo performance classification, mainly through the Reaction-to-Fire system (EN 13501[30,31]), which assesses fire resistance, flame spread, smoke production, and flaming droplets. Results are expressed in the Declaration of Performance (DoP) and shown through CE marking, which confirms CPR compliance but does not, in itself, guarantee safety.

A crucial distinction is that performance does not equal safety. Performance reflects how a product behaves in accordance with harmonised standards or European Technical Assessments (ETAs)[32] and is expressed through declared values, classes, or levels in the Declaration of Performance and Conformity (DoPC).[33] The EU imposes no minimum performance thresholds. It only requires transparent declaration. Safety, however, is determined at the national level and depends on the building context, intended use, declared performance, product documentation, and national rules. Thus, CE marking is not a safety approval, but a statement of conformity with the CPR.[13] Real safety depends on proper use within national regulatory frameworks.

Fire-safety objectives in buildings focus on preventing ignition, limiting fire spread, ensuring material compatibility, enabling safe occupant evacuation, and supporting safe operations for firefighting teams. Buildings must minimise ignition risks from materials, electrical systems, or building functions, limit fire spread across assemblies and integrated systems such as BIPV and ensure that materials do not interact in ways that increase fire hazards. At the same time, safe evacuation routes and structural stability must be preserved to protect occupants and emergency responders.

A comprehensive fire-safety assessment requires analysing multiple ignition scenarios.[34] These include Case A, ignition due to radiation from an adjacent fire, Case B, ignition from external flames, embers, or heat sources, Case C, internal ignition caused by electrical faults, appliances, or human activity, Case D, ignition on the rear side of PV modules due to hotspots or electrical faults, and Case E, ignition in a battery-energy-storage room, where thermal runaway or overheating cells can trigger fires that spread to other building zones.

Testing approaches must therefore consider both product-level behaviour and system-level interactions, recognising that materials, mounting systems, and electrical components respond differently when exposed to fire. Effective assessment begins by analysing system behaviour under realistic stresses, then selecting appropriate test methods for specific building elements, such as façades or roofs, according to installation geometry, substrate properties, and likely exposure types (external flames, embers, heat radiation). Since reaction to fire depends on the scenario, no single test captures all risks. Scenario-based testing is essential for reliably assessing BIPV fire performance.

In high-rise buildings, fire-safety requirements are more stringent, due to more complex evacuation routes, higher fire loads, and the operational challenges for firefighters at height. These buildings require stricter compartmentation, advanced detection, alarm, and automatic suppression systems, and higher fire-resistance ratings for structural elements and façades, including BIPV installations. Protected escape routes and safe firefighter access become critical, supported by firefighting lifts and smoke-free stairwells. In very tall buildings, additional measures such as pressurisation systems and refuge areas ensure that evacuation and intervention remain feasible even under severe fire conditions.

Applicable standards based on product family

Applicable standards for IGUs

For the IGU BIPV product family, end-products must meet both IEC PV standards and EN construction standards, with EN 1279[35–38] being the most relevant. This section summarises EN 1279 and its links to IEC requirements.

Typical IGU tests cover: gas permeability and seal durability, material compatibility, optical and visual quality, manufacturing quality, thermal and solar performance (U-value, g-value), acoustic performance, thermal stress and safety glass behaviour, aging/material stability, and electrical safety. Some of these tests partially overlap with IEC 61215[20,21] and 61730[18,19] (notably EN 1279–2/3/4,[36–38] EN 12150,[39,40] EN 14179,[41,42] ISO 12543-4[43]), but overlaps serve only as informative references. IEC-level retesting is still required when aiming for IEC certification.

Nine additional construction standards were also identified as relevant for this product family, covering thermal, solar, acoustic, and safety-related properties. IEC standards do not include U-value, g-value, or acoustic measurements, and only partially cover mechanical load testing; they also do not address glass fragmentation. A summary of the mentioned standards is presented in Table 1.

In case the functional PV component in the IGU is laminated glass, it must be CE-marked and compliant to EN 14449.[44] The CE marking guarantees that manufacturer has assessed the product quality, durability and performance characteristics according to the required Assessment and Verification of Constancy of Performance (AVCP) system compliant to EU CPR.[13]

Applicable standards for building claddings

For the building-cladding BIPV product family, which includes façade panels and roof-tile systems, end-products must comply with both PV-specific IEC standards and construction-sector regulations governing cladding safety and performance. Relevant construction standards include DIN 18516–1[45] for ventilated façades, NEN 6707[46] and NEN 6708[47] for façade and fixing safety, and DIN EN 1991–1-4[48] for wind actions. Fire behaviour requirements are addressed through DIN 4102–1[49] and EN 13501–1/2/3,[30,31,50] which set classification schemes and test procedures for reaction-to-fire, fire resistance, and external fire exposure. Table 2 summarises these standards.

These cladding-related standards cover mechanical resistance, fixing security, wind loading, fire behaviour, weathering, and material stability, properties not fully addressed by IEC PV standards. In many cases, only partial overlaps exist: IEC standards capture aspects of mechanical loading and electrical safety but do not evaluate façade-specific risks such as fixing failure, impact resistance, or fire propagation. Therefore, while overlaps can inform testing strategies, dedicated cladding tests remain necessary for compliance with construction regulations.

In case the building cladding BIPV is a laminated glass product, it must comply with EN 14449,[44] like in the IGU BIPV product family.

Table 1. Applicable standards for Insulated Glazing Units (IGUs).

Standard	Scope
EN 1279–1	System Configuration
EN 1279–2 & 3	Gas Permeability and Seal Durability
EN 1279–4	Material Compatibility
EN 1279–5[66]	Optical and Visual Quality
EN 1279–6[67]	Manufacturing Quality
EN 673,[68] **EN ISO 10077**[69,70]	Thermal Insulation (U-value)
EN 410[71]	Solar Heat Gain (g-value)
EN ISO 10140-2[72]	Acoustic Insulation
EN 12150, EN 14179	Thermal Stress/Safety Glass
ISO 12543-4, EN 1279	Aging and Material Stability

Table 2. Applicable standards for building claddings.

Standard for façade	Standard for roof tile	Scope
DIN 18516–1	**NEN 6707 NEN 6708**	Requirements and test principles for ventilated façades and roof tiles including static analysis (calculations and testing) and durability against environmental stressors
DIN EN 1991–1-4	**DIN EN 1991–1-4**	Actions on structures – Wind loads
DIN 4102–1/DIN EN 13501–1	**IEC 13501–1,2,3**	Fire behaviour of building materials and components

Insurance requirements

Insurance expectations for BIPV systems vary widely across Europe, largely because these technologies are still emerging and not yet fully reflected in standard insurance models. In the main markets relevant to this project (Italy, Switzerland and the Netherlands) manufacturers generally fall back on established PV and construction standards to demonstrate that their products are safe and compliant. This strategy is usually the most acceptable to insurers, who focus primarily on safety risks rather than guaranteeing long-term performance, which typically remains the manufacturer's responsibility.

However, relying solely on existing standards leaves important gaps. The interface between the SF and the final IPV product is often not covered by any certification. Moreover, assuming that some products fall under the Low Voltage Directive[14] can be misleading, since the combined voltage of several interconnected units may exceed the directive's limits. Micro-inverters could address this issue, but their suitability still requires further study.

France offers one of the few structured approval routes tailored to innovative construction products. Its process involves three stages[51] before insurance coverage is granted: the **Enquête Technique Nouvelle (ETN)**, which compiles technical information and identifies the tests to be carried out; the **Appréciation Technique d'Expérimentation (ATEx)**, which evaluates the product for a specific project; and the **Avis Technique (ATEC)**, which provides broader acceptance for repeated use. Although this pathway ensures a strong safety focus, particularly regarding fire, it requires multiple assessments, is costly, and often leads to delays during construction, with no guarantee of success.

Failure mode and effect analysis (FMEA)

Failure Mode and Effects Analysis (FMEA)[3] was selected as a central method because it can address the unique challenges that arise when combining building-envelope functions (roof, façade, and IGU applications) with PV energy generation. FMEA is a proactive approach that identifies how a system might fail, evaluates the consequences, and determines which risks require mitigation before they occur. It helps identify and tackle the main issues towards certification.

The process includes[3]:

- **Identifying the failure modes** by analysing component-level degradation mechanisms, stressors, and operating conditions.
- **Assessing effects** on performance, safety, and neighbouring components.
- **Determining root causes**, such as material degradation, design flaws, manufacturing issues, environmental exposure, or installation errors.
- **Rating severity, occurrence, and detectability** on a 1–10 scale to quantify the risks.
- **Calculating a Risk Priority Number (RPN)** by multiplying these three ratings to prioritise the most critical issues.
- **Defining mitigation actions**, which may involve design improvements, targeted testing, enhanced inspection methods, or updated quality controls, followed by reevaluation.

For the IPV product families studied in the MC2.0 project, the FMEA integrates building-specific, PV-specific and interface considerations. The resulting RPN values guide which mitigation actions should be prioritised, supported by the appropriate building or PV standards, with safety as the highest priority. This structured workflow is illustrated in Figure 4.

Certification paths for the MC2.0 products

Building cladding end-products with integrated PV

In this section, certification strategies for building cladding products integrating flexible PV modules (SFs) are addressed, focusing on aluminium façades and polymer roof tiles. Both products fall under BIPV applications, where the SF is a flexible PV module attached to the cladding. For the examples investigated here, it is assumed that the junction box is mounted on the PV module. An FMEA was conducted at three levels: SF, cladding, and their interface, to identify failure modes with the highest RPN.

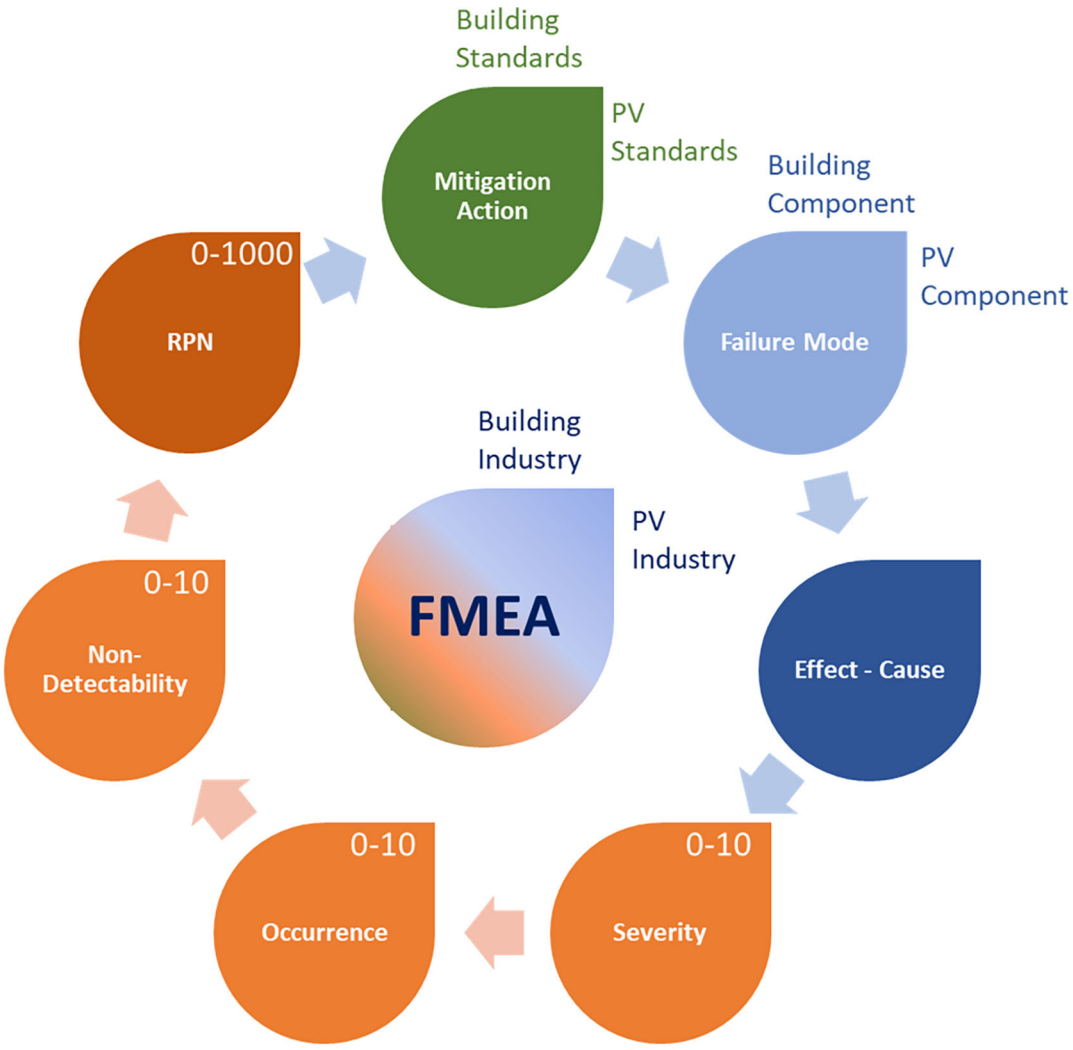


Figure 4. Workflow for Failure Mode and Effects Analysis (FMEA).

Most SF-related risks are covered by IEC 61730[18,19] and IEC 61215.[20,21] IEC 61730 is prioritised as it addresses safety, while IEC 61215 focuses on reliability. The full IEC 61730 standard can be applied at the SF level, except for the mechanical load test, which should be conducted at the IPV level, and the module breakage test, which is not applicable. Consequently, Sequence D from IEC 61730 should be removed from SF testing and applied at the IPV level. Likewise, the hot-spot endurance test is unsuitable for SFs since it requires the complete IPV product, due to different thermal properties after integration. Therefore, Sequence F from IEC 61730 should also be shifted to the IPV level. Reliability certification per IEC 61215 is meaningful only at the full product level, considering attachment type and mechanical integration. Certification can be performed by the PV module manufacturer (on representative samples for targeted markets) or by the end-product manufacturer if the SF is not pre-certified.

Aluminium façade case

The SF is adhesively bonded to aluminium cassettes. In addition to IEC standards, compliance with DIN 18516–1[45] for claddings is mandatory, requiring structural calculations for various load transfers (dead, wind, snow, seismic), static testing for joints and material durability against moisture, temperature, and UV. Wind load resistance follows DIN EN 1991–1-4.[48] Fire safety requires DIN EN 13501–1[30] classification (A2-s1-d0), necessitating interface-level fire testing due to polymer components. Corrosion protection must meet DIN EN ISO 12944.[52,53] Recommended interface tests include peel tests combined with humidity-freeze (HF) and damp-heat (DH) ageing, hail impact, and electrical integrity checks, such as I-V and electroluminescence (EL) measurements (Figure 5). It must be noted that the standards were selected according to the region of interest for this product, which is Switzerland.

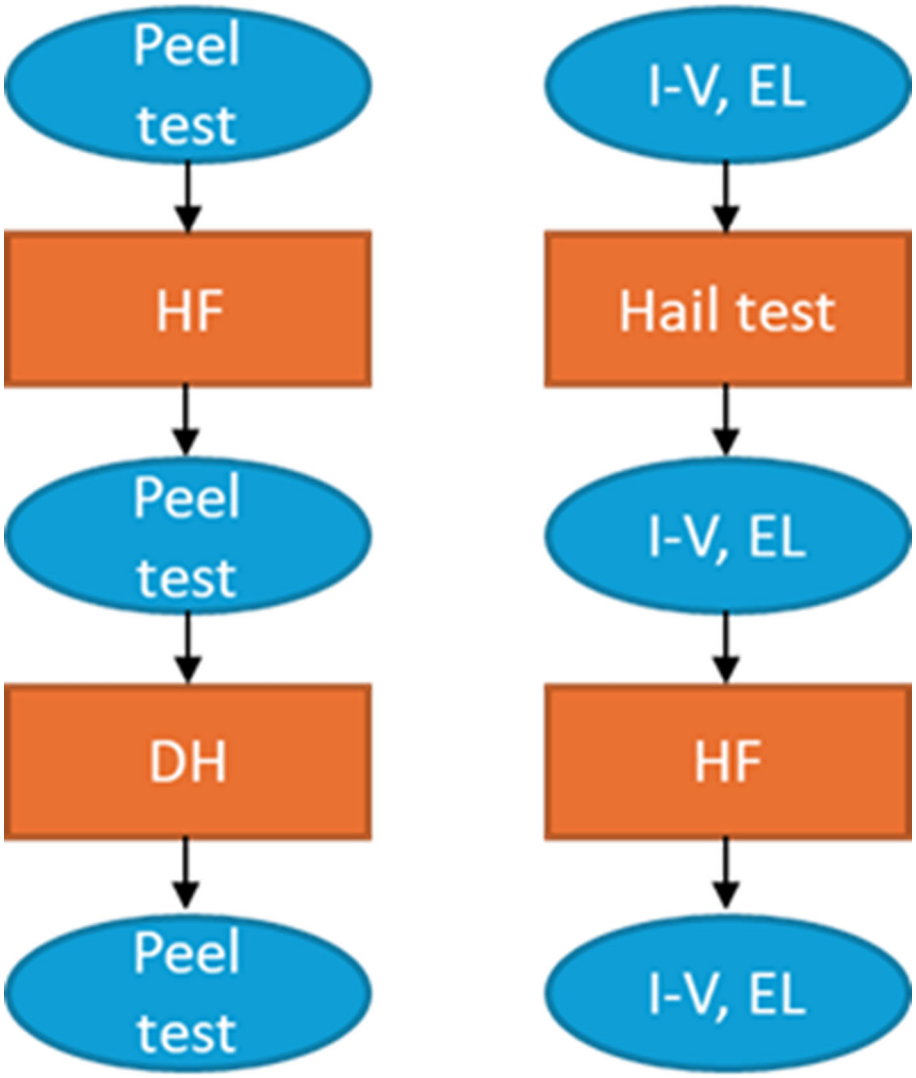


Figure 5. Testing suggestion for the attachment of the Semi-Fabricate (SF) to the cassette, where HF is Humidity Freeze and DH is Damp Heat.

Polymer roof tile case

Here, the SF is mechanically fixed to injection-moulded polymer tiles using integrated clips for easy dismantling. FMEA identified attachment reliability as critical. Certification follows NEN 7250[54] (requirements for construction elements with PV functionality), which mentions norms for airtightness (NEN 2686[55]), moisture proofing (NEN 2778[56]), noise protection (NEN 5077[57]), fire safety (NEN 6063[58]), attachment methods (NEN 6707[46] and NEN 6708[47]), assessment of structural safety in case of renovation (NEN 8700[59]), energy performance (NTA 8800[60]), basis of constructive design (NEN-EN 1990 + A1[61]), snow-, wind- and thermal loads (NEN-EN 1991–1-3,[62] 1991–1-4,[48] 1991–1-5[63]), uplift resistance of (clay or concrete) rooftiles (NEN-14437:2004[64]) and lightning protection (NEN-EN-IEC 62305[65]). Additional tests are advised for vibration risk under wind loads (e.g., wind tunnel testing) and hotspot formation under high-temperature operation, especially near cabling. It must be noted that the standards were selected according to the region of interest for this product, which is The Netherlands.

IGU BIPV end-products

In this product family, end-products must comply not only with PV-related IEC standards, but also with EN 1279 (Glass in Buildings: Insulated Glass Units).[35–38] The certification approach, based on the FMEA conducted, aims to identify which tests can only be carried out at the end-product level, minimising redundant testing at both SF and end-product levels. Tests at the SF level primarily focus on electrical properties and safety, while end-product tests focus on the

Table 3. Tests applicable exclusively at the Insulated Glazing Unit (IGU) Building Integrated Photovoltaic (BIPV) end-product level.

PV related tests	IGU related tests
Thermal cycling	Climate sequence test
Humidity freeze	Gas leakage rate
Damp heat	Physical attributes
UV test	U-value measurement
Mechanical load test	Solar factor and transmittance
Hail test	Glass structural requirements
Fire test	
Ignitability test	
Module breakage test	

integrity and safety of the full IGU assembly, considering structural, thermal, moisture, and long-term reliability when PV elements are integrated within IGUs.

Tests applicable exclusively at the end-product level are summarised in Table 3. These evaluate not only PV performance but also interactions between the SF, glass configuration, edge seal system, and mounting conditions (e.g., fixed SF or integration within venetian blinds).

Considering the SFs and their certification with IEC 61730,[18,19] similarly to the building claddings, it is recommended to perform Sequence D and Sequence F only at the end-product level. These sequences are not relevant at SF level because conditions (e.g., thermal, mechanical) differ significantly when the SFs are integrated into the IGUs, and Sequence F applies only after the final electrical connections are added.

Conclusions

This article addresses the distinctive challenges of Integrated Photovoltaic (IPV) certification that stem from wide variation in designs, integration contexts, and regulatory landscapes. Existing certification schemes built around standardised PV modules and high-volume product lines are not consistent with a larger deployment of mass-customised solutions or intermediate components. Semi-fabricates (SFs) are, by definition, incomplete; they may omit junction boxes, mechanical supports, or other critical elements, making full PV certification premature. At the other end, imposing full PV certification on niche IPV end-products can threaten bankability, particularly when construction codes and PV standards overlap, leading to duplicative testing.

To bridge this gap, we propose a stepwise workflow. It starts with a comprehensive review of product requirements, applicable standards, and national regulations, and proceeds with Failure Mode and Effects Analysis (FMEA) at the SF-, product-, and interface-level. This allows to select norms and, where appropriate create tailored test sequences. This targeted approach avoids redundant retesting while preserving safety and reliability.

To further streamline IPV certification, we advocate for harmonised guidance that aligns PV standards, Building Integrated Photovoltaic (BIPV) provisions, and construction regulations within a single framework. Close coordination with standardisation bodies and insurers is essential to keep safety a central element without imposing undue costs on manufacturers. Priority should be given to defining representative attachment scenarios for SFs so that meaningful certification can occur at the sub-assembly level when appropriate. In parallel, modular, family-based test sequences, rather than per design qualification, can materially reduce time and cost. Ongoing engagement with product owners, insurers, and authorities will be pivotal to adapting this framework and accelerating the uptake of innovative BIPV across various applications.

Achieving consistent IPV certification across Europe will require decisive steps at the EU level. The European Commission must issue Standardisation Requests (SReqs) to CEN defining what constitutes BIPV, which characteristics are essential, and what the future harmonised European Standard (hEN) must include. A clear deadline for development of the hEN, followed by its publication and listing in the Official Journal of the EU, will allow CE marking to begin under CPR 2024. Only then will Member States be required to remove national barriers that currently hinder BIPV market entry.

Addressing these structural gaps is critical: current certification practices impede the deployment of PV within the building envelope. Legislative and standardisation progress will not only streamline BIPV integration across Europe but will also support the European Commission's broader goal of revitalising PV manufacturing within the EU through safer, more coherent market access pathways.

Use of AI

The tool M365 Copilot, powered by the GPT-5–based chat model (provided by the host institution of the corresponding author), has been used to improve the writing style and the flow of the text. Moreover, it has been used for the description of some of the norms, which were then double-checked by the authors.

Ethics and consent

Ethical approval and consent were not required.

Disclaimer

The views expressed in this article are those of the author(s). Publication in Open Research Europe does not imply endorsement of the European Commission.

Data availability

This work is based on literature review of certification norms; therefore, no data was required.

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The manuscript deals with an important and very practical problem for integrated photovoltaics: how to certify product families when the photovoltaic component is only partially finished and its final behaviour depends on the building element, attachment method and intended application. I found the distinction between the semi-fabricate, the interface and the final IPV product particularly relevant. The three examples considered, an aluminium façade, a polymer roof tile and an insulating glass unit, also illustrate situations in which applying the same complete certification procedure to every possible configuration may be unrealistic.

The motivation for the work is clear. The manuscript explains that current certification procedures were mainly developed for standardised, high-volume PV modules, whereas integrated products may vary in dimensions, materials, mechanical integration and construction function. It also explains well why some tests cannot be meaningfully completed at the semi-fabricate level and why repeating PV and construction tests may increase cost without necessarily providing additional information.

My main concern is not the general idea of the workflow, which I find reasonable, but the lack of traceability between the proposed method and the certification decisions presented in the examples. I could understand why the authors propose moving some tests from the semi-fabricate to the final product, but I could not determine which precise rule would allow another manufacturer, laboratory or research group to reach the same decision for a different product family. In its current form, the workflow still depends strongly on expert judgement that is not documented in the manuscript.

I recommend that the following **major revisions** be made.

1. The novelty needs to be positioned more clearly.
The manuscript reviews several existing IEC, EN, ISO and national standards, together with the IEA-PVPS Task 15 report. However, it is not yet completely clear where the review of existing requirements ends and where the new method begins.

The current contribution appears to be more than a list of applicable standards. As I understand it, the real proposal is to use product-family definitions and an FMEA at the semi-fabricate, interface and end-product levels to decide where each test should be performed. This is potentially useful, but it should be stated more directly.

The authors should explain what the proposed method adds to the existing retesting and BIPV certification frameworks already discussed in the manuscript. A compact comparison table would help. It could compare the proposed workflow with the main existing standards and guidance in terms of:

- treatment of incomplete semi-fabricates;
- treatment of the interface with the building product;
- definition of product families;
- consideration of national construction requirements;
- selection of representative configurations;
- use of FMEA;
- final output of the procedure.

Without this comparison, the word “novel” in the title is not yet fully demonstrated.

The end of the Introduction would also benefit from one clear paragraph stating the research gap, objective and concrete contributions. A brief sentence describing the organisation of the manuscript could then be added, although the contribution paragraph is more important than a conventional section-by-section description.

2. The method used to identify standards and stakeholder requirements is not reproducible
The manuscript states that PV standards, BIPV guidance, construction regulations, national requirements and stakeholder input were considered. However, the procedure used to collect and select this information is not described. It would be useful to indicate:

- which databases, standards catalogues or institutional sources were consulted;
- the cut-off date and editions considered;
- why Italy, the Netherlands and Switzerland were selected;
- how standards were classified as mandatory, voluntary, informative or market-specific;
- how overlaps between PV and construction tests were identified;
- who performed this assessment;
- how uncertain or conflicting interpretations were resolved.

The same issue applies to the stakeholder analysis. Figure 1 identifies stakeholder categories, but it does not describe the actual consultation. How many people or organisations were consulted? Were they interviewed, involved in workshops or asked to review the workflow? Did insurers and certification experts validate the proposed certification routes, or did they only provide general observations?

If this was an informal consultation within the MC2.0 project, that is acceptable, but it should be described as such. At present, the expression “stakeholder analysis” suggests a more structured procedure than the one documented in the manuscript.

3. The FMEA needs to be shown, not only described
The FMEA is central to the proposed method, but the manuscript provides only a generic explanation of severity, occurrence, detectability and RPN. The actual FMEA tables for the three product families are not provided. This is, in my view, the most important issue to address. For each example, the authors should provide at least:

- the component or function analysed;
- the failure mode;
- the cause;
- the consequence for safety, performance or neighbouring components;
- the relevant environmental or operational stressor;
- severity, occurrence and detectability values;
- the justification for each score;
- the resulting RPN;
- the selected mitigation or test;
- the level at which the test is assigned: SF, interface or end-product;
- the residual risk after mitigation.

The authors should also explain who assigned the scores, whether several experts were involved and how disagreements were handled. The definitions associated with the 1–10 scales should be included.

RPN alone may also be insufficient for a certification method. A severe safety failure should not become a low priority only because its estimated occurrence is small. The authors should explain whether a severity override, criticality class or another rule is used for safety-related failure modes.

A recognized methodological standard or guidance for FMEA should also be cited. The current reference supports the use of criticality analysis in PV reliability, but it does not by itself fully define the FMEA procedure used in this study.

4. Explicit rules are needed to allocate tests to the SF, interface or final product
The manuscript proposes moving some IEC 61730 sequences to the final-product level and recommends additional interface tests. These decisions may be justified for the examples considered, but the general decision rule is not defined. The workflow should answer questions such as:

- Are all components needed for the test already present in the SF?
- Does integration modify the thermal, mechanical, electrical or fire behaviour?
- Is the pass/fail criterion meaningful before integration?
- Can a representative attachment or worst-case configuration be defined?
- Is the requirement mandatory for certification or only an additional reliability test?
- Does the selected test adequately reduce the risk identified by the FMEA?
- Is retesting necessary when the attachment, substrate, dimensions or bill of materials change?

I strongly recommend adding a traceability matrix. One row could correspond to each relevant

failure mode, with columns for the stressor, FMEA score, applicable standard and clause, test, test level, representative specimen, acceptance criterion and residual risk.

Such a matrix would make the contribution much clearer than Tables 1 and 2, which currently mainly list standards and their general scope.

The wording related to IEC 61730 should also be made more precise. The manuscript states that the “full IEC 61730 standard” can be applied at the SF level except for some tests. If required sequences are excluded or transferred, this is not a complete IEC 61730 qualification of the SF. It would be more accurate to refer to pre-testing or partial assessment of the requirements that remain meaningful at the SF level.

Likewise, IEC 61215 should not simply be described as “reliability certification”. It is a design qualification and type-approval procedure, not a direct prediction of field lifetime.

5. Product-family boundaries and representative samples need clearer definitions
The definition of a product family currently relies on products having the same application and “similar” semi-fabricates. The term “similar” is too open for certification purposes.

The authors should specify which variables may change within the same family and which changes require a new family or additional testing. Depending on the application, this could include:

- cell technology;
- encapsulant and backsheet;
- glass and interlayer configuration;
- dimensions;
- electrical interconnection;
- junction box;
- adhesive or mechanical fixing;
- substrate;
- mounting geometry;
- edge-seal system;
- ventilation conditions;
- fire-relevant materials.

The recommendation to test the largest or most failure-prone product should also be refined. The largest configuration may be the worst case for mechanical load, but not necessarily for hotspot formation, fire propagation, thermal behaviour or moisture ingress.

The method should therefore select a representative or worst-case specimen for each failure mode rather than assuming that one specimen is representative of all risks.

6. Environmental and operational conditions should be integrated into the analysis
The methodology briefly mentions boundary conditions such as environmental stress levels based on climate, but these conditions are not systematically defined in the case studies.

This is particularly important because the behaviour of an SF before integration may differ

substantially from its behaviour in the final building product. The substrate, rear ventilation, adhesive, glazing cavity, mounting geometry and electrical connection can modify module temperature, moisture exposure, mechanical stress and hotspot behaviour. The workflow should explicitly distinguish between:

- standard qualification conditions;
- intended-use conditions;
- non-standard or severe operating environments.

For each product family, the authors should identify the relevant ranges or exposure classes for temperature, irradiance, humidity, UV, thermal cycling, wind, vibration, snow, hail, water ingress, partial shading and fire scenario.

These conditions should then be connected to the FMEA and the selected test sequence. At present, the manuscript recognises that environmental stressors are important, but does not show how they affect the final decision.

The additional wind-tunnel and high-temperature hotspot tests proposed for the polymer roof tile are good examples, but the rationale should be formalised. Why are these tests necessary for this product? Which risk or operating condition triggered them? What would be the test configuration and acceptance criterion?

7. The performance of the method has not yet been demonstrated

The manuscript presents applications of the workflow, but it does not compare the proposed pathway with a conventional certification route. For each case, I suggest showing:

- the tests required under the conventional approach;
- the tests retained in the proposed approach;
- the tests transferred to another product level;
- the tests combined or removed;
- the number of specimens required;
- the expected reduction in time or cost;
- the remaining risks or unresolved certification gaps.

A quantitative cost analysis may not be possible if commercial information is confidential, but the authors could at least compare numbers of tests, sequences and specimens.

Until such evidence is provided, statements that the method reduces cost, avoids unnecessary testing, preserves safety or accelerates market entry should be presented as expected benefits rather than demonstrated results.

It would also strengthen the study to indicate whether the three proposed routes were reviewed or accepted by an accredited laboratory, certification body, insurer or regulatory expert. If they have only been proposed within the project, this should be stated clearly.

8. Data availability, limitations and conclusions

I do not agree with the statement that no source data are required. This is not an experimental study in the conventional sense, but it still produces analytical data and intermediate results: FMEA tables, risk scores, standards crosswalks, stakeholder input, product assumptions and

decisions about test allocation.

These materials are necessary to reproduce the method and should be made available as supplementary files or in a repository. Confidential commercial information could be anonymized. A dedicated limitations section is also needed. It should discuss at least:

- the restriction to three product examples;
- the geographical focus;
- the dependence on expert judgement;
- the subjectivity of FMEA scoring;
- the absence of accredited-laboratory validation;
- the absence of quantitative cost and duration results;
- the difficulty of generalising one representative configuration to a complete product family;
- the evolving status of European and national standards.

The geographic scope should be clarified as well. The manuscript links the aluminium façade to Switzerland and the roof tile to the Netherlands, but the market corresponding to the IGU example is not clearly stated. The use of DIN standards for a product targeting Switzerland should also be explained.

The Conclusions currently restate the problem and propose broader European standardisation actions, but they do not sufficiently summarise what was actually demonstrated in the three cases. The authors should first report the specific methodological results, then acknowledge the limitations, and finally discuss expected benefits and policy implications.

Claims concerning future harmonised standards and the removal of national barriers should also be carefully referenced and qualified.

In addition, I suggest the following **minor revisions**:

1. Figure 2 needs to be redrawn. Increasing the font size would help, but the main problem is the logic of the diagram. Step 3.B appears before Step 3.A, and the arrows do not make it clear whether the process is sequential, parallel or iterative. A decision tree with explicit yes/no questions would be easier to follow.

2. Figure 4 is a general FMEA diagram, but it does not add enough information about the method used in this study. It would be more useful to present a worked example or a study-specific sequence from failure identification to test selection and residual-risk evaluation.

3. Figure 5 should include more than the names of the tests. The text should specify whether the two columns are independent sequences, how many specimens are used, the exposure conditions, the measurements made before and after each stress and the acceptance criteria.

4. The figures should be provided at higher resolution or in vector format. The text in Figure 2 is currently difficult to read.

5. A glossary or nomenclature table would be useful because the manuscript uses many abbreviations, including IPV, BIPV, SF, IGU, FMEA, RPN, CPR, LVD, DoP, ETA, ETN, ATEx, ATEC, HF,

DH and EL.

6. The reference list and standard identifiers should be checked carefully. I noticed, for example:
- "IEC 13501" in Table 2, which appears inconsistent with the EN 13501 series cited in the text;
- NEN 6708 in the table and NPR 6708 in the reference list;
- an incomplete entry for NEN 7250;
- duplicated "Reference Source" text in Reference 51;
- inconsistent punctuation and formatting in several standard titles.

7. All standards should be cited consistently with issuing organisation, full identifier, edition or year and official title.

8. Regarding language, "this article" is not incorrect when referring to the document. "This study" is more appropriate when referring to the work or method itself, so a systematic replacement is not necessary. The possessive form in "the manufacturer's responsibility" is also correct. "For the examples investigated here" is acceptable, although "For the examples examined here" would sound slightly more natural.

9. The manuscript should preferably use "standards" rather than "norms" in most technical sentences. Expressions such as "This allows to select norms" should be revised, for example, to "This enables the selection of the relevant standards".

10. The manuscript states that M365 Copilot was used for some descriptions of standards. Since the interpretation of standards is a central input to the method, the authors should confirm that every technical and regulatory statement was checked against the primary text and the correct edition of the corresponding standard.

Is the rationale for developing the new method (or application) clearly explained?
Yes

Is the description of the method technically sound?
Partly

Are sufficient details provided to allow replication of the method development and its use by others?
No

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?
No

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: My research focuses on artificial intelligence and machine learning applied to photovoltaic systems, particularly for performance assessment, fault detection and diagnosis, reliability analysis, and the study of environmental and operating influences on PV behaviour. I also work on data-driven, physics-informed and hybrid modelling approaches for photovoltaic applications.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.