

INTEGRATION AND AUTOMATION OF EXISTING INTERRELATIONSHIP PROCESSES BETWEEN PHOTOVOLTAIC TECHNOLOGIES, AGRICULTURAL LAND PRODUCTION AND LANDSCAPE PROTECTION: THE GILDA PROJECT

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ABSTRACT: This work aims at presenting a detailed illustration of the key findings, integrated analyses, and methodological and application procedures developed in the context of the creation and management of the complex information assets relating to applications pertaining to the regulation of control procedures for the presence of certified crops in agricultural areas (specifically organic production, production registered with the national quality system for integrated production, production with a designation of origin and geographical indication, fodder produced in the area of origin of the Parmigiano-Reggiano DOP cheese) of the Emilia-Romagna Region affected by photovoltaic systems, aiming at locating these systems.

The extreme complexity of the above-described issues led to the development of the GILDA project, an acronym for Low-zero code Integrated Management of Authorization Applications, specifically based on the use of Low-Code Platforms for the integration and automation of processes. Its aim is to ensure effective, timely and efficient management of the investigation activity, archiving and evaluation processes of requests relating to the verification of the presence of certified crops on agricultural land affected by the construction of photovoltaic and agrivoltaic systems, by virtue of the contribution made by the organizational and technological innovation implemented.

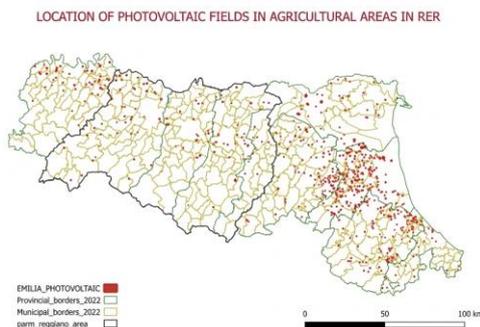
Keywords: Agrivoltaics (AgriPV), Automation, Landscape Protection, Renewable energy sources (RES), Low-No Code Platforms, Artificial Intelligence A.I.

1 INTRODUCTION

Currently, the agricultural and rural sectors are significantly affected by the installation of renewable energy systems, even in areas with vocation for agriculture. This aspect must be carefully evaluated — and, where necessary, implemented — to avoid any harm to agri-food production, particularly to the high-quality products that characterize the Emilia-Romagna region.

Specifically, with regards to the photovoltaic technology, we observe the onset of a complex transition phase, characterized by the likely feasibility of its installation on the ground, on rooftops, or alongside crops—agrivoltaic systems—aiming to optimally and contextually balance agricultural and energy production related to the land on which the agrivoltaic system is located, as well as landscape protection (Fig. 1).

Fig. 1: Location of photovoltaic fields in agricultural areas in the Emilia-Romagna region



It should be recalled, among others and by way of a completely non-exhaustive example, how the Soil Thematic Strategy has identified the loss of organic matter in soils (primarily agricultural soils) and the resulting loss of biodiversity as a serious threat likely to trigger and lead to complete land degradation, even to desertification.

Agricultural soil, in particular, is primarily related to several ecosystem services: food and biomass production;

water purification; regulation of microclimates, biogeochemical cycles, surface runoff and water infiltration; erosion control; groundwater recharge; carbon capture and storage and biodiversity conservation.

While it is essential to achieve a suitable combination of the necessary and complete development of renewable energy, achieved through the construction of related plants, with the preservation and protection of that fundamental resource – albeit vulnerable, limited, and non-renewable – consisting of agricultural land and the excellent agri-food products that characterize the Emilia-Romagna Region, on the other hand, we must not refrain from carrying out a general reflection aimed at understanding the "radically intrinsic and profound" economic motivations connected to energy production in these areas, its relationship with the continuity of the activities carried out there in their multiple aspects, with the structure of production locations within the territory, with the problems of efficiency and equity linked to the consumption of resources and the payment of the costs that the growing demand for plant installations entails.

The serious and alarming ecological and environmental problems, first, and the energy ones, subsequently, have led to the unequivocal recognition and clear observation of a current situation that is no longer defensible or supportable in any way, to the need for a rationally planned and focused articulation of the constraints, to the establishment of regulations no longer organized by rigid apodictic dictates but focused on alternative prescriptions that ultimately allow the needs for control to be reconciled with those of adaptation to temporally and territorially diversified situations.

The epochal and universal dimensions assumed today by the issues and themes recalled above necessarily imply a complete and integral reconsideration of the existing relationships between anthropic, agricultural and natural ecosystems, due to the rooting of the pre-eminent environmental disasters that have occurred there as well as the reaching of limits, thresholds and rates of development and chronological-temporal divergence that are such as to jeopardize their very own safety.

2 THE POTENTIAL USE OF INNOVATIVE TECHNOLOGICAL SOLUTIONS ALTERNATIVE TO THOSE USUALLY ADOPTED

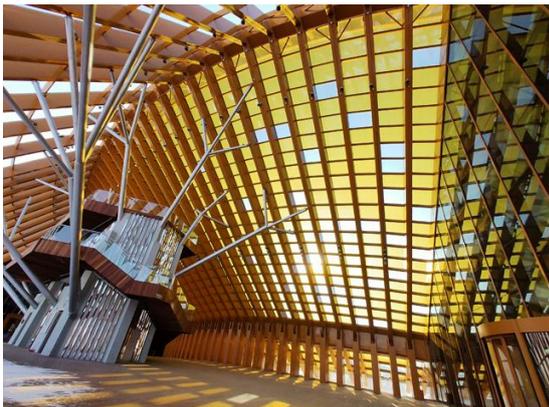
The adoption of photovoltaic solutions compatible with agricultural production represents one of the key challenges for truly integrating agri-food needs and energy transition objectives. In this context, the Sustainable Agriculture Area of the Emilia-Romagna Region is not limited to merely evaluating conventionally proposed solutions in this area, but is committed to evaluating and paying particular attention to the development of innovative modular and scalable systems, to valuable ongoing experimental activities adaptable to different agricultural and climatic contexts, and to the most relevant scientific validation projects related to them. This is done in order to objectively quantify the agronomic, energy, and environmental benefits associated with the use of innovative technologies in the primary sector.

In this regards, it is important to highlight how the use of semi-transparent photovoltaic glass elements installed in a vertical inter-row configuration presents itself as a functional and scientifically promising alternative to conventional agrivoltaic systems.

These modules, based on thin-film technology laminated between two glass panes, guarantee:

- uniform and adjustable transparency (depending on the species grown, latitude, and required photoperiod);
- greater mechanical strength (thanks to the glass-on-glass structure);
- stable energy performance even in suboptimal conditions (low solar angle, dust accumulation);
- enhanced landscape and environmental compatibility thanks to the possibility of tinting without reducing performance (post-active tinting technology, Fig. 2).

Fig. 2: Semi-transparent photovoltaic glass with post-active colouring technology



In vertical configuration, power densities between 100 and 140 W/m² per side are currently possible, with the potential for inter-row installation without decreasing the active agricultural area. This approach allows for a more rational use of cultivable space and reduces the structural and agronomic constraints resulting from suspended or inclined PV systems.

Another key advantage is the solution's high level of application flexibility, allowing for the integration of photovoltaic glass in agricultural greenhouses, machinery shelters, adjustable shading systems, and partial crop protection structures. Selective transparency, which can

be adjusted for different horticultural or floricultural species, optimizes the balance between photosynthesis-relevant radiation and energy production, while maintaining high agricultural quality standards.

The evolution of this technology will be strongly influenced by the integration of advanced photovoltaic junctions, particularly perovskite-based ones, a class of organic/inorganic materials capable of offering high conversion efficiency and selective transparency. Perovskite single-junction cells have already achieved laboratory efficiencies exceeding 31%, pursuing a growth trajectory that will lead to highly promising new application scenarios in agriculture and construction.

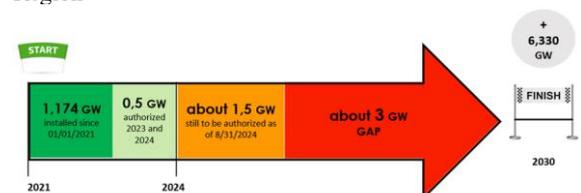
3 THE EXISTING AND EVOLVING REGIONAL REGULATORY FRAMEWORK

In order to actively promote development policies and the maximum diffusion of photovoltaic systems within its territory, the Emilia-Romagna Region, with Legislative Assembly Resolution No. 125 of May 23, 2023, established new criteria for the location of renewable energy plants. The objective is to clarify and integrate the framework resulting from current regional legislation with the provisions regarding suitable areas contained in Legislative Decree No. 199/2021, while identifying appropriate environmental and landscape protections, it aims at the preservation particularly valuable crops that represent the Emilia-Romagna Region's excellent agricultural production, also combating harmful land consumption.

As part of the current legislation regarding the identification of areas and sites suitable for the installation of electricity generation systems using renewable solar photovoltaic energy sources, Regional Council Resolution No. 693/2024 was also approved. This resolution specifies the criteria for identifying areas suitable for certified crops and the control procedures for the installation of photovoltaic systems in agricultural areas.

The aforementioned legislative acts are related to the Ministerial Decree of June 21, 2024, known as the "Suitable Areas" Decree, which defines the criteria that the Regions must observe when developing specific laws to regulate the identification of areas and sites suitable for the installation of renewable energy plants. It also indicates for each Italian region the amount of additional power, compared to the value established in January 2021, deriving from renewable energy sources to be produced by the end of 2030. The latter amounts to 6.33 GW for the Emilia-Romagna region (Fig. 3).

Fig. 3: Trajectory for achieving the overall power target to be achieved by 2030 assigned to the Emilia-Romagna Region



In this regards, a significant contribution, further demonstrating the pioneering and innovative evolutionary tendency pervading the many and diverse organic

approaches to territorial spaces and the interpretative dynamics of the relational components variously pertaining to them implemented by the Emilia-Romagna Region, shall derive from the decisive conversion of the draft Regional Law "Localization of plants powered by renewable energy sources in the regional territory", approved by Council Resolution no. 717/2025, which aims at regulating, among other things, suitable, unsuitable, and ordinary surfaces and areas for the location of renewable energy plants, while ensuring the minimization of impacts on the landscape, the environment, cultural heritage, the territory, and the agricultural sector, with particular reference to the valorization of local agri-food traditions.

Other key elements of the aforementioned draft Regional Law include the regulation of the installation procedure for advanced agrivoltaic systems, which requires the prior submission of a certified agronomic report; the definition of a forward-looking crop plan to be adopted for a period equal to the system's lifespan, including crops suitable for shading consistent with the area's prevailing production systems; the preparation of an agronomic monitoring report; and the assessment of the maintenance of agricultural productivity, carried out by comparing the crops present in the advanced agrivoltaic systems with the same crops grown without photovoltaic systems.

4 THE "GILDA (INTEGRATED MANAGEMENT OF LOW-ZERO CODE AUTHORIZATION APPLICATIONS)" PROJECT

4.1 Objectives and purposes underlying the GILDA project

The primary, broad-based objective is to enable the regional administration — which is variously involved in the multitude of proceedings involving the expression of an opinion/investigative outcome, an authorization, and/or subsidies granted following the preliminary investigation to be completed within extremely tight and timely deadlines — to communicate the procedural outcome in question to the interested stakeholders (citizens, entities/administrations, etc.) in a coherent, effective, timely, efficient manner, and plausibly consistent with similar requests from different senders, even over different time periods.

Specifically, the initial step of this far-reaching project consists in the development of the application for the management of requests relating to the regulation of control procedures relating to the presence of certified crops in agricultural areas (specifically organic productions pursuant to Regulation (EU) no. 848/2018, vegetal productions registered with the National Integrated Production Quality System SQNPI - art. 2 of Law no. 4 of 2011, products with Origin Denomination and Geographical Indication DO/IG, pursuant to Regulation (EU) no. 1151/2012 and Regulation (EU) no. 1308/2013, obtained from vegetal productions cultivated in the regional territory and subject to compliance with the relevant production specifications, fodder produced within the original area of the Parmigiano-Reggiano DOP cheese, identified in the Production Specifications approved with Regulation (EU) no. 794/2011 and subsequent amendments) of the Emilia-Romagna Region affected by photovoltaic systems for the purpose of locating the systems themselves (Fig. 4, Fig. 5, Fig.6).

Fig. 4: Mapping of DO and IG products in the Emilia-Romagna Region



Fig. 5: Organic crops and DO/IG area boundaries for crops and wine-growing

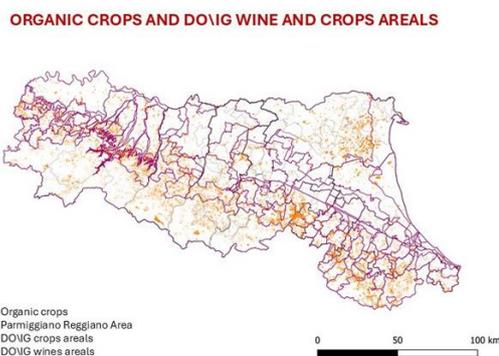
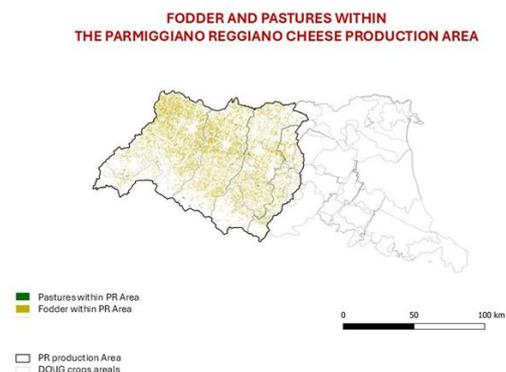


Fig. 6: Fodder crops and pastures within the Parmigiano Reggiano DOP cheese area



This effective achievement, which can only be achieved through careful and in-depth checks, controls, and analyses, lies in the project's fundamental vision and requires a suitable tool to fulfill these processes.

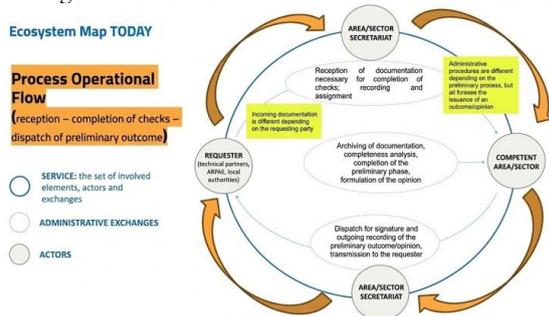
4.2 The operational challenge and the state of the art: description of the current situation (AS-IS)

The current procedure involves a complex series of phases, resulting in a costly, entirely manual process of investigation, verification, control, and feedback. Following the receipt of applications for assignment by the protocol via the AURIGA vertical application, over 5 databases are queried (Table 1). This creates a high risk of human error and processing times ranging from 1 hour to 1 day for each request (Fig. 7).

Table I: Databases consulted for the purposes of carrying out the verification and control procedures envisaged by Regional Council Resolution No. 693/2024

DATABASE DENOMINATION	MANAGER AUTHORITY
REGIONAL REGISTER OF AGRICULTURAL COMPANIES	SIAR
SURVEILLANCE DATABASE	SIAN
REGISTER OF MEMBERSHIP RESULTS/SQNP I CONTROLS	SIAN
AGRIBIO	SIAN
SITIFARMER	AGREA

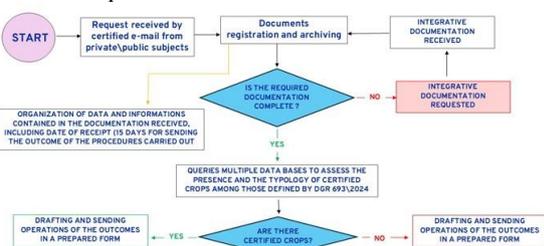
Fig. 7: Current ecosystem map and related document exchange



The actions carried out as part of the procedure described above include (Fig. 8):

- consultation of a large set of project documents archived by the competent authorities (municipalities, ARPAE, MASE, etc.) in various formats (PDF, Word, Excel, shape, etc.) in restricted-access folders on the cloud or dedicated servers;
- review of the documentation (minutes, authorizations, opinions, etc.) produced by the various parties potentially involved in the Services Conference;
- sending the proponent any requests for additional documentation, if necessary;
- individual querying of at least 5 different databases with qualified access, with a high risk of human error and resulting processing times;
- processing, signing, and forwarding via certified email (PEC) to the proponent or the competent authority of the final verification communications, archived in a searchable repository.

Fig. 8: A simplified current process for verifying certified crops



In order to prevent the implementation of the "tacit approval" mechanism by silent consent, the aforementioned requests must be responded to within 15 days, as there is a high risk of human error given the huge number of certified email (PEC) requests sent daily to the Sustainable Agriculture Area - since May 2024, over 250 from private individuals and over 90 from public bodies, corresponding to a total of approximately 350 requests covering a cultivated area of approximately 4,500

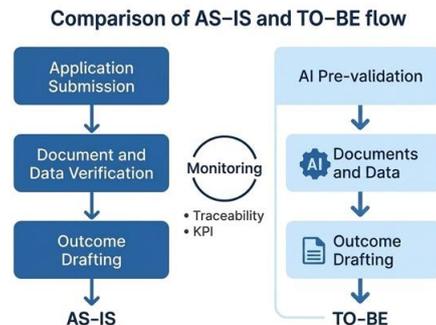
hectares (Used Agricultural Area) and with an additional power output obtainable from the installation of the relevant plants estimated to be in the order of 2.9 - 3.3 GW.

4.3 Genesis of the TO-BE enabling solution: the conception and design of GILDA, a strategic platform aimed at accelerating workflows and administrative procedures, optimizing and automating the authorization process through the use of a Low-Code/No Code platform and the integration of Artificial Intelligence tools

The methodology adopted for GILDA is based on an AS-IS process analysis, followed by the definition of a TO-BE architecture based on Low-/No-code components and AI agent integration (Fig. 9). Functional requirements (categorization, archiving, workflow automation), regulatory constraints and interoperability opportunities with regional and national databases have been identified.

The solution designed will allow the manual processes described above to be digitized and automated, providing for the configuration of a back-end service created using Power App and/or Low Code/No Code technology, appropriately integrated with the Auriga system for registering requests. The automated investigation service oversees the management of emails, certified emails and related documents, verifying them, archiving them in Sharepoint portal (or any other repositories to be evaluated), managing plausible queries from various databases and providing support for the investigation outcome, using text analytics and reporting with artificial intelligence tools.

Fig. 9: Comparison between AS-IS and TO BE operational flows



The resulting evidence is easily deducible: it is not a matter of simply eliminating jobs, but rather of transferring value by freeing technicians and decision makers from repetitive, high-volume activities to focus on high-value ones, thus placing them in the optimal position to make the related strategic decisions, improving the efficiency and accuracy of the service and its scalability towards other processes.

The evolution and digital transformation of what currently consists of an extremely burdensome manual process in terms of workload, resource usage, error rates, etc., will also allow:

- to greatly speed up the process - 95% reduction in the average verification times existing due to automated pre-validation - fully meeting the essential need to respect the unavoidable deadlines set, also avoiding the establishment of repeated exchanges of documents or explanatory/clarifying letters and guaranteeing end-to-end traceability;

- to minimize the workload of internal users by optimizing it to the greatest extent and in the best way achievable in relation to the limited human resources dedicated to it;
- to achieve the best qualitative performances in the improvement of company organizational and procedural processes.

5 THE GRADUAL EVOLUTION OF THE PATH TOWARDS A DIGITAL AND SMART PA, FOCUSED ON TARGETED EFFICIENCY, ON THE CREATION OF A COMPLETE ECOSYSTEM BASED ON AI AND ON THE CONSTRUCTION OF A SYSTEMIC AND CONTINUOUS DEVELOPMENT CAPACITY

5.1 The extensive evolution of the GILDA project

The broad, extensive evolution of the GILDA project could consist of the implementation of a prototype aimed at automating complex administrative procedures also within other sectors of the regional structure, potentially interoperable with similar services offered by other Administrations.

The proposed architecture consists of a scalable platform designed to serve as a single point of access for administrative procedures. Its core asset is a comprehensive mapping and categorization of the entire regional administrative framework, integrating a headless front-end (Table II) and a centralized knowledge hub to create a vast, unified internal dataset. Other key elements include an end-to-end administrative workflow digitalization engine, along with specialized artificial intelligence agents dedicated to document pre-validation, metadata extraction and CUUA Unique Farm Codes, multi-database querying, autonomous execution of complex checks, and automatic drafting of investigation results, transforming manual processing into intelligent automation.

The front-end will connect via API (Application Programming Interface) to the back-end as well as to any database (e.g., Dataverse/Oracle), making it custom, agnostic, and decoupled, respecting data neutrality while meeting the critical requirement of storing regional data on non-proprietary platforms, avoiding vendor lock-in.

Table II: Benefits of implementing a custom headless portal

ADVANTAGES of a CUSTOM HEADLESS portal		
ARCHITECTURAL advantage	STRATEGIC advantage	ECONOMIC advantage
The front-end connects via API to the back-end and any database (e.g., Dataverse/Oracle)	Creates a library of pre-approved components for all future services	Avoid creating an unsustainable OPEX model for a unified public-facing portal.
Agnostic and decoupled	Standardized design system	Removes the cost-per-user barrier
Custom front-end	Coherent and familiar user experience	Ensures long-term financial sustainability
Back-end LOWCODE	Built once, deploy many times	Achieve profitability by decoupling costs from user growth
Data neutrality	Accessibility "By Design"	

Pursuing the outlined Roadmap for the gradual evolution of the path towards a digital, unified, scalable, and smart PA (Fig. 10), focused on targeted efficiency, the target to aim for, starting from the aforementioned MVP - Minimum Viable Product - consists of the creation of an AI-based ecosystem within which data, platforms, and people work synergistically, simultaneously equipping itself with a systemic, structured, and continuous capacity to develop solutions that reach broad perspectives centered on a fully strategic vision.

Fig. 10: Strategic roadmap towards a digital, unified, scalable and smart PA



5 CONCLUSIONS

From the above, it is easy to see that the project outlined does not merely concern the digitization of legacy processes. It consists of a technological framework specifically designed to provide large-scale public value and support high-level policies and strategic planning. It also constitutes a replicable model for the digitization of procedures. Given these unique and distinctive characteristics, GILDA can effectively represent a strategic framework and a valuable opportunity to transform regional public administration processes.

While not failing to give due and appropriate importance to the imperative requirement underlying any decision-making process, consisting in the need to be able to access, and use, structured and organized information rationally and efficiently, it is also necessary to avoid formulating the erroneous assumption that the current considerable availability of advanced tools and methodologies can in itself allow for the systematic, explicitly rigorous and timely identification of solutions concerning the most dissimilar and varied problems.

The system in question, together with the procedures and application methodologies developed, constitute valuable tools for contextually considering the multitude of variables and constraints that need to be coordinated. The proposed approach promotes transparency, reduced operating times, efficiency, process replicability, optimal management of complex procedures, reallocation of resources to higher-value activities, and the establishment of a knowledge hub to support planning. This lays the foundation for a more resilient Public Administration oriented toward the energy transition, while also creating the conditions for artificial intelligence to become an integral part of business processes and decisions.

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10 LOGO SPACE



ASSESSING SUSTAINABILITY AND CIRCULARITY IN AGRIVOLTAIC SYSTEMS: BACKGROUND AND FUTURE WORK

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ABSTRACT: Agrivoltaic systems (AVS) co-locate photovoltaic (PV) electricity generation and agricultural production on the same land parcel. While their technical potential is increasingly recognized, the sustainability and circularity of their support structures remain underexplored. The objective of this work is to assess the sustainability of these elements, through aspects of circularity, environment and costs. To this end, the Integrated Value Model for Sustainability Assessment (MIVES) is applied to compare two material alternatives—galvanized steel and structural timber—for an elevated, single-axis AVS support structure designed to carry 28m² of PV modules. The decision model includes social, environmental and circularity requirements, 7 criteria and 24 indicators. Results show that timber achieves a substantially higher sustainability index (0,63) than steel (0,32) under the baseline weighting, driven by lower environmental burdens, reduced dependence on non-renewable resources and favorable end of life options. A sensitivity analysis, varying requirement weights, confirms the selection of timber as the most sustainable alternative. The study demonstrates how MIVES can integrate circularity and sustainability into design decisions for AVS and identifies priorities for future methodological development and data refinement.

Keywords: Agrivoltaics, AgriPV, Sustainability, Circular Economy, MIVES

1 INTRODUCTION

Agrivoltaic systems (AVS) or AgriPV, combine photovoltaic (PV) power generation with agricultural activities on the same land parcel, enabling dual use for energy and food production. The concept traces back to Goetzberger and Zastrow, who proposed elevated PV collectors that allow continued plant cultivation beneath the modules [1]. Subsequent studies and reviews have confirmed that AVS can enhance land use efficiency and, under suitable design, maintain or improve crop yields while producing electricity [2], [3]. The European Union's solar and climate strategies foresee a massive expansion of PV capacity by 2030, and recent analyses suggest that deploying AVS on a small share of agricultural land could contribute substantially to these targets [3], [4].

AVS are typically conformed by four main elements: (i) PV modules and electric balance of system (BOS); (ii) support structures; (iii) agricultural component; (iv) site-specific interfaces such as fencing. Technical reviews and project reports emphasize that support structures are central to AVS performance because they determine clearance height, shading patterns, microclimate and machinery accessibility, while also contributing significantly to embodied impacts and costs [2], [3], [5].

Research on AVS sustainability has so far focused primarily on land use efficiency, crop yields, water use and energy performance at the system level [2], [3]. Life cycle assessment (LCA) has been widely applied to PV systems and, increasingly to AVS, but few studies explicitly isolate or optimize the structural subsystem despite its relevance for material use and environmental impacts [6], [7].

Circularity adds a consideration by focusing on material loops, design for disassembly, durability, reparability and end of life strategies such as reuse or recycling. Frameworks such as Ellen McArthur Foundation's circularity indicators and related taxonomies demonstrate how these aspects can be quantified for products and structures [8], [9].

Policy-oriented reports on AVS in the European

Union stress the need for harmonized definitions, standards and evaluation methods to support coherent regulation and investment [4]. The objective of this work is to assess the sustainability of these elements, through aspects of circularity, environment and costs by applying a multicriteria decision making (MCDM) model called MIVES. This methodology have been applied in architecture and civil engineering to integrate economic, environmental and social dimensions into single sustainability indices and to compare design alternatives[10]. In this context, MIVES offers a way to combine economic, environmental and circularity indicators into a coherent assessment thereby contributing to foundations needed for evidence based AVS deployment.

2 METHODOLOGY

2.1 Model for sustainability assessment

MIVES is based on a hierarchical tree that decomposes a decision problem into requirements, criteria and indicators, and uses value functions to convert heterogeneous indicator values into dimensionless indices between 0 and 1, which can then be aggregated into a single sustainability index [10]. In this study, MIVES was implemented following the version 2.1.1 released in October 2016.

Key steps in the methodology includes:

- a. Definition of system limits
- b. Construction of decision tree
- c. Indicator quantification
- d. Application of value functions
- e. Aggregation and sustainability index

2.2 Case study

The case study is based on an elevated, single-axis AVS structure related to the SYMBIOSYST Project, calculations, inventory analysis and assessment were carried out by GRIC [5]. Table I, present the elements relative to the initial model conditions.

Table I. MIVES assessment considerations

Element	Description
Functional unit	A support structure capable of carrying 28m ² of PV modules
Boundaries	Cradle to grave
Inventory sources	Costs data, Ecoinvent 3.6
Impact assessment method	EF 3.0 method [11]

The assessed structural section is shown in Figure 1. The two material alternatives are steel and timber. For the steel option, galvanized carbon steel with zinc coating for foundations and the tube and module support system was considered. In the case of the timber alternative, structural softwood (German pine) with autoclave treatment was analyzed. Secondary components such as fasteners, rotation mechanisms, aluminum parts and stainless-steel elements remained unchanged for both material alternative scenarios. The total mass of steel structure was 625kg, whereas the timber option had a total of 351kg.

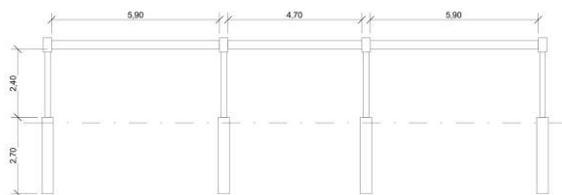


Fig.1 Structural section analyzed.

The common section is composed by 4 driven steel piles anchoring columns (2,7m), 4 columns (2,4m) and 3 beams (5,90m; 4,70m; 5,9m), forming 3 portal frames.

2.3 MIVES decision tree

The decision tree comprises 3 requirements (R1-R3), 7 criteria (C1-C7) and 27 indicators (I1-I24). Figure 2 presents the model tree and the relative value for each element.

All indicators were converted to value indices using linear functions, with decreasing functions for burdens (e.g. impacts, costs, virgin material share, irrecoverable waste) and increasing function for benefits (e.g. resource duration, utility, recycled material share).

Weights follow 3 principles: (i) equal weight for indicators within each criterion; (ii) criteria weights proportional to their number of indicators; and (iii) equal weight for environmental and circularity requirements (44,5%), with a smaller weight for the economic requirement (10%) for the baseline scenario. Five additional weighting scenarios are defined for the sensitivity analysis in Table II.

Table II. Sensitivity analysis weighting scenarios (%)

Scenario	Economic	Environmental	Circularity
S1	33	33	33
S2	5	30	65
S3	30	65	5
S4	65	5	30
S5	8	67	25

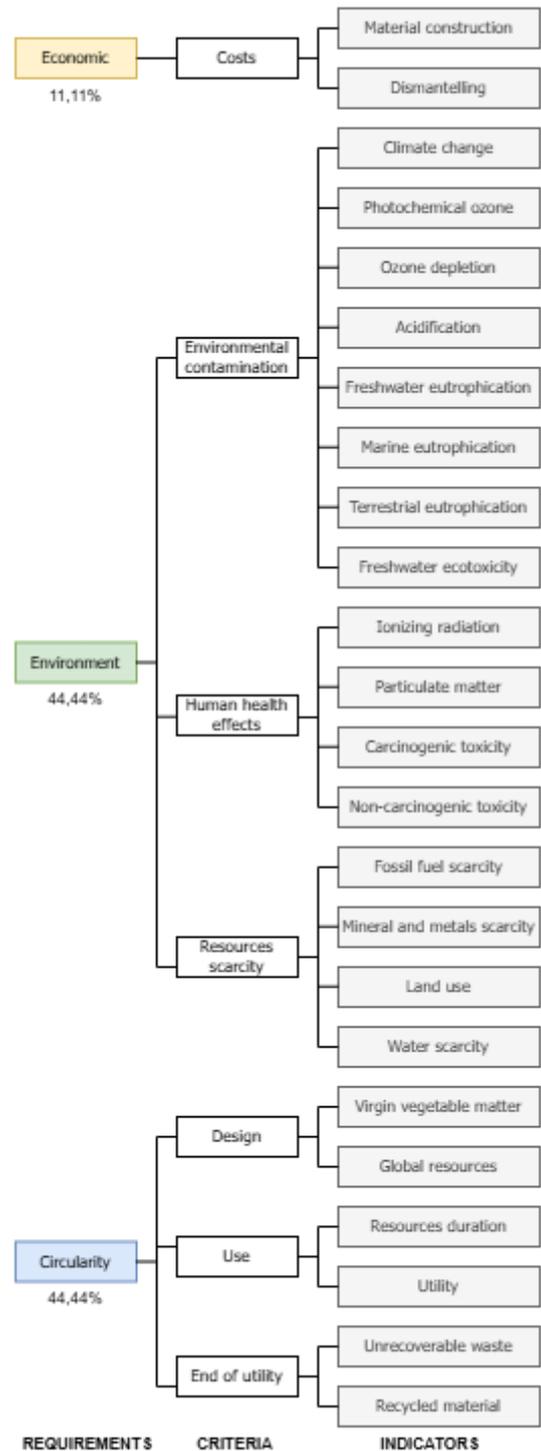


Fig. 2. Decision tree for the case study.

3 RESULTS

3.1 Main results

Figure 3 shows the global sustainability index for the baseline model scenario. For most environmental indicators (I3–I16, I18), timber displays substantially lower burdens than steel; for example, climate change impacts decrease from 928 to 408 kg CO₂ eq, fossil resource scarcity from 12425 to 5566 MJ, and freshwater ecotoxicity from 40969 to 14870 CTUe. Timber also

exhibits lower water scarcity (114 vs. 300 m³ depriv.) and a lower share of virgin raw material (0,30 vs. 0,71), as well as a more favorable global resource indicator (0,34 vs. 0,97).

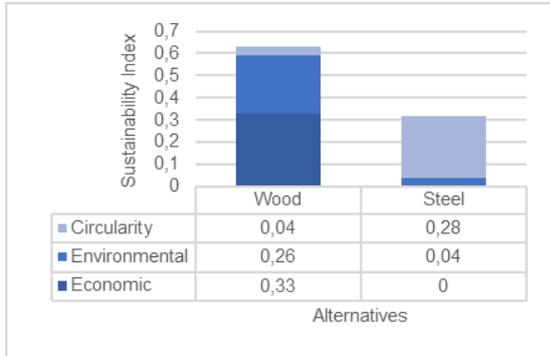


Fig. 3. Global sustainability index.

The economic criterion C1 shows very similar construction costs for both alternatives (approximately 2600 EUR), but dismantling costs are significantly lower for timber (21,5 vs. 59,6 EUR), yielding a much higher economic value index for timber.

For the environmental requirement R2, timber achieves higher value indices across pollution (C2), human health (C3) and resource scarcity (C4), reflecting the lower LCA impacts associated with lower mass, lower energy intensity of production and the carbon-storage function of wood under the assumed LCA modelling choices.

Regarding circularity (R3), both materials perform relatively well. Still, timber has an advantage in design (C5) due to lower virgin raw material use and better global resource performance, and a slightly higher value index for irrecoverable waste (I23). In contrast, steel performs strongly in recycled fraction (I24). Overall, circularity indices C5–C7 and R3 are higher for timber, with C7 (end of life) being similar for both materials.

In sum, the global sustainability index of timber alternative (0,63) has achieved a better result than the steel option (0,32).

3.2 Sensitivity analysis

Figure 4 shows the sensitivity analysis results according to the weighting distribution mentioned on Table II.

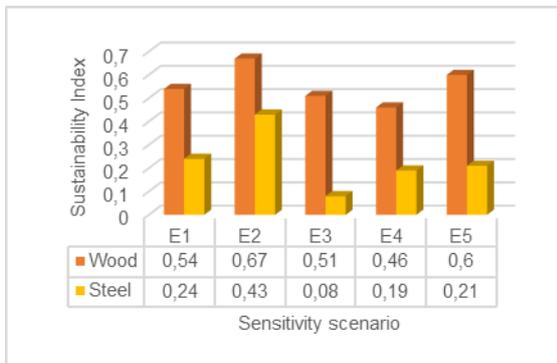


Fig. 4. Sensitivity analysis results.

In all scenarios, timber remains the more sustainable alternative. The performance gap is largest in scenarios that emphasize environmental and circularity aspects (E2

and E3) but persists even when economic aspects dominate (E4). This confirms that the ranking is not a result of a particular weighting configuration.

4 DISCUSSION AND CONCLUSIONS

4.1 Discussion of results

The analysis indicates that, for the AVS support structure considered, structural timber outperforms galvanized steel in terms of the integrated sustainability index across all weighting scenarios. Several drivers can be identified:

(i) Environmental benefits: Timber shows systematically lower environmental burdens across climate change, eutrophication, toxicity and resource depletion indicators, owing to lower material mass, lower energy intensity of production and the role of wood in carbon storage under the adopted LCA assumptions.

(ii) Economic performance: Construction costs are similar, but dismantling costs are substantially lower for timber, leading to a higher economic value index even when the economic requirement receives a relatively high weight.

(iii) Circularity performance: Timber uses a lower share of virgin material and exhibits a lower fraction of irrecoverable waste, while maintaining a high recycled fraction; steel benefits from well-established recycling routes but remains more dependent on primary metal inputs.

These results are consistent with broader LCA and circularity discussions on material choice for structural components and their role in environmental and resource footprints[8], [11], [12].The sensitivity analysis further shows that improving circularity does not necessarily conflict with economic performance; timber remains preferable in scenarios that emphasize costs, suggesting that higher circularity and lower environmental impacts can be achieved without sacrificing economic value in this case.

The study nonetheless has several limitations. It considers a single structural section and project configuration; different geometries, spans, loading conditions or design codes could alter the relative performance of materials [6], [9], [12]. Social aspects are not included, as the social requirement was judged more appropriate at system level rather than for a subsystem such as the structure. Economic indicators are restricted to construction and dismantling costs; operation, maintenance and revenue effects are outside the scope. Finally, some LCA and circularity data derive from project-specific inventories and assumptions that may evolve as the SYMBIOSYST project progresses.

4.2 Conclusions and future work

This work has presented a MIVES-based assessment of sustainability and circularity for AVS support structures, comparing galvanized steel and timber alternatives for an elevated single-axis structure supporting 28 m² of PV modules. The main conclusions are:

(i) Timber exhibits a higher overall sustainability index than steel in the baseline scenario (0,63 vs. 0,32) and in all five alternative weighting scenarios, driven by better performance in economic, environmental and circularity requirements.

(ii) Circularity indicators materially influence the

ranking of alternatives, highlighting the importance of design, use and end of life aspects in addition to environmental impacts and costs when selecting materials for AVS structures.

(iii) MIVES proves to be a suitable framework for assessing AVS structures, enabling transparent integration of LCA-derived indicators and circularity metrics into a single index that can accommodate different stakeholder preferences via sensitivity analyses.

Future work could build on this study in several directions:

(i) Broader design space: Extending the comparison to additional AVS structural typologies and hybrid solutions (e.g. steel-timber combinations, bio-based composites) to test the generality of the findings.

(ii) Refined circularity metrics: Further developing and harmonizing circularity indicators for AVS structures, including more detailed modelling of reuse, cascading and long-term material flows.

(iii) Integration of social and system level economic aspects: Incorporating social indicators and project-level economic metrics (e.g. levelized cost of electricity, farm income effects, participatory dynamics, landscape impacts and co-benefits) into MIVES models to support integrated AVS decision-making.

(iv) Improved data quality and scenario analysis: Enhancing LCA and circularity data with more detailed, region-specific inventories and exploring material durability and replacement scenarios under varying climatic and operational conditions. This includes the complementary use of other sustainability assessment methodologies such as LCA for costs, environmental and social impacts regarding the entire elements of AVS.

By including circularity within sustainability assessment for AVS structures, such work can contribute to more resource efficient, climate aligned and socially robust deployment of agrivoltaics in support of the energy transition.

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DATA-DRIVEN ANALYSIS OF CROP YIELD IN A CONTROLLED AGRIVOLTAIC INSTALLATION

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ABSTRACT: Agrivoltaics (APV) offer a promising solution to mitigate land-use competition between photovoltaic energy generation and agriculture, although the design requires a careful balancing of energy yield, crop productivity, regulatory constraints and economic profitability. This study presents a policy-aware, data-driven multi-objective optimization framework for APV system design, integrating experimentally validated crop yield responses, solar radiation and shading models with photovoltaic performance evaluation.

A real APV micro-plant equipped with agronomic sensors was used to experimentally derive crop yield response curves, enabling the validation and specialization of relationships previously obtained from meta-analytical studies. These functions were embedded into an integrated model of APV to finally perform a multi-objective optimization simultaneously maximizing agricultural yield and electrical energy production under Italian regulatory constraints.

The framework was applied to a 1 ha case study at the latitude of Naples (Italy), with 40% PV coverage and 2.5 m inter-row spacing. Panel tilt and installation height were considered as decision variables. The optimal configuration, identified using the utopia-point criterion, features a 50° tilt angle, achieving a 12.27% increase in total agricultural yield and producing 1009.6 MWh/y of electricity. An economic assessment results in a simple payback period of 11.8 years, reduced to 7.08 years when public incentives are considered.

1 INTRODUCTION

The increasing deployment of renewable energy systems, together with the growing demand for agricultural production, has intensified competition for land resources worldwide. This challenge is particularly evident in regions where high solar potential overlaps with fertile agricultural areas. Agrivoltaics, also referred to as agrophotovoltaics (APV), constitutes an integrated solution allowing photovoltaic electricity generation and agricultural production to coexist on the same land surface. The foundational concept of agrivoltaics was first formalized by Dupraz et al. [1], who demonstrated that appropriately designed PV installations can enable dual land use without necessarily compromising agricultural productivity.

The relevance of agrivoltaics has increased significantly in the context of climate change. Rising air temperatures, more frequent heatwaves and prolonged drought events are already reducing crop yields and are often determining increasing irrigation demand in many parts of the world or uncontrollable floods. Zhao et al. [2] showed that global crop yields are highly sensitive to temperature increase, even under moderate warming scenarios, while Lesk et al. [3] highlighted that extreme heat and drought events have already caused substantial yield losses at the global scale, underscoring the urgency of climate-adaptive agricultural strategies.

Partial shading provided by photovoltaic modules was identified as a potential mechanism to mitigate some of these climate-related stresses. Barron-Gafford et al. [4] experimentally demonstrated that APV reduce canopy temperature and evapotranspiration while maintaining or even increasing crop productivity in arid environments. Similarly, Marrou et al. [5] showed that modified radiation regimes under PV panels can alter crop microclimate in ways that are beneficial for plant growth, depending on crop type and environmental conditions.

A comprehensive and systematic synthesis of research on APV was recently provided by Campana et al. [6], who frame agrivoltaics as complex socio-technical systems rather than simple superpositions of agriculture and photovoltaics. Their review highlights that agrivoltaic performance emerges from interactions among solar radiation physics, microclimate dynamics, crop physiology, system geometry and socio-economic drivers. Evaluating APV requires integrated indicators that simultaneously account for agricultural yield, energy production, land-use efficiency, economic performance.

One of the central findings of the literature concerns the crop-specific response to shading. Laub et al. [7] conducted a large meta-analysis showing that crops can be classified into shade-benefitting, shade-tolerant and shade-sensitive categories, depending on how yield responds to reduced solar radiation. This classification was confirmed by field experiments on horticultural crops, where moderate shading was shown to improve yield and quality for selected species, such as tomatoes and leafy vegetables [8]. In contrast, cereal crops and other light-demanding species often exhibit yield reductions when shading exceeds crop-specific thresholds. The agronomic implications of these findings are substantial. Weselek et al. [9] emphasized that the temporal distribution of shading during the day and across the growing season plays a critical role in determining crop response, beyond the simple magnitude of radiation reduction.

From an engineering perspective, APV systems impose additional constraints on photovoltaic design. Valle et al. [10] showed that increasing panel height and row spacing can significantly modify shading patterns on the ground, directly affecting both crop performance and land-use efficiency. Schindele et al. [11] further demonstrated that system geometry strongly influences the trade-off between energy yield and agricultural productivity, highlighting the need for site-specific optimization.

Accurate modeling of solar radiation and shading dynamics is therefore a key requirement for agrivoltaic analysis. Perez et al. [12] developed foundational models for separating direct and diffuse radiation components, which remain widely used in solar energy applications. They also highlighted the importance of accounting for anisotropic diffuse radiation when evaluating PV performance under complex shading conditions. These modeling advances are directly applicable to APV, where shadows are unavoidably introduced on crops and dynamically evolve throughout the day.

Beyond technical performance, agrivoltaics were shown to deliver broader environmental and socio-economic benefits. At the policy level, the European Commission has explicitly recognized agrivoltaics as a strategic tool to support both renewable energy deployment and sustainable agriculture within the EU Solar Strategy [13].

Despite these advances, several knowledge gaps remain. Wolfert et al. [14] highlighted that the integration of real-time sensing and data-driven control strategies is still limited in agricultural energy systems, despite their strong potential for performance optimization.

Within this context, the present work aims to provide experimental evidence from a controlled micro-scale agrivoltaic installation. By combining high-resolution environmental monitoring with image-based assessment of crop development, the study delivers quantitative insights into crop responses under different shading configurations. The collected experimental data are subsequently used as inputs for a multi-objective optimization analysis, aimed at identifying the agrivoltaic system configuration optimally balancing the trade-off between agricultural productivity and energy generation. This approach is consistent with the emerging concepts of data-driven and adaptive APV, which are increasingly recognized as a key research frontier in the field [6].

2 MATERIALS AND METHODS

2.1 Solar radiation model

The solar radiation numerical model is implemented in MATLAB and is based on refs. [15] [16] [17]. These are used to describe the global solar radiation (G_{TR}), as:

$$G_{TR} = B_{TR} + D_{TR} + G_{RR} \quad [\text{W/m}^2] \quad (1)$$

where B_{TR} , D_{TR} , G_{RR} are the component of the global radiation, namely the direct radiation on the surface, the diffuse radiation on the surface and the ground reflected radiation.

2.2 Photovoltaic and shading model

The developed model of the PV, also written in MATLAB, is based on a well-established formulation that describes the power produced by the PV based on the area of the PV (A_{PV}), the global radiation (G_{TR}), described in the previous paragraph, and the efficiency of the PV (η_{PV}).

$$P_{PV} = \eta_{PV} \cdot A_{PV} \cdot G_{TR} \quad (2)$$

2.3 Shading model

The shading model represents a core element of the agrivoltaic framework, as it governs the spatial and temporal distribution of solar radiation reaching the cultivated surface. Unlike conventional photovoltaic installations, where shading is typically avoided due to its negative impact on energy production, agrivoltaic systems are deliberately designed to introduce partial shading. In this context, in fact, shading acts as a controllable design parameter that directly affects the local microclimate, plant physiological processes, and, ultimately, agricultural yield. Consequently, an accurate representation of the shadow geometry generated by the photovoltaic modules, as well as its temporal evolution over daily and seasonal cycles, is required. The projected shadow length of the photovoltaic panels is evaluated using expression (3)

$$L_{shadow} = \frac{H_{panel}}{\tan(\alpha)} \quad (3)$$

In this formulation, H_{panel} denotes the height of the photovoltaic panel, while α represents the solar altitude angle. The adopted approach [18] allows the shadow projection on the agricultural surface to be described by accounting for the apparent motion of the sun during the day and for seasonal variations in solar declination. The relative orientation between the photovoltaic modules and the solar direction makes it possible to identify the instantaneous position of the shadow with respect to the panel rows, as well as the extent of the partially shaded area, which is governed by the module geometry and tilt angle. The impact of shadow projection is quantified through two dimensionless coefficients, reported in equations (4) and (5), which respectively modify the beam radiation (BTR) and the diffuse radiation (DTR) components.

$$f_B = \frac{A_S}{A_G} \quad (4)$$

$$f_D = \frac{\iint f_B \cdot R \cdot \cos(AOI) \cdot \cos(\alpha) d\alpha dAOI}{\iint R \cdot \cos(AOI) \cdot \cos(\alpha) d\alpha dAOI} \quad (5)$$

In equation (4), A_S denotes the shaded area, while A_G represents the total ground area covered by the photovoltaic installation. In equation (5), R refers to the sky radiance contribution. Both dimensionless coefficients vary between 0 and 1, where a value of 0 indicates the absence of shading and a value of 1 corresponds to complete shading of the underlying surface. As a result, the beam and diffuse radiation components are accordingly adjusted as follows:

$$BTR_S = BTR \cdot (1 - f_B) \quad (6)$$

$$DTR_S = DTR \cdot (1 - f_D) \quad (7)$$

2.4 Crop yield model

The estimation of agricultural yield in agrivoltaic systems can be addressed through different modelling approaches. One widely adopted method relies on meta-analyses of experimental studies, which correlate crop yield variations with reductions in available solar radiation induced by photovoltaic shading. A notable example is

the meta-analysis conducted by Laub et al. [7], in which crops are classified into three main categories: shade-benefiting, shade-tolerant, and shade-sensitive, based on their yield response to decreasing radiation levels.

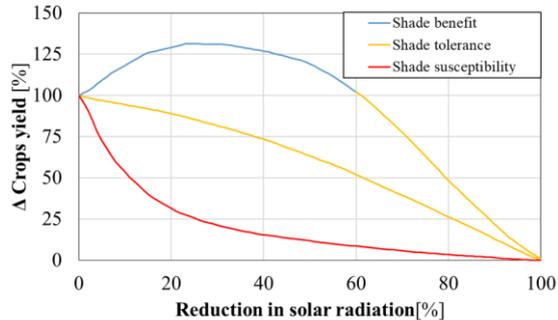


Figure 1. Crops yield vs. reduction in solar radiation: The curves in the graph represent the tolerance of crops to shading effects (from [7] with minor revision).

The upper curve (blue) represents crops that can benefit from the shading effect as long as the shading does not exceed 60%. Beyond this threshold, these crops experience a lower tolerance to the shading effect, as shown by the orange part of the curve. The second curve, also in orange, is positioned in the middle and represents crops with moderate tolerance to shading. The last curve, shown in red, represents crops that do not benefit from the shading effect.

In the present work, the meta-analysis by Laub et al. was used as a reference framework to describe the general behavior of crops under shading conditions. Building on this consolidated literature basis, an experimental micro-scale agrivoltaic installation was developed to validate and specialize the crop yield response for some given crop species.

The agrivoltaic micro-plant, as shown in Figure 2, consists of six raised cultivation boxes, divided into two groups. Each group includes three boxes characterized by different shading configurations induced by photovoltaic panels:

- Box 1: covered by a 100 W photovoltaic panel, providing almost complete shading of the soil;
- Box 2: without photovoltaic panels, representing a conventional open-field agricultural condition.
- Box 3: equipped with four 5 W photovoltaic panels mounted at the four corners, resulting in partial shading.

To support environmental monitoring of the agrivoltaic system, a multifunctional weather station was installed, consisting of a set of sensors designed to measure key meteorological and agronomic parameters. The data acquisition system includes:

- rain gauge.
- air temperature and relative humidity sensor.
- anemometer for wind speed and direction.
- barometer for atmospheric pressure.
- solar radiation sensor.
- PAR sensors for photosynthetically active

radiation.

- soil temperature and moisture sensors.

All sensors and devices of the weather station are powered by a 20 W polycrystalline silicon photovoltaic panel coupled with a 17 Ah battery storage system, ensuring continuous operation even in the absence of solar irradiance. Energy management and data acquisition are handled by a control unit (microcontroller), which coordinates sensor readings and enables real-time data transmission to a remote server, allowing visualization through a mobile application or a web-based interface.



Figure 2. Micro-scale agrivoltaic installation and meteorological monitoring system

As an example, one of the measurements acquired by the meteorological station is reported in Figure 3, which shows the evolution of ambient air temperature during the monitoring period.

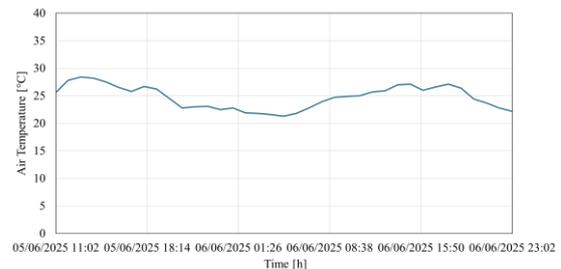


Figure 3. Temporal evolution of ambient air temperature measured by the meteorological station

Strawberry and zucchini were selected and cultivated in May under controlled agrivoltaic conditions, allowing crop-specific yield response curves to be derived directly from experimental data, as shown in Figure 4.



Figure 4. Representative image of zucchini plants cultivated under the agrivoltaic micro-plant in the partially shaded configuration.

A dedicated image-based algorithm for the evaluation of green canopy coverage was used as a proxy for vegetative growth.

Figures 5 and 6 show the weekly evolution of the green cover percentage for strawberries and zucchini, used as an indicator of plant growth.

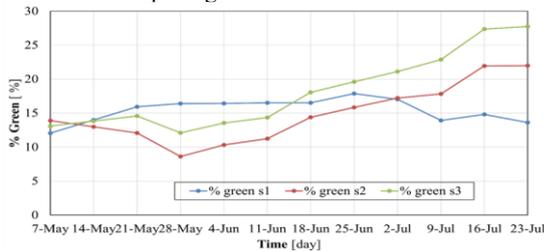


Figure 5. Weekly evolution of green cover percentage – Strawberries

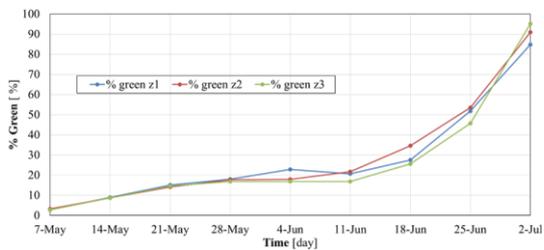


Figure 6. Weekly green cover percentage – Zucchini

Among the strawberry box configurations, F3 (partially shaded) exhibited the highest green cover percentage, thus representing an optimal balance between incident solar radiation and protection from excessive heat.

In the case of zucchini, additional considerations are required. Up to June 4, configuration Z1 (fully shaded) showed the highest green cover. However, after this date, Z1 developed a powdery mildew infection, likely promoted by microclimatic conditions characterized by high humidity and low solar radiation. Unlike strawberries, zucchini monitoring was interrupted on July 2, as extreme summer temperatures caused premature plant desiccation, making further data acquisition unreliable due to crop deterioration.

Based on the obtained results, for both analyzed crops the partially shaded configuration ensured the highest agricultural yield, benefiting from the protective effect of photovoltaic panels, which contributed to mitigating increasingly frequent extreme climatic events associated with climate change. In support of these findings, Figures 7 and 8 report the daily evolution of soil surface moisture and soil temperature.

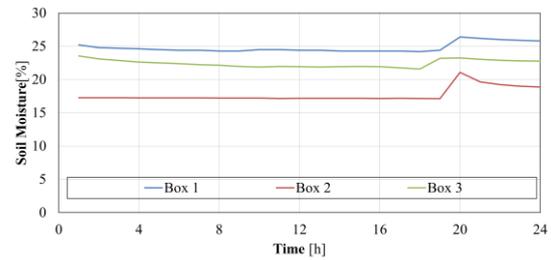


Figure 7. Daily soil moisture trends under the three shading configurations

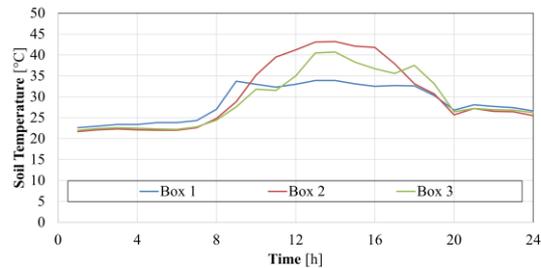


Figure 8. Daily soil surface temperature trends under the three shading configurations

These graphs highlight how the different shading configurations significantly influenced the microclimate of the three experimental boxes:

- **Box 1 (full coverage with photovoltaic panel):** The soil surface temperature was on average lower than in the other boxes, due to complete shading that limited direct solar irradiance. However, this condition also reduced evaporation, resulting in persistently high soil moisture levels. While this configuration provided protection against extreme heat, it promoted excessively humid microclimatic conditions, which in practice are associated with the development of fungal diseases, such as the powdery mildew observed in zucchini.
- **Box 2 (no photovoltaic panels, conventional agronomic control):** In this configuration, soil surface temperature reached the highest values, significantly exceeding those recorded in the other boxes during the central hours of the day. Similarly, soil moisture remained consistently lower than in the other two configurations, promoting water stress conditions. This exposed crops to increased summer thermal stress, with a consequent risk of premature desiccation, as effectively observed in more sensitive crops.
- **Box 3 (partial coverage with four panels installed at the corners):** The intermediate configuration exhibited an optimal balance: soil temperatures did not reach the high peaks observed in Box 2, nor did they remain as low as in Box 1, allowing for regular crop development. Likewise, soil moisture was maintained at intermediate levels, sufficient to prevent water stress without creating conditions favorable to fungal

diseases. This balanced microclimate resulted in a higher green cover percentage and, consequently, superior agricultural yield.

Overall, the data confirm that the partial shading provided by Box 3 represented the most favorable condition for vegetative development. This configuration enabled:

- mitigation of thermal peaks, preventing damage from excessive temperatures.
- maintenance of adequate soil moisture, reducing both desiccation risk and fungal infection susceptibility.
- improved balancing of light and water resources, with positive effects on crop productivity.

These results reinforce the hypothesis that agrivoltaic configurations with partial shading can offer significant agronomic benefits, particularly under conditions of increasing climatic stress.

By correlating the experimentally measured reduction in photosynthetically active radiation (PAR) with the temporal evolution of canopy coverage, crop-specific yield responses were reconstructed for strawberries and zucchinis, as shown in the following Figure 9.

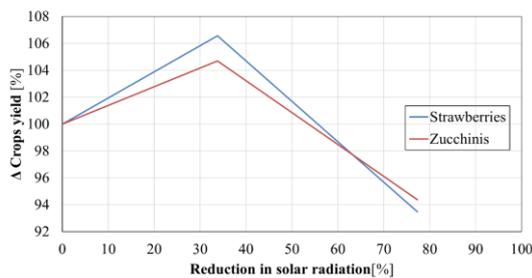


Figure 9. Crop yield variation for strawberries and zucchinis as a function of solar radiation reduction, experimentally measured in the micro-scale agrivoltaic installation

The resulting trends are consistent with the qualitative classification proposed by Laub et al., while exhibiting quantitative differences that reflect crop physiology, local climatic conditions and system geometry. This approach enables the specialization of literature-based yield models into experimentally calibrated functions, subsequently integrated into the numerical optimization framework.

3 MULTI-OBJECTIVE OPTIMIZATION FRAMEWORK AND RESULTS

A multi-objective optimization framework was developed to maximize both agricultural yield and electrical energy production of a real scale agrivoltaic (APV) system. The case study refers to an agrivoltaic installation located at the latitude of Naples (Italy), with a total land availability of 1 ha. According to the Italian agrivoltaic regulation, the photovoltaic surface is limited to a maximum of 40% of the agricultural field, resulting in 4,000 m² of installed PV modules [19]. Additional regulatory constraints require a minimum inter-row spacing of 2.5 m between adjacent PV rows to allow the passage of agricultural machinery; this spacing was fixed at its minimum allowable value to maximize land-use efficiency [19].

The decision variables of the optimization problem are:

- the tilt angle of the PV modules, varying from 0° to 90° with a step of 10°;
- the minimum panel height above ground, varying between 2.1 m, corresponding to the regulatory lower bound, and 4.1 m, representative of elevated agrivoltaic structures [19].

The objective functions are defined as:

1. maximization of annual electrical energy production;
2. maximization of total agricultural yield, computed as the cumulative variation of crop yields over the entire agricultural cycle.

A representative crop rotation was defined based on typical Mediterranean agricultural practices: romaine lettuce (January–February), zucchini (March–June), tomato (July–October), and lettuce (November–December).

Electrical energy production, shading effects, and crop yield variations were calculated using the models described in Section 2 (Materials and Methods). In particular, for zucchini, crop yield response was quantified using experimental field data, while for lettuce and tomato the yield–radiation relationships were adopted from the meta-analysis by Laub et al.

The optimization process generated 50 feasible configurations, each corresponding to a unique combination of tilt angle and panel height. The optimal solution was identified using a Pareto-front analysis (Figure 10), adopting the utopia-point criterion to balance the trade-off between the two objectives.

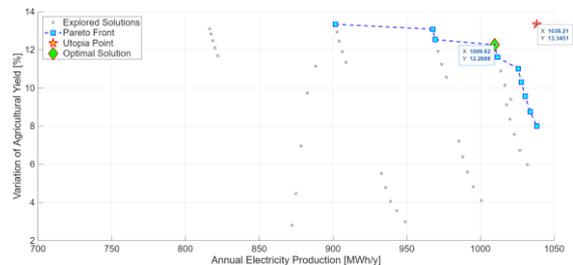


Figure 10. Pareto front of the bi-objective optimization

The selected optimal configuration corresponds to a tilt angle of 50° and a minimum panel height of 4.1 m, yielding an annual electrical energy production of 1009.62 MWh/y and a total agricultural yield increase of +12.27%, computed as the sum of yield variations across the four crops.

This result clearly highlights the intrinsic trade-off between energy and agriculture: while the energy-optimal tilt in Naples would be approximately 30°, and the agriculture-optimal configuration would tend towards vertical panels (~90°), the optimized solution represents a balanced compromise between the two objectives.

Based on the total crop yield increase, an incremental agricultural revenue of €48,301/y was estimated. All the produced electricity was assumed to be sold to the national grid at the tariff defined by the Italian agrivoltaic

regulation, equal to 93 €/MWh [19].

Considering a total investment cost of €1,088,560, including PV modules, agronomic sensors required by regulation, inverters, supporting structures, and annual maintenance, the resulting annual revenues amount to €92,195, leading to a simple payback period (SPB) of 11.8 years. When accounting for the 40% non-repayable public incentive provided by the Italian agrivoltaic framework [19], the SPB is reduced to 7.08 years. It should be noted that this payback analysis represents a conservative worst-case scenario, as it assumes that all electricity is sold to the grid. In practical applications, partial or full on-site self-consumption would significantly improve economic performance, as it would offset electricity purchases from the national grid at prices considerably higher than the selling tariff, typically in the order of 250 €/MWh.

4 DISCUSSIONS

The results of the multi-objective optimization highlight the intrinsic trade-off that characterizes APV system design, where photovoltaic energy production and agricultural productivity compete for the same radiative resource. The Pareto-based analysis confirms that configurations optimized exclusively for energy yield or crop performance lead to suboptimal outcomes when evaluated from a land-use efficiency perspective.

The optimal configuration identified in this study, characterized by a PV tilt angle of 50°, represents a meaningful compromise solution between these competing objectives. From an energy standpoint, this tilt deviates from the conventional energy-optimal configuration for Southern Italy ($\approx 30^\circ$), leading to a moderate reduction in annual PV yield. Conversely, from an agronomic perspective, the selected tilt avoids excessive shading. The selected solution, therefore, embodies the agrivoltaics design philosophy, in which neither energy nor agriculture is prioritized unilaterally.

The experimental validation of crop yield response plays a central role in strengthening the reliability of the optimization framework. While the meta-analysis by Laub et al. [7] provides a robust general classification of crop sensitivity to shading, the experimentally derived yield curves for strawberries and zucchinis reveal quantitative deviations that reflect local climatic conditions, crop-specific physiology, and system geometry. These differences demonstrate that literature-based yield functions, if used without local calibration, may lead to biased optimization outcomes. The integration of micro-scale experimental data into the numerical framework, therefore, represents a significant advancement toward site-specific and crop-oriented agrivoltaic design.

Although the experimental validation is conducted at the micro-scale, the measured crop yield responses are integrated into a hectare-scale optimization framework through physically based radiation and shading models. This multi-scale coupling allows experimental observations to inform system-level design decisions while preserving consistency with geometric and regulatory constraints.

From an economic perspective, the results confirm that

APV can achieve competitive payback periods even under conservative assumptions. The estimated simple payback period of 11.8 years, reduced to 7.08 years when accounting for public incentives, is consistent with recent techno-economic assessments of innovative agrivoltaic installations. Importantly, the assumption of full electricity export to the grid represents a worst-case scenario. In real-world applications, partial self-consumption would substantially improve economic performance by offsetting electricity purchases at retail prices significantly higher than feed-in tariffs.

Finally, the regulatory constraints imposed by the Italian agrivoltaic framework emerge not merely as boundary conditions but as fundamental design drivers. Constraints on PV surface coverage, minimum panel height and inter-row spacing directly shape the feasible solution space, reinforcing the necessity of policy-aware optimization approaches. The proposed methodology demonstrates how regulatory requirements can be systematically embedded within the design process rather than treated as ex-post limitations.

5 CONCLUSIONS

The present work focuses on a data-driven and policy-aware framework for the optimization of agrivoltaic systems, integrating experimental crop yield measurements, solar radiation and shading models, photovoltaic performance evaluation and multi-objective optimization. By experimentally validating and refining literature-based crop yield response functions, the study bridges the gap between meta-analytical knowledge and site-specific agrivoltaic system design.

The results demonstrate that Pareto-based optimization approaches enable APV configurations to simultaneously enhance agricultural productivity and maintain high levels of energy generation. For the considered case at the latitude of Naples, the identified optimal configuration achieves a total agricultural yield increase of 12.27% while producing more than 1 GWh/y of electrical energy, confirming the effectiveness of balanced design strategies.

The economic analysis highlights the financial viability of agrivoltaic systems under current regulatory frameworks, particularly when public incentives and self-consumption strategies are considered. While the presented payback analysis assumes full electricity export to the grid, this conservative scenario underestimates the potential benefits achievable in real-world applications.

The proposed framework is inherently replicable and transferable to different geographical locations, crop portfolios and regulatory contexts, provided that site-specific climatic data and experimental crop response measurements are available. Future developments will focus on extending the experimental dataset across multiple growing seasons and on investigating adaptive control strategies to further enhance agrivoltaic system resilience and performance.

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ADVANCED AGRIVOLTAIC SYSTEMS FOR ORCHARDS, VINEYARDS AND OLIVE GROVES

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ABSTRACT: iGreen System was created through the synergistic collaboration between Romagna Impianti, a leader in agricultural plant engineering, and Eco Energia, one of the leading EPC Contractors in the renewable energy market since 2007. We operate in the agrivoltaic sector, using state-of-the-art technologies to ensure that each intervention is perfectly tailored to the specific needs of each company and each crop. iGreen System Advanced Agrivoltaic Systems are provided on a turnkey basis, complete with a DSS (Decision Support System) and an agronomic, photovoltaic, and data-collection monitoring platform, enabling integrated and optimized management of the systems. The agrivoltaic solutions we offer range from orchards to elevated trellis and single-row adjustable systems, as well as extensive field crops. As part of our innovation journey, we inaugurated the first agrivoltaic system on citrus crops in Italy, a project developed in Sicily that represents a major recognition and a significant milestone in the application of innovative agrivoltaic models in the agricultural sector.

Keywords: Agrivoltaics, Design, Feasibility Study

1 AGRIVOLTAIC SOLUTIONS

Agrivoltaic technology makes it possible to generate income through diversification of revenue streams, as both agricultural production and electricity generation are carried out on the same land area.

1.1 Orchards – Elevated

Single-axis tracking structures suitable for and adaptable to all the main training systems used in fruit growing: a perfect synergy capable of optimizing and improving production (Fig.1).

Particularly suitable for kiwifruit, citrus, pome fruits, stone fruits and berries.



Figure 1

1.2 Trellis Systems - Elevated

Single-axis tracking structures designed for all trellis training systems: thanks to their configuration, these systems do not hinder the mechanization of the main operations, both for management and harvesting (Fig. 2). Particularly suitable for vineyards and almond orchards.



Figure 2

1.3 Trellis Systems – Adjustable Single-Row

Inter-row, highly versatile single-axis tracking structures that can be perfectly adapted to the main trellis training systems. An excellent compromise between sustainability and production (Fig. 3).

Particularly suitable for olive groves, almond orchards, and vineyards.



Figure 3

1.4 Extensive Crops – Adjustable Single-Row

Inter-row, highly versatile single-axis tracking structures that can be perfectly adapted to all types of field crops (Fig. 4).



Figure 4

2 DDS – DECISION SUPPORT SYSTEM

The iGreen System DSS, proprietary and customizable according to the project, integrates the three secondary-level platforms, making the overall system management both effective and efficient. The DSS autonomously controls the position of the panels throughout the day,

constantly ensuring the optimal conditions necessary for plant growth.

Management ranges from maximum shading to maximum sunlight exposure, while ensuring compliance with construction regulations and guidelines for monitoring the continuity of agricultural activity in the following years.

2.2 Monitoring and data collection platform

The data collected by the DSS are stored in a proprietary platform. Analysis and preservation of this information, combined with other system parameters, form the basis for comparing the in-field results of the underlying crops' response. This enables increasingly in-depth investigations and continuous operational improvements in agronomic management.

2.3 Agronomic monitoring platform

Each system is provided complete with the field agronomic sensors required for the specific crop, agreed upon in the preliminary phase between the parties. The platform, connected to the sensors and provided to the client, collects data in real time, processes it, and makes it immediately available. This allows for detailed analyses and the ability to make proactive decisions.

2.4 Photovoltaic monitoring platform

The System is equipped with a photovoltaic monitoring device, which allows real-time tracking of electricity production and consumption. Thanks to the event history and status and error codes, the software promptly alerts any anomalies or issues. This enables optimization of the plant's performance, improving its overall lifespan.

3 INAUGURATION OF THE FIRST ADVANCED AGRIVOLTAIC SYSTEM ON CITRUS IN ITALY

On November 7, 2025, iGreen System completed and inaugurated the first Advanced Agrivoltaic System on citrus crops in Italy. Located in Terrasini (PA), this system represents a one-of-a-kind achievement and marks the beginning of a new era for the integration of renewable energy with agriculture (Fig. 5).



Figure 5

Designed, authorized, and built by iGreen System, the Advanced Agrivoltaic System, combined with citrus cultivation, was commissioned by Land Impresa Agricola Sociale; a historic organization that immediately embraced the vision of a future in which agriculture and solar energy production can coexist harmoniously and sustainably.

The design and construction of an Advanced Agrivoltaic System require multidisciplinary expertise and a cohesive team: it is, in fact, a complex ecosystem that integrates building, electrical, electronic, agricultural, and agronomic components. iGreen System approached the project with a clear strategy: to design the system starting from the preliminary feasibility study with a 360-degree vision, thus ensuring efficiency and effectiveness during the authorization phase, punctuality and precision during construction, and also providing a simple, efficient, and integrated management of the system in the years to come.

A unique and innovative feature of the system is the DSS (Decision Support System), developed and patented by iGreen System and accessible via web or iOS/Android app. The platform monitors the synergy between photovoltaics and agriculture to ensure that the system operates optimally both agriculturally and energetically.

The inauguration of the first Advanced Agrivoltaic System in Italy represents a concrete example of how agriculture and energy can truly coexist, creating added economic, social, cultural, and territorial value. A serious, professional, and virtuous approach to Advanced Agrivoltaics is now essential to successfully address the challenges of the agro-energy sector.



AGRIVOLTAICS AS A CATALYST FOR NATURE-POSITIVE TRANSITIONS: TERRITORIAL POTENTIAL AND POWER PLANT REGENERATION IN THE PO VALLEY

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ABSTRACT: The convergence of energy and ecological transitions presents a unique opportunity to reimagine the relationship between energy production, environment, and territory. This paper explores how agrivoltaic systems can serve as catalysts for territorial regeneration through a nature-positive approach that delivers measurable ecosystem benefits. Moving beyond traditional compensatory models, we propose a framework where energy infrastructure becomes the foundation for ecosystem restoration and biodiversity enhancement. Drawing upon the theoretical foundations of the Super Valley research project and the practical application at the Castelguglielmo agrivoltaic plant in the Veneto region, this study demonstrates how strategically designed agrivoltaic installations can contribute to the EU's dual 2030 goals of 65% renewable energy production and 20% restoration of degraded ecosystems. The case study reveals how compliance with both energy and ecological mandates can become an opportunity for territorial innovation rather than regulatory constraint.

Keywords: agrivoltaics, landscape integration, nature-positive, territorial transition, energy landscapes, ecosystem restoration.

1 INTRODUCTION

The current decade marks a pivotal historical moment characterised by the convergence of energy and ecological transitions. The climate change challenge demands a radical rethinking of the relationship between energy production, environment, and territory—where energy infrastructure can serve as a catalyst for regeneration and shared value creation rather than an environmental burden requiring mitigation.

The European Union has established ambitious 2030 targets: 65% of energy production from renewable sources and restoration of 20% of degraded ecosystems [1]. In Italy specifically, the national energy strategy aims for 70 GW of installed capacity from new renewable plants, with an average of 10 GW annual installations required to meet these objectives [2]. This dual transition presents a unique opportunity to develop a new energy landscape paradigm that transcends traditional compensatory approaches in favour of a nature-positive model capable of generating net positive ecosystem benefits.

The Nature Restoration Law, adopted by the Council of Europe, mandates the restoration of terrestrial and marine habitats, guaranteeing 25,000 km of natural connectivity of waterways, reversing the decline of pollinator populations, and ensuring differentiated management of agricultural ecosystems [3]. These policy frameworks create both an imperative and an opportunity for landscape architects and urbanists to reconceptualise the agrarian space as a site of ecological transition.

This paper positions agrivoltaic systems as territorial infrastructure capable of addressing this dual mandate. Drawing upon the theoretical foundations of the Super Valley research project and its practical application at the Castelguglielmo site, we demonstrate how energy landscapes can be cultivated as rehabilitators of nature and activators of place, moving beyond the extractive and compensatory paradigms that have characterised renewable energy development to date.

2 THEORETICAL FRAMEWORK: LANDSCAPE AS A PLATFORM FOR TRANSITION

2.1 The agrarian space in transition

Contemporary landscape urbanism demands a radical reconceptualisation of energy landscapes as productive territorial systems. The pressure of humanity on bio-geo-chemical earth systems is today unprecedented; from water to land, passing through the atmosphere, the effects of contemporary life are affecting directly and indirectly many geographies around the world [4]. Processes of urbanisation, specifically under the form of land use change, contribute to widespread processes of ecosystem degradation and environmental depletion.

Within polycentric city agglomerations—the urban phenomenon of our age—defined by declining and redistributing densities and processes of peri-urbanisation, there has been a growing focus on the structural and functional importance of open spaces in urban planning, design, and practice. This is evident in the latest disciplinary developments of urbanism toward landscape and ecological urbanism, and in the rise of new epistemologies related to operational landscapes as geographies of primary production which generate and support processes of urbanisation [5].

The European Landscape Convention, adopted by the Council of Europe in Florence on 20 October 2000, represents the first international legally binding instrument dedicated entirely to landscape [6]. Twenty-five years later, its mandate for integrated landscape planning and management becomes ever more critical as territories face the compounded challenges of climate change, biodiversity loss, and energy transition.

2.2 From net zero to nature positive

A paradigm shift is underway in how we conceptualise energy infrastructure's relationship with the environment. The Paris Climate Agreement of 2015 established the net zero framework, focusing primarily on climate mitigation through carbon neutrality. However, the Kunming-Montreal Global Biodiversity Framework of 2022 introduces the nature-positive paradigm, which integrates climate action with biodiversity conservation and ecosystem restoration [7].

The nature-positive approach represents a fundamental departure from compensatory and

mitigatory frameworks. Where conventional practice operates through hierarchies of avoidance, reduction, and offsetting—ultimately accepting a net loss or, at best, neutrality—the nature-positive paradigm demands that every intervention leaves more nature than it found. The objective shifts from minimising harm to actively restoring and regenerating ecosystems, improving baseline conditions through each project rather than merely compensating for their impacts [8], [9]. Within this framework, energy infrastructure is conceived not as an environmental burden requiring mitigation, but as a catalyst for ecological restoration—a trigger capable of initiating regenerative processes that enhance biodiversity, rebuild ecosystem functions, and generate net positive territorial value.

Applied to energy landscapes, this paradigm shift moves beyond the extractive approach—where energy production comes at the expense of nature and people—past the compensatory approach that characterises current practice, toward a transformative approach where energy, nature, and people all benefit synergistically (Figure 1). Agrivoltaic systems, which integrate solar energy production with agricultural activity, represent a prototype of this transformative model.

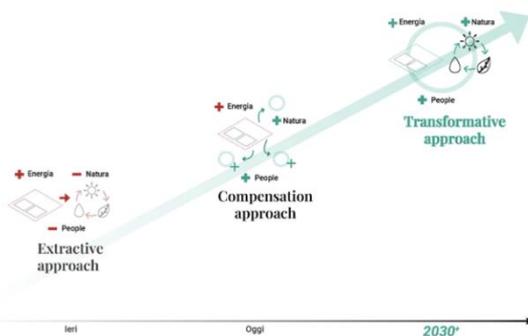


Figure 1: Energy landscapes within the nature-positive paradigm: from compensation to transformation. The diagram illustrates the evolution from extractive approaches (energy gains at the expense of nature and people) through compensatory models (current practice) toward the transformative approach where energy, nature, and people all benefit synergistically. The trajectory toward 2030+ positions energy landscapes as "rehabilitators of nature and activators of places." Image by LAND.

3 TERRITORIAL POTENTIAL: THE SUPER VALLEY FRAMEWORK

3.1 Geography of investigation

The Po Valley represents a paradigmatic case study for investigating the transformative potential of agrarian space. As the defining urban phenomenon of our age, post-metropolitan polycentric agglomerations made of concentrated and extended urbanisation create continuous city-territories that become ideal laboratories for testing alternative urbanisation pathways and possible futures [10]. The Alpine-Padano-Adriatic megaregion, encompassing approximately 4.95 million hectares, presents a critical geography where 83% of the territory is dominated by arable land,

primarily non-irrigated agricultural production (Figure 2).

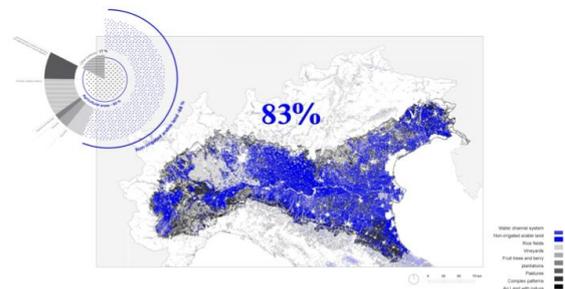


Figure 2: The Alpine-Padano-Adriatic megaregion: territorial structure and land cover composition. The diagram illustrates the spatial dominance of agricultural land (83%) within the 4.95 million-hectare territory, highlighting the transformative potential of agrarian space as a platform for ecological transition. Image by F. LaFleur.

The Super Valley research project, developed through a joint PhD programme between Politecnico di Milano and TU Delft, establishes an agro-ecological planning and design framework for this territory. The project employs research-by-design methodology combined with backcasting to envision transformative futures for agrarian space, positioning soil regeneration as foundational infrastructure for life-sustaining systems [11].

3.2 Spatial grammar for agro-ecological transition

The Super Valley framework develops a spatial grammar comprising compositional elements that respond to the desirable future under an agro-ecological planning and design model. These elements include environmental field margins, agroforestry systems, silvopasture, renatured rice fields, wetlands, and critically for this study, agrivoltaic installations (Figure 3). Each element is parameterised with quantifiable performance metrics enabling scalable territorial application.

The methodology employs a 25-hectare landscape unit as the fundamental building block for analysis and design intervention (Figure 4). This pixel-based approach allows systematic territorial transformation while respecting local conditions and landscape character. Within a 180,000-hectare study transect, the research demonstrates how minimal land conversion—approximately 6% of total agrarian space dedicated to agrivoltaic systems—can achieve transformative energy capacity whilst maintaining agricultural productivity and enhancing ecological function [12].

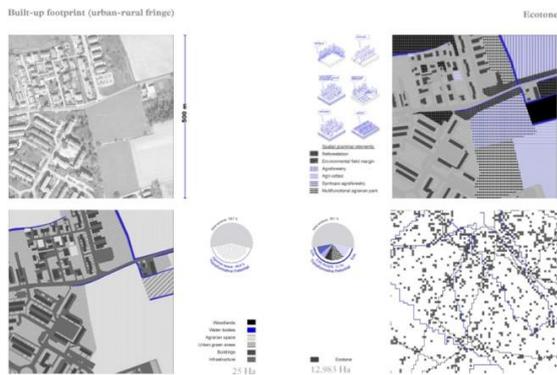


Figure 3: The 25-hectare landscape unit in a peri - urban-built up spatial prototype: from baseline condition to agro-ecological transformation. Left: satellite imagery revealing homogeneous monoculture patterns. Right: project scenario demonstrating the integration of spatial grammar elements including environmental field margins, agroforestry, and agrivoltaic systems. Image by F. LaFleur.

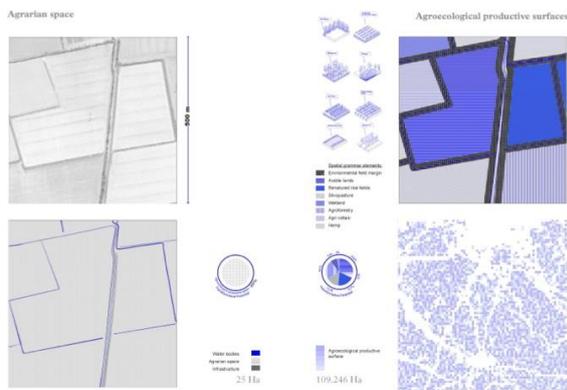


Figure 4: The 25-hectare landscape unit in a typical agricultural spatial prototype: from baseline condition to agro-ecological transformation. Left: satellite imagery revealing homogeneous monoculture patterns. Right: project scenario demonstrating the integration of spatial grammar elements including environmental field margins, agroforestry, and agrivoltaic systems. Image by F. LaFleur.

3.3 Quantifiable outcomes and scalable parameterisation

The Super Valley framework enables scalable parameterisation with benefits per hectare quantified across multiple domains: 3 tonnes of CO₂ sequestered, 44 watts of electricity produced, 13,700 litres of increased water holding capacity, and 795 trees introduced. These parameters provide a flexible framework for assessing interventions across the broader mega-regional scale.

Applied to the 180,000-hectare transect, agrivoltaic installations covering 9,685 hectares could generate 7.7 GW of renewable energy annually. Upscaled to the full 4.95 million hectares of the Alpine-Padano-Adriatic megaregion, the transformative potential reaches 267.8 GW—exceeding Italy's 2030 renewable target of 131 GW and equivalent to 134 large nuclear power plants (Figure 5). This demonstrates how the regeneration of soil and territory as agro-ecological-energy landscapes can address both energy and ecological transition mandates simultaneously.

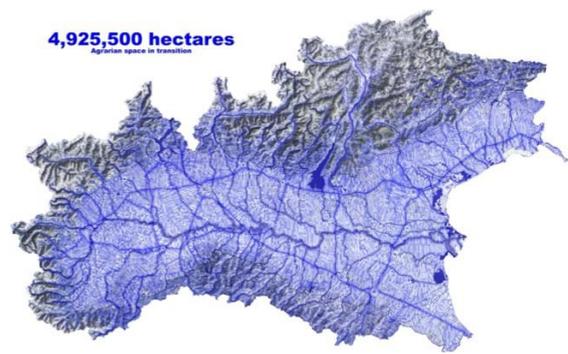


Figure 5: Upscaling the Super Valley: megaregional transformation potential. 4.95 million hectares in transition in the Alpine-Padano-Adriatic plain. Image by F. LaFleur.

4 CASE STUDY: CASTELGUGLIELMO AGRIVOLTAIC PLANT

The theoretical framework and territorial potential outlined above establish a comprehensive vision for agro-ecological transition across the Po Valley megaregion—a vision grounded in the Super Valley spatial grammar and animated by the nature-positive paradigm. Yet systemic territorial ambitions remain abstractions until tested through concrete spatial practice. The translation from regional strategy to site-scale intervention requires pragmatic demonstration projects that operationalise the framework's principles within real-world constraints. The Castelguglielmo agrivoltaic plant provides precisely such an opportunity: a working laboratory situated within the broader megaregional context, where the compositional elements of the spatial grammar—agroforestry, wetlands, field margins, and integrated agrivoltaics—can be assembled, monitored, and validated (Figure 6). As one node within the potential network of 267.8 GW across the Alpine-Padano-Adriatic territory, the site exemplifies how individual interventions gain strategic significance when conceived as components of a larger territorial transformation.

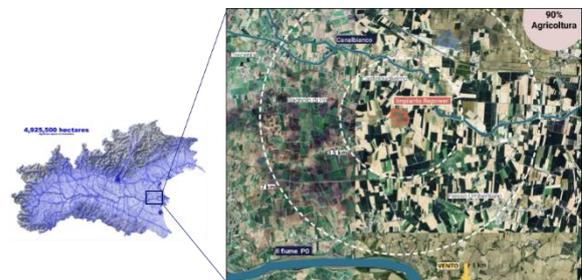


Figure 6: Castelguglielmo territorial context: the Repower agrivoltaic facility within the Po Valley landscape. Located 3.5 km from the Po River in Rovigo Province, the 34-hectare site exemplifies the monocultural conditions characteristic of the broader megaregion—a prototype for nature-positive interventions replicable across thousands of similar contexts. Image by LAND.

4.1 Territorial context and project genesis

Located in the Province of Rovigo within the Veneto region, the Castelguglielmo site embodies the conditions that characterise much of the broader megaregion: 3.5 km from the Po River, within a territory dominated by 90% agricultural land use, the site exemplifies the Po Valley's agricultural desert—monocultural landscapes shaped by intensive arable production with minimal ecological infrastructure. As such, the site serves not merely as an isolated intervention but as a prototype replicable across thousands of similar contexts throughout the Alpine-Padano-Adriatic territory.

The Repower facility comprises 34 hectares with 7.5 MW installed capacity, featuring bifacial photovoltaic panels integrated with agricultural production of wheat, soybean, and protein pea. Operational since 2013, the plant represents an early example of agrivoltaic integration in Italy. LAND Italia was engaged to develop a landscape enhancement strategy that would transform the installation from a productive energy facility into a catalyst for territorial regeneration.

4.2 Nature-positive design strategy

The design strategy positions the Repower plant as an agro-ecological-energy oasis within the Po Valley agricultural desert. The intervention operates across three integrated dimensions: ecosystem restoration, socio-economic-cultural activation, and recognisability-identity enhancement.

The ecosystem restoration component addresses biodiversity through morphological requalification of canals, introduction of tree rows, creation of flowering strips for pollinators, establishment of forest areas for infiltration, provision of wildlife refuges, and implementation of sustainable agricultural management models. These interventions directly respond to the Nature Restoration Law's mandates for pollinator support, habitat connectivity, and differentiated ecosystem management.

The design creates four principal intervention areas (Figure 7). The Threshold establishes a highly recognisable gateway through paired tree plantings and wayfinding signage. The Central Spine introduces new ecological infrastructure along the main circulation route, featuring transversal tree rows, flowering meadows, and expanded wetland areas along existing drainage channels. The Square creates an attractive stopping point with e-bike and electric vehicle charging stations, panoramic viewing terrace, and integrated social amenities. The Farmstead Entrance Avenue becomes a colourful landmark for pollinators, featuring flowering shrub strips, wildlife refuges, and apiaries (Figure 8).

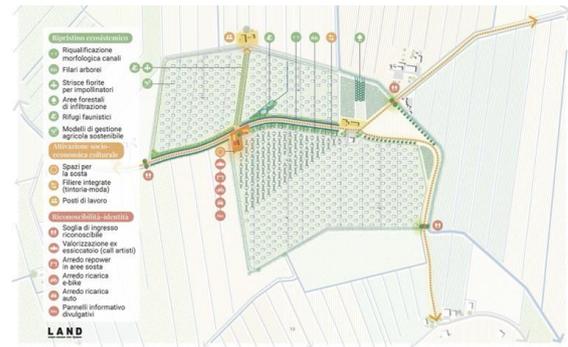


Figure 7: Nature-positive masterplan: the four principal intervention areas. The design strategy transforms the energy facility into an agro-ecological-energy oasis through the Threshold (gateway plantings), Central Spine (ecological infrastructure corridor), Square (social amenities and charging stations), and Farmstead Entrance Avenue (pollinator habitat and apiaries). Image by LAND.



Figure 8: The Farmstead Entrance Avenue: a colourful landmark for pollinators. The visualisation illustrates the transformation of the historic farmstead access into an ecological gateway integrating wildlife refuges, flowering shrub strips supporting pollinator populations, informational-educational totems, and apiculture facilities adjacent to the bike path. Image by LAND.

4.3 Positive energy landscape measuring framework

The project develops a measuring framework with specific key performance indicators across the three intervention dimensions (Figure 9). For ecosystem restoration: 183 trees planted, 78 plant species introduced, 0.12 hectares of new wetland areas, 0.4 hectares of new forested areas, and 10 hectares under sustainable agricultural management models—representing 30% of the total agricultural surface.

For socio-economic activation: 1 rest area, 1 integrated supply chains (dye production and apiculture), while for recognisability and identity: 4 informational-educational panels, 1 e-bike charging station, 1 automobile charging station, and 1 integrated artistic element through valorisation of the former grain dryer through an artist call. These metrics demonstrate how the project transforms regulatory compliance into an opportunity for generating multiple forms of territorial value.

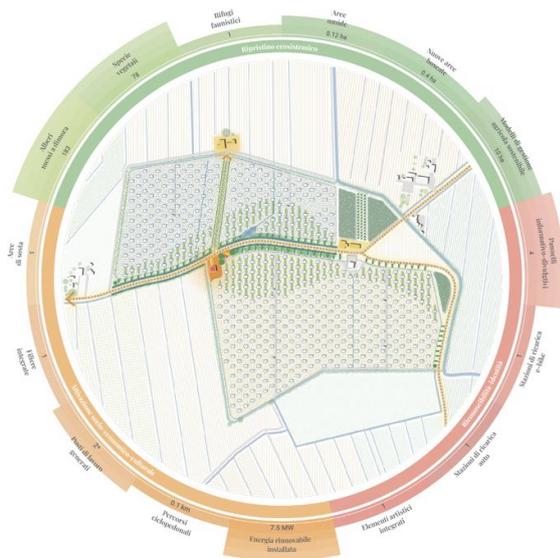


Figure 9: Positive energy landscape measuring framework: key performance indicators across three intervention dimensions. The diagram quantifies ecosystem restoration outcomes (183 trees, 78 species, 0.12 ha wetland/forest areas, 10 ha sustainable agriculture), socio-economic activation (rest area, supply chains, employment), and recognisability enhancement (educational panels, charging infrastructure, artistic intervention). Image by LAND.

5 DISCUSSION

The Castलगuglielmo case study demonstrates how the theoretical framework of nature-positive energy landscapes can be translated into concrete spatial interventions with measurable outcomes. Situated within the Super Valley's territorial vision—where 9,685 hectares of agrivoltaic installations could aggregate into 7.7 GW of regional capacity—the single-site intervention acquires strategic significance beyond its immediate boundaries. The project moves beyond viewing renewable energy as a disruptive element requiring compensation; instead, energy infrastructure becomes an opportunity to revitalise and regenerate territories, each installation contributing to a cumulative territorial transformation.

This approach not only streamlines authorisation and permitting processes but also builds positive social consensus around projects, transforming them into exemplary models of integration between energy development and landscape enhancement. Regulatory compliance thus evolves from a constraint into an opportunity for innovation and territorial value generation.

The integration of the Super Valley's spatial grammar elements—environmental field margins, wetlands, agroforestry, and agrivoltaic systems—creates a hybrid landscape that synergistically supports environmental and economic needs. This multifunctional and diversified mosaic, where each element amplifies the benefits of others, addresses climate, food, water, and energy challenges concurrently.

The project validates the hypothesis that strategically designed agrivoltaic systems can contribute simultaneously to energy and ecological transition

goals. By positioning energy installations as green-social infrastructure that generates multiple forms of territorial value, the approach demonstrates practical pathways for achieving the EU's dual 2030 mandates whilst creating local benefits for communities and ecosystems.

6 CONCLUSIONS

This paper has demonstrated how agrivoltaic systems can serve as catalysts for nature-positive territorial transition, positioning landscape as the fundamental platform upon which the convergent energy and ecological transitions must unfold. The landscape—understood not as scenic backdrop but as dynamic infrastructure mediating flows of energy, water, carbon, and biodiversity—emerges as the essential substrate for decarbonisation. The theoretical framework developed through the Super Valley research project establishes both a spatial grammar and quantifiable metrics that enable systematic territorial transformation—moving from isolated interventions toward coordinated regional strategies. From the 25-hectare landscape unit to the 4.95-million-hectare megaregion, the framework demonstrates how landscape architecture provides the operative language through which transition can be spatially articulated. The Castलगuglielmo case study provides concrete evidence that this approach can be implemented within operational contexts, generating measurable ecosystem benefits whilst maintaining energy production objectives.

Key findings include: (1) Arable land conversion—approximately 6% of total agrarian space—can exceed national renewable energy targets set at 2030 whilst enhancing ecological function; (2) the nature-positive paradigm reorients energy landscape design from minimising harm toward actively generating ecosystem benefits, in this sense it suggests a clear shift from do not significant harm toward do significant improvement; (3) integrated measuring frameworks can quantify biodiversity impact, ecosystem services, and social benefits; and (4) individual site interventions gain strategic significance when situated within broader territorial frameworks that aggregate site-scale benefits into regional transformation.

The findings underscore the essential role of interdisciplinary collaboration in achieving nature-positive outcomes. The complexity of territorial transition—where energy systems, hydrological networks, agricultural practices, and ecological corridors must be orchestrated simultaneously—cannot be addressed through disciplinary silos. Energy transition, in this framing, is not primarily an engineering challenge but a spatial-ecological project requiring new coalitions of professionals toward common decarbonisation goals. Landscape architects, urbanists, ecologists, agronomists, hydrologists, and energy specialists can work in concert, their respective competencies integrated through the medium of the territory itself. The landscape discipline, with its inherent capacity to synthesise ecological, social, and technical dimensions across scales, emerges as a critical integrating platform for coordinating these diverse expertise domains. Landscape urbanism, in particular, offers methodological frameworks capable of bridging

analytical rigour with design imagination—transforming the abstract imperatives of decarbonisation into spatially legible, implementable strategies. The formation of such interdisciplinary teams and the recognition of landscape as their common operational ground, represents a precondition for achieving the scale and speed of transformation that the climate emergency demands.

The next phase for the Castलगuglielmo project moves from vision and feasibility to execution in 2026, providing an opportunity to monitor and validate the projected outcomes through empirical measurement. More broadly, this research contributes to the emerging discourse on energy landscapes as territorial infrastructure, demonstrating how landscape urbanism methodologies can guide the transformation of energy systems toward nature-positive outcomes. In this framing, agrarian space is reconceptualised not as passive territory awaiting development, but as an active agent in the ecological transition—a platform through which energy, water, carbon, food, and biodiversity systems can be integrated and regenerated simultaneously. The convergence of the energy and ecological transitions thus presents an unprecedented opportunity for landscape architecture and allied disciplines: to move from consultants on individual projects toward key strategists in complex multi-actor, multi-scope transitions. The landscape, as both material substrate and conceptual framework, becomes the medium through which landscape architects as decarbonisation and regeneration professionals can translate policy mandates into spatial realities. The dual mandate of the EU's 2030 targets thus becomes not a constraint but an invitation to reimagine the productive landscape as the foundation for a regenerative territorial future.

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8 ACKNOWLEDGEMENTS

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9 LOGO SPACE

LAND



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NEXT-LEVEL AGRI-PV: VERTICAL TRIPLE-MODULE STACK FOR FUTURE-READY FARMING

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ABSTRACT:

Vertical bifacial (VB) agrivoltaic (APV) systems represent a promising **dual-use concept** that enables the simultaneous production of food and renewable energy. This study examines the technical, agricultural, and energy-economic performance of Next2Sun’s vertical Agri-PV system. Moreover, a particular showcase from the world’s first 3-module-stack vertical Agri-Solar Park Löffingen (4.3 MWp, Germany) is provided.

Several agronomic advantages of the VB System are highlighted such as **uniform light and rain distribution, reduced wind speeds, and minimized shading**, which result in high land usability and preserved crop cultivation between module rows. First agricultural results from comparable European installations indicate stable or even **enhanced crop yields** for wheat, barley, and millet, provided that soil compaction from construction is mitigated. Microclimatic analyses show typical light availability of around 80% at the Löffingen spacing (13.5 m), wind speed reductions of ~50%, and homogenized rain distribution. These factors collectively decrease evapotranspiration by 5–40%, while increasing water availability for crops - an advantage under rising climate stress.

The east–west oriented bifacial design further **supports a demand-oriented electricity generation profile**, improved grid integration, and less negative market-price hours. Early electrical performance data from 2025 demonstrate that the vertical east–west system already outperforms the conventional south-oriented PV section in **energy yield and revenue per MWh**. The data also indicates that vertical generation profiles are less affected by curtailment due to their broader and more market-aligned output. An optional battery storage further increases revenue potential by shifting energy into high-price periods. Overall, the Löffingen case confirms that VB-APV systems can enable profitable renewable electricity generation while maintaining full agricultural productivity.

Keywords: Agrivoltaics, grid-friendly PV generation, 3-row vertical PV, dual-use land management

Next2Sun’s Vertical Bifacial (VBPV) for Agrivoltaics

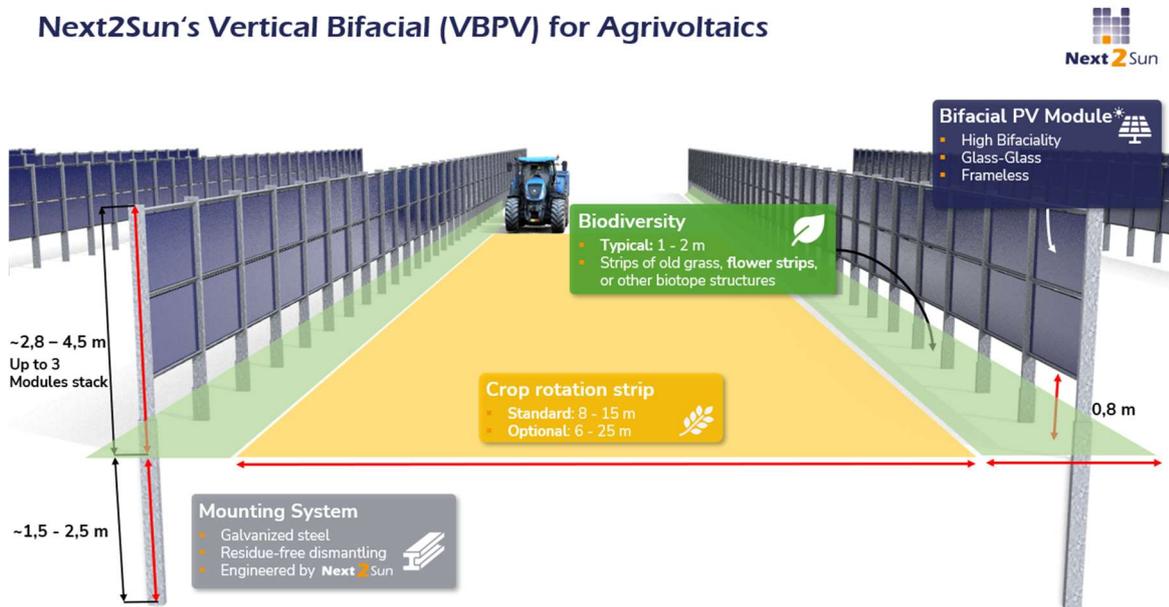


Figure 1: Typical system setup of a vertical PV powerplant designed by Next2Sun

1 INTRODUCTION

Various solutions exist for installing PV modules in agrivoltaics (APV), such as tilted but spaced (fixed or tracked) ground-mounted systems or elevated systems (fixed or tracked). This study focuses on fixed vertical bifacial (VB) systems, as depicted in Figure 3. The multiple benefits of VB systems for agriculture, as described in the literature, include uniform light and rainwater distribution for crops and protection against strong winds from directions perpendicular to the PV module orientation [1]. In addition to these agricultural benefits, the profitability and grid serviceability of vertical bifacial PV systems, discussed in [2], are confirmed in previous work [3, 4, 5, 6].

2 CONCEPTS OF VERTICAL AGRI PV

Traditional agriculture and sophisticated forms of energy generation are not mutually exclusive. Next2Sun's vertical Agri-PV concept, as shown in (Figure 1), represents a combined solution with minimal ground coverage (<1%) land-use (<15%) and renewable energy production which is mostly demand-oriented by design. The installation uses a robust racking structure made of high-quality steel with pile-driven posts capable of supporting up to three vertically stacked PV modules, reaching system heights of up to 4.5 m. Next2Sun engineered the racking system and module design together to minimize self-shading losses in the system. Moreover, the vertical arrangement minimizes shading on adjacent agricultural areas as well as soiling on the modules while ensuring structural stability against wind loads. Wide crop rotation strips, typically ranging from 8 to 15 m, ensure full agricultural usability.

From an energy generation perspective, the system employs high-efficiency bifacial PV modules, which are optimally suited to capture diffuse irradiation as well as direct sunlight from both east and west directions. This design leads to a generation profile with a broader distribution of electricity production throughout typical days, better aligning with consumption patterns and enhancing grid integration [3, 7].

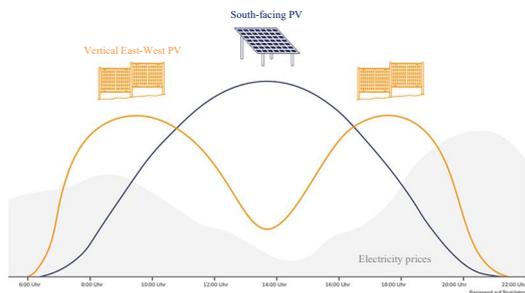


Figure 2: Typical power production profile for clear-sky conditions of a conventional south-facing PV system and the vertical bifacial PV by Next2Sun

Combined with the preserved agricultural productivity, this dual-use approach increases overall land-use efficiency and can contribute to both food and energy security.

Summing up the key points of Next2Sun's vertical AgriPV System:

- **Dual use of land**
- **Agricultural compatibility / low shade impact to crops**
- **Longevity due to robust racking**
- **High specific electrical yield**
- **Demand-oriented electricity production**

3 USE-CASE SP LOEFFINGEN

The Agri-Solar Park in Löffingen, seen in Figure 3 combines electricity generation with active agriculture on an area of 11 ha. Operation to the grid started in May 2025. Across the site, a total PV power of 4.3 MWp is installed, split into a conventional fixed-tilt south-oriented PV of about 1 MWp and vertically east-west facing 3.3 MWp. Combined an annual output of around 4,800 MWh is fed into the grid. Thereby the vertical system is supported by battery storage of 1288 kWh (and 736 kW), which further increases the profitability by shifting energy into high-price periods.



Figure 3: Vertical bifacial power plant built by Next2Sun in Löffingen (Germany)

To maximize electricity yield despite optimal spacing for the needs of the farmer, it was decided to arrange three modules on top of each other for most of the module rows. Thereby the row-spacing is set to 13.5 m. Next2Sun mastered the associated challenges, in particular the increased wind loads, through its proven technical expertise.

Both arable farming and grassland are practiced between the rows of modules, as part of the site is used for cattle farming. The arable part is used to grow crops such as spelt, oats and buckwheat.

Table 1: Technical Details of SP Löffingen

Annual Energy	Approx. 4800 MWh / a
Installed power	4.3 MWp (3.3MWp VB + ~1MWp FT South)
Azimuth	Mostly vertical East-West (90°/-90°)
Row distance	13.5 m
Agricultural use	Arable farming, grassland, pasture farming
Electricity usage	Grid feed-in according to EEG + integrated battery storage in INNO

4 MEASUREMENTS / RESULTS

Aside from the ramp-up of the power production in May 2025, the agricultural stewardship started at the end of 2024. Therefore, major parts of the land were used for mustard cultivation, which was successfully harvested in August 2025. A picture of the harvesting in between the rows is shown in Figure 4.



Figure 4: First harvesting of mustard at the plant in August 2025

4-1 Agricultural / Environmental Aspects

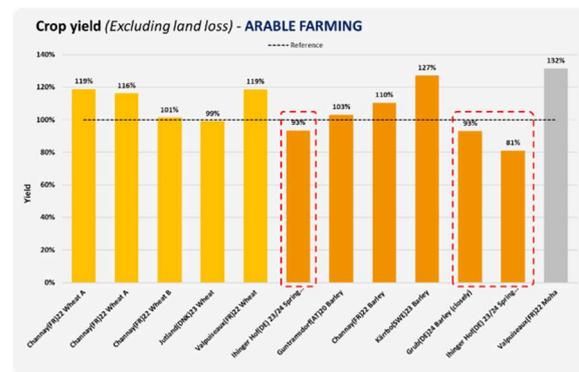
Researchers from the LAZBW (Agricultural Center Baden-Württemberg) are currently conducting surveys on grassland growth, biodiversity, and microclimate on the site in Löffingen as part of the "Model Region Baden-Württemberg" project led by Fraunhofer ISE. Unfortunately, as the project is still in its early stages, no evaluations of the measurements and surveys on the site are available yet. Therefore, in the following section, we will attempt to describe the results we expect for the Löffingen site based on previous results and experiences.

Crop yields

Regarding crop yields, we can draw on cultivation results for three different crops that are suitable for the location and planned crop rotation: wheat, barley, and millet (Figure 5). The results all originate from European Next2Sun installations (except for one shading net trial) and were collected and published by independent research institutions. The crop yields of winter wheat and winter barley (except for the results affected by soil compaction) as well as moha millet were lower at the various locations in different years, with average plant yields¹ of 111% (wheat), 100% (barley)² and 132% (millet) appear very

¹Excluding land losses of typically 10-15%

promising. Consequently, on average, a maintenance or increase in crop yield can be expected. However, it should be noted that various factors may limit this. Studies show that the first yield after construction of the plant can be negatively affected by soil compaction due to the construction process [8], [9] Accordingly, a soil-conserving construction process and suitable after-treatment of the soil (e.g., deep loosening and soil-loosening follow-up crops) are crucial for rapid soil regeneration. Another limiting factor with regard to the yield data is that these are annual results per location. Evaluations from subsequent years are therefore important to be able to derive a more representative yield picture in the future, especially depending on the weather conditions of the year.



Author emphasizes influence of soil compaction on results

Figure 5: Crop yields of Wheat (yellow), Barley (orange) and millet (grey) within Next2Sun facilities; Results marked in red are negatively affected by soil compaction, according to the authors and therefore less representative

Crop quality

In addition to yield quantity, yield quality plays an equally important role. This determines marketability and, consequently, the value of the crop.

With regard to **protein content**, empirical values are available for wheat and barley. Various wheat varieties in France showed no significant deviations in protein content compared to the unshaded reference [10]. According to current knowledge, protein contents of barley behave somewhat differently. A study from Sweden showed slight, but not significant, reductions in protein content, whereas two studies from France and southern Germany found protein levels to have increased by around 8% [9] [10] [11]. Despite the sometimes-significant increases, all three protein levels in barley between the vertical rows of modules still showed optimal range protein content of between 12-14% [12].

Further empirical values based on scientifically evaluated field data are available with regard to **harvest moisture**. Both in cultivation trials in France (wheat, barley, and millet) as well as in Austria Contrary to expectations, comparable to minimally lower harvest moisture levels were consistently detected (soybeans) [10] [13]. Due, in particular, to lower solar radiation and lower convective moisture removal as a result of lower wind speeds within the system, it was previously assumed that there could be challenges with increased harvest moisture levels in connection with vertical bifacial APV systems. The

²Accounting the negative impact of soil compaction

studies conducted to date refute this assumption at this point in time.

Microclimate

The microclimate within the facility, together with the soil conditions, determines the growth potential of the crops to be cultivated. Next2Sun has developed a very solid understanding of the microclimatic conditions prevailing within vertical APV facilities with the help of its own measurements, specially developed simulation tools, and cooperation with research partners.

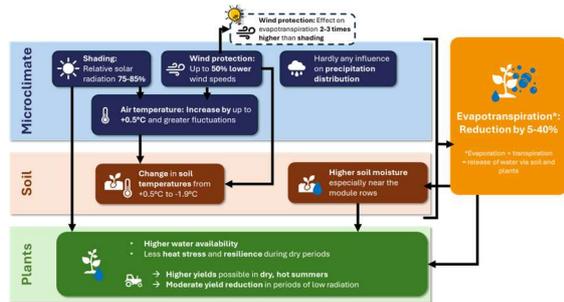


Figure 6: Overview of microclimatic effects in vertical bifacial APV systems

Starting with what is probably the most popular scientific parameter, **light availability**: with the help of measurements supplemented by ray tracing simulation tools, the light available to plants (PAR) can be predicted with astonishing accuracy. Consequently, in Central Europe, with typical row spacings of 9-15 m, light availability is 75-85% and shading is 15-25%. In the specific case of Löffingen, the extended row spacing of 13.5 m means that, despite the high module rows (3 modules on top of each other), light availability of approx. 80% can be expected.

Wind

Another characteristic feature of vertical APV systems is their ability to block the wind, particularly in module orientations that are perpendicular to the main wind direction at the site. Previous measurements and results show an impressive consensus that wind speeds between the rows are reduced by an average of 50% compared to undeveloped agricultural land. With regard to the plant in Löffingen, even higher average wind reductions can be expected due to the higher module rows at ground or plant level, which will have a positive effect on reduced wind erosion and evapotranspiration (= increased water availability for plants). Another interesting and often underestimated finding is that the reduced wind speed has a 2-3 times greater impact on reduced evapotranspiration than the reduction in solar radiation, which is a unique selling point of vertical APV.

Rain distribution

In addition, vertical mounting enables very homogeneous rain distribution across the surface and prevents water-eroding drip edges. Tests show that rain availability is only 5% lower in the areas close to the modules, which illustrates the homogeneous water distribution.

Evapotranspiration

All of the microclimatic conditions described above interact and contribute to increased water availability for plants, which can be quantified by a lower

evapotranspiration rate. The latter (lower evapotranspiration rate) is quantified in vertical systems by measurements in combination with simulations in relevant publications depending on the site conditions at 5-40%. The main beneficiaries of this are cultivated crops, which benefit from the increased water availability, particularly during increasingly frequent dry periods with water stress. The relevant accompanying research in Löffingen will show whether the positive effects described here can also be observed in this area.

4-2 Electrical Performance

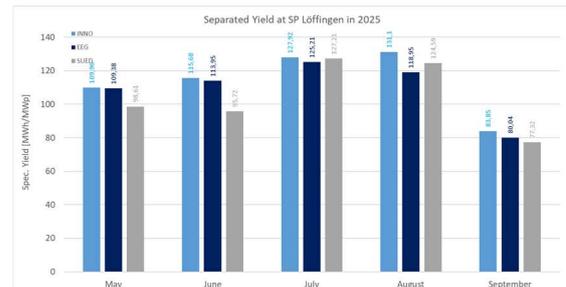


Figure 7: Measurements of specific yield separated in the different trade-zones in SP Löffingen (vertical east-west in light-blue INNO and dark-blue EEG, south-facing fixed-tilt in grey)

Since feed-in began in April 2025, no full year of production is available yet. However, the accessible data (shown in Figure 7) already shows that the vertical east-west facing systems feed more energy into the grid than the conventional south-facing part. Unless the number of negative hours is low, as for example in July and August 2025. Note, all subsystems (Vertical, Vertical + Storage and Conventional) exhibit curtailment during periods of negative spot-market prices. The INNO subpart featuring the battery storage introduces slightly more energy into the grid in all months of 2025 (except for August). Presented Data is measured on 5-minutes resolution at the AC side of the inverters.

4-3 Revenues of electricity trading

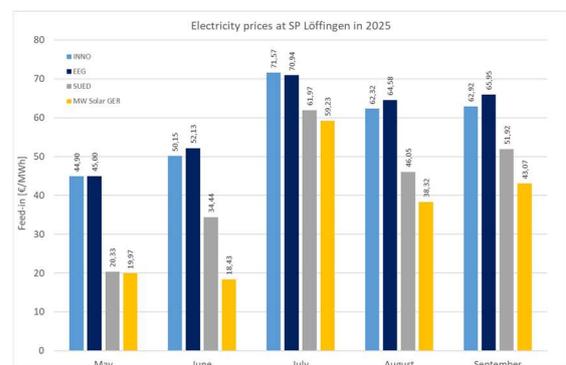


Figure 8: Electricity prices in SP Löffingen for 2025, separated in the trading zones

In addition to the depicted specific yield, it is also worth mentioning the measured electricity prices for the three subsystems (Vertical, Vertical + Storage and Conventional) in Löffingen. While the curtailment activated in June 2025 leads to a reduced amount of energy introduced to the grid, the absolute revenues benefit by the cut-off and lead to significantly higher specific

remuneration as presented in Figure 8. When compared to the average market-value of the PV portfolio Germany ("MW Solar GER"), all 3 subsystems outperformed the portfolio in every month after activation. July 2025 recorded no negative prices and therefore no curtailment, hence the profile values converge. Months with higher number of negative prices impact on all 3 trading zones, but as can be seen in the bar chart the vertical east-west profile is impacted less significant when compared to the south-fixed curtailed and portfolio prices. Note that the extra feed-in of the battery in the INNO part is not yet included in the graph and will further benefit the revenue.

CONCLUSION & OUTLOOK

Vertical bifacial agrivoltaics approaches designed by Next2Sun demonstrate that agriculture and photovoltaics can be synergistically combined without compromising land use or crop productivity. The use-case Löffingen confirms the robustness and agricultural compatibility of the Next2Sun system, while early performance data show clear electrical and economic advantages over conventional PV installations. With stable crop yields, improved microclimatic conditions, high land-use efficiency, and strong market-aligned energy generation, vertical Agri-PV stands out as a scalable dual-use solution. It can contribute simultaneously to food and energy security, climate adaptation, and the further expansion of renewable energy.

In addition to the accompanying research currently being conducted at the Löffingen solar park, additional research in the field of microclimate research will be carried out in the next years. The Löffingen solar park is particularly suitable for this purpose, as it has sections with single-row and triple-row vertical arrays as well as a section with elevated inclined modules with three different module occupancy densities. This experimental design offers a unique comparison of microclimate parameters. A Swedish institute, in cooperation with German researchers, will use this to gain further insights, particularly into rain and water distribution among the various APV concepts.

Research institutions which are interested in data on this specific case should not hesitate to contact us.

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SHADING-TOLERANT COLORED FAÇADE BIPV MODULES USING BACK-CONTACT CELLS WITH INTEGRATED BYPASS PROTECTION

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ABSTRACT: Façade-integrated photovoltaics (BIPV) are increasingly recognized as a key contributor to net-zero energy buildings in dense urban environments. However, vertical PV installations are particularly exposed to complex and dynamic shading conditions, leading to disproportionate power losses, accelerated material degradation, and increased system complexity. This paper presents a shading-tolerant colored façade BIPV module platform developed by INVITAIC, based on advanced back-contact (BC) monocrystalline cells with integrated on-cell bypass protection. By embedding shading resilience at cell level, the system significantly reduces energy losses under partial shading while eliminating the need for module-level optimizers or micro-inverters. Combined with color-matched glass laminates, the approach enables architecturally integrated PV façades that behave more like conventional building materials—robust, predictable, and easy to plan. Laboratory measurements and field observations indicate energy yield improvements of 15–25% in shaded façade applications, while simultaneously reducing planning effort, system cost, and lifetime risk.

Keywords: Shading Effects, BIPV facades, High-efficiency cells, Color PV, Degradation mechanisms, Module design

1 INTRODUCTION

Building-integrated photovoltaics are transitioning from niche architectural elements to core components of urban energy systems. As roof areas in cities become increasingly constrained, façades represent a largely untapped surface for solar electricity generation. At the same time, façade applications impose fundamentally different boundary conditions compared to roof-mounted PV, particularly with respect to shading, orientation, and aesthetic integration.

Unlike rooftops, façades are subject to permanent and transient shading caused by balconies, neighboring buildings, vegetation, and urban infrastructure. Even geometrically simple buildings exhibit complex shading patterns throughout the day and year. Conventional crystalline silicon PV modules react poorly to such conditions, suffering from severe mismatch losses, hotspot formation, and accelerated aging.

This contribution presents a BIPV module platform that addresses shading not at system level, but intrinsically at cell level. By combining back-contact cell architecture with integrated bypass functionality and colored glass laminates, INVITAIC aims to make façade photovoltaics electrically robust, visually adaptable, and economically predictable.

2 BACKGROUND: SHADING AS A SYSTEMIC LIMITATION IN FAÇADE BIPV

2.1 Shading Effects in Conventional PV Modules

In standard front-contact PV modules, cells are connected in long series strings. Partial shading of a single cell forces it into reverse bias, causing immediate power loss and local heating. While module-level bypass diodes limit catastrophic failure, they operate at string level and do not prevent localized thermal stress within the cell.

Repeated shading cycles initiate a cascade of degradation mechanisms, including encapsulant

browning, delamination, solder joint fatigue, and diode overstress. Over time, these effects reduce efficiency, compromise electrical safety, and shorten module lifetime.

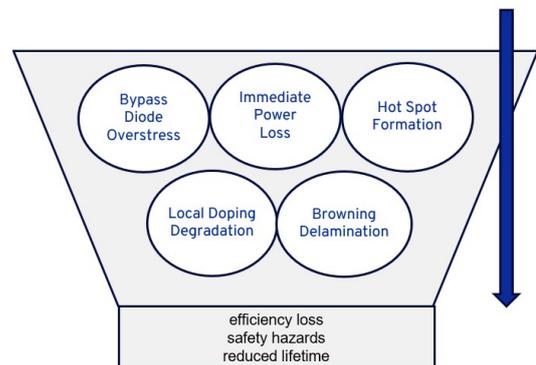


Figure 1: Shading triggers a cascade of degradation effects over time, finally reducing the performance of the module and increasing safety hazards

2.2 Planning and Cost Implications

To mitigate shading losses, conventional BIPV systems often rely on power optimizers, micro-inverters, and detailed 3D shading simulations. While effective, these measures increase system complexity, component count, and interface effort between architects, planners, and electrical engineers. In high-labor-cost regions, engineering and coordination costs increasingly dominate total system cost, offsetting the declining price of PV modules.

3 TECHNOLOGY PLATFORM: BACK-CONTACT CELLS WITH INTEGRATED SHADING PROTECTION

3.1 Evolution of Shading-Tolerant Cell Architectures

INVITAIC builds upon technology developed within the AE Solar Group. Early shading-robust modules employed discrete surface-mounted bypass diodes on each cell, significantly improving partial shading

behavior compared to conventional designs. This approach demonstrated the feasibility of distributing bypass functionality beyond the module junction box.

The current generation advances this concept further by integrating bypass structures directly into the semiconductor architecture of back-contact cells. Local parallel current paths are formed via engineered P/N junction arrangements on the rear side of the cell.

3.2 Functional Principle

In normal operation, current flows uniformly through the back-contact grid without front-side metallization. Under partial shading, the locally shaded region activates its embedded bypass path, allowing current to circumvent the affected area without forcing the cell into destructive reverse bias.

This distributed protection mechanism reduces hotspot risk, stabilizes operating temperature, and preserves output under non-uniform illumination.

4 ELECTRICAL PERFORMANCE UNDER PARTIAL SHADING

Laboratory tests and outdoor demonstrations confirm the effectiveness of the cell-level shading concept. Under partial shading conditions of 30–50% active area obstruction, back-contact modules with integrated bypass protection retain approximately 90% of nominal output. Comparable conventional modules typically drop below 80% under identical conditions.

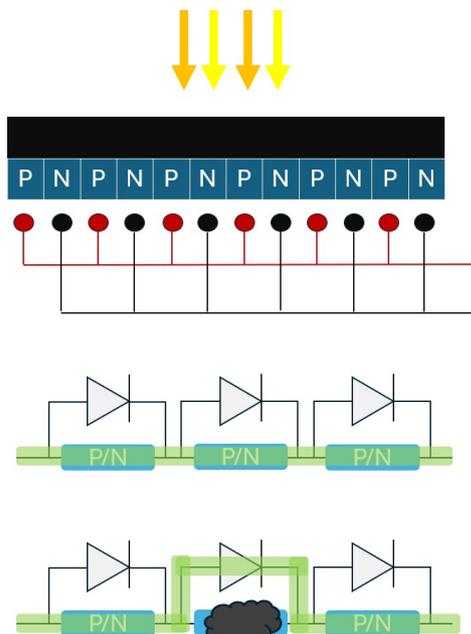


Figure 3: The backside junctions form a diode grid which allows the current to flow even with partial shadings

Field simulations across typical urban façade geometries indicate annual energy yield gains of 15–25%, depending on shading frequency and orientation. Importantly, these gains are achieved without active electronics at module or string level.

5 AESTHETICS AND ARCHITECTURAL INTEGRATION

Beyond electrical performance, façade PV must meet architectural expectations. Back-contact cells inherently eliminate front-side busbars, resulting in a uniform, homogeneous appearance. This visual neutrality forms an ideal substrate for colored glass solutions.

INVITAIC employs ceramic coloration and digitally printed glass layers to achieve façade-compatible surfaces resembling stone, metal, or composite panels. These layers maintain sufficient optical transmittance while visually integrating PV into the building envelope.



Figure 3: Especially colored BIPV gains additional aesthetics when there are no visible busbars on the front

The resulting modules can be mounted using standard façade substructures, with either visible or concealed fixations, allowing seamless integration into conventional construction workflows.

6 SYSTEM-LEVEL BENEFITS AND SUSTAINABILITY IMPACT

Embedding shading tolerance at cell level shifts complexity away from system design toward intrinsic material behavior. This approach reduces the need for detailed shading simulations, minimizes wiring segmentation, and eliminates active power electronics in many applications.

The reduction in components improves system reliability and simplifies maintenance, while lower engineering effort shortens project timelines. For small and medium-sized façade projects in particular, these factors significantly improve economic viability.

From a sustainability perspective, longer module lifetime and reduced balance-of-system components lower the overall environmental footprint per kilowatt-hour generated.

7 CONCLUSION

Shading represents one of the most persistent barriers to widespread adoption of façade-integrated photovoltaics. By addressing this challenge at the cell level rather than through external system components, INVITAIC's back-contact BIPV modules offer a fundamentally robust solution.

The combination of intrinsic shading tolerance, architectural flexibility, and simplified system design enables façade PV systems that are easier to plan, safer to operate, and more predictable over their lifetime. As cities increasingly rely on vertical surfaces for renewable energy generation, such technologies will be essential to

scaling BIPV from bespoke projects to mainstream building practice

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9 LOGO SPACE



TWO YEARS OF OPERATION OF SOLAR BRISE-SOLEILS AT GERMINARE INSTITUTE IN BRAZIL: PERFORMANCE MONITORING AND BIMSOLAR SIMULATIONS

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ABSTRACT: This paper evaluates two years of operation of the photovoltaic brise-soleil system installed on all four façades of the Germinare Institute in São Paulo, Brazil. The 70.5 kWp BIPV installation uses 564 CIGS modules integrated into vertical shading elements. Daily inverter-level generation data (June 2023–October 2025) and irradiance measurements were analyzed to assess seasonal and annual performance. Updated BIMSolar simulations using detailed 3D geometry and PVGIS irradiation were compared with monitored results and with initial pre-installation estimatatives. The façades showed strong seasonal complementarity, with north-facing modules performing best in winter and south-facing modules in summer. BIMSolar provided improved accuracy over simplified models, though still overestimating outputs due to higher satellite-based irradiance in some months. The study reinforces the potential of façade-integrated photovoltaics in Brazil.

Keywords: BIPV (Building-Integrated PV), Analysis, Design tools and software, Facade systems, Functional integration, Monitoring and diagnostics.

1 INTRODUCTION

Buildings have the potential to not only enhance their energy efficiency but also generate clean and renewable energy. Among the various sources, photovoltaic (PV) solar energy is particularly notable for its adaptability to buildings and the urban environment. In Brazil, solar energy account for 99% of distributed generation, with 89,4% of the photovoltaic generators installed on rooftops and slabs of residential and commercial sectors [1]. Despite this expressive number, PV modules are still mostly applied in existing buildings without compromising aesthetics, either composing rows on flat slabs, or simply placed on existing sloped roofs.

However, an emerging market is centered on multifunctional PV module solutions that can be integrated into buildings as coatings, roofs, and brises, enabling the so-called building-integrated photovoltaic (BIPV) systems [2]. On BIPV systems, energy is generated at the point of consumption and without using any added area, since PV modules are either overlapping or playing the role of skin elements in buildings [3,4].

The International Energy Agency (IEA) encourages and facilitates the adoption of PV modules by architects and engineers as a design element by presenting guidelines and inspiring them through good examples of high-quality architectural integration [5,6]. Knowledge on the concurrent, and sometimes conflicting, consequences between the way in which modules are installed and the associated energy generation then becomes a matter of technical, scientific, as well as of economic interest [7-9].

In a pioneering example of solar-integrated architecture, photovoltaic brise-soleils were installed on all four façades, combining energy generation with thermal and visual comfort at the Germinare Institute of J&F, located in São Paulo, Brazil, a six-story educational building focused on business education for youth.

Recognized by national media and highlighted in international forums, the project has become a notable reference for solar-integrated architecture in Brazil, demonstrating the growing interest in façade-integrated photovoltaic solutions.

This BIPV solution was developed through a multidisciplinary collaboration between Edo Rocha Arquiteturas, Arquitetando Energia Solar, and Garantia Solar BIPV (Figure 1).



Figure 1: Germinare building with photovoltaics brise-soleils in São Paulo, Brazil.

This paper presents a technical evaluation of the brise-soleil system after two years of operation, analyzing measured data to assess each façade's contribution and comparing expected simulated energy with real outputs.

2 BIPV OVERVIEW

The BIPV system consists of 564 CIGS modules (125 W each), totaling 70.5 kWp, connected to eight string inverters, as shown in Table I.

Table I: Configuration of the Germinare brise-soleils PV system.

Inverter	System configuration				
	Number of PV modules	Nominal Power (W)	Installed capacity (kWp)	Inverter Power (kW)	Overload
North #1	112	125	14	12	117%
North #2	26	125	3.25	2	163%
East #1	90	125	11.25	12	94%
East #2	66	125	8.25	12	69%
West #1	90	125	11.25	12	94%
West #2	42	125	5.25	3.6	175%
South #1	112	125	14	12	117%
South #2	26	125	3.25	2	163%
Total	564	125	70.5	67.6	104%

The modules were integrated into custom vertical brises (3.3 m × 0.35 m), tilted at 30°, and spaced 66 cm apart across all four façades (North, South, East, and West). The brises are supported by fixed aluminum structures with ACM backplates, anchored to continuous façade beams through custom top-and-bottom framing. This configuration ensures structural stability while preserving the visual lightness of the building envelope (Figure 2).



Figure 2: Structure of the photovoltaics brise-soleils.

3 METHOD

This study employed a sequential workflow composed of five main stages, ranging from the acquisition of measured operational data to simulation-based modeling and comparative analysis.

3.1 Energy data collection

The first stage involved acquiring generation data from the FusionSolar monitoring platform, which records the operation of each inverter. Daily energy generation values were extracted for the period June 2023 to October 2025.

Data were obtained individually for each inverter, enabling the identification of seasonal trends, detection of operational anomalies, and the association of performance variations with module orientation.

3.2 Irradiance data

To represent the real solar resource at the site, this study used global horizontal irradiance (GHI) measurements from the INMET São Paulo – Mirante A701 weather station.

3.3 Performance analysis

Performance analysis was carried out daily, monthly, and annual basis to obtain a comprehensive understanding of the system's behavior over time.

Generation values were segmented by inverter and by orientation, as shown in Figure 3, allowing the identification of performance variations resulting from installation geometry, shading patterns, and orientation-specific irradiance availability.

3.4 Simulation

Before the system was implemented, an initial computer simulation was carried out using satellite-based irradiation data, transposed to the tilted module orientations and applied to the energy generation model. In 2025, with the release of the new BIMsolar [10,11]

software, the Germinare BIPV system was simulated again.

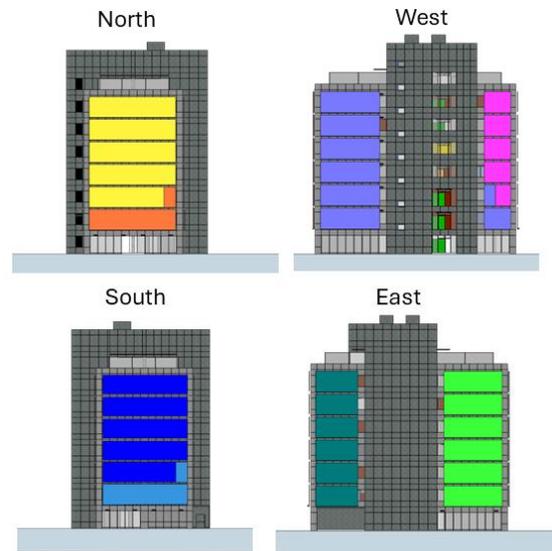


Figure 3: Subsystem configuration. Each color represents one inverter.

The simulation involved a detailed system modeling in BIMsolar, incorporating architectural geometry, orientations, inclinations, and potential shading obstructions.

The models were driven by solar radiation data sourced from PVGIS, which provides long-term climatological irradiance for the region.

Simulation outputs were used to estimate theoretical energy production for each subsystem, establishing a benchmark for comparison with field measurements and enabling the assessment of the influence of shading, orientation, and electrical configuration on system performance.

3.5 Comparison of measured and simulated results

The final stage consisted of a direct comparison between measured and simulated irradiation (INMET vs. SWERA and PVGIS) and measured energy with simulated energy outputs.

This comparison aimed to evaluate the degree of alignment between real and theoretical values and to identify deviations related to model assumptions.

4 RESULTS

4.1 Energy generation, available irradiation, and performance analysis

The system began operating in June 2023; however, it remained offline from the middle of July 2024 to January 2025 due to infrastructure issues in the building's electrical grid.

Considering the total system, the average of monthly energy generation was 2,422 kWh/month; the average of monthly global horizontal irradiation was 137 kWh/m²/month; and the annual yield of the system was 466.1 kWh/kWp.

4.2 Seasonal performance per façade orientation

To evaluate the system's performance by façade

orientation, four months were selected to represent each season: March, June, September, and December.

As shown in Figure 4, energy generation varies by season and façade orientation. During autumn and spring, the east façade produced the highest energy, while in winter the north façade dominated. In summer, the south façade showed the highest generation. Figure 5 presents the daily energy generation on selected clear-sky days of each season.

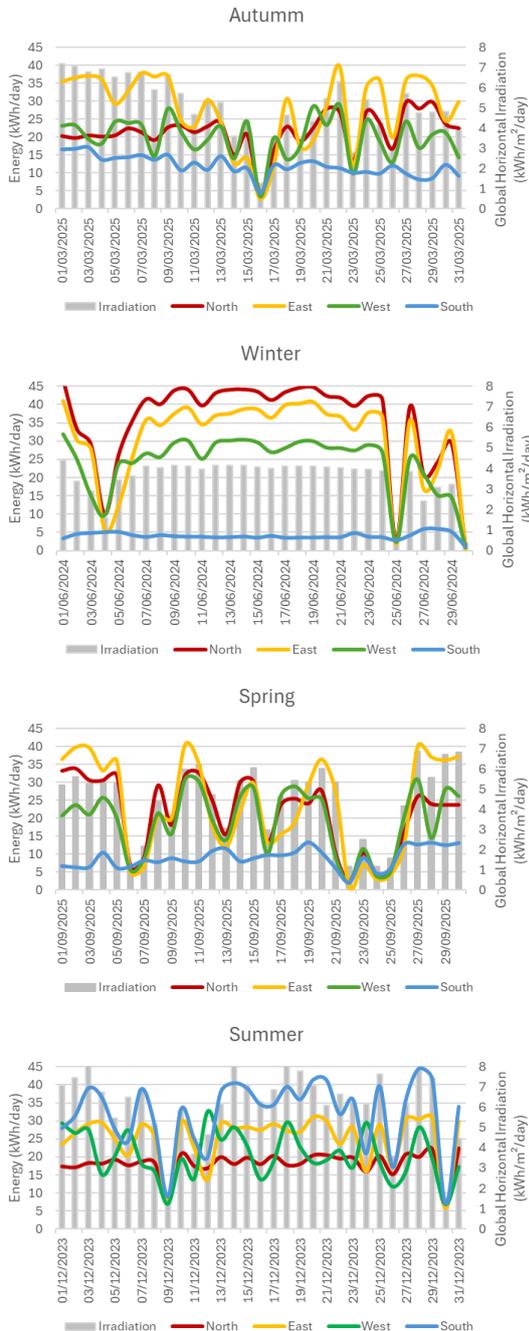


Figure 4. Daily energy generation in four seasons.

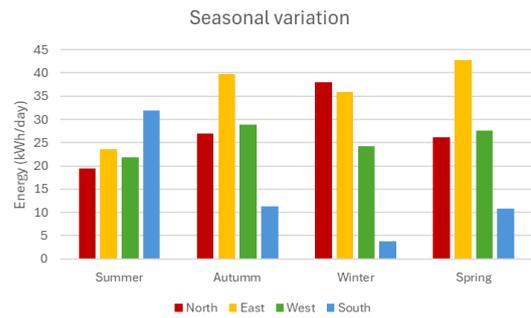


Figure 5. Daily energy generation on selected clear-sky days of each season.

To normalize energy generation by installed capacity, a yield analysis was performed. On a monthly basis, the north façade generated substantially more energy than the others façades from March to October. However, during the summer months, the south façade presented the highest yield, as can be seen in Figure 6.

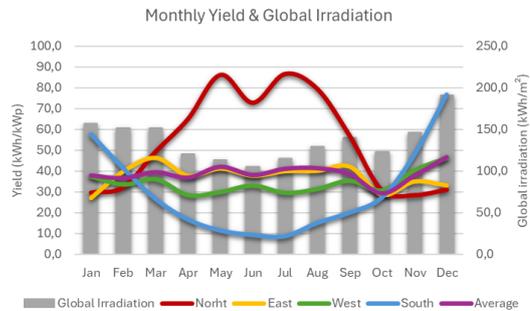


Figure 6. Daily energy generation on selected clear-sky days of each season.

On an annual basis, the north façade achieved the highest annual yield (647.3 kWh/kWp), followed by the east (449.8 kWh/kWp), west (412.8 kWh/kWp), and south (359.2 kWh/kWp) (Figure 7).

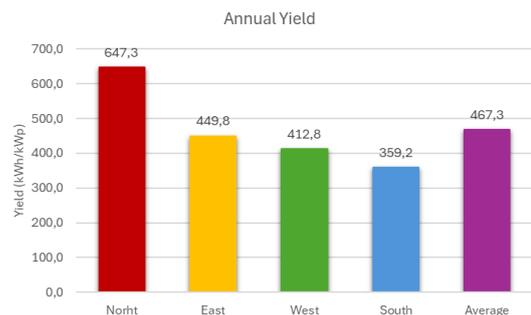


Figure 7. Annual yield per façade orientation.

4.3 Computer Simulations

Figure 8 presents some steps of BIM Solar modelling and energy simulations.

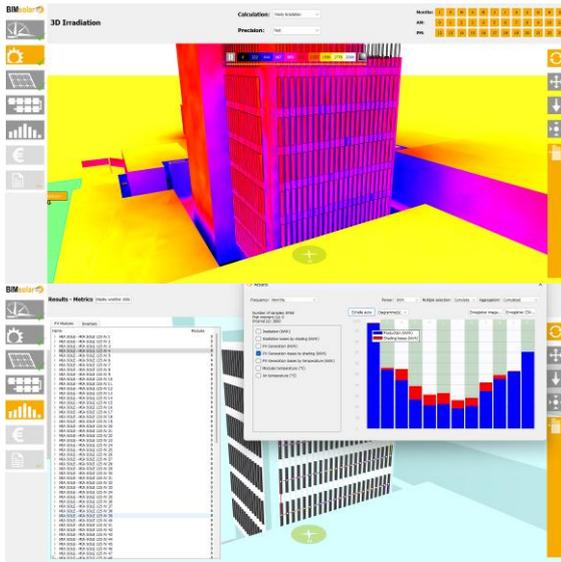


Figure 8. BIMsolar simulation for the Germinare brise-soleil system.

The initial simulations were then compared with the updated BIMsolar simulations, and both simulations were compared with the measured total energy generation, and the results are presented in Figure 9.

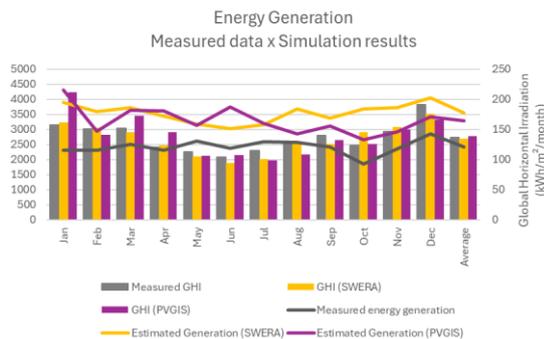


Figure 9. Comparison between simulated and measured total energy generation.

Additionally, Figure 10 shows the comparison between BIMsolar simulated results and measured data for each façade orientation.

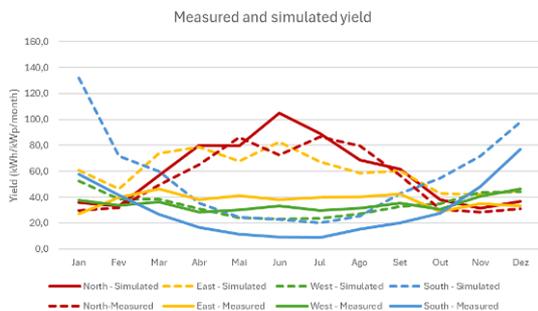


Figure 10. Simulated vs. measured energy generation per façade orientation.

As can be seen in Figure 9 and Figure 10 the formula-based simulation predicted 7% more energy than the BIMsolar simulation, while the BIMsolar results were 36% higher than the measured data.

One possible reason for this output is that PVGIS irradiation data for January and April were 35% and 20% higher, respectively, than the measured irradiation values.

5 CONCLUSIONS

The Germinare BIPV project demonstrates both the architectural and technical feasibility of integrating photovoltaic brise-soleils into building façades in Brazil. Although some orientations are traditionally considered more favorable for energy generation, all façades contributed meaningfully throughout the year. A clear seasonal complementarity was observed, with south-facing modules compensating during periods of lower northern irradiance, and vice versa.

The comparison between pre-installation energy simulations performed using a simplified energy-generation formula and the new BIMsolar BIPV software showed that BIMsolar provides more accurate results, as it incorporates a wider range of input parameters.

This study reinforces the potential of façade-integrated photovoltaics in institutional buildings and provides a valuable case study for future BIPV applications in Brazil.

6 ACKNOWLEDGMENTS

- Edo Rocha Arquiteturas: for embracing our design recommendation and contributing to the development of the final BIPV solution.
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- Instituto J&F: for believing in this photovoltaic façade concept and making its implementation possible.
- PV Doctor: for initiating detailed data acquisition that will enable extensive performance analyses in the future.

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FIREPROOFING BIPV: OVERVIEW AND COMPARISON OF BUILDING FIRE SAFETY REGULATIONS IN INCREASE DEMONSTRATION SITE COUNTRIES

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ABSTRACT: This paper presents a comparative analysis of fire safety regulations governing building integrated photovoltaics (BIPV) across Belgium, Estonia, France, Spain and Switzerland, the countries hosting INCREASE demonstration sites. BIPV systems face unique regulatory challenges, as they must comply with both electrical safety and building fire safety standards. The study focuses on the impact of national building codes and the Euroclass system defined by EN 13501, which classifies construction products according to their reaction to fire. Building height is identified as the principal determinant of facade fire safety requirements, with stricter standards for mid- and high-rise buildings often restricting BIPV deployment. The absence of harmonised European standards and the limitations of current fire testing methodologies, including those specified in EN 13501, contribute to regulatory uncertainty and hinder widespread adoption. The paper discusses alternative compliance pathways, such as large-scale fire testing and the implementation of national guidelines, which provide project-specific routes for demonstrating fire safety and facilitating BIPV integration. Policy recommendations include the harmonisation of BIPV standards at European level, the development of BIPV-specific fire testing methods, performance-based compliance options, clear national guidelines and enhanced research and data sharing to support safe and effective BIPV deployment in buildings.

Keywords: BIPV (Building-Integrated PV) ; Fire safety ; Codes and regulations ; BIPV facades ; BIPV roofs.

1 INTRODUCTION

Fire safety is a critical consideration in the design and construction of buildings, underpinning the protection of lives, property and the continuity of essential services. As the built environment evolves to incorporate innovative technologies such as building integrated photovoltaics (BIPV), ensuring robust fire safety standards becomes increasingly complex. BIPV modules uniquely serve dual functions, they generate renewable electricity while simultaneously acting as construction elements. This dual role introduces new challenges in fire risk management, as BIPV systems must comply with both electrical safety requirements and building fire safety regulations.

The integration of BIPV into building envelopes presents specific fire safety challenges. Notably, the materials used in photovoltaic modules often prevent them from achieving the highest non-combustible classifications required by certain building codes. Furthermore, existing fire testing methods, such as the Single Burning Item (SBI) test, may not adequately capture the fire behaviour of BIPV products, prompting the need for more representative assessment techniques. The absence of a harmonised European standard tailored specifically to BIPV compounds regulatory uncertainty, with national and local variations in fire safety requirements potentially hindering broader adoption of BIPV.

This paper addresses the importance of fire safety in relation to BIPV systems, focusing on the regulatory frameworks that govern their deployment in buildings. The scope encompasses a comparative analysis of national fire safety regulations in INCREASE demonstration site countries, namely Belgium, Estonia, France, Spain and Switzerland, with particular attention to the Euroclass system defined by EN 13501-1 and EN 13501-5. Although fire testing and classification standards for construction products are unified across the EU, each Member State is responsible for its own building regulations and sets its own fire safety requirements. In practice, EN 13501-1 entails that BIPV products, due to their combustibility, are not able to

classified A1 or A2.

The paper first provides an overview of the regulatory framework for construction products in Europe, including the Construction Products Regulation (CPR) and EN 13501, and how they impact BIPV deployment in buildings. Secondly, the paper delves into a description of the regulatory requirements in the INCREASE demonstration site countries. The section considers building classification and fire safety requirements for facade and roof elements in each country. Thirdly, a comparative analysis of the national regulations is done, highlighting commonalities and differences. Based on the analysis, a typology of BIPV projects is proposed based on fire safety requirements for construction elements. Finally, the paper includes a discussion of the limitations in existing fire testing approaches and an exploration of ongoing efforts to develop more effective fire safety assessments for BIPV products.

Fire safety rules for building facades differ across Belgium, Estonia, France, Spain and Switzerland, with requirements tightening as building height increases. Low-rise buildings usually allow more combustible facades, making BIPV installation easier, while mid-rise structures encounter stricter standards but BIPV is often still possible. High-rise buildings require non-combustible facades classified A1 or A2, significantly limiting BIPV options. Each country has its own nuances but, overall, building height is the main factor affecting facade fire safety and BIPV feasibility in Europe. Alternative pathways exist in a few countries, such as Belgium, France and Switzerland to allow for BIPV deployment in high-rise buildings with large-scale testing. In the absence of harmonised standards for BIPV, alternative routes, while currently costly, location dependent and time consuming, appear as the most suitable pathway to unlock BIPV deployment in high-rise buildings.

Overall, to support safe and widespread BIPV adoption, there is an urgent need for harmonised European standards, performance-based compliance options, BIPV-specific fire testing methodologies, clear

national guidelines and enhanced research and data sharing across stakeholders.

2 EUROPEAN FRAMEWORK FOR CONSTRUCTION PRODUCTS

The essential feature of BIPV modules lies in their ability to both produce electricity and function as a fundamental part of the building structure. Hence, BIPV elements must comply with two different standards and regulations derived from building requirements and from PV electrical requirements (Low Voltage Directive, LVD). This dual regulatory approach ensures that modules generate clean electricity while integrating seamlessly into the design and functionalities of the built environment. This dual framework also presents certain challenges, which can hinder BIPV deployment. In this paper, the focus is on building requirements and fire safety standards.

The Construction Products Regulation (CPR) provides a harmonised European framework for product performance and fire safety [1]. In turn, each Member State sets up its own minimal fire safety requirements in buildings. As construction elements, BIPV systems are classified using EN 13501-1, but due to their materials, they cannot achieve the highest fire safety categories (A1 and A2). This limitation restricts BIPV use where non-combustible classifications are required. Furthermore, the current testing approach, based on the Single Burning Item (SBI) test, does not fully reflect BIPV-specific fire risks. Some countries are developing larger-scale fire tests and alternative methods to address these gaps and support BIPV deployment.

2.1 Regulatory framework for construction products

The unification of the regulatory framework for construction products in the European Union began with the introduction of the Construction Products Directive (CPD 89/106/EEC) [1]. The CPD aimed to harmonise national regulatory systems, establish essential requirements for construction materials and components, and create conditions for the free circulation of products within the internal market.

This framework was later replaced by the Construction Products Regulation (CPR 305/2011), which simplified procedures for assessing and verifying the performance of construction products. The CPR sets out harmonised rules for expressing product performance in relation to essential characteristics and governs the use of CE marking. It also defines the “Basic Requirements for Construction Works” (Annex I), including “safety in case of fire”. The CPR was updated in 2024 (Regulation (EU) 2024/3110), reinforcing the regulatory framework. All BIPV systems fall under the scope of the CPR, as they meet the definition of construction products [1].

Fire safety requirements for construction products are determined by national and local building regulations. As such, they differ in each Member State. Nonetheless, they have to follow the harmonised Euroclass system of fire safety standards as defined in EN 13501-1 (reaction to fire) and EN 13501-5 (external fire exposure to roofs). Fire safety requirements are usually defined based on building height or use.

The classification system under EN 13501-1 ranges from A1 (non-combustible) to F (highly combustible) and includes sometimes additional classifications for smoke production (s1, s2, s3) and flaming droplets (d0, d1, d2).

The standard includes various tests to evaluate the combustibility, flame spread, heat release, smoke production, and occurrence of flaming droplets when materials are exposed to fire.

Furthermore, the EN 50583 standard on ‘Photovoltaics in buildings’ applies to photovoltaic modules used as construction products and refers to the CPR. However, it is not a harmonised standard and therefore does not provide a basis for manufacturers to issue a Declaration of Performance or affix the CE marking. In the absence of a harmonised standard specific to BIPV, national or local regulations apply, particularly regarding fire safety. Hence, the only common reference at EU level remains the classification scheme defined in EN 13501.

2.2 Implication of EN 13501-1 and EN 13501-5 for BIPV products

Whilst fire testing and classification methods for individual construction products are harmonised at EU level, building regulations, including fire safety requirements, remain the responsibility of individual Member States. Each Member State determines its own fire safety level. As such, the same building types might have different minimal fire safety requirements in different Member States. As EN 13501 is the harmonised standard in the EU for construction products, BIPV elements are subject to the required test and classification. Table I details BIPV elements and their corresponding construction products in legislations.

In practice, EN 13501-1 entails that BIPV products, due to their combustibility, are not able to be classified A1 or A2. Indeed, the classification defined in EN 13501 is based on the Single Burning Item (SBI) test. Based on the SBI test, BIPV elements can only achieve B to F classification. This is mainly due to the combustibility of the encapsulant. As part of the Increase project, heat of combustion of different encapsulant materials used in PV modules were collected in Ollagnon *et al.* [2]. As a result, if a national building code requires A2 or higher classification for building elements, BIPV cannot be installed.

Table I: Correlation between BIPV products and construction elements

BIPV product	Construction element
Ventilated façade	External walls
Rainscreen cladding	Ventilated façade
Double-skin façade	
Curtain walls	
Roofing (discontinuous or continuous)	Roof
Skylight	
Balustrade	Barriers
Parapet	
Greenhouse window	Window
Winter garden window	
Pergola	Ancillary elements
Shading	
Canopy	

Besides the regulatory limitation on BIPV deployment that SBI and EN 13501 pose, these test methods are not entirely adequate to assess fire behaviour of façades overall and BIPV elements in particular. The SBI test is a small-scale test that has been developed to allow for easier and less costly study of the fire reaction of

building materials. In practice the test is undertaken to simulate a scenario of combustion of an isolated object in a bin burner in a corner of a room. There are currently discussions on the suitability of such test to assess a façade, as the fire scenario of a fire occurring in a façade is different from a small item in terms of heat power or sample size, measurement parameters and observations.

Thus, some countries have developed mid- and large-scale fire tests to palliate for these shortcomings. At European level, the harmonisation of large-scale testing methods are also being investigated. Such method would be more suitable for BIPV testing and thus support BIPV deployment. Indeed, Belgium and the Netherlands, for example, are permitting other alternatives to justify safety in case of fire, through other type of tests.

Regarding BIPV elements, the standard does not address BIPV particularities. Notably, there is no specification regarding where the junction boxes or cables should be added. Furthermore, SBI and EN 13501 assumes passive materials, whereas BIPV can generate heat and electrical faults. More details on these shortcomings are provided in the discussion section.

3 OVERVIEW OF FIRE SAFETY REGULATIONS IN INCREASE DEMONSTRATION SITE COUNTRIES

3.1 Belgium

Belgium has a multi-layered approach to fire safety, with responsibilities shared between federal, community, regional and municipal authorities.

The Arrêté royal du 7 juillet 1994 (Royal Decree of 7 July 1994) and its amendments set the basic fire prevention standards for new buildings and extensions, including fire resistance of structural elements, reaction to fire of materials, fire compartmentation and evacuation and specific rules for façades, roofs and technical installations. The Decree provides general provisions and detailed ones in its annexes (Annex 1 Terminology, Annex 2 Low-rise buildings, Annex 3 Mid-rise buildings, Annex 4 High-rise buildings) [3].

The 2022 amendment to the Decree introduced explicit fire safety requirements for façades, which apply to BIPV when integrated into the external wall system. One major change affecting BIPV is the introduction of a minimum requirements of A2 class for high-rise buildings. However, the Belgian legislation offers an alternative compliance route to allow for materials not meeting the A2 requirements with large-scale testing of the façade.

3.1.1 Building classification

The Decree details a building classification based on height (distance between the finished floor level of the highest floor and the lowest level of the roads surrounding the building) [4]:

- High-rise building (*bâtiments élevés* - BE): above 25m
- Mid-rise building (*bâtiments moyens* - BM): between 10m and 25m
- Low-rise building (*bâtiments bas* - BB): lower than 10m

3.1.2 Minimum fire safety classification requirements for façades

Fire safety requirements are outlined in Annex 5 of

the Decree (§6.1.1). Requirements for external surfaces of façades are as follows:

- High-rise buildings: A2-s3, d0 or large-scale testing
- Mid-rise buildings: B-s3, d1
- Low-rise buildings: C-s3, d1 for single-wall façade and D-s3, d1 for double-wall ventilated façade

Section 6.2 “*Essai à grande échelle*” of Annex 5/1 in the Belgian Arrêté royal du 7 juillet 1994 introduces a complementary testing method for façades [4]. The large-scale test is designed to evaluate the global fire behaviour of a façade system under realistic conditions, beyond what small-scale Euroclass tests EN 13501-1 can show. It addresses fire spread via the external envelope, including vertical and lateral propagation and the risk of flames reaching upper storeys. If a façade system passes a recognised large-scale fire test (BS 8414-1 and LPS 1581, BS 8414-2 and LPS 1582 and LEPiR 2 with the related Decree of 10 September 1970) and meets the performance criteria defined in the referenced documents, then the A2 requirement does not apply to that façade.

As such, Belgium has an alternative compliance route, in which a high-rise façade does not need to meet Euroclass A2 if the entire system is successfully tested at large scale and satisfies the prescribed performance limits. This applies only if the test is done according to the listed standards and the criteria in the annex are met, the system must demonstrate controlled fire spread and integrity under severe conditions.

3.1.3 Minimum fire safety classification requirements for roofs

Roofing products must be classified as B_{ROOF} (t1) as stated in §8.1 of Annex 5 of the Decree [4]. Furthermore, balconies and walkways must also have a B_{ROOF} (t1) class.

3.2 Estonia

In Estonia, the Building Code aims to ensure the safety, purposeful functionality and usability of the built environment, as well as to promote sustainable development [5]. Fire safety is mentioned among the requirements for construction works (§11(2)). The Fire Safety Act provides general requirements, obligations, rights and liabilities related to ensuring fire safety of legal persons and governmental entities [6].

Fire safety requirements for buildings are detailed in a dedicated regulation from 2021 [7]. This document notably outlines the fire safety classes of buildings, from TP1 to TP3 (§5), building classifications based on usage (Annex 1), fire safety requirements for roof and roof coverings (§16), balconies (§17) and external walls (§21 and Annex 7).

3.2.1 Building classification

Buildings are classified based on their usage and described in Annex 1 of the Fire safety requirements for buildings regulation [7]. Seven categories of use exist, based on the occupants’ familiarity with the building and able to ensure their own safety in case of fire and whether or not the occupants are expected to sleep in the building. Building categories, based on use are summarised below.

- Use I: Residential buildings
- Use II: Accommodation buildings
- Use III: Welfare and detention buildings

- Use IV: Assembly buildings
- Use V: Offices
- Use VI: Industrial and warehousing buildings
- Use VII: Garages

Buildings are also divided into classes according to their fire safety, TP1 fire-resistant (*tulekindel*), TP2 fire-retardant (*tuldtakistav*), TP3 fire-sensitive (*tuldkartev*) (§5) and detailed in Table II. This classification is determined by use of the building, the purpose of the premises, the number and area of floors, the height of the building, the number of users, the specific fire load density and the fire hazard of the activities taking place in the building (§5(1)). Different part of a building can have different fire safety classes in so far as there a fire protection structures and that the lower floor has a higher safety class than the upper levels.

Table II: Overview of building fire safety classes in Estonia

Fire safety designation	Description
TP1 fire-resistant	The building's load-bearing structure must not collapse during the specified time in the event of a fire; generally, such a structure does not collapse during a fire.
TP2 fire-retardant	The building's load-bearing structure must not collapse during the specified time in the event of a fire; however, the specified time is shorter than that required for a fire-resistant building.
TP3 fire-sensitive	The fire resistance of the building's load-bearing structure is not specified, provided it does not affect the fire resistance of fire compartments.

Building classifications come with specific restrictions on the number of storeys, height and number of users of the building and enclosed area of the building. TP1 buildings do not have specific restrictions as their fire safety is higher. However, TP2 and TP3 buildings have restrictions, which are specified in Annex 2 of the legislation. TP2 buildings can be up to 2 storey and 9 m high, except residential and office buildings which can go up to 8 storey and 14 m for 3-4 storey and 28 m for 3-8 storey. TP3 buildings should be up to 2 storey and 9 m high. Essentially, bigger or riskier buildings must be TP1 and smaller, lower-risk ones can be TP3.

3.2.2 Minimum fire safety classification requirements for façades

Fire safety requirements for building elements are detailed in the Fire safety requirements for buildings regulation, including fire safety requirements for roof and roof coverings (§16), balconies (§17) and external walls (§21 and Annex 7) [7]. Table III provides an overview of the fire safety requirements for façade elements based on building classification, use and related restrictions on height and number of storey.

Estonia requires B, d0 for external walls for high-rise buildings and specific uses, such as welfare and educational buildings, and mid-rise office and residential buildings. As a results, BIPV is challenging to install on these buildings. It is worth noting that A2 requirements for insulation system do not pose an issue for BIPV

installation.

The requirement for a B-s1, d0 fire classification on the outer surface of the ventilation cavity facing the external cladding is also challenging. This surface often contains combustible materials, including plastic backsheets, junction boxes and electrical connectors. Standard fire tests may struggle to achieve the required classification when these components are present and the actual installation may involve even greater quantities of combustible material not fully represented in laboratory samples. In contrast, the fire classification for the cavity surface opposite the supporting wall or insulation is contingent upon the insulation material selected, specifying an insulation product that meets the necessary fire rating can facilitate compliance for this interface.

The fire performance requirement for balconies, loggias and terraces is D-s2 for buildings up to two storeys, B-s1 for buildings between 3 and 8 storeys and A2-s1 for buildings with a height of over 28m (§17(2)). Surface layers of balconies are also restricted in terms of fire safety requirements, with a minimum of D_{fl}-s2 for buildings up to five storeys and B_{fl}-s1 for buildings above five storeys (§17(2)).

Table III: Overview of fire safety requirements for façade elements in Estonia

Building class and use	External wall	Outer surface of the ventilation gap	Inner surface of the ventilation gap
TP1 Generally	B, d0	B, d0	B-s1, d0
TP1 For medical and welfare institutions (Use III) of more than 2 storey, kindergarden (Use IV) of more than 2 storey and school buildings (Use IV) of more than 3 storey	B, d0	B, d0	B-s1, d0
TP2 Generally	D, d2	D, d2	D-s2, d2
TP2 Buildings in use III (welfare, detention)	B, d0	B, d0	B-s1, d0
TP2 Use I (residential buildings) and V (offices) use with 3-8 storey	B, d0	B, d0	B-s1, d0
TP3 Generally	D, d2	D, d2	-

3.2.3 Minimum fire safety classification requirements for roofs

External fire resistance for roofing materials should be B_{ROOF}(t₂-t₄) (§16(3)) or lower if the building does not possess any fire source or if it is located at least more than 40 m away from other constructions (§16(4)) [7].

3.3 France

In France, the Building and Housing Code (*Code de la construction et de l'habitation*, CCH) is the Code that brings together the legislative and regulatory provisions

relating to construction, property development, social housing and other property-related matters [8]. In addition, certain building regulations are contained in other codes or are not included in any code.

3.3.1 Building classification

France separates building types into residential and non-residential buildings (called in French *établissement recevant du public* (ERP)). Residential buildings are classified into four “families” or groups, as specified in Article 3 of the “Arrêté du 31 janvier 1986 relatif à la protection contre l'incendie des bâtiments d'habitation” [9]. Residential buildings are classified depending on height, number of storey and disposition (in a row or independent). The four “families” can be summarised as follows:

- Family 1 and 2: low-rise houses and low-rise buildings (up to 3 stories),
- Family 3: mid-rise buildings, 4-8 stories or up to 28 m,
- Family 4: high-rise buildings, between 28 and 50 m.

The rules of non-residential buildings (ERP), are specified in the CCH from Articles R 143-1 to R 143-47. ERP are defined as premises and buildings in which persons are admitted, either freely or for a fee or contribution of any kind, or in which meetings open to the general public or by invitation, whether paid or free of charge, are held [8]. General rules regarding fire safety apply to all non-residential buildings and particular rules apply to specific types of buildings.

Non-residential buildings are classified doubly, depending on the use of the building (type) and the number of people the building can accommodate (category). Whatever their type, non-residential buildings fall into five categories depending on the number of people they can accommodate, as follows:

- 1st category: more than 1500 people
- 2nd category: from 701 to 1500 people
- 3rd category: from 301 to 700 people
- 4th category: less than 300 people, except for buildings included into the 5th category
- 5th category: small buildings, the number of people does not reach the minimum number set by the safety regulations for each type of building usage.

The types of building, depending on use, are outlined in Article GN1 §1 of the “Arrêté du 25 juin 1980” [10].

Other types of non-residential buildings have specific conditions set by different ministries, such as establishments dependent on public law entities, buildings necessary for the functioning of public railways, prisons, military establishments and administrative detention centres.

3.3.2 Minimum fire safety classification requirements for façades

Before Euroclasses, France used a M classification based on combustibility and flammability of the materials. The M classification tends to disappear and is not used in practice but still present in the legislation. The M classification was translated into Euroclass with the Arrêté du 21 novembre 2002 [11]. Regarding façades, minimum fire safety requirements are outlined in Euroclasses, however for roofs, they are described using the M classification.

Fire safety requirements for residential buildings façades are outlined in Euroclass, in Articles 12 and 13 of the Arrêté du 31 janvier 1986 and are as follows [9]:

- 1st family: at least D-s3, d0
- 2nd family: at least D-s3, d0
- 3rd family: at least A2-s3, d0
- 4th family: at least A2-s3, d0

General fire safety requirement for non-residential buildings (ERP) are outlined in the “Arrêté du 25 juin 1980 portant approbation des dispositions générales du règlement de sécurité contre les risques d'incendie et de panique dans les établissements recevant du public (ERP)”, more specifically in Livre II, Titre Ier, Chapitre II [10].

Article CO 20 from the Arrêté du 25 juin 1980 sets fire safety rules for façades. For most cases, the façade components must be made of M3 materials or have a European fire classification of D-s3, d0 [10]. There are stricter requirements if the C+D rule from Article CO 21 §3 is not applied to the entire façade (i.e. no vertical fire barrier between floors), then external cladding and shutters and blinds must meet higher fire performance M2 materials or classified as C-s3, d0.

In addition, laboratory assessments are possible following Technical Instruction 249 (IT 249) [12]. IT 249 supplements the fire safety regulations for ERP buildings, residential buildings and high-rise buildings. It outlines provisions relating to façades and their connection with floors. Its role is to limit the risk of fire spread to the levels above or laterally via the façades. Laboratory assessments of the fire performance of an innovative process are also possible with a Technical Experimentation Assessment (ATEX). However, in this case, the fire performance of the tested solution is project specific and cannot be replicated and the process is timely and costly. The administrative burden is further exacerbated by the fact that there is no validation ensured and that the tests might have to be undertaken again.

3.3.3 Minimum fire safety classification requirements for roofs

For roofs, the French legislation uses its own classification system, from M0 to M4. The French fire classification for roofing includes two components, the T/x (e.g. T/5, T/15, T/30) indicates how long the roof resists fire penetration from the outside (in minutes) and the Indice de propagation (1, 2, 3) shows how well the roof limits fire spread to nearby buildings. Indice 1 is the best (low spread risk), Indice 3 is the least protective. The Arrêté du 14 février 2003 relatif à la performance des toitures et couvertures de toiture exposées à un incendie extérieur translated the French system into the Euroclasses, as outlined in Table IV below. In France, only Test 3 (t3) is recognised for regulatory use.

Table IV: Overview of the correlation between the French classification for roofing materials and the Euroclasses

French classification	Euroclasses
T30	B _{ROOF} (t3)
Indice 1	
T15	C _{ROOF} (t3)
Indice 2	
T 5	D _{ROOF} (t3)
Indice 3	

Construction elements from M0 to M3 (corresponding to B_{ROOF}) can be used without restrictions if built on continuous incombustible material. Roofs with M0 to M3 materials are automatically considered Indice 1.

Roof coverings in category M4 must meet two fire safety criteria regarding resistance to fire penetration (T/x) and control of fire spread to neighbouring buildings. Resistance to fire penetration must meet the below requirements depending on the building family:

- 1st family: T/5, T/15 or T/30
- 2nd family: T/15 or T/30
- 3rd and 4th families: T/30

The control of fire spread to neighbouring buildings (*Indice de propagation*) depends on the distance to the neighbouring building or property line and the Indice of the neighbour's roof. The propagation index (1 to 3) is not directly included in CEN TS 1187 but is partially reflected in flame spread criteria.

Overall, the French roofing fire protection requirements by housing family for residential buildings can be summarised as follows in Table V.

Table V: Summary of fire rating requirements for roofing materials for residential buildings in France based on building families

Building family	French fire penetration class	Euroclass equivalent	Propagation index required
1 st family	T/5, T/15 or T/30	D _{ROOF} (t3), C _{ROOF} (t3), B _{ROOF} (t3)	Depends on distance (Indice 1 to 3)
2 nd family	T/15 or T/30	C _{ROOF} (t3), B _{ROOF} (t3)	Depends on distance (Indice 1 to 3)
3 rd and 4 th family	T/30	B _{ROOF} (t3)	Depends on distance (Indice 1 to 3)

Fire safety requirements for roofing in ERP aims to protect the roof from fire originating from a neighbouring building. If buildings are contiguous, the roof must also comply with isolation rules in Article CO 7 (§2 and §3) of the 25 June 1980 Arrêté [10].

Table VI: Summary of fire rating requirements for roofing materials for non-residential buildings in France based on building families

Category and purpose of the ERP	Distance to neighbour			
	Less than 8 m		Between 8 and 12 m	
1 st family, or 2 nd , 3 rd and 4 th with sleeping areas	T 30 Indice 1	B _{ROOF} (t3)	T 15 Indice 1	C _{ROOF}
2 nd , 3 rd and 4 th family without sleeping areas	T30 Indice 2	B _{ROOF}	T 15 Indice 2	C _{ROOF} (t3)

Requirements depends on the distance to other buildings. If the ERP is more than 12 metres from the neighbouring building or property line, no fire protection requirement applies to the roof. If another building is located less than 12 metres from the ERP, the roof must meet one of the following:

- Made of M0 materials (non-combustible),
- Made of M1 to M3 materials, installed on continuous support in M0 material or continuous support in wood or equivalent,
- Made of M1 to M3 materials not installed as above, or M4 materials with minimum class and propagation index based on building category and distance (described in the Table VI).

3.4 Montenegro

Montenegro is an EU candidate country. Accession negotiations with Montenegro started in June 2012 and EU candidate countries must meet a set of criteria (*acquis*) before joining the Union. The European Commission supports these countries in implementing reforms during the accession process and comply with the EU *acquis*. When the accession negotiations and the reforms have been completed the country can join the EU, if all current Member States agree.

Future EU countries need to be able to join the EU Single Market. For Montenegro and the Western Balkans, this area of integration is supported by the launch of the Western Balkans Common Regional Market structured around free movement of goods, services, capital and people. The aim is to integrate the region before accession to the Single Market. As an essential element of the free circulation of construction products in the EU, the CPR must also be implemented in Montenegro to align its standards with EU requirements.

As such, Montenegro has adopted a Law on Construction Products that partially transposes the EU Construction Products Regulation. This law and its bylaws are the legal basis for the use of harmonised European standards, including those related to fire safety and Euroclass. A Rulebook on Construction Products was published in 2017, it regulates construction products in Montenegro [13]. However, the publicly available summary does not specify if it directly references Euroclass or EN 13501-1. The full text would need to be checked for explicit mention.

In addition, Montenegro generally accepts building materials with certificates from the country of origin, especially if they are CE-marked and compliant with EU standards. There is no mention of local testing or additional national standards for fire classification, suggesting that Euroclass (EN 13501-1) is accepted in practice for CE-marked products [14].

Given the difficulty to find relevant information about the regulation, Montenegro will not be analysed in the rest of the document.

3.5 Spain

The Spanish Building Code or *Código Técnico de la Edificación* (CTE) provides the regulatory framework governing the basic quality requirements that buildings, including their installations, must meet in order to satisfy basic safety and habitability requirements. It is organised in two parts, with the first one containing the general provisions and conditions of application of the CTE and the basic requirements that buildings must comply with [15]. The second part is composed of "Basic Documents" for the fulfilment of the basic requirements of the CTE. These Basic Documents provide the technical characterisations and procedures to meet the requirements.

The Basic Documents cover structural security, fire safety, safety in use, hygiene, health and environmental protection, noise protection and energy saving and thermal insulation. The relevant one for fire safety is the *Documento Básico Seguridad en caso de incendio* (DB-SI), it specifies parameters and procedures to comply with the fire safety requirements of the Building Code, except for industrial buildings, which are covered in another document.

It is worth noting that the Spanish Ministry of Housing and Urban Agenda has initiated the public consultation process for a draft Royal Decree amending the Building Technical Code (*Real Decreto* 314/2006), with the consultation period open until 9 December 2025, which includes updated fire safety requirements for building envelopes, among other key revisions. Once the Decree is released, an updated version of this paper will be published.

3.5.1 Building classification

Building classification are determined by the use of the building and spelt out in Annex SI A “Terminology” [16]. Building usage include: administrative, warehouse, parking, commercial, educational, hospital, public residential and residential uses. Buildings across various sectors serve distinct purposes, each defined by their primary function and the nature of activities conducted within them.

3.5.2 Minimum fire safety classification requirements for façades

In Spain, the facade fire reaction class requirements do not vary by occupancy, they are set by the height of the facade.

The fire classification for façade “construction system” occupying more than 10% of the surface area depend on the total height of the façade and are the following (SI 2 §4 [16]):

- D-s3, d0 for façades up to 10 m high;
- C-s3, d0 for façades up to 18 m high;
- B-s3, d0 for façades over 18 m high.

Insulation systems inside ventilated chambers must have at least the following reaction to fire classification depending on the total height of the façade (SI 2 §5 [16]):

- D-s3, d0 in façades up to 10 m high;
- B-s3, d0 for façades up to 28 m high;
- A2-s3, d0 for façades higher than 28 m.

Spain also has a special rule to prevent fire spread at ground level (SI 2 §6 [16]). For buildings up to 18 m, if the facade is accessible to the public (ground floor or roof terraces), the first 3.5 m of facade from the ground must be at least Class B-s3, d0, even if the rest of the facade can be C or D. This is to mitigate arson or fire exposure where people can reach the facade.

3.5.3 Minimum fire safety classification requirements for roofs

With regards to roof, materials, products or systems covering more than 10% of the roof surface should have a B_{ROOF} (t1) classification.

3.6 Switzerland

Switzerland is not an EU Member State, however it signed a Mutual Recognition Agreement (MRA) with the European Community (now the EU), which entered into force in 2002. The MRA aims to promote trade in goods between the EU and Switzerland by removing technical

barriers, via the recognition of conformity assessments for several products, including construction products.

At the Swiss level, the fire protection regulations are issued by the Association of Cantonal Fire Insurance Institutions (VKG/AEAI). They include the fire standard (*norme de protection incendie*) and the directives (*directives de protection incendie*) together with explanatory notes on fire protection, as well as thematic support publications and references to specific sectors of use [17]. The fire protection standard establishes the framework for fire safety, covering general duties, construction, fire protection equipment, organisation and related fire defence measures. It sets the applicable safety standards and is supplemented by fire protection guidelines, which detail the specific requirements and implementation measures.

Fire protection requirements for buildings and other structures are determined in particular by [18]:

- a) the type of construction, location, risks in relation to neighbouring properties, size and intended use;
- b) the geometry of the building and the number of storeys;
- c) the number of occupants;
- d) the thermal load and fire behaviour of materials, as well as the risk of smoke emission;
- e) the activation hazard inherent to the building’s use and the activities carried out within it;
- f) the intervention capabilities of the fire brigade.

3.6.1 Building classification

Buildings are classified according to their “geometry”, that is to say, their size, according to Article 13 (3) of the “Norme de protection incendie” [18]. The classification is summarised as follows:

- Low-rise building: up to 11 m
- Medium-rise building: up to 30 m
- High-rise building: above 30 m
- Small-scale building: up to 2 levels above ground and up to 1 underground
- Annex building: single-storey

Article 13 (1) also outlines building classification according to their intended use [18]. Uses include accommodation establishments, large shops, premises accommodating large numbers of people, car parks, high-bay warehouses and temporary structures.

The fire protection directive, “Directive de protection incendie: Matériaux et éléments de construction”, defines the classification of materials and construction elements according to both the EN and VKG/AEAI systems and sets the required EN fire resistance classes for different construction elements in Switzerland [19]. Indeed, construction materials can be classified according to the EN 13501-1 standard or according to the VKG/AEAI classification.

Construction materials are classified into the following groups according to their fire behaviour (RF), as described in 2.1 (1) of the “Directive de protection incendie: Matériaux et éléments de construction” [19]:

- RF1: no contribution to fire
- RF2: low contribution to fire
- RF3: acceptable contribution to fire
- RF4: unacceptable contribution to fire

The legislation also considers materials that have critical fire behaviour (cr). That is to say, materials that may have unacceptable effects in the event of a fire, due

to smoke production, the formation of burning droplets or particles, or corrosion.

The legislation also propose a correlation table between the EN 13501-1 classification and the VKG/AEAI classification for construction products and for roofing materials.

3.6.2 Minimum fire safety classification requirements for façades

The fire protection directive on use of construction materials (Directive de protection incendie: Utilisation des matériaux de construction) sets out the requirements that building materials must meet in terms of their reaction to fire [20]. Detached houses must meet the requirements for ‘low-rise buildings’, regardless of the geometry of the building (§12(1)). For medium-rise buildings, if the exterior wall cladding and/or thermal insulation consists of combustible building materials, it must be ensured that the fire brigade can access the affected façade to fight the fire (§3.1.1(1)). The external wall and the external wall cladding system of high-rise buildings (*bâtiments élevés*) must be made of RF1 category materials (§3.1.2(1)). Table VII provides a detailed overview of minimum fire safety requirements for façades using both the Swiss and Euroclass classifications.

Translucent elements made of combustible materials may only be used for limited areas (§6). Window frames and essential elements with a negligible surface area (connectors, joints, insulating crossbars, edge strips, etc.) must be made of materials that at least meet the requirements of category RF3 (cr). They may be used regardless of the specifications concerning the choice of materials (§7).

Ventilated facades (§3.2.3) used on medium-rise buildings must be of a design recognised by the AEAI or equivalent if the cladding and/or insulation on either side of the air gap, or the solid layers, are made of combustible building materials. Cladding on low and medium-rise buildings may be fixed to laths made of RF3 (cr) materials. Fixings and point anchors that hold the cladding of ventilated façades and are located in the thermal insulation must be made of materials that are at least RF3 (cr), regardless of the height of the building (including high-rise buildings).

Double-skin façades (§3.2.4) extending over several storeys must be made of RF1 materials. However, linear window profiles made of combustible materials are permitted. The use of combustible building materials is possible, subject to additional measures.

The regulation outlines two complementary concepts for fire protection in buildings. The construction-based concept (concept de construction) relies on passive measures such as fire-resistant materials and structural design to meet safety objectives. Depending on the building’s use, additional fire protection equipment may be required. The extinguishing system concept (*concept d’installation d’extinction*) integrates certified fixed fire suppression systems (e.g. sprinklers) into the building’s fire safety strategy, particularly in cases where passive measures alone are insufficient. Depending on which concept is used, fire safety requirements may differ.

Furthermore, accommodation establishments [a], that is to say hospitals, care homes and medico-social facilities accommodating 20 or more people, either permanently or temporarily, who require assistance from others, require higher fire safety protection, mostly RF1.

In addition to the requirements set out in the legislation, Swissolar developed a transitional guide for planning and demonstrating fire protection in ventilated PV façade installations, valid until 31 December 2026 [21]. The guide aims to address the lack of a definitive technical standard for fire safety in PV façades and complements existing VKG/AEAI and Swissolar guidelines.

The guide explains which façades, under what conditions and with what fire protection verification procedures, BIPV installations can be planned and, if authorised, implemented. It also outlines technical principles specific to façades, supplementing the VKG/AEAI fire protection guidelines for solar panels. This document simplifies planning and justification for fire protection specialists, and makes evaluation easier for fire protection authorities. However, it does not grant automatic approval, each project must be individually assessed. The guide is not a definitive technical standard, but serves as a transitional document until such a standard is available.

Fire risks are detailed and different BIPV ventilated façade systems are described. PV façade systems are classified into three categories: System 0, with no verification required (mainly for low-rise buildings), System 1 with verification by argumentation/report and System 2 with verification by fire testing. The procedure for fire protection verification defines protection objectives that must be submitted to the fire protection authority for approval. Since there is no established technical standard, compliance with these protection objectives for system category 2 must be demonstrated through fire tests.

In the case of mid-rise buildings (up to 30 m), bi-glass with minimum thickness BIPV modules with a B-s3, d1 classification according to EN 13501-1 are allowed with further fire safety measures (System 1) or testing showcasing fire safety protection is achieved (System 2). BIPV can be allowed for mid-rise and high-rise buildings if strict fire protection measures are implemented and, where necessary, compliance is demonstrated through fire tests and detailed verification reports, all subject to approval by the fire protection authority. For high-rise buildings, up to 100 m, bi-glass BIPV modules with a B-s3, d1 classification can be installed with several requirements. The façade and cladding (excluding PV modules) must be made of RF1 materials or encapsulated systems, horizontal fire protection measures must be implemented at each floor in the ventilated cavity and cable ducts and no inverters are allowed in the rear ventilation space. In this case as well, fire tests are required.

3.6.3 Minimum fire safety classification requirements for roofs

Minimum fire safety requirements for roofing materials are RF3 (cr), corresponding to C_{ROOF} (t3), C_{ROOF} (t4), D_{ROOF} (t3), D_{ROOF} (t4), except for specific roof structures such as warm roofs with single or double ventilation (*toiture chaude à ventilation simple et double*) and flat roofs (*toiture plate*), which require RF1 materials. In addition, surface limitations apply to insulated roof types (*toiture isolée*) classified under roof categories 6, 7, 8, and 9, with 600 m² for categories 6 and 7 and 1200 m² for categories 8 and 9 [20].

Table VII: Overview of minimum fire safety requirements for façade elements depending on building geometry and specified EN 13501-1 classification and the VKG/AEAI classification (in bold)

	Construction-based concept	Extinguishing system concept	
Low-rise buildings	Overall façade	D-s1,d2 ; D-s2,d2 ; D-s3,d0 ; D-s3,d1 ; D-s3,d2 ; E ; E-d2 (RF3 (cr))	D-s1,d2 ; D-s2,d2 ; D-s3,d0 ; D-s3,d1 ; D-s3,d2 ; E ; E-d2 (RF3 (cr))
	Exterior wall cladding	D-s1,d2 ; D-s2,d2 ; D-s3,d0 ; D-s3,d1 ; D-s3,d2 ; E ; E-d2 (RF3 (cr))	D-s1,d2 ; D-s2,d2 ; D-s3,d0 ; D-s3,d1 ; D-s3,d2 ; E ; E-d2 (RF3 (cr))
	Thermal insulation layers	D-s1,d2 ; D-s2,d2 ; D-s3,d0 ; D-s3,d1 ; D-s3,d2 ; E ; E-d2 (RF3 (cr))	D-s1,d2 ; D-s2,d2 ; D-s3,d0 ; D-s3,d1 ; D-s3,d2 ; E ; E-d2 (RF3 (cr))
	Semi-transparent panels	D-s1,d0 ; D-s1,d1 ; D-s2,d0 ; D-s2,d1 (RF3)	D-s1,d0 ; D-s1,d1 ; D-s2,d0 ; D-s2,d1 (RF3)
Medium-rise buildings	Overall façade	A2-s1,d2 ; A2-s2,d2 ; A2-s3,d0 ; A2-s3,d1 ; A2-s3,d2 ; B-s1,d2 ; B-s2,d2 ; B-s3,d0 ; B-s3,d1 ; B-s3,d2 ; C-s1,d2 ; C-s2,d2 ; C-s3,d0 ; C-s3,d1 ; C-s3,d2 (RF2 (cr))	D-s1,d2 ; D-s2,d2 ; D-s3,d0 ; D-s3,d1 ; D-s3,d2 ; E ; E-d2 (RF3 (cr))
	Exterior wall cladding	A2-s1,d2 ; A2-s2,d2 ; A2-s3,d0 ; A2-s3,d1 ; A2-s3,d2 ; B-s1,d2 ; B-s2,d2 ; B-s3,d0 ; B-s3,d1 ; B-s3,d2 ; C-s1,d2 ; C-s2,d2 ; C-s3,d0 ; C-s3,d1 ; C-s3,d2 (RF2 (cr))	D-s1,d2 ; D-s2,d2 ; D-s3,d0 ; D-s3,d1 ; D-s3,d2 ; E ; E-d2 (RF3 (cr))
	Thermal insulation layers	D-s1,d2 ; D-s2,d2 ; D-s3,d0 ; D-s3,d1 ; D-s3,d2 ; E ; E-d2 (RF3 (cr))	D-s1,d2 ; D-s2,d2 ; D-s3,d0 ; D-s3,d1 ; D-s3,d2 ; E ; E-d2 (RF3 (cr))
	Semi-transparent panels	A2-s1,d1 ; A2-s2,d0 ; A2-s2,d1 ; B-s1,d0 ; B-s1,d1 ; B-s2,d0 ; B-s2,d1 ; C-s1,d0 ; C-s1,d1 ; C-s2,d0 ; C-s2,d1 (RF2)	D-s1,d0 ; D-s1,d1 ; D-s2,d0 ; D-s2,d1 (RF3)
High-rise buildings	Overall façade	A1 ; A2-s1,d0 (RF1)	A1 ; A2-s1,d0 (RF1)
	Exterior wall cladding	A1 ; A2-s1,d0 (RF1)	A1 ; A2-s1,d0 (RF1)
	Thermal insulation layers	A1 ; A2-s1,d0 (RF1)	A1 ; A2-s1,d0 (RF1)
	Semi-transparent panels	A1 ; A2-s1,d0 (RF1)	A2-s1,d1 ; A2-s2,d0 ; A2-s2,d1 ; B-s1,d0 ; B-s1,d1 ; B-s2,d0 ; B-s2,d1 ; C-s1,d0 ; C-s1,d1 ; C-s2,d0 ; C-s2,d1 (RF2)

Translucent roof coverings are permitted under Swiss fire regulations provided they are made of materials classified at least RF3, cover no more than 30% of the total roof surface, and do not exceed 40 m² above evacuation routes or 120 m² above other areas. Individual sections of translucent roofing must be spaced at least 2 metres apart. If the materials used are classified RF1, these surface limits do not apply (§3.3.1(4)).

4 COMPARATIVE ANALYSIS OF FIRE SAFETY REGULATIONS IN INCREASE DEMONSTRATION SITE COUNTRIES

This section presents a comparative analysis of fire safety regulations in the countries hosting Increase demonstration sites, namely Belgium, Estonia, France, Spain and Switzerland. It aims to investigate how national building classification systems, fire rating requirements and regulatory approaches shape the requirements for both façade and roofing materials, with particular focus on their implications for the deployment of BIPV across a range of building types and heights. The analysis highlights common trends, distinctive national practices and specific challenges encountered when integrating BIPV into construction. A typology of buildings and their suitability for BIPV installation is also proposed. By systematically examining the minimum fire safety standards and the feasibility of BIPV installation in residential and non-residential contexts, this section provides a foundation for understanding the regulatory landscape and identifying opportunities for solar integration in European buildings. Figure 1 provides an overview of commonalities and differences in regulatory approaches.



Figure 1: Overview of commonalities and differences in regulatory approaches for fire safety in buildings in Belgium, Estonia, France, Spain and Switzerland

4.1 Building classification and fire rating

Building classification systems across Belgium, Estonia, France, Spain and Switzerland vary in structure but converge in their role of shaping fire safety requirements. **Belgium, Spain and Switzerland** primarily classify buildings by height, with thresholds triggering progressively stricter fire safety measures. **Spain** classifies buildings by use, though fire safety obligations ultimately depend on height. **Estonia** adopts a dual system based on building use and fire resistance class, which directly governs permissible height, number of storeys and occupancy. **France** distinguishes between residential and non-residential buildings. The former including categories (“families”) depending on height,

number of storeys and disposition (in a row or independent), and the latter being categorised by both use and capacity, with fire safety rules tailored accordingly in dedicated regulations. Overall, these systems reflect national priorities, whether structural resilience, occupant vulnerability or building function, and determine the scope of fire protection measures, evacuation planning and material standards.

Additionally, **France and Switzerland** have their own classification system for fire rating with corresponding Euroclasses. **France** historically used its own “M” combustibility ratings from M0 incombustible and M1 non-flammable, down to M4. In practice, the use of the M classification is phasing out but still present in the legislation and for products certified before 2022. These have been translated into Euroclasses. France uses a unique system for roof fire performance: classifications like T30, T15, T5 coupled with “Indice de propagation” 1-3 (spread index). **Switzerland’s** classification system is based on the fire behaviour of the materials with a ranking from RF1 (no contribution to fire) to RF3 (acceptable contribution to fire), with RF4 representing an unacceptable contribution to fire. Critical fire behaviour of the materials are represented with (cr). This classification has been translated into Euroclass terms in the Swiss legislation.

4.2 Commonalities and differences in regulatory approaches

Overall, the Grenfell Tower fire (June 2017) has led to stronger fire safety requirements in buildings in Europe, including stricter rules for high-rise buildings. The studied countries also witnessed this effect, with changes and updates in regulations in **Belgium** in 2022, in **Estonia** in 2021, in **France** in 2019 and upcoming in **Spain**.

In terms of regulatory approaches, the analysis of the regulations in the five countries showcases two approaches, one with fire safety requirements based on building height only (**Belgium, Spain and Switzerland**) and a dual approach based on height and use of the building (**Estonia, France**). **Estonia’s** approach also stands out with its fire safety classes for the overall building (TP1-TP3), with TP2 and TP3 inducing restrictions on height, number of storeys and number of users. In effect, TP3 and TP2 are allowed for low-rise buildings, up to 9 m and TP2 is allowed for mid-rise buildings for residential (Use I) and office buildings (Use V). TP1 is therefore mandatory for high-rise buildings. **Switzerland** also have higher requirements for welfare buildings (accommodation establishments [a]).

Furthermore, **Swiss** regulations also present another particularity, they define two complementary approaches to fire protection in buildings. The construction-based approach (*concept de construction*) relies on passive measures, including fire-resistant materials and structural design, to achieve safety objectives. Depending on the building’s function, additional fire protection equipment may be necessary. The extinguishing system approach (*concept d’installation d’extinction*) incorporates certified fixed fire suppression systems, such as sprinklers, into the building’s fire safety strategy, particularly where passive measures alone are inadequate. Fire safety requirements vary depending on the approach adopted.

France adopts a distinct regulatory approach by maintaining separate fire safety regimes for residential

and non-residential buildings (ERP). The requirements for ERP are somewhat less stringent than those for residential buildings. For instance, façades must achieve at least D-s3, d0, with an upgrade to C-s3, d0 mandated in the absence of fire-stops between floors. As such, a mid-rise office building in France may employ a BIPV system rated as Class C, whereas a residential building of comparable height would be required to meet the higher A2 standard. In contrast, most other countries apply a single set of facade classification rules across building types, with only limited exceptions for particular cases. As a result, France's regulatory framework imposes greater constraints on BIPV deployment in residential settings than in offices.

Finally, Belgium, France and Switzerland allow large-scale testing for façades to be installed on mid- and high-rise buildings. In **Belgium**, large-scale fire testing is permitted, allowing for the evaluation of the overall fire behaviour of façade systems in realistic scenarios, offering a more comprehensive assessment than smaller Euroclass tests. **France** provides performance-based routes for BIPV façades, enabling laboratory assessments to demonstrate fire safety compliance. Products typically require a ATEEx from CSTB, certifying fire performance when installed. However, ATEEx are project specific, lengthy, difficult and very costly processes, in practice limiting BIPV adoption to a few prestige projects. In addition, insurance challenges remain limiting the use of innovative BIPV installation in buildings in France [22]. In **Switzerland**, Swissolar has introduced a transitional guide for planning and verifying fire protection in ventilated PV façade installations, supplementing existing guidelines and facilitating BIPV deployment in mid- and high-rise buildings, provided strict fire measures and thorough testing are undertaken, subject to approval by the fire protection authority.

4.3 Fire safety requirements

This section analyses fire safety requirements in each country for residential and non-residential buildings, from low- to high-rise buildings. Table VIII summarises these requirements.

4.3.1 Residential buildings overview: façade requirements

For **low-rise residential buildings** (single-family homes or 1-3 story apartments), all five countries allow relatively combustible facades (Euroclass D or similar). As a result, BIPV deployment on houses and small-rise residential buildings faces minimal fire code barriers.

Belgium requires C-s3, d1 for single-wall façade and D-s3, d1 for double-wall ventilated façade for buildings lower than 10 m. **Estonia** requires D-s2, d2 for TP2 and TP3 buildings up to 9 m and B, d0 for TP1 buildings and residential buildings with less than 3 storeys require D, d0. In **France**, low-rise residential buildings (up to 3 stories and 8 m from the ground to the floor of the highest level), which are equivalent to family 1 and, require D-s3, d0. **Spain** require D-s3, d0 for buildings up to 10 m. **Switzerland** requires D or E classes for low-rise buildings.

Mid-rise residential buildings have a wide range of requirements from Class B to D, with the notable exception of France, which requires A2. As a result, BIPV is possible in most cases.

Belgium requires B-s3, d1 for buildings between 10 and 25 m. **Estonia** requires B, d0 for residential buildings

with 3-8 storeys (up to 14 m for 3-4 levels and up to 28 m for 3-8 levels). In **France**, A2-s3, d0 is required for the 3rd family of residential buildings (4-8 stories or up to 28 m). **Spain** require C-s3, d0 for buildings up to 18 m. **Switzerland** requires Class C or Class D if fire extinguishing systems are in place in mid-rise buildings.

Regarding **high-rise residential buildings**, all countries converge on very stringent requirements. Typically non-combustible facades (Euroclass A2 or RF1) are mandated, reflecting the high risk. As such, BIPV installation is nearly impossible in some countries for high-rise buildings.

Table VIII: Comparison of fire safety requirements for facades and roofs in Belgium, Estonia, France, Spain and Switzerland

Country	Facade fire rating requirements (for typical buildings)	Roof fire requirements
BE	High-rise (>25 m): A2-s3, d0 Medium-rise (10-25 m): B-s3, d1 Low-rise (<10 m): C or D (depending on system)	B _{ROOF} (t1)
EE	Tall facades (>22 m): B, d0 and A2 thermal insulation Mid-rise buildings: facade outer layer can be D or B depending on building class and use Low-rise buildings: B or D	B _{ROOF} (t2-t4) generally required, unless very isolated situation.
FR	Residential: Low (Fam. 1-2) D-s3, d01 Mid (Fam. 3 ≤ 28 m) A2-s3, d0 or approved test High (Fam. 4 ≤ 50 m) A2-s3, d0 (minor parts allowed if protected). Non-residential (ERP): D-s3,d0 C-s3,d0 if no fire-stops between floors	Residential: B _{ROOF} (t3) With exceptions for individual houses and less than 2 storey buildings (Fam. 1 & 2) Non-residential: B _{ROOF} (t3) C _{ROOF} (t3) if neighbouring buildings over 8 m away
ES	to 10 m: D-s3, d0 Up to 18 m: C-s3, d0 Over 18 m: B-s3, d0 Additionally insulation ≥A2 for >28 m facades. Ground-level 3.5 m of facade to B if accessible public area.	B _{ROOF} (t1) minimum for >10% roof area.
CH	High-rise (>30 m): A2-s1 Medium-rise (11-30 m): B/C class Low-rise: D/E class	C _{ROOF} /D _{ROOF} certain roof types require RF1

Belgium requires A2-s3, d0 for buildings higher than 25 m. In **Estonia**, high-rise buildings would fall into TP1, requiring B, d0. In **France**, A2-s3, d0 is required for the 4th family of residential buildings (between 28 and 50 m). **Spain** require B-s3, d0 for buildings over 18 m, with B-s3, d0 insulation for façade up to 28 m and A2-s3, d0 above 28 m. **Switzerland** requires A2-s1, d0 for high-rise buildings.

Fire safety requirements for residential building facades vary by height across Belgium, Estonia, France, Spain and Switzerland. Low-rise residential buildings in

all five countries permit relatively combustible facades (Euroclass D or similar), posing minimal barriers to BIPV deployment. Mid-rise buildings generally require stricter standards, ranging from Class B to D, except in France, which mandates non-combustible A2 facades. For high-rise residential buildings, all countries enforce stringent, typically non-combustible (Euroclass A2 or equivalent) facade requirements, significantly restricting BIPV options in tall buildings.

4.3.2 Non-residential buildings overview: façade requirements

For **low-rise non-residential buildings**, all five countries allow relatively combustible facades (Euroclass D or similar), except for specific buildings linked to care and welfare activities. As a result, BIPV on houses and small-rise buildings faces minimal fire code barriers.

Similarly to residential, **Belgium** requires C-s3, d1 for single-wall façade and D-s3, d1 for double-wall ventilated façade for buildings lower than 10 m. **Estonia** requires D-s2, d2 for TP2 and TP3 buildings up to 9 m and B, d0 for TP1 buildings and for welfare and detention buildings up to 9 m. Office buildings with less than 3 storeys require D, d0. In **France**, low-rise non-residential (except specific buildings) require C-s3, d0 if no fire barriers exist between floors or D-s3, d0. **Spain** require D-s3, d0 for buildings up to 10 m. **Switzerland** requires D or E classes for low-rise buildings, with the exception of medical buildings, which require A2-s1, d0.

Mid-rise non-residential buildings have a wide range of requirements from Class B to D, making BIPV deployment possible.

Belgium requires B-s3, d1 for buildings between 10 and 25 m. **Estonia** requires B, d0 for office buildings with 3-8 storeys (up to 14 m for 3-4 levels and up to 28 m for 3-8 levels) and B, d0 in general for mid-rise buildings (TP1). In **France**, mid-rise non-residential (except specific buildings) require C-s3, d0 if no fire barriers exist between floors or D-s3, d0. **Spain** require C-s3, d0 for buildings up to 18 m. **Switzerland** requires Class C or Class D if fire extinguishing systems are in place.

Similarly to residential buildings, **high-rise non-residential buildings** require higher safety standards, with A2 in most cases. Here France stands out with lower requirements.

Belgium requires A2-s3, d0 for buildings higher than 25 m. In **Estonia**, high-rise buildings would fall into TP1, requiring B, d0. In **France**, high-rise non-residential (except specific buildings) require C-s3, d0 if no fire barriers exist between floors or D-s3, d0. **Spain** require B-s3, d0 for buildings over 18 m, with B-s3, d0 insulation for façade up to 28 m and A2-s3, d0 above 28 m. **Switzerland** requires A2-s1, d0 for high-rise buildings.

In Estonia and Switzerland, rules are more stringent for specific non-residential buildings, which are deemed higher risk. In **Estonia**, for TP2 class, welfare and medical institutions (Use III) buildings and residential buildings (Use I) and offices (Use V) use with 3-8 storeys require B, d0 for external walls, instead of D, d2 for other buildings. In **Switzerland**, accommodation establishments class [a], that is to say hospitals, care homes and medico-social facilities accommodating 20 or more people, either permanently or temporarily, who require assistance from others, require higher fire safety protection compared to other building uses, mostly RF1 (A1 ; A2-s1,d0). While these A2 requirements represent an issue for BIPV deployment in these buildings, these

specific uses are rather limited and are not as impactful as other challenges. In **France**, specific non-residential buildings (ERP) also have dedicated rules.

Fire safety requirements for non-residential buildings also tighten with height, but some occupancy or use-based nuances exist. **France** stands out by separating them into a distinctive category with slightly relaxed facade criteria (balanced by other requirements like alarms, compartmentation for ERPs), and dedicated requirements in separate regulations. **Switzerland** allows fire engineering (sprinklers, fire curtains) more in commercial projects, which can indirectly ease BIPV integration by compensating for combustibility with safety systems. Meanwhile, critical facilities such as hospitals tend to face stricter rules, effectively narrowing BIPV options unless those are low-rise. Both **Switzerland** and **Estonia** have specific requirements for welfare buildings.

In summary, fire safety requirements for building facades vary significantly by height, building type and country, with low-rise structures in Belgium, Estonia, France, Spain and Switzerland generally permitting more combustible materials and thus facilitating BIPV deployment. Mid-rise buildings face stricter regulations, but BIPV remains feasible in many scenarios. For high-rise constructions, stringent non-combustible standards typically restrict BIPV integration, especially in residential towers, while some non-residential occupancies such as hospitals and care homes face additional limitations. National nuances, such as France's differentiated approach for non-residential buildings and Switzerland's allowance for fire safety engineering solutions, influence BIPV possibilities, but the overarching trend is that height is the major determinants of facade fire safety and consequently, the viability of BIPV across Europe.

4.3.3 Requirements for roofs

Regarding roofing fire safety requirements, most countries have requirements regardless of building use. France and Estonia allow for lower requirements if buildings are isolated. Only France has detailed roofing requirements based on building classification.

For roofing products, **Belgium** requires B_{ROOF} (t1). **Estonia** requires B_{ROOF} (t2-t4) or lower for isolated buildings. **France** defined requirements for residential buildings depending on building families, Family 1 allows Classes D, C and B, Family 2 requires Classes C and B with and Family 3 and 4 require B_{ROOF}. All roofs must follow Test 3 (t3). Roof requirements for non-residential buildings in France depend on the number of users and whether they sleep in the building, as well as the distance to a neighbouring building. For non-residential buildings, France requires B_{ROOF} (t3) for the 1st family or 2nd, 3rd and 4th with sleeping areas if the next building is less than 8 m and C_{ROOF} if the building is located between 8 and 12 m away. For the 2nd, 3rd and 4th family without sleeping areas, the legislation requires B_{ROOF} if the next building is located less than 8 m away and C_{ROOF} (t3) if it is located over 8 m away. **Spain** requires B_{ROOF} (t1) if the roof materials or systems are covering more than 10% of the total roof surface. In **Switzerland**, minimum safety requirements for roofing materials are RF3 (cr), that is to say C_{ROOF} (t3), C_{ROOF} (t4), D_{ROOF} (t3), D_{ROOF} (t4). Translucent roof covering up to 30% of the total roof area require RF3.

In practice, minimum fire safety requirements for roofing materials outlined in the different legislations do not prevent the deployment of BIPV elements on roofs. However, PV presents a different characteristic, PV and IPV can act as a source of fire [23]. For roofs, EN 13501-5 applies, using CEN/TS 1187 test methods (B_{ROOF}(t1-t4)) to assess external fire exposure scenarios, propagation and penetration. These tests were designed for conventional roofing materials, focusing on flame spread and resistance under conditions like burning brands, wind and radiant heat.

CEN/TS 1187 tests do not account for electrical ignition sources, such as DC arcs, or the interaction between PV components and roofing membranes. EN 13501 assumes passive materials, whereas BIPV can generate heat and electrical faults. Complementary standards, such as EN 50583, and research initiatives are trying to bridge the gap.

Regardless of use, high-rise structures have the most demanding fire safety provisions, which makes high-rise BIPV the most challenging sub-sector. A common principle across all five countries is that external fire spread must be minimised in tall buildings, lessons from past high-rise fires are reflected in rigorous facade rules. All countries studied require facades on high-rises to be of limited or no combustibility.

4.4 Typology of IPV projects and associated fire safety considerations

Fire safety regulations apply different requirements depending on building type (residential and non-residential) and building height (low-, mid-, high-rise). Hence, BIPV feasibility is strongly influenced by these factors. While thresholds for low-, mid- and high-rise buildings varies in each country, categories can be made based on the building height.

A common trend is visible for all categories of buildings in Figure 2, as building height and risk increase, regulators either raise the bar on material fire class or demand compensating measures. For BIPV, this typology analysis reveals a clear pattern: the lower and smaller the project, the easier the fire approval (virtually no issues for single-family homes or small public buildings), mid-sized projects are feasible with careful product selection (often needing Class B or C products), high-rise demand higher fire safety requirements. All five countries share this gradient of difficulty, what differs is exactly where they draw the lines (height thresholds) and whether they allow flexibility (testing, sprinklers) to accommodate BIPV. In addition, extra safeguards are required for certain high-risk occupancies, such as hospitals and educational buildings, sometimes independent of height.

Hence, based only on fire safety requirements, a typology of buildings and their impact on BIPV is possible and illustrated in Figure 2. Buildings can be classified into four groups: low-rise, mid-rise, high-rise and high-risk buildings. In the typology, fire safety requirements increase with height, with BIPV elements being easier to integrate in low-rise buildings and less feasible on high-rise and high-risk buildings.

An additional layer should be added to the typology, which has a major impact on the feasibility of BIPV project via alternative routes, that is to say the possibility of large-scale fire testing of facade in the legislation. Such alternative routes in mid- and high-rise buildings are essential to support BIPV deployment. Indeed, in

cases where BIPV elements cannot comply with the fire safety requirements set out in the building codes for construction products, BIPV facades can prove their safety with adapted test following proven standards. In that case, BIPV feasibility in mid- and high-rise buildings would increase. Given the specificities of high-risk buildings, they are not considered in the large-scale testing section.

Figure 2: Typology of buildings and their impact on BIPV elements, based on fire safety requirements in building codes

	Low-rise building	Mid-rise building	High-rise building	High-risk building
Height	< 10-11 m	11-30 m	> 30 m	Variable
Fire safety requirements	D-C classes	C-B classes	B-A classes	B-A classes
BIPV feasibility	High - Moderate	Moderate - Low	Low - Impossible	Low - Impossible
BIPV feasibility with large-scale testing	High - Moderate	Moderate - High	Moderate	-

5. DISCUSSION AND POLICY RECOMMENDATIONS

5.1 Discussion

The lack of harmonised standards for BIPV has been widely documented in the literature, the IEA PVPS Task 15 report on “Advancing BIPV Standardization: Addressing Regulatory Gaps and Performance Challenges” provides an overview of the challenges in this domain [24]. The current lack of harmonisation leads to increased costs and delays for manufacturers, ultimately impeding the broader adoption of BIPV in the market. Establishing clear and comprehensive standards is therefore critical. Achieving this requires coordinated action among all relevant stakeholders, in order to avoid unnecessary duplication and overlap in testing arising from both building and electrical regulations.

Nonetheless, until BIPV standards are harmonised at European level, BIPV products have to comply separately with both construction and electrotechnical regulations. This paper is only focusing on fire safety requirements for construction products, which are determined at national level, and how they affect BIPV deployment in selected European countries. Fire safety requirements are primarily determined by the height and use and a building with national differences. Based on regulatory requirements, the feasibility of BIPV project is highest in low-rise buildings and moderate in mid-rise buildings. High-rise buildings represent the most challenging type of building, with in most cases the impossibility to deploy BIPV.

Current regulatory frameworks in many European countries restrict the use of combustible elements by requiring Euroclass A materials notably in high-rise buildings, which hinders BIPV deployment in those buildings. However, alternative routes with large-scale fire testing can allow for BIPV deployment on a case-by-case basis. These tests need to be made possible in the legislation, as it is the case in Belgium and France, as well as, in Switzerland with the transitional guidelines by SwissSolar. While these large-scale testing are costly,

allowed in a few Member States and must be repeated for every product and project variation, they allow for alternative routes to deploy BIPV.

In the **Belgian** regulation large-scale fire testing are allowed to evaluate the global fire behaviour of a façade system under realistic conditions, beyond what small-scale Euroclass tests (EN 13501-1) can show.

France's regulations also offer performance-based pathways in which a BIPV façade can be subjected to an assessment by a laboratory to demonstrate that the system limits fire spread as required. In practice, France relies on its Technical Assessment system for novel facade products. BIPV modules often require a DTA (Document Technique d'Application) or ATec (Avis Technique) from CSTB to be used, which includes fire performance evaluation. Several BIPV products have obtained such approvals, typically certifying that when installed per certain methods, they meet the facade fire regulation (often via large-scale tests). In practice, these assessment are project specific, lengthy, very costly and other issues can arise even with a large-scale test due to insurance coverage challenges [22]. Hence, performance-based pathways in France are limited to a few prestigious projects able to absorb cost, time and administrative burden.

In **Switzerland**, Swisssolar developed a transitional guide for planning and demonstrating fire protection in ventilated PV façade installations, valid until 31 December 2026 [21]. The guide aims to address the lack of a definitive technical standard for fire safety in PV façades and complements existing AEAI and Swisssolar guidelines, thus supporting BIPV deployment in mid- and high-rise buildings, when strict fire protection measures are implemented and, where necessary, compliance is demonstrated through fire tests and detailed verification reports, all subject to approval by the fire protection authority.

Furthermore, current construction products standards often misalign with BIPV needs and applications and there is a gap in testing methodologies for BIPV to accurately assess risks. BIPV present unique fire safety challenges that are not accounted for in current fire safety regulations for buildings.

Currently, fire risks associated with BIPV are predominantly covered under electrical codes for PV modules, which focus on module electrical safety and associated testing procedures. However, these standards do not take into account the possibility that the fire performance of PV modules may change when the modules are both heated and electrically active during normal operation. To properly address the hazards of fire propagation across BIPV façades, it is essential to evaluate both vertical and horizontal fire spread, whether the fire originates from the PV system itself or is introduced from an external source. Presently, neither PV-specific nor general building codes set out explicit fire safety requirements for BIPV cladding, curtain wall assemblies, double-skin façades, or integrated glazing systems.

Euroclass roofing fire tests (EN 13501-5, CEN/TS 1187) are not fully adapted to BIPV because they ignore active electrical risks and integration-specific factors. While they remain mandatory for CE marking, complementary standards (EN 50583) and research initiatives are trying to bridge the gap. For now, compliance often requires dual certification and sometimes bespoke testing. Codes and standards fall

short in adequately addressing the fire risks posed by BIPV roof covers integrated within roofing systems, particularly where combustible or flammable materials are present. Laboratory fire tests currently in use, which measure the fire resistance of roof coverings in response to external ignition sources, fail to accurately replicate the real fire conditions encountered with PV roofs. Owing to the rapid fire propagation across extensive PV installations and the potential for significant fire damage and penetration to roof structures. There is a need to establish new testing methodologies specifically for BIPV roofs [25].

Another critical fire hazard associated with BIPV modules arises from the fact that these systems may remain electrically active during a fire event. Assessing the fire resistance of BIPV modules must therefore go beyond evaluating material performance and reaction to fire, it should also account for the risks presented by an operational system under fire conditions. Currently, only a limited number of tests consider this operational aspect, as BIPV modules are not consistently kept active during fire testing procedures. This gap indicates a clear need for further research and the development of testing methodologies that ensure BIPV modules remain operational during relevant fire tests, enabling a more accurate assessment of real-world hazards [26].

5.2 Policy recommendations

Harmonise BIPV standards at European level

There is an urgent need to harmonise standards for BIPV across Europe. At present, BIPV products must comply separately with construction and electrotechnical regulations, which hinders widespread deployment and creates uncertainty for manufacturers and developers. A unified European approach would streamline compliance, reduce duplication and provide greater clarity for all stakeholders. Complementary standards, such as EN 50583 should be integrated and their testing protocols updated to reflect BIPV-specific risks.

Introduce performance-based compliance pathways with large-scale fire testing

National regulations should allow for performance-based compliance options, including large-scale fire testing of BIPV systems. Countries such as Belgium and France have already introduced such pathways, enabling BIPV deployment in mid- and high-rise buildings where Euroclass requirements are incompatible with BIPV elements and small-scale tests are insufficient. While these alternative routes are still challenging, especially in France, they should be formalised in legislation across Europe to facilitate BIPV deployment while ensuring safety.

Develop BIPV-specific fire testing methodologies

Existing fire testing standards, such as Euroclass tests and roofing fire tests (EN 13501-5, CEN/TS 1187), are not fully adapted to the specific risks posed by BIPV, particularly the combination of electrical activity and integration with building materials. There is a clear need for new, BIPV-specific fire testing methodologies that accurately assess both vertical and horizontal fire spread, and account for operational electrical risks during fire events.

Establish national guidelines until harmonisation

Until harmonised European standards are adopted, national authorities should issue clear guidelines to address the current regulatory gaps. For example, Switzerland's Swisssolar guidelines provide a practical

framework for demonstrating fire protection in ventilated PV façades, supporting safe BIPV deployment in mid- and high-rise buildings. Other countries should develop similar interim measures to bridge the gap and facilitate safe BIPV adoption. All relevant BIPV stakeholders should be involved in the development of such guidelines.

Support further research and data sharing

There remains a significant need for research into the fire behaviour of BIPV systems, especially under operational conditions. Data sharing between Member States, testing laboratories and industry stakeholders will be essential to build a robust evidence base, inform future standardisation, and support the development of effective fire safety solutions for BIPV.

6. CONCLUSION

A comparative analysis of fire safety regulations for BIPV in Belgium, Estonia, France, Spain and Switzerland reveals that building height is the primary factor influencing facade fire safety requirements and BIPV feasibility. Low-rise buildings generally permit more combustible facades, enabling straightforward BIPV integration. Mid-rise structures face stricter standards but remain accessible for BIPV deployment. High-rise buildings are subject to stringent non-combustible requirements, which significantly restrict BIPV options. National differences exist, yet the overall trend is consistent across countries.

Roof requirements also play a crucial role in BIPV deployment. Most countries set minimum fire safety standards for roofing materials, typically requiring B_{ROOF} or equivalent classifications. These standards are generally less restrictive than those for façades, meaning BIPV integration on roofs is widely feasible, regardless of building height or use.

The absence of harmonised European standards for BIPV creates regulatory uncertainty, increases costs and impedes widespread adoption. Current fire testing methods for construction products do not fully capture the fire behaviour of BIPV products and existing standards fail to address the unique risks posed by electrically active modules.

Alternative compliance pathways, such as large-scale fire testing, offer a practical solution in several jurisdictions. Belgium, France and Switzerland have introduced performance-based routes that allow BIPV systems to be assessed through comprehensive fire tests simulating real-world conditions. These pathways enable the deployment of BIPV in mid- and high-rise buildings where standard Euroclass requirements would otherwise prohibit their use. Although large-scale testing is more costly and time-consuming, it provides a robust means of demonstrating fire safety for innovative facade systems. In Switzerland, transitional guidelines further support BIPV integration by outlining technical principles and verification procedures, subject to approval by fire protection authorities. Such approaches facilitate flexibility and innovation, but their adoption remains limited and project-specific.

Policy recommendations are as follows:

1. Harmonise BIPV standards at European level to streamline compliance and reduce duplication.

2. Introduce performance-based compliance pathways, including large-scale fire testing, in national regulations.
3. Develop BIPV-specific fire testing methodologies that address both material and operational risks.
4. Establish clear national guidelines to bridge regulatory gaps until harmonisation is achieved.
5. Support further research and data sharing to inform future standardisation and improve fire safety solutions.

Harmonised standards, adapted testing methods and coordinated policy action are essential to unlock the full potential of BIPV in European buildings while ensuring robust fire safety in buildings. Realising these measures will enable BIPV to play a central role in decarbonising the built environment and advancing the energy transition.

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9 LOGO SPACE



ELECTRICAL INTEGRATION OF PHOTOVOLTAICS INTO BUILDINGS

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ABSTRACT: This work outlines how advances in the electrical system of buildings can aid in the integration of photovoltaics (PV) and a holistic system optimization. In a time of urgently needed defossilization of new or deeply renovated buildings, they are essential to achieving (Near-)Zero Energy Buildings (ZEB). Key points are a better integration into the planning process, prefabricated elements, smart power converters, plug & play interconnection solutions and advanced, self-learning energy management systems (EMS), with direct-current (DC) networks as a forthcoming alternative to the alternating-current (AC) standard. In addition to a high degree of self-sufficiency, they also support the handling of grid constraints and advanced grid requirements, while enabling financial optimization of the design and operational aspects. Several technological developments are required to enable the implementation, and we are outlining novel approaches for key elements.

Keywords: BIPV, Electric vehicle charging, Energy Management System, Power electronics, Zero-emission building.

1 INTRODUCTION

The global building-integrated photovoltaics (BIPV) market has reached a volume of EUR 20 bn and is expected to grow substantially, reaching a CAGR of 21.2% over the next five years [1]. In Europe, which currently has a market share of 37%, the growth is expected to exceed the global average. Here, the increase in installations will be fostered by the Energy Payback Directive for Buildings with its latest recast published in 2024 [2], requiring new buildings to reach zero-emission status latest in 2030. It is further complemented by the Renovation Wave Strategy [3] as well as national and regional plans.

Next to the generation of electrical energy in buildings or their surroundings, effective power conversion, energy management and electricity storage are required to ensure effective use of the generated energy and ensuring maximal self-sufficiency. This will require advanced solutions for each of these sectors. We consider that this aspect of building integration is as of yet undervalued and should receive more attention of the research and industrial communities.

At the same time, BIPV implementation is still hampered by the fact that it is not fully integrated into the value chain of buildings. A lot of individual planning is needed for every project, bespoke design is the rule, and the integration is a complex, multi-party venture. This is effective when producing highly individual, often very attractive, building solutions, but is not conducive to a wide roll-out of the technology to serve the purpose of defossilization at scale. Conversely, building-*applied* PV has established its own sales channels, largely by being sold as an add-on instead of integrally.

Buildings of the future will have to be energy-active units, and every owner of a building – new or renovated – will have to consider in the next few years how to deal with electrical energy in an effective manner, and to implement an electrical system that serves this purpose. This also creates opportunities for enhanced self-sufficiency, backup functionality, and trading grid services providing extra revenues. In a joint exercise of the partners of EnergyVille – KU Leuven, VITO, imec and UHasselt, we want to address the underlying issues and provide novel solutions that foster the uptake of PV in and on buildings. We are therefore also looking for partnerships to address the various aspects of this task.

2 TECHNICAL BACKGROUND

The subject field is grouped into four topical areas. The following subchapters outline briefly the state of the art, and room for improvement which we identified and aim to address.

2.1 PV in Building Elements

In order to reduce the amount of work, especially on the construction site, efforts are made by the building industry to prefabricate elements as much as possible. A typical example are curtain wall elements containing insulation and glazing, being installed at e.g. office buildings by attaching them to the floors of the structure. But also in renovation, prefabrication is increasingly used, such that the on-site work can be executed quickly, and methods have been developed to tailor these elements to the specifics of the respective building, as depicted in Figure 1. In order to integrate PV, and preferably also converters, into these structures, novel techniques are still to be developed; see the following paragraph.

2.2 Power Converters

The installation situation of PV in buildings is characterized by high variability in sizing and irradiance, especially owing to shading. Microinverters are used in some cases to provide sufficient flexibility, while string inverters are the most prevalent solution, often complemented by power optimizers for better adaptation to variations in irradiance. For either solution, integrating them into façade or roof elements is critical, with uncertain reliability under the challenging thermal conditions. While control is normally executed through a Modbus connection, data extraction uses the same or the manufacturer's cloud space.

2.3 Electrical System

BIPV systems are generally connected similar to building-attached installations, requiring wiring at the time of installation, with additional complications due to the need to integrate into the building elements and the fact that the thermal insulation and moisture barrier function need to be maintained. The main electrical system of a building is realized in alternating current owing to standards and the large availability of components as well as the fact that the main supply is provided by the AC electrical grid. Meanwhile, a lot of

appliances use DC systems internally, such as lighting, desktop equipment, and nearly all equipment employing variable-speed electrical motors, often including HVAC components and heat pumps. For the latter, the availability of DC-supplied devices is currently still limited. Obviously, novel systems such as PV, batteries and increasingly electric vehicle (EV) charging, run on DC, opening the consideration whether novel systems should be designed according to emerging standards for this technology.



Figure 1: Schematic visualization of building renovation with prefabricated elements. Image courtesy of BuildUp Offsite

2.4 Energy Management

While conventional grid-supplied buildings only offer limited flexibility and thus do not require energy management aside of load limiting, this need clearly arises with the implementation of PV generation and additional appliances that offer the opportunity of load scheduling, e.g. with heat pumps and vehicle charging. This is complemented by the fact that efficient management can enhance self-sufficiency and self-consumption of the generated energy as a means of economic optimization. Further to that, on the grid side time-variable pricing and the opportunity to offer flexibility of load and/or grid injection are becoming key points of optimization. Increasingly, limitations in the load capacity of the grid, especially in local feeders, lead to time-dependent constraints of either injection or withdrawal that need to be taken into account in the scheduling. A variety of EMS's is available today, covering the main functionality described here, and increasingly implementing machine learning of generation and consumption patterns in addition to grid pricing and weather forecasts.

3 NOVEL CONCEPTS

We are proposing a set of novel technologies that can help foster the integration of (BI)PV into buildings and the optimal use of the generated electrical energy. They

generally consist of parts that have reached medium Technology Readiness Levels (TRL) already and can be demonstrated as prototypes, parts that are working in the laboratory and others that require initial testing before deciding about their further development.

3.1 Integration of PV into Building Elements

On the side of the PV modules themselves, novel cell interconnection technologies are being developed that allow flexible form factors and remove the need for busbars connecting adjacent strings. This helps to streamline the manufacturing process and can be done with multi-wire techniques and in-laminate soldering, while embedded reverse diodes can reduce the risk of overheating cells due to shading. For the integration of the PV element into the building element, advanced planning methods need to be established. They should comply to Building Information Modeling (BIM) standards to simplify the design and manufacturing processes. Part of the process also needs to be the modeling of energy yield such that reliable predictions become possible.

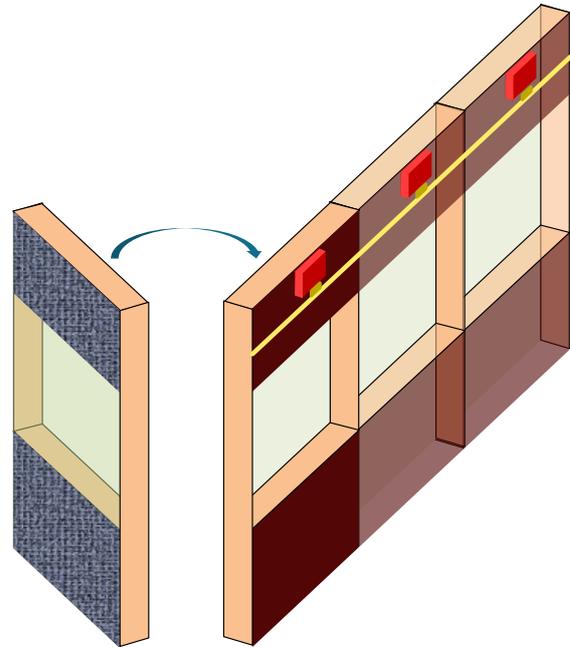


Figure 2: Curtain wall element with integrated PV, power converters and bus interconnection

3.2 Smart Power Converters

In order to simplify the integration into NZEB, we are aiming to develop a new class of power converters that can adapt smartly to the irradiance situation and ensure optimal extraction of energy from the PV panel without detailed planning. They need to feature self-monitoring to ensure continuous performance and, if required, preventive maintenance, and they should communicate the runtime status of energy production towards a management system in order to enable machine learning for performance prediction. Ideally, they should be integrated into prefabricated elements as depicted in Figure 2, whereby thermal stress and reliability aspects require particular attention.

3.3 Building Nanogrid

While AC systems form the backbone of a building's electrical grid for some time to come, DC systems can form a better solution eventually owing to less complex converters, less conversion losses, and, ultimately, lower overall system costs. Their introduction may start with the PV converters described above, whereby we aim to interconnect them with a power collection bus in a "plug & play" system, reducing the need for on-site wiring work. It can then be extended to hybrid systems with batteries, adding vehicle chargers, and, as they become available, DC-powered appliances, see Figure 3. The building-internal electrical system is thus independent of the grid constraints, and advanced requirements for inverters, as imposed e.g. by the new Requirements for Generators 2.0 [4], only need to be implemented in a single, albeit more complex, unit per building.

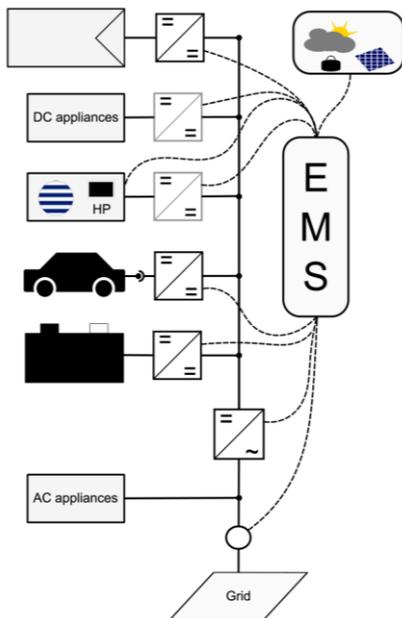


Figure 3: Schematic of a building DC nanogrid controlled by an Energy Management System

3.4 Advanced Energy Management

For the improvement of energy management systems compared to the state of the art, there are various options. A key element is machine learning, letting the system adapt to the energetic situation, and forecast energy-related parameters, regarding energy generation, consumption, also accounting for usage patterns, grid pricing, flexibility trading options and grid connection constraints. Advanced forecasting solutions contribute to this, relating geo-information with weather forecasts and taking into account physical information about the PV system, improving the parameterization with learnings from the operational phase. Adaptive thermal grey-box models of the building allow for improved leverage of heat pumps as flexible loads in combination with thermal inertia, while parameters of the devices can be steered in a more detailed approach than the current "smart-grid ready" techniques. Similarly, a learning system can leverage electrical storage and vehicle charging, and soon

also vehicle-to-grid power transfer, for enhanced flexibility.

4 CONCLUSIONS & OUTLOOK

In this work, we described how advanced solutions for the electrical integration and energy management can improve the utilization of PV in and on buildings. They contribute to the valorization of the generated electrical energy. We envision that in the next few years, building owners will increasingly see the value and opportunities of PV generation in combination with storage, while the usage of heat pumps and electric vehicles will create an additional need. Effective management of the electrical system in combination with thermal aspects is becoming a must, aiding them in effectively utilizing the energy and minimizing their costs respectively obtaining additional earnings on dynamic energy markets while dealing with grid constraints and advanced requirements.

Improvements in several aspects of the electrical system can aid a full integration of BIPV into the value chain of the building industry, opening the space for collaborations between research institutions and companies. Smart integrated converters, the combination with prefabricated building elements, advanced energy management and eventually DC microgrids will provide solutions that facilitate the implementation, but need further R&D and testing before being ready for the market. Current research programs provide only moderate support for these integrative tasks.

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7 LOGO SPACE



DEVELOPMENT AND APPLICATION OF NEW EXTENDED-STRESS TESTING SEQUENCES TO CHARACTERIZE DURABILITY OF BIPV MODULES

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ABSTRACT: As current standards do not necessarily guarantee the long-term performance of building integrated photovoltaic modules, new extended-stress testing sequences for BIPV modules have been developed and put into practice. Three sequences have been proposed based on existing standards and methods: 1) Mechanical Stresses and Environmental Actions; 2) Thermal Fatigue; 3) Combined UV and Thermal Fatigue. The sequences have been tested by application in two innovative BIPV products, the Flexbrick BIPV module and a composite BIPV module developed by Tecnalia, as well as conventional glass-glass PV modules used as reference samples. The characterization of the samples along the degradation tests shows their performance evolution in front of combined stress agents inherent to the building integrated environment, and it validates the use of the developed sequences in the evaluation of the long-term durability of BIPV solutions in real operation conditions.

Keywords: Accelerated Testing, BIPV (Building-Integrated PV), Durability and reliability, Performance testing.

1 INTRODUCTION

As global PV installations reach new record highs every year, many efforts aim at developing and implementing distributed integrated photovoltaic (PV) technologies that bring energy production and consumption closer together. In this line, building integrated PV (BIPV) is an innovative technology solution that turns traditional building components into active energy producing devices. It offers a path towards the decarbonisation and energy resilience of the urban environment, by reducing energy consumption and greenhouse gas emissions of buildings. However, so far the adoption of this technology has been restricted by lack of knowledge and guidance on designing BIPV systems.[1]

One of the key aspects difficulting the application of BIPV at european level is the widely varied regulatory framework that changes from country to country.[2] On the other hand, there is a lack of standards tailored for BIPV products that will guarantee their long-term performance in the building environment.

Current sequences described in IEC 61215, and required for BIPV products by IEC 63092-1, are not intended or able to demonstrate long term performance in all locations. [3,4] Because of that, codes like IEC TS 63209-1 already proposed extended-stress sequences for common PV modules, but nothing equivalent exists for BIPV modules. [5]

For this reason, in this work new extended-stress testing sequences for BIPV modules have been developed and put into practice based on existing standards and methods. These would allow already established BIPV modules and technologies to demonstrate their reliability for the long-term durability, safety and efficiency requirements of building integrated applications.

Three sequences have been developed: 1) Mechanical Stresses and Environmental Actions; 2) Thermal Fatigue; 3) Combined UV and Thermal Fatigue. The sequences have been developed so that different sequences of the

IEC 61215 and ISO 12543-4 standards are also complied with in order to avoid duplication of effort.

2 METHODOLOGY

2.1 Mechanical Stresses and Environmental Actions sequence

A new extended-stress sequence has been proposed for BIPV products combining mechanical testing with environmental ageing actions, based on IEC 63092:2020, sequences C and E of IEC 61215-1:2021, and sequence 2 of IEC TS 63209-1. Figure 1 shows the testing procedure defined for the Mechanical Stresses and Environmental Actions sequence. 1 sample is subjected to the whole sequence, 3 samples are subjected to every test except for the hail test, and 2 samples only undergo the environmental actions.

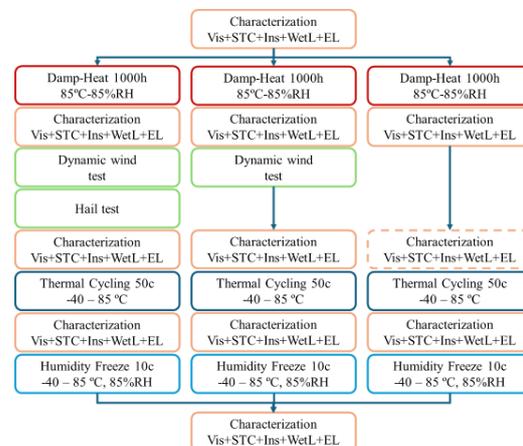


Figure 1: Testing procedure defined in the Mechanical Stresses and Environmental Actions sequence

One of the main novelties is the replacement of the static and dynamic load tests by the new and more realistic wind load test. The dynamic wind test consists of

applying different wind level loads using a fan to verify how it affects the test specimen. However, this new test has been included for research purposes, and the sequence could also be performed applying the static and dynamic mechanical load tests of IEC 61215-1:2021 instead. The hail test is performed using steel balls with increasing impact energy.

At intermediate stages of the testing sequence, the BIPV modules are characterized with several techniques including: Visual inspection, to detect any visual defects in the module (IEC 61215-2 MQT 01); Performance at STC, to determine the electrical performance of the module at standard test conditions (STC) i.e. 1000 W/m² and 25 °C, obtaining its IV curve and their parameters (Voc, Vmmp, Isc, Immp, Pmmp, Rs, Rsh) (IEC 61215-2 MQT 06.1); Insulation test, to detect whether or not the module is sufficiently well insulated between live parts and accessible parts (IEC 61215-2 MQT 03); Wet leakage current test, to evaluate the insulation of the module under wet operating conditions (IEC 61215-2 MQT 15); and electroluminescence (EL) imaging, to detect potential cracks or defects in the cells or interconnections. The execution of this sequence takes approximately 2 months.

2.2 Thermal Fatigue sequence

An extended-stress sequence has been proposed for BIPV products based on extended thermal stresses. The Thermal Fatigue sequence is the sequence 1 of IEC TS 63209-1 (three times 200 cycles of thermal cycling) with intermediate characterizations, as shown in Figure 2. The execution of this sequence takes approximately 2.5 months, and performing it also includes the sequence D of IEC 61215-1 (200 cycles of thermal cycling).

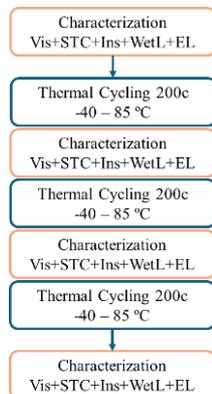


Figure 2: Testing procedure defined in the Thermal Fatigue sequence

2.3 Combined UV and Thermal Fatigue sequence

The new Combined UV and Thermal Fatigue sequence (see Figure 3) is based on IEC TS 63209-1 sequence 3 but replacing the UV test by the ISO 12543-4 UV test, which includes slightly higher quantity of UV accumulated irradiation together with visible radiation. The ISO 12543-4 is the reference standard for laminated glass durability testing. Additional samples are necessary for the humidity and high temperature test also required by the ISO 12543-4, so that this standard can be fulfilled when completing the sequence.

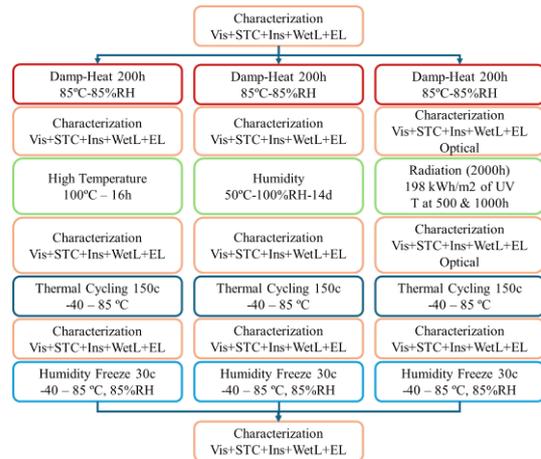


Figure 3: Testing procedure defined in the Combined UV and Thermal Fatigue sequence

In the development of the subsequence containing the extended 198 kWh/m² UV exposure, an additional optical characterization of the samples is performed before and after this specific test, according to ISO 12543-4. The execution of the whole sequence takes approximately 4.5 months.

3 EXPERIMENTAL

3.1 Samples for experimental application

The sequences were applied on different innovative BIPV module technologies (see Figure 4), including photovoltaic bricks (Flexbrick BIPV module), lightweight BIPV modules based on composite developed by Tecnalía, and reference laminated glass PV modules.



Figure 4: Flexbrick BIPV modules (top), composite BIPV modules (center), and reference glass PV modules (bottom).

The photovoltaic brick product is the evolution of a construction system for external façade panels called Tejido Flexbrick® with some modifications to integrate photovoltaic panels. This can be applied in an interwoven steel wire mesh to control sunlight for energy production and lighting. The composite BIPV modules consist of monocrystalline silicon 5 busbar solar cells encapsulated in composite material providing a 3 mm-thickness to the modules. Finally, reference glass PV modules comprise monocrystalline silicon 5 busbar solar cells laminated with EVA between 4 mm-thick tempered extraclear glass. Table 1 shows the test-sequences performed in each type of module technology.

Table I: Test-sequences performed in each type of BIPV module technology

	Flexbrick BIPV module	Composite BIPV module	Reference glass PV module
Mechanical Stresses & Environmental Actions	X	-	X
Thermal Fatigue	-	X	X
Combined UV & Thermal Fatigue	-	X	X

In the case of the Flexbrick BIPV modules, 8 samples were tested on the Mechanical Stresses and Environmental Actions sequence. Half of them had a rubber framing (G samples) and half had a textile framing system (T samples). From each kind of frame one sample underwent the subsequence with no mechanical test, one module performed the dynamic wind test, and two samples went through the dynamic wind test followed by hail impact testing.

As for the composite BIPV modules, 3 replicas were tested on the Thermal Fatigue sequence. Besides, 3 replicas went through each subsequence of the Combined UV and Thermal Fatigue sequence (9 samples in total).

Finally, the same number of reference glass PV modules as the composite samples went through the Thermal Fatigue sequence and the Combined UV and Thermal Fatigue sequence. Besides, a glass reference PV module sample was tested for the non-mechanical tests in the Mechanical Stresses and Environmental Actions sequence.

3.2 Module characterization

Current-voltage (IV) curves were recorded for the BIPV modules employing an Endeas QuickSun 600 lab solar simulator (class A+). This equipment’s integrated high resolution electroluminescence (EL) image acquiring system was used for EL imaging of the samples. For the insulation test and wet leakage test, a Sentry 30 Plus AC//DC/IR Hipot Tester by QuadTech was employed.

3.3 Accelerated degradation test equipment

The environmental degradation tests based on IEC 61215 Damp-Heat, Thermal Cycling and Humidity Freeze assays were carried out in CTS C-70/350S and CS-70/2000/S climatic chambers.

The extended UV degradation test was performed in accordance with EN ISO 12543-4:2021. To this end, the test specimens were placed 1,100 mm away from the 16 ULTRAVITALUX lamps that formed a field of (1 x 1) m. The positioning of the test specimens was as established by standard EN ISO 12543- 4:2021 and their temperature was maintained at (45±5) °C.

4 RESULTS AND DISCUSSION

4.1 Flexbrick BIPV modules

Figures 5 and 6 show the evolution of the electrical parameters of the Flexbrick BIPV modules in the development of the Mechanical Stresses and Environmental actions sequence. During the tests the measurements of the maximum power (MP) point was unstable, causing large fluctuation, either positively or negatively, of the relative parameters (Pmp, Imp, Vmp). Apparently, this fact was due to the partial oxidation of the cable during the tests, causing variations in the series resistance. This defect seems to be not due to the product itself but rather to an insufficient protection of the cable terminals after the cut, even if they were protected with Kapton tapes as shown in the previous picture. Since the Pmpp is the parameter to be checked to evaluate the result of each test, this fact caused uncertainty. The performance at STC was checked by evaluating the Isc and Voc parameters instead, which are in principle not significantly affected by changes in the series resistance.

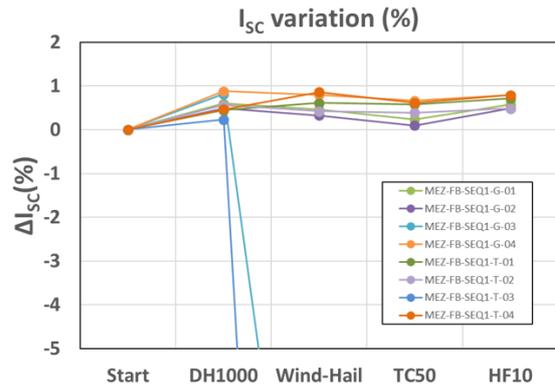


Figure 5: Cumulative percentage variation of Isc after each test of Mechanical Stresses and Environmental actions sequence for Flexbrick BIPV modules.

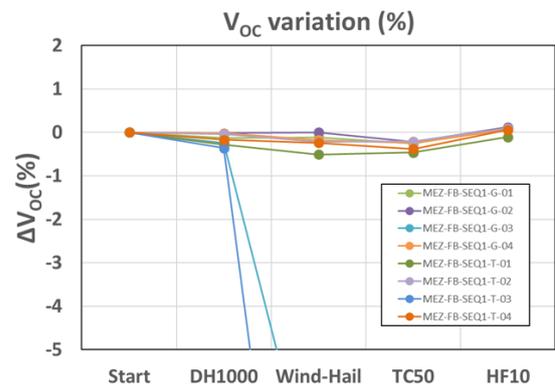


Figure 6: Cumulative percentage variation of Voc after each test of Mechanical Stresses and Environmental actions sequence for Flexbrick BIPV modules.

The evolution of Isc and Voc values indicate that very small variations were observed in the combined test sequence. The slight increments in the Isc parameter may be due to slight variation in the optical characteristics of the front layers or related to other unknown effects. Also, a variability of ±0.5% due to the measuring system should be considered. Only the samples undergoing the

7J impact test suffered fractures causing the loss of Isc and Voc. However, the products withstood the 2J hail impacts and the dynamic wind test with no disturbance. In general, the visual inspection, EL imaging, insulation tests and wet leakage test showed no significant variation in the samples. Therefore, the sequence shows that the Flexbrick BIPV module offers a robust solution for combined mechanical and environmental factors inherent to the building environment.

4.2 Composite BIPV modules

Figures 7 and 8 show the evolution of the electrical parameters of the composite BIPV modules in the development of the Thermal Fatigue sequence and the Combined UV and Thermal Fatigue sequence.

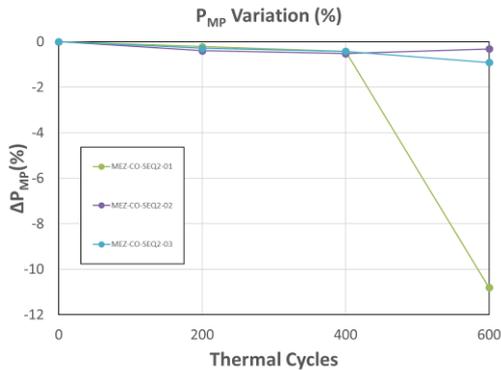


Figure 7: Cumulative percentage variation of Pmp after each test of Thermal Fatigue sequence for composite BIPV modules.

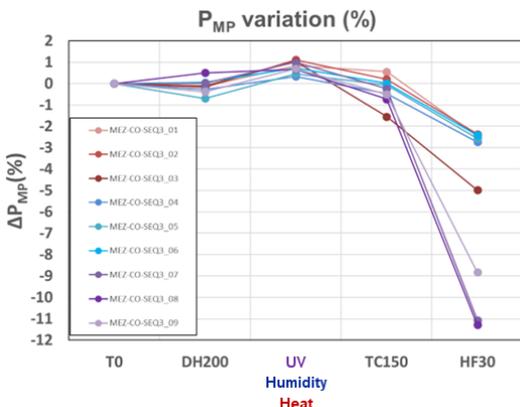


Figure 8: Cumulative percentage variation of Pmp after each test of Combined UV and Thermal Fatigue sequence for composite BIPV modules.

The Thermal Fatigue sequence caused only minor degradation of the electrical parameters of the composite BIPV modules. The outlayer sample showing >10% Pmp loss suffered a fracture of its connectors during characterization and a FF reduction after reparation, so the power loss was not related to the test itself.

Regarding the Combined UV and Thermal Fatigue sequence, the TC150 and HF30 tests resulted in the strongest performance loss. In particular, the samples undergoing the strong UV radiation exposure showed a very sharp performance decrease in the Humidity-Freeze test. This was clearly observed in the visual inspection as the composite of these modules got an orange color after the final test causing a ~10% Isc loss. The effect

underlines the importance of combined stressors in the degradation of BIPV modules, which can be evaluated by combined extended-stress test sequences as the ones proposed.

In both sequences, the EL imaging indicated no major variation in the samples. The insulation tests were also passed in all cases. The visual inspection revealed a strong coloration of the composite modules after the final humidity-freeze test, which was more severe in the sample that went through the strong UV radiation test.

The information provided could imply that the tested product would perform well integrated in BIPV systems, regarding the endurance against different environmental factors, except for a combination of high UV exposition together with strong freezing events with high relative humidity. Therefore, an increased UV protection could benefit the design of the BIPV solution.

4.3 Reference glass PV modules

Figures 9, 10 and 11 show the evolution of the electrical parameters of the composite BIPV modules in the development of the Mechanical Ageing and Environmental Actions sequence, the Thermal Fatigue sequence and the Combined UV and Thermal Fatigue sequence, respectively.

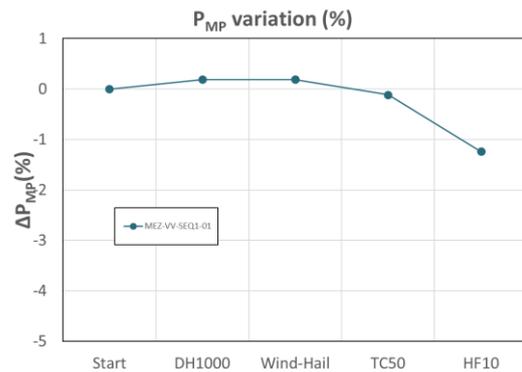


Figure 9: Cumulative percentage variation of Pmp after each test of Mechanical Stresses and Environmental Actions sequence for reference glass PV modules.

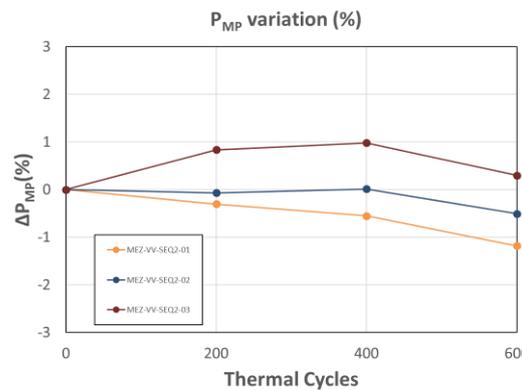


Figure 10: Cumulative percentage variation of Pmp after each test of Thermal Fatigue sequence for reference glass PV modules.

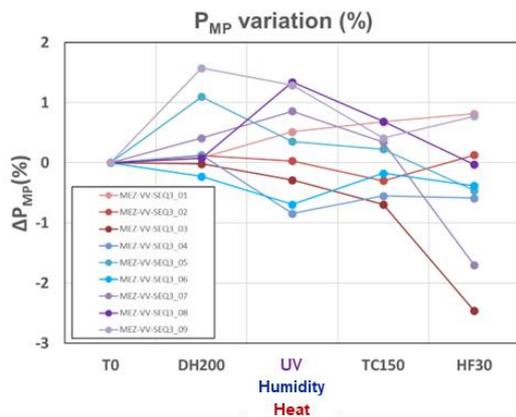


Figure 11: Cumulative percentage variation of Pmp after each test of Combined UV and Thermal Fatigue sequence for reference glass PV modules.

Throughout the Mechanical Stresses and Environmental Actions sequence, the reference glass PV module did not show any major degradation. It must be stated that only the environmental action tests were performed, skipping the mechanical stress tests, as this module was used as a reference for other BIPV module samples following the full sequence.

The Thermal Fatigue sequence caused minor degradation of the electrical parameters of the samples. The first 200 thermal cycles did generate some faults visible by EL imaging directly related to ribbon connection faults (see Figure 12), but these did not get worse in the following 400 cycles.

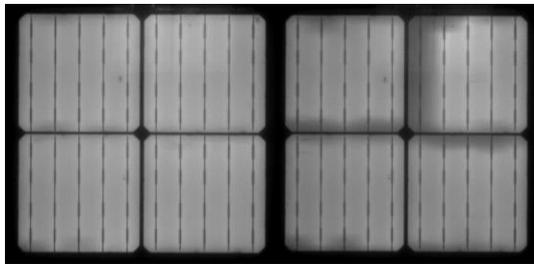


Figure 12: EL imaging of a reference glass PV module at the beginning (left) and after TC200 (right) in Thermal Fatigue sequence.

Regarding the Combined UV and Thermal Fatigue sequence, in general the cumulative variation of the power performance was below 5% in all cases. The degradation of the samples according to the visual and electroluminescence inspection was minimum (although the EL revealed again a slight disconnection of some ribbons due to thermomechanical movements in thermal cycling). Generally, the visual inspection of the samples showed no significant variation throughout the test sequences. The samples passed the insulation tests in all cases too. Therefore, it can be stated that the reference glass PV modules adequately withstood the test combinations comprising the different extended-stress sequences.

5 CONCLUSIONS

In this work 3 new extended stress sequences have been developed for and applied on innovative BIPV module concepts, which enable testing for their long-term reliability.

Although the sequences combine many stress factors and extended tests that could seem harsh for the devices, a significant part of the samples resisted them with no major degradation. The Thermal Fatigue was passed by all tested modules with little degradation. In contrast, the strong UV radiation test in the Combined UV and Thermal Fatigue sequence resulted to be severe for some BIPV solutions. All tested samples withstood the new dynamic wind load test and the Mechanical Stresses and Environmental Actions sequence with no disturbance, except for the fracture of some modules in higher energy levels of hail impact testing, with the added hardness of employing steel balls instead of ice balls, representing a worse case scenario.

During the development of the sequences, combined effects of different tests were observed in sample degradation. This highlights the importance of performing intermediate characterization steps during the sequences, in order to properly identify and understand the faults generated by these combined effects.

The proposed sequences provide information on the reliability and design improvement capabilities of innovative BIPV modules. This information can be key in the standardization of these new products and their acceleration towards commercialization.

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7 ACKNOWLEDGEMENTS

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8 LOGO SPACE



**BIPV FOR TEGOLA CANADESE ROOFING:
PHOTOVOLTAIC INTEGRATION WITHOUT SUBSTRUCTURES**

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ABSTRACT: In the context of the building sector’s significant contribution to global emissions, Building Integrated Photovoltaics (BIPV) represent an effective strategy for improving energy performance. This research presents the development of a fully adhered BIPV roofing system for metal asphalt shingles by Tegola Canadese, developed in collaboration with Università Iuav di Venezia. The work addresses a key technological gap: as existing BIPV solutions for metal roofs typically require ventilated substructures, limiting architectural compatibility and installation efficiency. The methodology included: (1) analysis of existing BIPV systems and integration barriers, (2) design of a configuration compatible with full-adhesion metal shingle technology, and (3) prototyping and installation testing. The system integrates custom flexible CIGS thin-film photovoltaic modules directly onto Ultimetal HD© Slate shingles using high-strength adhesive bonding, preserving waterproofing, structural integrity, and visual continuity. Tailored protective components matching material and finish ensure cable routing and maintain aesthetic uniformity. Validation demonstrated technical feasibility, electrical performance, simplified installation, and architectural integration. The system offers competitive advantages such as elimination of substructures, reduced system costs, lower weight, and backward compatibility with existing products. This solution supports wider BIPV adoption and contributes to decarbonization goals in the building sector.

Keywords: Architectural integration, BIPV (Building-Integrated PV), BIPV roofs, Flexible PV, Metal Asphalt Shingles, Metal Roofs.

1 INTRODUCTION: PROBLEM CONTEXT

The energy and environmental transition in the building sector represents one of the most significant challenges for achieving climate neutrality by 2050. The construction sector is responsible for a substantial share of global greenhouse gas (GHG) emissions [1][2]: in 2023, buildings accounted for about 32% of global energy demand and 34% of CO₂ emissions, including 9.8 Gt from operations and 2.9 Gt from embodied carbon (Fig. 1) [3]. Other analyses indicate that global building energy consumption exceeds 30% [4], and historical CO₂ emission values reaching up to 39% [1][5][6]. In 2022, buildings sector emissions represent around a third of total energy system emissions, including buildings operations (26%) and embodied emissions (7%) associated with the production of materials used for their construction (Fig. 2) [28].

This situation largely derives from an obsolete and poorly efficient building stock, the result of decades of limited attention to environmental issues. High energy consumption and the use of high-carbon intensity materials make the construction sector a critical point for climate mitigation [1][2]. The Global Status Report for Buildings and Construction 2024/2025 (UNEP/IEA) indicates the decarbonization of the sector as a necessary condition to achieve carbon neutrality by 2050 [7].

2 REGULATORY CONTEXT

2.1 Regulatory Framework on Building Energy Efficiency: NZEB and ZEB

In response to these critical issues, the European regulatory framework—particularly the EPBD Recast (Energy Performance of Buildings Directive, 2024)—introduces binding targets for the zeroing of operational emissions and the progressive reduction of Embodied Carbon (EC) [3][6][8], that measures the overall environmental impact and GHG emissions associated with materials and building processes across the entire

life cycle of the building (from raw material extraction to end-of-life management). This analysis considers all stages, including raw material extraction, transport, manufacturing, installation, and end-of-life phases [27]. The Directive promotes the adoption of integrated renewable technologies, such as Building Integrated Photovoltaics (BIPV), to reduce reliance on fossil fuels and foster on-site energy self-generation. BIPV systems integrate photovoltaic modules directly as construction materials and energy generators [2][5][7][9].

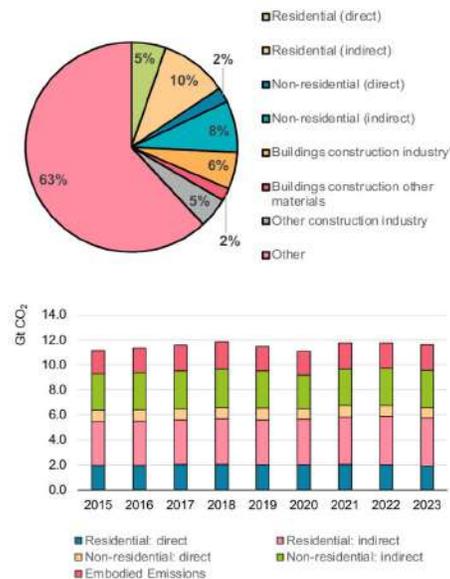


Figure 1: Global share of energy demand and CO₂ emissions attributable to the building sector, including operational and embodied components (2023).

European policies are founded on two key concepts:

the Nearly Zero-Energy Building (NZEB) and the Zero-Emission Building (ZEB). NZEB is defined “a building that has a very high energy performance [...] The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby” [29]. Operationally, an NZEB must balance its annual consumption with renewable energy production, thereby achieving an overall neutral energy balance [5][10]. Meanwhile, ZEBs represent the natural evolution of NZEBs, characterized by zero operational emissions and relying on total energy coverage from on-site or nearby renewable energy. ZEB is defined as “a building with a very high energy performance [...] requiring zero or a very low amount of energy, producing zero on-site carbon emissions from fossil fuels and producing zero or a very low amount of operational greenhouse gas emissions”. By 2030, all new buildings must adhere to the ZEB standard, while the entire existing building stock is mandated to achieve carbon neutrality by 2050 [3][5][8][10]. These regulatory objectives align with the trajectory outlined in the IEA Net Zero Emissions Scenario (NZE), according to which operational emissions from the building sector must be reduced by approximately 50% compared to 2022 levels by 2030, while embodied emissions must decrease in parallel—by 25% for steel and 20% for cement within the same timeframe (Fig. 2) [28].

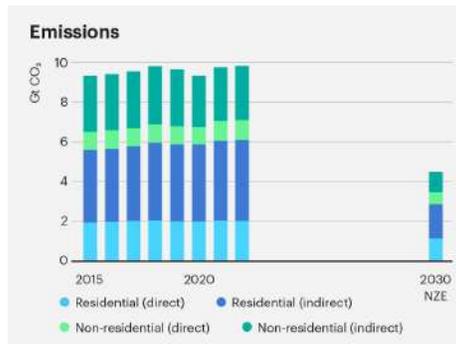


Figure 2: Breakdown of operational and embodied emissions of the building sector within total energy system emissions, with decarbonization targets toward the IEA Net Zero Emissions Scenario (2022).

2.2 Role of BIPV in the Energy Transition

To successfully achieve the Nearly Zero-Energy Building (NZEB) and Zero-Emission Building (ZEB) standards, energy policies robustly advocate for energy efficiency, the utilization of low-carbon materials, and localized energy production [7]. The incorporation of renewable energy sources, particularly BIPV, is recognized as a pivotal component of this strategy. ZEB mandates require the integration of local renewable energy sources, where technically viable, such as photovoltaic (PV) systems, solar thermal collectors, and geothermal energy [7][8]. BIPV systems are among the most promising technologies for this transition. They facilitate the seamless integration of energy production directly into the building envelope, concurrently reducing construction costs and minimizing negative aesthetic impact [5][4]. The diffusion of BIPV is bolstered by specific economic and financial incentive policies, such as subsidies and concessional loans [2]. Owing to their

inherent architectural and functional versatility—which permits application across roofs, façades, windows, and shading elements—BIPV systems represent a strategic asset necessary for attaining carbon neutrality objectives within the building sector.

3 STATE OF THE ART REVIEW AND RESEARCH GAPS

3.1 Building Integrated Photovoltaics (BIPV): A Comparative Analysis with Building Applied Photovoltaics (BAPV)

Building Integrated Photovoltaics (BIPV) systems constitute a technology that integrates solar energy generation with the structural and aesthetic functions of buildings [13][19][22]. The fundamental distinction from Building Applied Photovoltaics (BAPV) resides in the integrative approach: while BAPV systems are considered add-ons or PV products added on or mounted onto the building without replacing conventional building envelope materials, BIPV modules are specifically designed to replace the conventional building materials or roofing materials themselves, functioning simultaneously as both a building envelope component and an electricity generator. This dual functionality results in compelling cost savings [5][13][14][15]. In contrast, BAPV systems, despite potentially maximizing electricity production through optimal orientation, necessitate additional supporting structures, such as brackets and rails, which generally increase structural loads and may negatively impact the aesthetic integration. Furthermore, traditional BAPV installation often relies on mechanical fixings, which can lead to water tightness issues due to required penetrations into the building structure or envelope.

Conversely, BIPV modules become an integral component of the envelope, providing significant advantages for building retrofitting and renovation, a context where BIPV technology is considered essential. BIPV systems are required to fulfil all the requirements of the building envelope skins they are substituting, including essential performance criteria like weather protection and durability [5][13][14][15].

Economically, BIPV systems offer a reduction in the total construction material costs and mounting expenses. These financial advantages are obtained by offsetting the expenditure associated with conventional envelope materials (such as standard roofing membranes) that are replaced by the BIPV elements. Crucially, BIPV eliminates the need for additional assembly components such as specialized brackets and rails, which are typically required for non-integrated PV systems [5][13][14][15].

The lightweight nature of BIPV components, particularly when utilizing thin-film PV modules (photovoltaic panels where semiconductor layers, only a few micrometres (μm) thick, are deposited onto flexible substrates), makes them inherently suitable for structures with limited load-bearing capacity or for applications on curved architectural surfaces [15][14][16].

Energetically, BIPV systems enhance the thermal performance of the host building by providing a higher insulation value and effectively mitigating the thermal load imposed on the Heating, Ventilation, and Air Conditioning (HVAC) systems [5][9][18]. For instance, studies have demonstrated that BIPV systems can achieve substantial energy savings, including reductions of 12–21% in the annual energy consumption and 14–26%

in the peak cooling demand. Additionally, generating electrical energy directly at the point of use (on-site) leads to savings by avoiding transmission and distribution (T&D) losses associated with centralized power networks [17].

Architecturally, BIPV systems afford considerable design flexibility through the customization of colour, shape, and transparency. This capacity allows for both harmonious aesthetic integration with existing/traditional building materials and the creation of technologically advanced envelope designs. The appearance of BIPV systems is a pivotal factor in adoption decisions [9][18][22].

3.2 Analysis of the BIPV Market for Roofing Systems

Roof systems currently constitute the most widespread BIPV application area, accounting for approximately 80% of global BIPV installations [21]. Rooftops are generally the preferred location for solar module deployment, primarily due to the abundance of solar irradiance [15][21] and their tendency to be less susceptible to shading effects caused by adjacent buildings or vegetation compared to façades [12][15]. Pitched or sloped roofs (often referred to as discontinuous roofs) are frequently considered the ideal setting for BIPV applications as they often provide the best energy harvesting conditions [11]. The ability to integrate PV into existing building surfaces negates the need for additional land allocation, which is a significant advantage given the scarcity of ground space [13][14][15][21]. This benefit is particularly pronounced in high-density urban environments [12][16].

BIPV solutions designed for metal roofs primarily focus on systems leveraging flexibility and low weight, particularly suited for flat roofs (or low-slope roofs) and curved surfaces. Alternatively, specific modules are engineered to replace traditional metal roofing components [13][16][23]. Metal roofs typically belong to the category of "continuous roofs", which are structurally defined by an uninterrupted, water-resistant layer [23]. The technological development of BIPV systems for metal roofing has primarily bifurcated into two major directions: Crystalline Silicon (c-Si), which is the dominant PV technology in this segment favoured for its high efficiency, and Thin-Film Photovoltaics (TFPV), valued for its inherent flexibility and capacity to provide a uniform aesthetic appearance [16][17][23].

The significant cost reduction documented in recent years, coupled with regulatory evolution that has established reliable technical standards, made these systems economically viable and created new opportunities, particularly for retrofitting interventions on the existing building stock [9][25][26]. BIPV systems are widely recognized as a fundamental solution for achieving the objectives of NZEB. Furthermore, it is anticipated that the acceptance and market penetration of building-integrated PV will increase progressively after 2020, driven by the mandatory nature of stricter energy regulations [5][9][11][22].

Despite these inherent advantages, significant barriers to adoption persist. For example, BIPV solutions designed for metallic roofs typically necessitate the provision of ventilated roofs using dedicated substructures. This requirement effectively compromises the distinctive advantages of fully adhered roofing systems and alters the original functional identity of the non-PV component.

A recent internal analysis of the European BIPV market validates this trend: 79% of the products still requires a ventilated substructure. The study examined 54 products sourced from 32 manufacturers, focusing exclusively on solutions marketed within the European context; aesthetic or highly customized modules were excluded from the scope of the survey (Fig. 3).

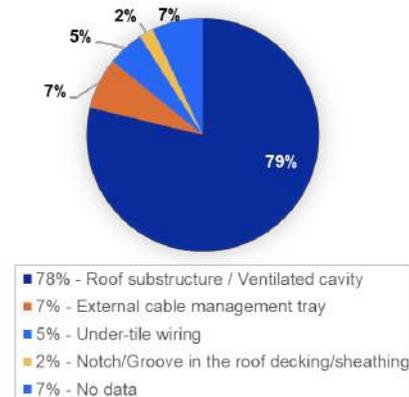


Figure 3: Internal market analysis, 2025 – sample: 55 products from 32 EU manufacturers

4 RESEARCH OBJECTIVE

This research project aims to address a technological and scientific gap identified in the literature and the building market. Specifically, fully adhered metal roofing systems are currently scarcely investigated in the BIPV domain, and most of the existing systems necessitate the installation of ventilated substructures. Consequently, the primary objective of this study is to develop a new generation of BIPV for metal roofs capable of overcoming the typical limitations of currently available solutions. Specifically, the development goals are :

- (A) to eliminate the requirement for ventilated substructures, thereby maintaining the characteristic full adhesion installation method typical of metal roofing, preserving the original waterproofing performance and mechanical resistance of the roof;
- (B) to ensure simple and rapid installation method, alongside facilitating easy maintenance;
- (C) to guarantee a high-quality aesthetic outcome, ensuring that the photovoltaic elements are coherently integrated with the architectural design and the overall building envelope.

This work starts from a collaboration between Università Iuav di Venezia and Tegola Canadese S.r.l., a leading company in the production of metal roofing. The initiative is part of a broader joint research program aimed at enhancing the architectural and functional integration of photovoltaic systems into building envelopes.

The article presents the outcomes of this development process, emphasizing how the proposed BIPV solution offers a concrete contribution toward achieving the EU decarbonization targets and promoting the large-scale dissemination (or wider adoption) of BIPV technologies, recognized as a pivotal component for future zero-carbon built environments.

5 RESEARCH OBJECTIVE

The development and validation methodology of the BIPV system was organized into three sequential phases. To ensure consistency between theoretical analysis and practical application, the research employed a combination of analytical and experimental tools, including a comparative analysis of existing BIPV systems, physical prototyping of components, and installation tests on roof sections. This integrated and iterative approach allowed for progressive validation of the developed solutions and guided the project toward outcomes aligned with the technical, architectural, and aesthetic requirements of the sector.

5.1 Phase 1: Sector Overview and Market Analysis

This phase was dedicated to analysing the technological and competitive context of the BIPV sector, with a specific focus on current market trends and the types of photovoltaic solutions available. This preliminary investigation provided the reference framework for understanding sector dynamics and identifying innovation opportunities. The primary objective of this phase was twofold: to understand dominant technological trends and to guide the development of a solution fully compatible with the distinctive characteristics of Tegola Canadese's fully adhered roofing. Phase 1 highlighted that the main limitation of current BIPV systems lies in their dependence on additional substructures, which are incompatible with the construction principles of fully adhered metal roofs. The new solution aims to overcome this limitation.

5.2 Phase 2: BIPV Solution Development

Phase 2 focused on the development of a BIPV solution specifically for Tegola Canadese's fully adhered shingles. The design emphasis was placed on achieving full functional and architectural integration while preserving the mechanical integrity and waterproofing performance of the existing roof. The developed solution maintains the distinctive characteristics of Tegola Canadese roofing (direct adhesion, absence of rigid substructures) by applying flexible photovoltaic modules directly onto the surface of the shingles. Engineering development requirements dictated that the system should feature inherent technological upgradability—allowing modules to be replaced or updated without compromising the functionality of the roofing system—high maintainability, facilitating access and intervention on PV components, construction simplicity, and maximum ease of installation.

5.3 Phase 3: Prototype Validation

Phase 3, the final stage of the methodology, focused on validating the developed solution. Validation was conducted through physical prototyping and installation testing on a real-scale roof section. The objective was to assess the overall technical feasibility of the system, specifically evaluating waterproofing effectiveness, mechanical resistance under load, and the quality of the final aesthetic integration.

6 RESEARCH OBJECTIVE

6.1 Base Roof System by Tegola Canadese

To understand our solution, it is essential to describe the base roofing system. The Tegola Canadese system is characterized by lightweight metal-bitumen shingles, installed in full adhesion without ventilated layers or mechanical substructures (Fig. 4). This configuration ensures waterproofing and resistance to extreme weather conditions.



Figure 4: Design Ultimetal HD© Slate

Installation occurs directly on the roof's supporting structure, typically over 18 mm OSB panels fixed to the framework. A self-adhesive waterproofing membrane (Safety R-evolution T©, 3 mm) is applied above these panels, followed by the metal-bitumen shingles. The Ultimetal HD© Slate shingles (1000 × 340 × 4.7 mm) combine a durable bituminous base with a pre-painted aluminium sheet 300 µm thick (Fig. 5).

Fixing is achieved through a combination of interlocking geometry, adhesion between layers, and nailing or hot welding onto the membrane. This existing system provided the foundation for our BIPV development: the main challenge was to integrate photovoltaic functionality without compromising the original characteristics of the roofing system.

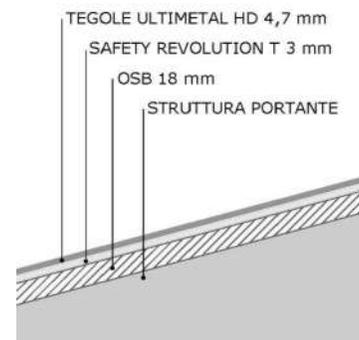


Figure 5: BIPV system components

6.2 Developed Solution: Tegola Canadese BIPV System

The developed BIPV system combines Ultimetal HD© Slate shingles with custom flexible Copper Indium Gallium Selenide (CIGS) photovoltaic modules (17% efficiency, 150 Wp/m²) (Fig. 6). This technology was selected for its flexibility, low weight, and compatibility with curved or irregular substrates. The custom modules have an extremely low profile (thickness < 2 mm) and feature a high-strength adhesive back sheet that bonds directly to the shingle. The combination of flexible modules and the robust shingle structure creates a unified roofing element, maintaining the mechanical strength,

waterproofing, and durability of the original system. Furthermore, the choice of flexible CIGS material is advantageous for non-ventilated roof solutions as it exhibits comparatively better performance at elevated temperatures than traditional crystalline silicon [13][14].

During the development phase, the main challenges centred on managing electrical connections and ensuring cable accessibility, while simultaneously preserving the high aesthetic quality of the roof surface.

Aesthetic integration is achieved through two coordinated components made from materials and finishes identical to the Tegola Canadese shingles (Fig. 7). The first component consists of arched vertical covers that protect the junctions between shingles and the junction boxes, ensuring maintainability and facilitating cable installation. The curved geometry was chosen for its softer, less intrusive appearance compared to squared profiles, while maintaining full technical functionality.

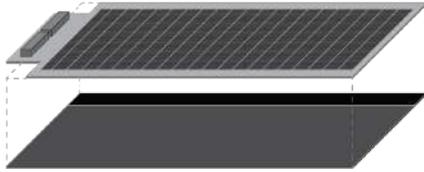


Figure 6: BIPV system components: Custom CIGS modules and Ultimetal HD Slate metal-asphalt shingles.



Figure 7: Render of a portion of the BIPV highlighting the two components: arched vertical caps and ridge caps

The photovoltaic modules are connected in vertical series configuration, while the horizontal electrical connections are discreetly housed within the second element: horizontal ridge that link all vertical elements. This design establishes a continuous, integrated cable protection and wiring management system within the roof geometry (Fig. 8). Collectively, these components enable clean architectural integration while ensuring complete accessibility for technical inspection and repair.



Figure 8: Simplified diagram of the electrical configuration

7 RESULTS

Validation confirmed both the technical feasibility and aesthetic integration of the system (Fig. 9). The

curved protective elements transform what is typically a technical requirement into a coherent design feature, consistent with the material identity of the roof (Fig. 10). Performance assessment demonstrated the full operational capacity of the photovoltaic system while maintaining the distinctive characteristics of Tegola Canadese roofing: fully adhered installation without dedicated substructures, simplified installation processes, and guaranteed maintainability. The system thus presents the following competitive advantages: elimination of substructures, reduction of systemic costs, backward compatibility with existing Tegola Canadese systems, superior ease of installation compared to conventional systems, and optimal architectural integration.



Figure 9: Installation of the BIPV system in the test room



Figure 10: BIPV system installation rendering

8 CONCLUSIONS

The collaboration between Università Iuav di Venezia and Tegola Canadese resulted in the development of a fully functional BIPV system, technically mature and coherent with the identity of the original product. The system integrates photovoltaic technology without altering the distinctive features of the metal roof, preserving performance, durability, lightweight characteristics, and aesthetic continuity.

Beyond the technical outcome, the work demonstrates how energy generation can be integrated into architectural design without formal compromises. In this perspective, BIPV is not a mere technological add-on but a building component capable of transforming solar

generation from a limitation into a design opportunity.

The proposed solution is fully adhered, free of ventilated substructures, and characterized by a simplified installation approach. The final configuration, based on modular vertical strips, is readily transferable to the market, offering a competitive advantage in terms of architectural integration, reversibility, and reduced installation complexity. This positions Tegola Canadese within a strategic segment of the rapidly growing BIPV market.

Future steps include life cycle assessment (LCA), cost optimization, certification, and preparation for industrial implementation. This work contributes to promoting the adoption of BIPV and supports European decarbonization targets, facilitating the transition toward Zero-Emission Buildings.

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RESOURCE EFFICIENCY WITH BUILDING INTEGRATED PV IN CONSTRUCTION

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ABSTRACT: The growing, intensive and unsustainable use of resources at local, regional and global level causes direct and indirect environmental problems such as climate change, soil and water degradation, land consumption, water shortage or biodiversity loss. Measures to reduce resource consumption are measures to reduce greenhouse gas emissions and thus contribute indirectly to climate protection. In the long term, the current use of resources endangers the basis of life for all people. At present, German policy makers are increasingly focusing on resource efficiency (efficiency gains), but this approach alone will not lead to a fair use of resources within the planetary boundaries, taking into account rebound effects. The debate about resource consumption does not stop at consumers. Public discourses clearly show that the way of life to date and one's own consumption patterns are being increasingly questioned, especially in the industrialized nations. Increasingly, consumers feel insecure in their purchasing decisions. At the same time, politics and business are being criticized by consumers. LCA as a tool must therefore be reconsidered. Building-integrated PV is capable of saving large quantities of non-mineral building materials.

Keywords: BIPV, CO₂-Emissions, Resource Efficiency, Green Building certification, LCA

1 INTRODUCTION

At over 90 billion tonnes, global material use has more than tripled compared to the 1970s. According to current UN estimates, this trend will continue. Forecasts expect a doubling to 180 billion tonnes by 2050 [1,2]

Resource consumption is not only a direct cost factor, but a key driver of major global environmental problems [1] Through the accompanying degradation of ecosystems and biodiversity and the acceleration of climate change, resource consumption is already having a negative impact on our livelihoods. The link between climate change and resource consumption is becoming increasingly apparent in society and the call for a resource transition is growing louder [3]. Its goal is to ensure equitable resource use within the limited capacities of our planet [4,5,6,7].

For example, a standardised procedure has been established through eco-balancing in accordance with ISO 14040/44 (1), but strategic control is lost in the complex presentation of input-output analyses.

Life cycle assessments need to be redefined and reconsidered.

2 LCA A1-A3, THE MOST IMPORTANT VALUES

2.1 Background:

German and European legislation on climate and resource protection in buildings is limited to improving energy efficiency during building use. Systems for assessing the sustainability of buildings such as German Sustainable Building Council (DGNB)(2), Assessment System for Sustainable Building (BNB) (3), Leed or Breeam, on the other hand, use an unmanageable number of indicators and are complex and expensive. At the same time, they do not address three major challenges of the 21st century in a concise and communicable way: climate protection, resource and energy transition.

So far, the systematic improvement of the environmental performance of buildings and settlements in Germany and Europe has been limited to increasing energy efficiency. In Germany, this was started very successfully in the late 1970s with the first Thermal

Insulation Ordinance. To date, the specific energy consumption for heating buildings and supplying hot water has been reduced from more than 350 kWh/m²/a to around 50 kWh/m²/a with the current Energy Saving Ordinance. This corresponds to about 7/8 of what is theoretically possible. A further increase in energy efficiency is hardly possible, as the expected marginal expenditure of further measures necessary for this often exceeds the achievable marginal benefit.

In Europe, the Performance of Buildings Directive and the Energy Efficiency Directive also focus exclusively on energy consumption during building use.

Greenhouse gases and mass flows - and thus also the recycling of raw materials - have not been considered so far.

Systems for assessing the sustainability of buildings such as DGNB (2), BNB(1), Leed or Breeam use a variety of indicators. The DGNB (2) system for residential or office buildings, with its 139 criteria and sub-criteria, is more a comprehensive assessment system for the quality of buildings than for their environmental performance. An assessment according to these systems is comparatively costly and hardly economically feasible, especially for smaller or medium-sized buildings, and therefore only reaches a niche market. Moreover, indicators on mass flows and greenhouse gases - if available at all - only account for a negligible share of the overall assessment.

For the challenges of the energy transition, climate neutrality and the resource transition away from the linear economy based on non-renewable, mineral and metallic raw materials towards a cycle-oriented economy relying more and more on renewable raw materials, the existing certification system do not offer any outstanding, easily recognizable and well communicable criteria.

In addition, credits are possible in the life cycle assessment of the building, which are justified by a recycling of a building material after deconstruction. However, this is highly controversial. It is completely unclear whether and when a building will be deconstructed. One example of this is the completely deconstructible showroom of a furniture manufacturer in Baden-Württemberg, which was built in 2022 by Ludloff Ludloff Architects. This multi-award-winning building

was simply demolished in 2025 due to a change of ownership. If you now calculate the life cycle assessment for the three-year lifetime, including the thermal recycling of the wooden components, you get a disastrous result in contrast to the LCA that was created when construction was completed. Only the PV system on the roof was reused. Furthermore, it is hardly possible to seriously estimate which disposal technology will be available in 50, 80 or more years and what resource demands will then be associated with it. It is equally unclear whether in 50 or 80 years there will be an interest in secondary raw materials that could be extracted from the deconstructed building.

Even more serious, however, is the fact that a CO₂ molecule released into the atmosphere with the production of the building materials will remain there for at least 1500 years. A CO₂ credit for a recycling that hypothetically takes place at the end of the building's useful life does not reduce this entry of greenhouse gases into the atmosphere. The same applies to the damage to ecosystem services as a result of raw material extraction. If credits are applied for any recycling that may take place at a later date, the sum of the greenhouse gases actually released into the atmosphere as a result of the construction and operation of a building does not match the amount of greenhouse gases indicated by the life cycle assessment according to DGNB (2).

2.2 Methodology

Focusing on CO₂ emissions in life cycles A1-A3 allows real emissions to be considered. In addition, these also accurately reflect the use of recycled building materials and biogenic building materials, as these emit significantly fewer emissions.

A distinction should also be made between active and inactive components. Inactive components are all non-renewable energy-generating components, while active components generate renewable energy.

In the case of building-integrated PV in particular, this allows the emissions avoided by not installing non-metallic building materials to be represented.

Below, we present the potential emissions that could be avoided in Germany through the use of roof-integrated PV.

3 SAMPLE CALCULATION:

The German Brick Association [9] states that around 90% of roofs in Germany are pitched roofs. 600 million bricks are produced annually. From this, the following assumption could be outlined:

- if bricks are used evenly in all directions in renovation or new construction (assumption)
- 25% each for south, west, east, and north roofs
- South, west, and east would be interesting for PV
- Approximately 75% of the 600 million roof tiles could potentially be replaced with PV roof tiles
- If we subtract areas where this is not structurally possible or where there are similar obstacles, we could assume a potential of 60%, for example
- This means that 60% of the 600 million tiles could be replaced.

3.1 Component layer analysis

Given the above requirements for increasing sustainability ambitions and classifying the relevance of modules A1-A3 of the classic life cycle phases according

to DIN EN 15978:2012-10, there is a need to reduce potential material flows in order to minimize the amount of emissions caused during the construction of buildings. While classic optimization approaches for reducing GWP values are limited to changing building materials (e.g., concrete to wood) or the use of recycled building materials, the consideration of envelope-integrated PV surfaces reveals the potential to eliminate classic facades or roof coverings in the overall structure, thereby actively dispensing with building materials in the construction. Within a classic roof structure, the following roof structure is usually created for a pitched roof.

Reference – sample roof cladding structure:

Interior:

Sloping roof structure (material according to structural and fire protection properties)

- Between-rafter insulation or above-rafter insulation
- Integration of various membranes for sealing and air regulation
- Roof covering substructure (1)
- Roof covering made of tiles or metal roofing (2)
- Substructure for photovoltaic system (1)
- Photovoltaic system

Exterior

Individual market participants are primarily promoting the development of roofing with photovoltaic-integrated energy generation potential in the roofing sector. The spectrum ranges from individual roof tile-like PV modules to bundled PV elements that can be integrated into a roof tile system and do not require any additional sealing.

Integrating this potential into the model structure outlined above offers the potential to reduce the substructure (1) by one substructure and, at the same time, to minimize the area of necessary roof covering (2) by the area of the PV-integrated materials. This integration enables the promotion of self-sufficiency through self-generated electricity and, at the same time, the reduction of emission-intensive materials such as fired roof tiles, which, similar to bricks, have a high energy and thus GWP impact on the overall construction due to the production process.

In a sample comparison, ÖkoBauDat 2023 and the ELCA Baustoffe tool were used to outline materials that can be eliminated from the building construction with a PV-integrated solution.

Facade:

1. Facing bricks: A1-A3 GWP = 60.78 kg CO₂ equiv. / m²
2. Fiber cement: A1-A3 GWP = 14.05 kg CO₂ equiv. / m²
3. Artificial stone: A1-A3 GWP = 28.35 kg CO₂ equiv. / m²
4. Sheet metal: A1-A3 GWP = 12.94 kg CO₂ equiv. / m²

Roof covering:

1. Roof tiles: A1-A3 GWP = 15.38 kg CO₂ equiv. / m²
2. Sheet metal: A1-A3 GWP = 12.94 kg CO₂ equiv. / m²
3. Slate: A1-A3 GWP = 9.57 kg CO₂ equiv. / m²

If we take a classic single-family home measuring 10 x 10 m with a roof pitch of 45% as a prime example, the potential roof area for a gable roof is around 140.00 m². Assuming a west-east orientation, which allows both roof surfaces to be used for solar energy, and assuming that half

of the area is used for PV, this results in around 70.00 m² of roof area that can be used for PV-integrated modules. This leads to the elimination and savings of the following idealized GWP values:

Roof covering:

1. Roof tiles: A1-A3 GWP = 15.38 kg CO₂ equiv. / m² x 70 m² = 1,076.6 kg CO₂ equiv. savings

2. Sheet metal: A1-A3 GWP = 12.94 kg CO₂ equiv. / m² x 70 m² = 905.8 kg CO₂ equiv. Savings

3. Slate: A1-A3 GWP = 9.57 kg CO₂ equiv. / m² x 70 sqm = 669.9 kg CO₂ equiv. Savings

For classic roofing with fired clay tiles, the use of roof-integrated PV elements results in a reduction of around 1 ton of CO₂ equivalent, which is achieved by not using the building material.

4 OUTLOOK AND POTENTIAL

If the reference values outlined above are scaled up to an entire country, despite the relatively small-scale analysis, there is considerable potential to be gained from the sensible combination of PV-integrated solutions and the elimination of additional building materials.

Taking Germany as an example and referring to information from the brick industry that around 90% of roofs in Germany are pitched roofs and 600 million roof tiles are produced each year, this results in a potential saving of 300,000 tons of CO₂ equivalent [9].

A:
600,000,000 (roof tiles per year) / approx. 11 tiles per m² = approx. 54,000,000 m² (cover area)

B:
approx. 54,000,000 m² (cover area) / 4 (cardinal direction) x3 (cardinal direction with PV potential) = approx. 40,900,000 m²

Implementation of 50% of approx. 40,900,000 m² as PV-integrated area instead of roof tiles plus PV system.

20,450,000 m² x 15kg CO₂ equiv. /m² (roof tiles according to ÖkoBauDat) = approx. 300,000,000 kg CO₂ equiv

Corresponds to approx. **300,000 tons** CO₂ equiv.

This assumption is based on the space requirement of around 11 tiles per square meter of roof area, which, with a requirement of 600 million roof tiles, would enable a potential coverage of around 54 million square meters of roof area.

Assuming that the roof areas are evenly distributed across the cardinal directions north, south, east, and west, this results in a potential PV usable area of 75%, which is primarily suitable for solar use (west, east, south). This means that there is a remaining area of around 40 million square meters that is suitable for PV-integrated modules in new buildings or renovations.

Under a conservative assumption that only 50% of this potential area will be used, there remains around 20 million square meters of tile surface that can be replaced by PV-integrated modules. In this case, the PV system is

not installed directly on the roof tiles, but replaces this building material in the overall construction. Based on an estimate of 15.38 kg CO₂ equivalent per m² of roof tile and a usable area of 20 million m² of roof space, this would result in a conceptual reduction of around 300,000 tons of CO₂ equivalent in newly produced roof tiles that would no longer need to be installed due to PV integration. This does not take into account metal substructures, which are required in many areas for PV integration on roof surfaces in order to attach the large-area modules.

A similar potential and methodology can be derived for the facade area, which is primarily limited to curtain walls. This typology is mostly used in standardized buildings and could reveal new potential for industrial buildings.

In summary, it can be outlined that the consideration of A1-A3 building materials also offers short-term reduction potential in the small-scale area in order to actively reduce current emissions in pursuit of climate targets.

A reliable determination of emission savings requires further detailed basic research and varies depending on the country and industrial orientation. The dependence here is on building typology, regional material selection, and roof orientation, which must be determined.

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6 LOGO

INIW INSTITUT FÜR NACHHALTIGE
IMMOBILIENWIRTSCHAFT

WATTWAY: THE FIRST COST EFFICIENT PAVEMENT INTEGRATED PV FOR ELECTRICITY PRODUCTION

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ABSTRACT: The rapid expansion of photovoltaic (PV) energy faces constraints such as land use and biodiversity impacts. Integrated Photovoltaics (IPV), which embed PV modules directly into infrastructures, provide a solution by making use existing artificial surfaces. Among IPV technologies, pavement-integrated photovoltaics (PIPV) stand out for their large surface potential, high social acceptance, and structural resilience. Wattway, developed through a decade-long collaboration between Colas and CEA-INES, is the first PIPV system to combine robustness and cost efficiency. Its design leverages standard PV cell architecture while innovating in encapsulation materials and bonding techniques, resulting in a thin, glass-free module adapted to traffic loads. A comprehensive validation process, including IEC certification and road-specific tests, ensures a lifetime of 15 to 25 years. Continuous improvements have increased energy density by 51% and reduced installation costs through mechanized processes, achieving system prices below 2.5 €/Wp. Wattway now delivers competitive electricity costs for self-consumption applications in areas where conventional PV is difficult to deploy, such as cycle paths, marinas, and forecourts. Future developments aim to further reduce LCOE below 100 €/MWh through advanced module designs and work automation.

Keywords: Pavement PV, Ressource Efficiency, Landscape protection, LCOE (Levelized Cost of Electricity), Resilience, Acceptance criteria

1 CONTEXT

The massive development of photovoltaics (PV) [1], which reaches globally 1 TW in 2024 and 3.5 TW in 2030 [2] is already encountering, or will soon encounter constraints that limit further growth (lack of free areas, biodiversity impacts...) that PV on artificialized surface can circumvent.

Unlike ground mounted PV or canopy systems, dual use of photovoltaic modules on existing infrastructures has environmental benefits, avoiding land artificialization and using less concrete and/or metal, resulting in a **life cycle assessment benefit of more than 20%** [3]. This is why **Integrated PhotoVoltaic (IPV)** – where photovoltaic modules are directly incorporated into existing structures – has become a a major focus of research and development.



Figure 1 - Pavement-integrated photovoltaic illustrations, bicycle lane made near Amsterdam in Netherland (left), electrified seaport in South of France (right).

Pavement-integrated photovoltaics (PIPV) which comprise bicycle paths (1), parking lots, forecourts, piers, share all these advantages while also benefiting from:

- higher social acceptance, as the system is out of sight, not impacting the visual surroundings.
- structural resilience: PIPV systems are not subject to wind load, making them safe from storm damage.
- high available surface potential: unlike BIPV, PIPV faces fewer property constraints, enabling

the development of large-scale solar installations at a lower price. Moreover, one road forecourt could supply multiple buildings, increasing self-consumption rate of the installation.

The chart (Fig.2) provides a qualitative comparison of IPV to other types of PV solutions such as Build-Applied (BA) systems (a superimposed solution) as well as floating and utility scale installations. In this chart, cost efficiency is assessed in relation to environmental impacts and risks.

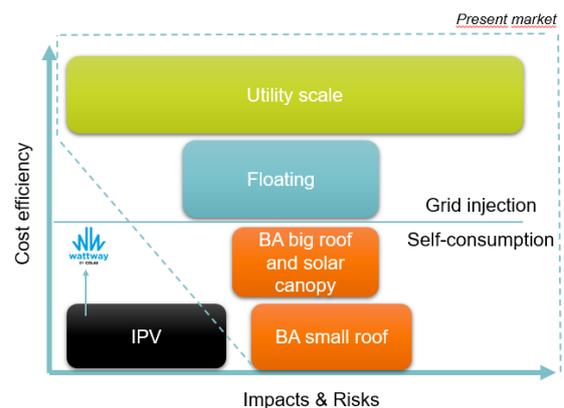


Figure 2 - Chart representing the cost efficiency vs impact & risks. IPV presents low risks and impacts but needs lower cost for massive adoption.

In IPV, the issue of cost may seem secondary compared to aesthetics and compliance with regulatory standards. These two aspects dominate Building Integrated PV (BIPV) as normative frameworks address critical issues such as fire resistance, wind resistance and more. Furthermore, these frameworks differ from country to country, resulting in fragmented markets, particularly

across Europe. Pavement-integrated photovoltaics (PIPV) benefit from a simpler regulatory framework compared to BIPV, making cost the primary factor driving market size. The key question therefore is how the price of grid electricity compares to the cost of electricity generated by PIPV, considering both systems costs and long-term performance.

The two primary challenges for PIPV are then combining robustness and cost efficiency: Can a PV module be designed to withstand traffic loads [4,5,6], and can a profitable system be achieved with modules installed at suboptimal tilt angles (2)?

Wattway, developed through a **10-year collaboration between Colas and CEA-INES**, is the **first PIPV solution to successfully address both challenges**. Its innovations in **module design and installation processes** have made it possible to overcome these obstacles, delivering a durable and economically viable solution.

2 DESIGN

Wattway's module design strategy is to align with mainstream PV technology for cells and interconnect, while differentiating through innovative encapsulation materials. We use a standard electrical architecture featuring PERC cells, soldered strings of half-cut cells and a butterfly layout.

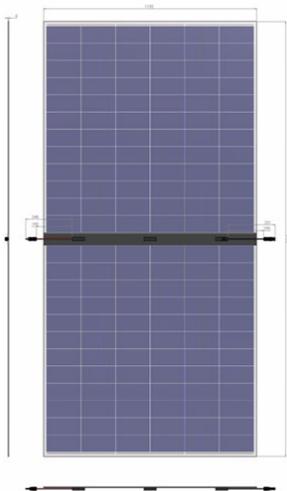


Figure 3 - Wattway Module 475 GC Electrical layout

The key innovations lie in the materials stack - eliminating glass and using specifically selected encapsulants -, in the top coating for skid resistance and in the glue-based bonding to the pavement. Module thickness is 4 mm and weight less than 6,5 kg/m².

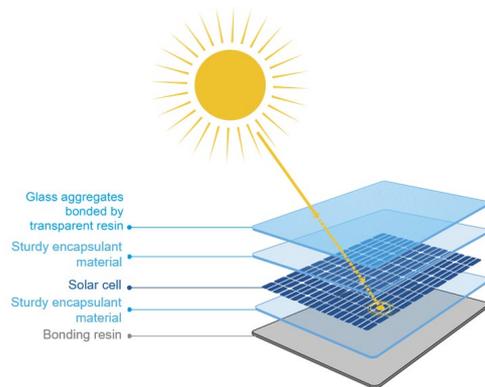


Figure 4 - Schematic representation of Wattway PIPV system.

3 ROBUSTNESS, PV/VALIDATION

Through a decade of module engineering and field feedback (3), we have developed a validation process to ensure 15 to 25 years lifetime (depending on traffic) for our PIPV solution, combining tests from PV and road-specific protocols. In 2024, Wattway became the first and only PIPV module to obtain certification according to the IEC61215 and IEC61370 standards for PV products. IEC certification alone is not sufficient to validate a product integrated into pavement under traffic conditions. Therefore, we add more rigorous road-specific tests, mechanical ones as well as combined climatic-mechanical tests:

- Rutting: no deformation of the module after 1-million-wheel passages (4)
- High pressure cleaning: according to IPX9 standard (5)
- Immersion test: 500 hours of immersion in deionized water at ambient temperature
- Impact resistance: no damage to the PV cells (EL images) at IK9 level (6)
- Skid resistance: not slippery after 2 years of high traffic (7) according to legislation (Fig.5)

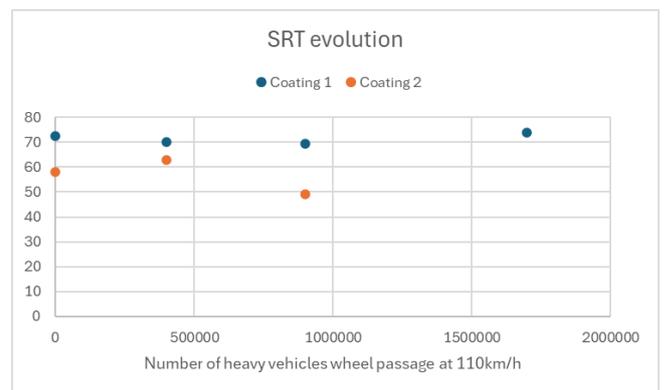


Figure 5 - Evolution of skid resistance test (SRT) as a function of the number of heavy vehicle wheel passages at 110 km/h. Two different coatings in compliance with road regulations are compared.

- Real traffic conditions ageing: no damage to the module or the cells (*in situ* EL, Fig. 7) after 400.000 passages in test campaigns (Fig. 6) done in France (8) and Japan (9).



Figure 6 – Real condition traffic ageing with heavy vehicles in France (left) and in Japan (right).

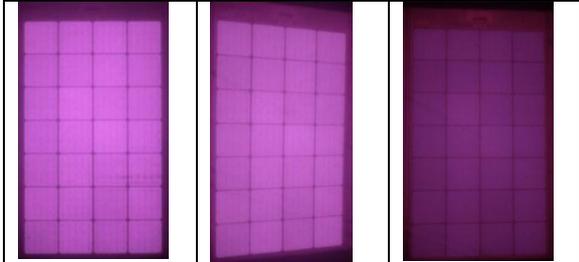


Figure 7 - Electroluminescence image after 200k, 400k and 600k passages

The combination of qualification tests and the creation of experimental sites around the world have enabled the validation of the technology: all components of Wattway PIPV solution (module stack, top coating, pavement bonding) successfully pass this validation process for the targeted 15 to 25 years lifetime.

4 COST EFFECTIVNESS

4.1 Cost of the system

Wattway began the development of prototypes in 2016. At that time, the main challenge was to deploy prototype technology from the laboratory in a public environment. The first PIPV panels were designed to withstand traffic while maintaining high transparency. The installation of these panels was very manual to ensure quality of the deployment. The electrical architecture was 60V to limit risks to users in case of prototype failure. The prototype installation costs were around €15/Wp, even for large demonstrators (330 kWp).

In subsequent years, we have driven Wattway’s cost reduction through three main axes:

- Electrical architecture: with technological maturity to ensure users’ safety, the architecture shifted from 60V to 1000V DC, allowing the use of standard PV electrical BOS equipment.
- Panel: the panel reached a standard PV panel size, lowering the PV panel unitary cost. It was designed to be compatible with a standard photovoltaic panel production line, decreasing fabrication costs. Bill of materials (BOM) has been optimized along with module lamination time.
- Mechanization of installation process: it has not only improved the quality of installation but also made it possible to increase panel size. Using civil engineering machines, we have developed a mechanized installation process of the module on the pavement; reducing the time for surface preparation and module bonding more than 10x.

This 10 years cost killing approach has divided by 6 Wattway’s sales price from 15.2€/Wp in 2016 to

2.5€/Wp in 2026 (Fig 7), Since this has been achieved without any economies of scale in production, a clear potential for further cost reduction exists when sales volumes ramp up.

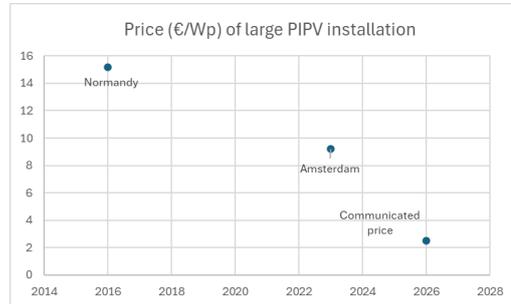


Figure 8 - Large scale installation price (€/Wp) of total Wattway installation as a function of the year

4.2 Performance

Over the past decade (2016 to 2025), the PV industry has achieved a 20 % improvement in cell efficiency. The Wattway has also profited from this increase. In addition, a strong push has been made to densify the solar cells grid and increase the front side transparency, without compromising on mechanical robustness of the system. This fine balance between materials choice and stack architecture has allowed a total module power density gain of 36% in Wp/m² from the initial 2016 prototype to the current 475 GC product [4] at 180 Wp/m².

Ultimately, in terms of performance, the key metric for the customer is energy production. To assess our performance over the years, we have monitored our largest installations and normalized their actual energy production to the condition of Versailles (France). The normalization includes shading correction from PVSYS and adjustments for yearly local irradiation compared to the irradiation level at Versailles. The energy produced was 97 kWh/year/m² by our Normandy installation in 2016, after renormalizing. Fig. 8 shows a 94% increase in areal energy production from 2016 to 2026.

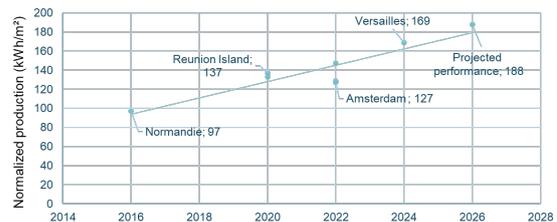


Figure 9 - Evolution of the normalized energy production density (kWh/m²) as a function of the years. Different production sites monitoring

As a result, we now reach a full system price below 2,5 €/Wp for a 200 kWp turnkey solution. Combining price and performance improvements, the kWh production cost decreased by a factor of 12.

At this price level, Wattway is today a cheaper solution for sourcing electricity than buying it from the grid electricity providers (10), for local self-consumption applications. For example, the levelized cost of energy (LCOE) for a 200 kWp bicycle path with 25 years lifetime in Florence is 127 €/MWh.

6 PERSPECTIVES

Wattway PIPV solution is today a cost-efficient solution for electricity production, it is proven robust and IEC-certified. We continue to pursue improvements in performance and cost, e.g. in module stack optimization and automation of the installation process. A TOPCon Wattway module is in development. Our target is to reach a LCOE below 100 €/MWh across a large part of Europe (excluding the northernmost countries) by 2030.



5 NOTES

- (1) In Europe for example, 10 % of the 190 000 km bicycle path networks alone could harbour more than 8 GWp
- (2) In European latitudes, energy production of a module flat on the ground is 14% lower in South Italy and 19 % in North UK compared to an optimal tilted one.
- (3) Over this period, more than 100 experimental and commercial sites have been deployed in different weather (cold, moderate, hot, humid...) and traffic conditions
- (4) NF EN 12697-22 standard: 0,6 MPa tire pressure, back and forth at 5 km/hour (worst case)
- (5) IEC 60529 standard: 110 bars with 95°C water , no delamination or degradation of the module
- (6) EN 62262 standard: resistant to 20 joules impact test
- (7) EN 1824 standard: SRT > 0.45 after 2 millions wheel passages on a real motorway (RN2)
- (8) A circulating arm driving an 8 tons axle tree resting on 2 truck tires (equivalent to 16t axle truck) at 50 km/hr
- (9) Tele-operated 13t axle trucks
- (10) Depending on local solar irradiation (the higher the better) and end user electricity price.

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CASE STUDY OF BIFACIAL PV BASED NOISE BARRIERS IN LITHUANIA
2ND INTEGRATED PHOTOVOLTAICS CONFERENCE – IPVC 2025

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ABSTRACT: In this work, installed PV noise barrier (PVNB) projects by Solitek in Lithuania have been reviewed from technical and economical perspectives. Bifacial PV modules were integrated with aluminum frames and rubber gaskets to be replaced with standard sound barrier panels (perforated aluminum) where such mounting structures enable simple retrofitting option for noise barriers. Modules in series were connected to DC/AC Inverter and grid. Data from inverter, weather station and 3 pyranometers have been employed for performance evaluation of PVNB. In addition, electromagnetic properties of PVNB in cellular network band (900 - 2000 MHz) have been explored. Energy generation pattern of PVNB corresponds to typical generation curve of vertical PV installations where two energy peaks are visible. Calculated and simulated performance ratio differs around ~0.15 which is explained due to shading structures above PV noise barriers which affects irradiance absorbance both from east and west sides. The different designs of PVNB with different distance between supporting pillars (2.5m and 4m) in the segment shows price difference from 8% to 16% comparing with standard noise barriers and by having fixed prices such of electricity 110 eur/MWh and 150 eur/MWh, the payback time for both designs range from 2-3 (when d = 2.5m) to 5-7 (when d = 4m) years accordingly. The findings after experiments of signal transmittance and reception of the electromagnetic radiation passing through PV module indicate the module similarities to metallic plate in terms of attenuation and signal strength properties for cellular network applications.

1 AIM AND APPROACH

The purpose of this work is to demonstrate economical and renewable energy benefits of retrofitting infrastructure objects with PV energy. In this work, PV project of 22kW have been installed in Lithuanian railways with bifacial PV modules. Panels have been integrated into segments where such objects contained 4 portrait-oriented PV modules, and the orientation azimuth of system was -77.9° . Frameless PV panels were integrated with aluminum frames with rubber gaskets and replaced with standard sound barrier panels (perforated aluminum) where such mounting structures enable simple retrofitting option for noise barriers. Modules were connected in series to AC/DC Inverter and grid. Daily and monthly energy generation values from inverter and climatic sensors (weather station and pyranometers) have been used for quantitative evaluation.



Figure 1. Picture of retrofitting procedure and finished work of PV noise barriers in Lithuania, Juodšiliai

2 SCIENTIFIC INNOVATION AND RELEVANCE

The usage of renewable energy, specifically PV energy, has become fast growing market where installation capacity increased worldwide from 240 GW (2022 year) to 407 GW (2023 year) [1]. Despite widely employed building-applied PV and building-integrated PV projects and installations, the market potential for infrastructure integrated PV (IIPV) is sizeable, considering the extensive availability to retrofit built and installed infrastructure objects along the road [2]. Yet, IIPV market is more relevant where land is sparse or very expensive which results in small amounts of available economical and technical data to evaluate the main benefits of decarbonizing existing infrastructure.

The study presents financial and technical evaluation (e.g., energy yield data, PR evaluation and other related parameters) of IIPV modules where such information gives the realistic view on possibilities of retrofitting already-built objects. In addition, for measuring solar panels' radio frequency scattering parameters, reflection and transmission coefficients of vertically arranged solar panels were performed in frequency range 500-2000 MHz. Wide aperture antennas have been used to provide homogeneous illumination and low spillover of RF radiation besides solar panels. Both vertical and horizontal polarizations were considered.

3 RESULTS (OR PRELIMINARY RESULTS) AND CONCLUSIONS

Fig 2. presents energy generation pattern of PVNB (on 10th of July) which corresponds to typical generation curve of vertical PV installations where two energy peaks are visible. Although, the second power peak is reduced due to additional shadowing which is caused by the metal

constructions above PV system which could be spotted in Figure 1 in the right picture.

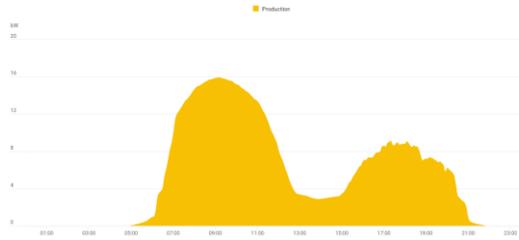


Figure 2. Energy generation representation

In Fig 3, for additional evaluation, performance ratio has been calculated using irradiance data from pyranometers and monthly energy yield from DC/AC inverter. The higher values for November and January compared with e.g., September and August could be explained due to more diffusive irradiance which translates into less sharp shadowing and lesser contrast between affected and non-affected surfaces of PV module.

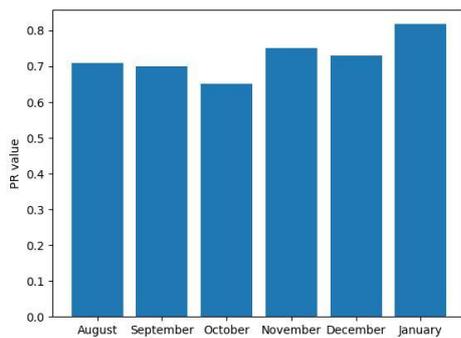


Figure 3. Calculated monthly PR of PV noise barrier system.

The different designs of PVNB with different distance between supporting pillars (2.5m and 4m) in the segment shows price difference from 8% to 16% comparing with standard noise barriers and by having fixed prices such of electricity 110 eur/MWh and 150 eur/MWh, the payback time for both designs range from 2-3 (when $d = 2.5\text{m}$) to 5-7 (when $d = 4\text{m}$) years accordingly.

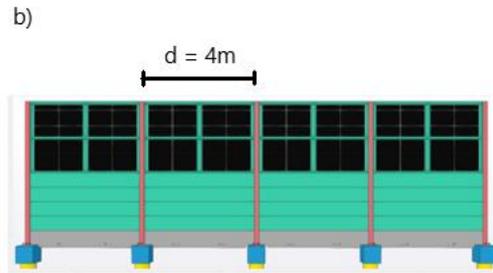
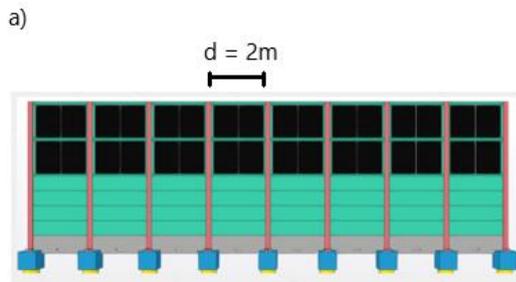


Figure 4. PV noise barrier segments with different distance between pillars.

The findings after experiments of signal transmittance and reception of the electromagnetic radiation passing through PV module indicate the module similarities to metallic plate in terms of attenuation and signal strength properties for cellular network applications.

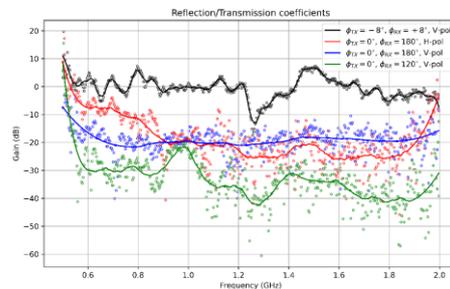


Figure 5. Reflection and Transmission coefficient gain dependence on frequency for different polarizations.

4 CONCLUDING NOTE – SUBSEQUENT DEVELOPMENT

Following the implementation of the two pilot projects in Lithuania, the experience gained was further consolidated through the realization of a first pilot project in Italy.

The project was implemented along a section of the E80 roadway, in proximity to the ANAS Smart Road Center, and involved photovoltaic integration within an existing noise barrier. The intervention included the installation of 45 segments composed of aluminum-framed solid bifacial photovoltaic modules rated at 435 W, resulting in a total installed capacity of approximately 19.5 kW, distributed over 100 m of noise barrier length.

The estimated annual energy production of the system amounts to 18,283 kWh/year, confirming the technical feasibility and energy performance of the infrastructure retrofitting approach previously observed in the Lithuanian case studies.

The project was carried out in collaboration with ANAS, acting as the road infrastructure authority, GSM Continental as the installation contractor, and SoliTek as the supplier of photovoltaic modules, integration structures, and technical know-how.

This installation represents a concrete step toward more sustainable, safe, and intelligent infrastructure, highlighting the strong potential for scalability and replication of photovoltaic noise barriers as an Infrastructure Integrated Photovoltaics (IIPV) solution within the European context.



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VIPV SHADING MODEL APPROACH BASED ON LAND USE TYPE

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ABSTRACT: Yield prediction of VIPV is very important in order to be able to determine the impact VIPV can have in supporting the energy transition. The first step in predicting the yield is to determine the irradiance on the vehicle. For this the shading on the vehicles need to be known. However shading modelling of VIPV is quite difficult due to the dynamic behavior resulting from the movement of the vehicle. Previously we reported on the use of a generic shading model. In this paper we report on the specific challenges regarding the use of that model and propose an improved model for determining the shading factor for VIPV.

Keywords: VIPV

1 INTRODUCTION

As the number of electric vehicles (EVs) increases, the dependency on charging from the electricity grid increases. To be less dependent on the charging infrastructure, there is an increasing interest in innovative technical solutions that enhance the driving range of EVs without the need for grid charging. Vehicle integrated PV (VIPV) is one of the solutions. To estimate the impact of VIPV on the reduction on grid demands, yield models are needed that accurately describe the effect of shadow on the PV yield. Different shading models have been developed, [1-9] but only a few of them have been (partly) validated by experimental data [10, 11]. In the SolarMoves project [12] we have used a generic shading model to determine the average shading for vehicles. [13] This model distinguishes between different road types, but uses the same shading factor for different vehicle types and use cases. This generic shading function has been validated using experimental irradiance data from irradiance sensors that are mounted on different vehicles driving across Europe. [14] The results show that the shading function used in the model overestimates the real shading function. Below we determine the challenges in the model validation and suggest an improved model for the shading on VIPV.

2 SHADING MODEL VALIDATION

2.1 Generic shading model

In our previous work we used the generic shading model as shown in Fig. 1, with a sinusoidal seasonal distribution of the daily average shading factor. It is a combination between the work from Cobbenhagen [2], who introduced the sinusoidal behavior, and Araki [15] who made the distinction between different route types. The numbers have been adapted slightly to better match the Dutch situation.

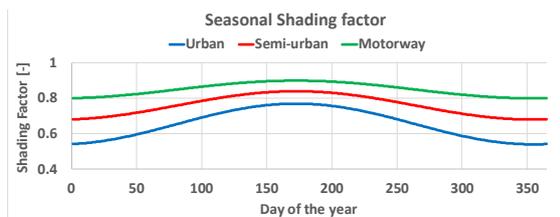


Figure 1: Seasonal shading factor for different road types. The shading factor is the fraction of the solar light received by the VIPV during a trip on a certain road type in comparison to the amount of solar light received on a trip without any shading losses.

2.2 Measurement campaign

To validate the model, 31 sensors (see Fig.2) have been installed on various vehicles, ranging from passenger cars to heavy duty vehicles. The vehicles have been driving through Europe since March 2024 and for the current analysis data has been collected until beginning of March 2025. In total the sensors have traveled a distance of over 1.028.219 kilometers. To determine the shading factor, the measured irradiance has been compared to satellite data. Details on the sensor and on the analysis can be found in [16,17].



Figure 2: Picture of the sensor unit as developed by Fraunhofer ISE and used for the irradiance measurements.

2.3 Model validation

As a first step, solar elevation and azimuth angles were calculated using the python-based programming library PVlib for the given location and timestamps of all data points. This information was used to filter the dataset. Next, land use types were added to the dataset by integrating OpenStreetMap (OSM) land use types. The data obtained from OpenStreetMap was categorized based on land use types into three primary groups: 'Urban Road', 'Semi-Urban Road', and 'Motorway'. This classification allowed to group the dataset and calculate the average energy ratio for each day of the year per road type. The result is shown in Fig. 3.

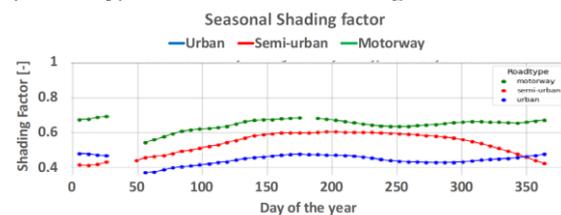


Figure 3: Seasonal shading factor for different road types as determined from the measurement campaign

Overall, a distinct separation between the three classifications can be observed, similar to the modeled distribution of Fig. 1, with 'Motorway' experiencing the

least shading, followed by Semi-Urban and, lastly, Urban roads, which incur the most shading loss. However, the measurement data reveals that all categories demonstrate a lower energy ratio, indicating a larger shading loss in the dataset compared to the assumptions made in the model.

Further data analysis showed that it is extremely difficult to make an accurate prediction of the actual irradiance on the vehicles at a specific point along the route because:

- The shading loss at a specific route point on partially clouded days cannot be determined as the reference irradiance is always measured at a different location compared to the vehicle sensor. As a result, irradiance dips due to clouds occur at a different time and thus the ratio of the reference dataset to the vehicle dataset does not reflect the shading at that time.
- As a result, a direct relation between the shading loss and a specific road type on these kind of days cannot be derived.
- The derived general shading loss is influenced by the conditions during parking. In the measurement campaign it was noted that parking was often done in the shade, which strongly increases the overall shading factor.
- The derived general shading loss for a day, is influenced by the different land use types during the trip.

When looking at individual trips and taking into account the major road type, in some cases a good match is achieved between the shading model and the measured shading loss.

3 IMPROVED SHADING MODEL

To improve the shading model and derive more accurate road type specific shading factors, a more detailed analysis of the land use distribution along a trip is performed. To do this, the road points along the trip are plotted using ArGIS which are overlaid on the the Bestand Bodemgebruik (Land use) map from the Bureau of Statistics (CBS) in the Netherlands distinguishing 7 different land types the land types: [18]

- Traffic Terrain
- Built
- Semi-built
- Recreation
- Agricultural
- Forest and open
- Inland Waters

The land type distribution at each road point along the trip is analyzed by looking at the land type distribution in a circle around the road point, where the diameter of the circle is determined by the sensor gps accuracy. See an example in Fig. 4 for 3 road points.

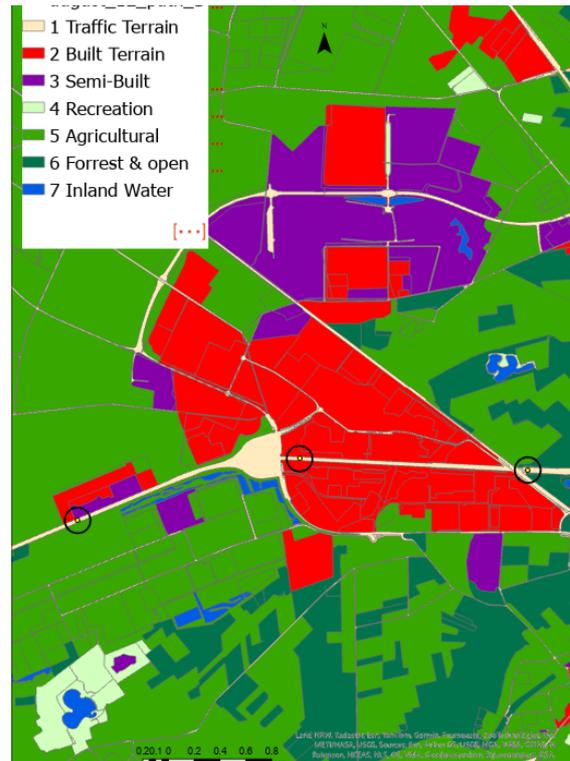


Figure 4: Example of an ArGIS overlap of 3 road point data (black circles) with the different land use types.

This approach was used on a trip with a truck that drove in the Netherlands on August 12, 2024. The total trip is shown in Fig. 5.



Figure 5: Overlap of the trip (yellow points) on ArcGIS map.

Fig. 5. Shows the distribution in land use types for the trip.

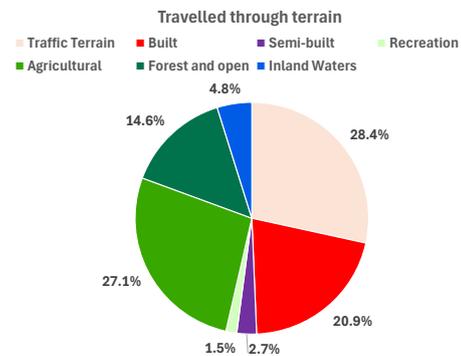


Figure 5: Distribution of land use type over the total trip.

The resulting land type distribution at each road point is shown in Fig. 6.

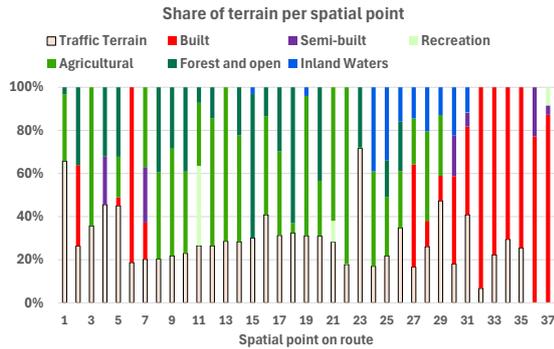


Figure 6: Distribution of land use type per road point for the specific trip.

As can be seen there is not a single point where only one land use type is present, but there are several for which one type is dominating. However, the majority of the points has a mix of land use types.

The shading factor at each of the road points is then parameterized assuming a linear combination of shading factors per land use type.

$$Irr(truck)_j = Irr(Sat) * \sum_{i=1}^7(a(j, i) * sf(i)) \quad \text{Eq.1}$$

Where:

- Irr(truck), measured truck irradiance
- Irr(Sat), satellite irradiance data
- a(j,i), fraction of land type i at route point j
- sf(i), shading factor for the specific land type

Fig. 7 shows the measured truck irradiance on August 12, 2025 as well as the irradiance measured at a nearby weather station. As can be seen in the morning and in the afternoon there are two time slots without any clouds, whereas the truck was parked in the shade around 9AM and 3PM and some clouds were passing by between those parked moments. For this reason we only looked at the trip in the morning to ensure that there was no influence of a possible time difference in the effect of clouds on the irradiance.

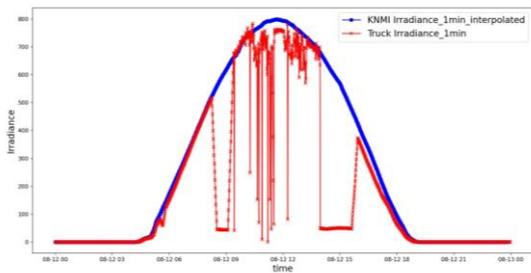


Figure 7: Measured truck irradiance data (red) and measured irradiance from a nearby weather station (blue).

Fitting the factors of Eq. 1 using the measured data at each point then results in the specific shading factors per land use type. The fitted irradiance is shown in Fig. 8 together with the measured data for the truck.

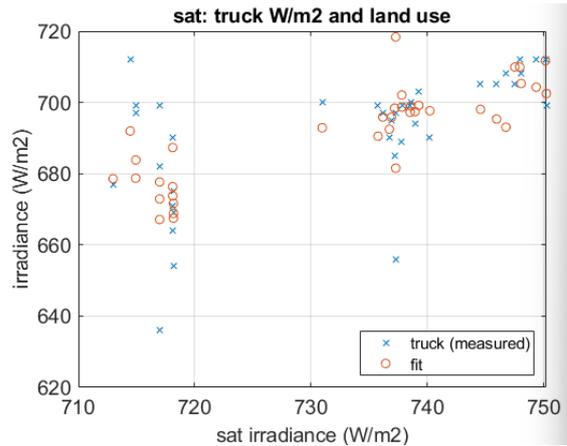


Figure 8: Measured truck irradiance data (blue crosses) versus satellite irradiance data together with the fitted truck irradiance (red circles) data using Equation 1.

The resulting fit gives a correlation factor of 0.70 and the following numbers for the shading factor are found:

Traffic Terrain	0.91
Built	0.94
Semi-built	0.97
Recreation	0.94
Agricultural	0.96
Forest and open	0.96
Inland Waters	1.02

As can be seen, the inland water shading factor is 1.02 which means that the truck irradiance for that land type would be more than the satellite irradiance. This is not realistic. Also the rather low correlation factor indicates that the obtained shading factors are not yet accurately describing the measured shading and more analysis on the specific road points is needed to determine possible outliers due to:

- Overpasses
- Tunnels
- Land type ‘forest and open’ combines two opposite land types when it comes to shading, which could influence the fit

4 CONCLUSIONS & OUTLOOK

A first attempt has been made to define the measured irradiance loss on a truck at several route points and correlate that to the shading factor of 7 different land use types. A linear model fit resulted in a correlation factor of 0.7 and a non-physical shading factor for Inland waters of 1.02. This data set was limited and might contain route points which deviate from the typical land types due to overpasses or tunnels. Besides that, the combination of ‘forest and open’ combines two extremes when it comes to shading and should be split. A more detailed data analysis on these points will be performed for this dataset, as well as additional data in order to improve the fit. Next step will be to use the model to predict the shading factor for other trips as well and compare them with measured data.

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