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Final report

BIPVdSHADING

Dynamic solar shading system for transparent façades

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Summary

The project demonstrates the market for a highly aesthetic and prefab BIPV dynamic shading technology by realising the system in a real building and facilitating a technical and economic appraisal with activities aimed at validating the market introduction of the product. An integrated approach involving a multidisciplinary consortium of key partners combine scientific and economic value creation in Switzerland with good prospects of implementation in conformity with the Energy Strategy 2050. Starting from a TRL5 and validating cost-effectiveness, energy efficiency and reliability of the product, the technology innovation of this BIPV solution will demonstrate the technology consistency with low process and maintenance costs in the real full-scale building and in compliance with a TRL7. Demonstrating the aesthetic, energy and economic benefit ratio, this BIPV system will also be capable of attracting users' interest for high replicability.

Riassunto

Il progetto ha lo scopo di dimostrare il potenziale di mercato di un dispositivo di ombreggiamento dinamico BIPV di elevato valore estetico e prefabbricato, oltre che di facilitare la sua valutazione tecnica ed economica con attività volte a convalidarne l'introduzione sul mercato. Un approccio integrato che coinvolge un consorzio esperto e multidisciplinare, si prefigge di coniugare la creazione di valore scientifico ed economico in Svizzera con solide prospettive di implementazione in conformità con la Strategia Energetica 2050. A partire da un TRL5 e convalidando la competitività dei costi, l'efficienza energetica e l'affidabilità del prodotto, l'innovazione tecnologica di questa soluzione BIPV dimostrerà la competitività della tecnologia mediante bassi costi di processo e di manutenzione in un edificio reale conforme a un TRL7. La dimostrazione del rapporto tra benefici estetici, energetici economici per questo sistema BIPV sarà inoltre rivolto ad attrarre l'interesse degli utenti per un'elevata replicabilità.

Zusammenfassung

Das Projekt demonstriert den Markt für eine hochästhetische und vorgefertigte dynamische BIPV-Beschattungstechnologie, indem das System in einem realen Gebäude realisiert wird und eine technische und wirtschaftliche Bewertung mit Aktivitäten zur Validierung der Markteinführung des Produkts ermöglicht wird. Ein integrierter Ansatz, an dem ein multidisziplinäres Konsortium von Schlüsselpartnern beteiligt ist, verbindet die wissenschaftliche und wirtschaftliche Wertschöpfung in der Schweiz mit guten Aussichten auf eine Umsetzung im Einklang mit der Energiestrategie 2050. Ausgehend von einem TRL5 und der Validierung der Kosteneffizienz, Energieeffizienz und Zuverlässigkeit des Produkts wird die technologische Innovation dieser BIPV-Lösung die technologische Konsistenz mit niedrigen Prozess- und Wartungskosten in einem realen, vollwertigen Gebäude und in Übereinstimmung mit einem TRL7 demonstrieren. Dieses BIPV-System wird das ästhetische, energetische und wirtschaftliche Nutzenverhältnis demonstrieren und auch in der Lage sein, das Interesse der Nutzer für eine hohe Replizierbarkeit zu wecken.

Résumé

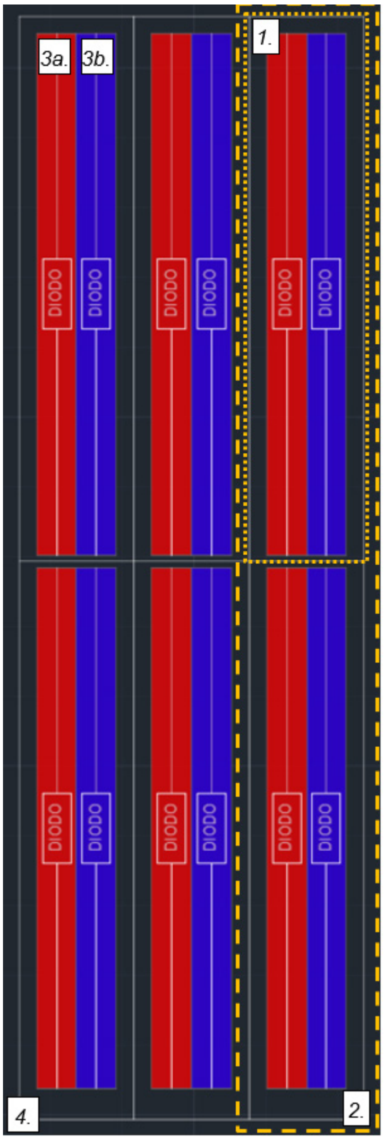
Le projet démontre le marché pour une technologie d'ombrage dynamique BIPV hautement esthétique et préfabriquée en réalisant le système dans un bâtiment réel et en facilitant une évaluation technique et économique avec des activités visant à valider l'introduction du produit sur le marché. Une approche intégrée impliquant un consortium multidisciplinaire de partenaires clés combine la création de valeur scientifique et économique en Suisse avec de bonnes perspectives de mise en œuvre en conformité avec la stratégie énergétique 2050. En partant d'un TRL5 et en validant la rentabilité, l'efficacité énergétique et la fiabilité du produit, l'innovation technologique de cette solution BIPV démontrera la cohérence de la technologie avec de faibles coûts de processus et de maintenance dans un bâtiment réel en grandeur réelle et en conformité avec un TRL7. En démontrant les avantages esthétiques, énergétiques et économiques, ce système BIPV sera également en mesure de susciter l'intérêt des utilisateurs en raison de sa grande reproductibilité.

Contents

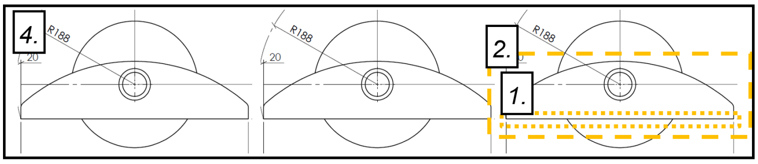
Abbreviations

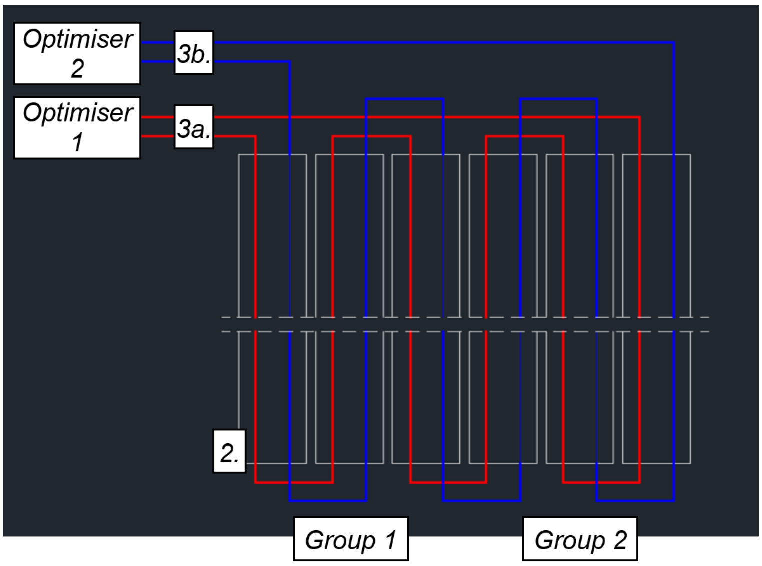
PV	photovoltaics
BIPV	building integrated photovoltaics
PVSD	photovoltaic shading device
TRL	technology readiness level
nZEB	nearly zero energy building
NPV	net present value

Taxonomy



ID	DESCRIPTION (pilot installation)
1.	PV module: photovoltaic glass-glass module made of 22 or 28 c-Si cells. Each PV module is made of two strings of 11 or 14 cells.
2.	PV slat: multifunctional kit including PV module and metal extrusion; each PV slat is bonded with two PV modules.
3.	String: vertical red hatch made of 66 or 84 cells in series (left string, "3a") and vertical blue hatch made of 66 or 84 cells in series (right string, "3b").
4.	Group: union of three PV slats in the façade, controlled by one motor.





1 Introduction

1.1 Background information and current situation

The building industry is responsible for about 40% of the CO_2 emissions globally. Without changes to current trends, global CO_2 emissions are set to increase in the following years. To mitigate catastrophic consequences, international directives are pushing towards a decarbonisation roadmap to improve the quality of cities and the health of citizens.

Among other strategies to move toward nearly zero energy buildings (nZEB), the use of photovoltaic shading devices (PVSD) contributes to reducing the energy footprint by protecting buildings from direct solar radiation and overheating while producing renewable electricity on-site and increasing the users' thermal comfort. Even though the potential of PVSD is considerable, the sector's development is still scarce and few studies or products on the topic are available, especially considering the application of PVSD in buildings. Firstly, the solution bridges the building skin and the building integrated photovoltaic (BIPV) complexity with technology and a process that involves different competencies and non-conventional construction and management challenges. Secondly, conventional BIPV shading solutions' high initial costs discourage investments, particularly by investors who have experience in the traditional solar industry where photovoltaic (PV) is a means for producing electricity and many advantages as architectural and functional elements of the construction are not considered.

1.2 Purpose of the project

In this context, the project team has previously developed and engineered the technology with a validation of the small-scale multifunctional product at the technology readiness level (TRL) 4. In particular, the basic technological components have been further engineered to establish that the pieces will work together in a design system configuration similar to the final application. The project's scope is to achieve a technological readiness enhancement and demonstrate the substantial implementation of PV dynamic solar shadings by optimising the technical and economic aspects for a TRL7.

1.3 Objectives

The project demonstrates the techno-economic potential of a highly aesthetic and prefab BIPV dynamic shading technology by realising the system in a real building and facilitating a technical and economic appraisal with activities aimed at validating the market introduction of the product. After validating the technology in a relevant environment at TRL5/6 and assessing the cost-effectiveness, energy efficiency and reliability of the product, this BIPV solution will demonstrate the technology consistency with process and maintenance cost targets in the real full-scale building and in compliance with a TRL7. Demonstrating the aesthetic, energy, and economic benefit ratio, it is expected to attract users' attention by offering high replicability. To this end, the following goals were set:

- Holistic technology assessment towards a cost reduction;
- Technology validation (from TRL 5 to TRL 6);
- Technology demonstration (from TRL 6 to TRL 7);
- Replicability and market exploitation strategies.

This final report presents the results achieved in the project (during the year 2021 and 2024).

2 Description of the demonstration facility

2.1 Context

The photovoltaic generation system of Franklin University Switzerland (FUS) in Sorengo is made up of several production plants of different types Figure 1. The project's first phase was completed in 2018 when 45.60 kWp were installed on two flat roofs. This part of the plant has already been commissioned and tested and supplies approx. 51'000 kWh/year of energy to the building. In 2020 the building owner wanted to upgrade the current photovoltaic system by exploiting the surface area of the new flat roof and the auditorium facade. 66.42 kWp were added to the existing system for a conventional rooftop installation. 18.36 kWp is the PVSD capacity that will be added to the façade (Figure 2). The total power of the PV generation will correspond to 130.38 kWp. The new building will also supply thermal energy to the entire complex via a new heat pump and will be equipped with a home automation system. The overall estimate of energy production will be approx. 150'000 kWh/year.

Figure 1: Franklin University Campus in Sorengo; the BIPV system is installed on the new auditorium's facade on the complex's west side.

Figure 2: Franklin University Auditorium. Two different configurations of the shading system. Source: Flaviano Capriotti Architetti.

2.2 BIPV system for the new auditorium FUS in Sorengo

The first project challenge was to integrate the new production plant, in the form of a PVSD integrated in the facade, with the existing PV rooftop system, defining all the necessary details with the electrical designers, engineers and architects. The spaces assigned to the various appliances, the various passages of the cables from the surfaces to the technical rooms, the modification of the new electrical panels to integrate the production plants and all the aspects related to safety in the electrical field were therefore defined. The design and sizing of the production plant were developed on the basis of the PV modules used. The latter, having been made to measure for the project by Sunage, have non-standard technical and electrical specifications for which it was necessary to carry out a dedicated study for sizing.

After analysing the solar potential and the feasibility of making active the building volume with a dynamic shading system, an in-depth study was conducted to assess the impact of shading on PV modules. From the result obtained, the use of power optimisers became indispensable. The system consists of two SolarEdge inverters connected to the PV modules on the ground and first floor. As previously defined, the groups of PV modules are equipped with power optimisers to manage shading. They guarantee maximum production and safety (blocking voltage). In addition, power optimisers significantly reduce wiring (Figure 3).

Due to the curved facade and the different orientations, the PV slats have been divided into groups. After a thorough study, it was decided to control three PV slats simultaneously, thus forming 21 active groups with 63 PV slats per floor. Each group will be managed by a motor, which will simultaneously regulate the position of each group of PV slats. The PV slats are made up of two PV modules in series divided in half on the vertical axis to overcome the problem of shading carried over from one PV slat to the other at the extremes of opening. The plant also includes a non-active part on the east side of the pavilion, in which PV slats have been installed but not electrically connected due to low irradiation. The non-active PV slats work as a supply in case the active PV slats break or malfunction. Further details of the BIPV system and PV slats are available in the chapter "Taxonomy".

The movement of the PV slats is managed by a Programmable Logic Controlle (PLC), which manages all the various processes through dedicated programming and a specific algorithm: solar tracking and manual control. The solar tracking function refers to a solar calendar based on the location's geographic coordinates. The rotation limits of the PV slats, the start and end times and the movement accuracy (accuracy 0.1°) are defined remotely with software specifically implemented. The PLC is connected to a KNX home automation system of the building, which allows the user to manually intervene in the position of the PV slats to adjust the light intensity in the environment or position them for maintenance.

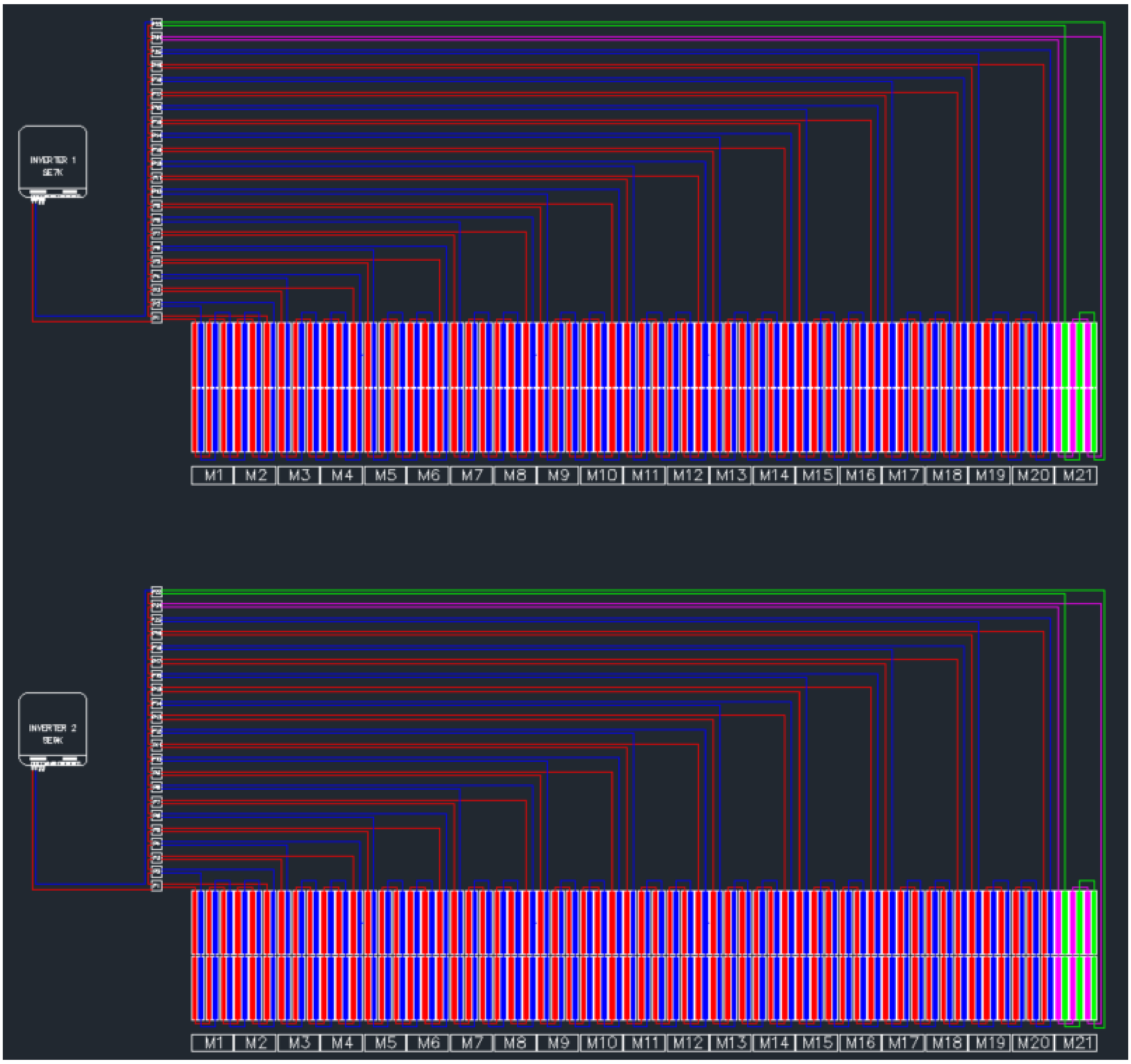


Figure 3: Electric schema BIPV installation. Up: first floor; down: ground floor. Mn represents the group which is managed by a motor.

3 Energy and economy assessment of PVSDs

This study identifies under which conditions, both energetic and economic, a photovoltaic shading device (PVSD) is cost-competitive by evaluating the most influencing parameters typical of its application context. The goal is to define the maximum current investment of a PVSD to achieve a NPV equal to zero in 15 or 30 years. This activity assesses cost competitiveness scenarios in relevant architectonic situations (building typology, technological systems) and at different conditions (climate conditions, control system, orientation), which are crucial for a BIPV system. The results allow the definition of the key elements that ease the replicability of the technology at different conditions with a perspective towards the technology market introduction.

The study is structured in three sections: i) the current (2022) status of PVSD and its analysis in terms of the status of the research, ii) an investigation of the potential energy production for PVSD performed at different conditions of solar irradiation and iii) an economic analysis, which serves to compare PVSDs in terms of cost competitiveness and cost-effectiveness. Only the energy performance of PVSD in terms of PV generation have been considered. The energy savings due to the blind shadowing function, despite the recognised potential, have not been included in this research.

3.1 Literature analysis

This systematic review aims to present an exhaustive overview of the current literature on state-of-the-art PVSDs by analysing the scientific framework in terms of the status of the research. It presents a performance-based approach focusing on innovative products, PVSD design strategies, and energetic performance in distinct climate conditions and configurations. In particular, 75 articles and about 250 keywords were identified, selected, and analysed.

The literature review serves as a basis for further R&D activities led by both the industrial and the academic sectors. The investigation on PV shading devices for transparent facades is performed on the bibliographic database of scientific publications Science Direct and Scopus. The field of research has been limited by identifying keywords clustered in three parameters: photovoltaic, shading system and building, as shown in Table 1. The type of technology has been defined based on the insights presented within the analysed papers. The authors provided a universal terminology and schema of the technologies analysed to classify the technological systems and align the terminology registered within the papers analysed.

Table 1: Field of research clustered in parameters and keywords

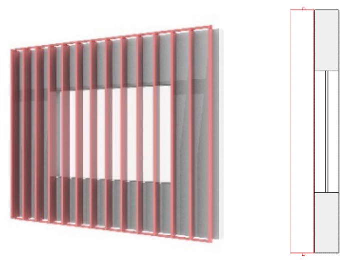
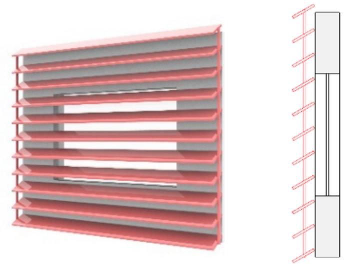
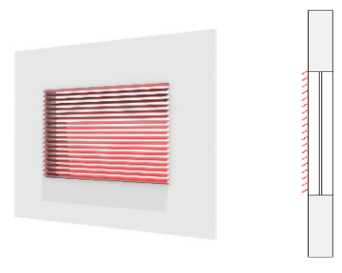
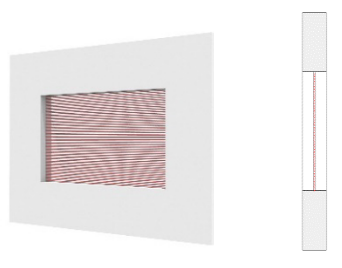
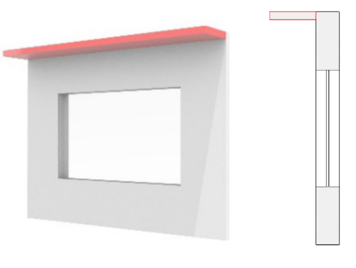
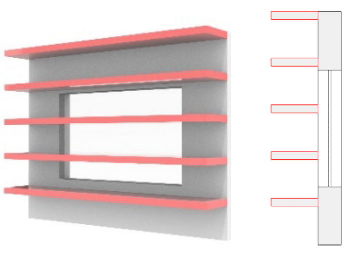
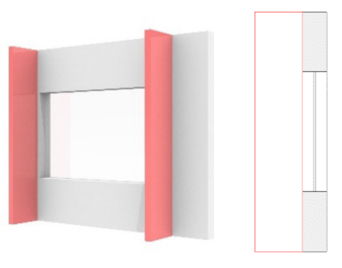
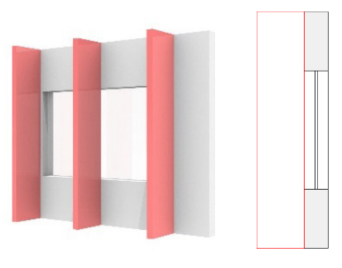
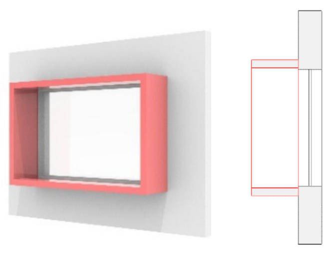
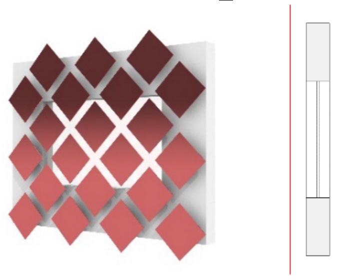
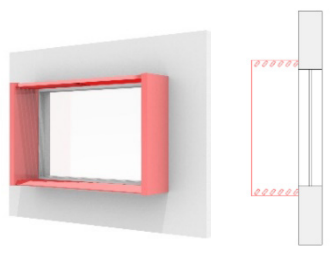
PARAMETER	KEYWORD
Photovoltaic	PV, BIPV, Building Integrated Photovoltaic, solar, renewable energy, energy production, module, electricity
Shading system	Blind, Venetian blind, shading device, louver, louvre, overhang, canopy, fin, eggcrate, innovation, design strategies
Building	nZEB, nearly Zero Energy Building, construction, energy demand, renovation, energy saving

The study revealed that PVSDs require a customised design in each climate and environmental condition between the tilt angle, the blind spacing, and the width to maximise the benefits between energy production and energy savings. In most of the research analysed, which was located in the northern hemisphere, horizontal slats were recommended for surfaces oriented towards the south, east, and west. Even though PV fins were also recommended for east and west facades, vertical slats represented the optimal solution for facades oriented towards the north. The mutual shading effect between slats, in the case of louvres, window blinds, and multiple repeated PVSDs, increased by increasing the width of the slat. This influenced the decrease in energy production. Movable shading systems performed better than fixed PVSDs in energy demand and production. Multi-oriented PV systems allowed savings of up to 80% in net energy compared to equivalent static PVSDs.

A structured classification of PVSD defines the PVSD examined within the following research. For the original terminology, refer to the related journal paper. An overview of the system categories and their features, combined with a simplified representation explaining the technology, is shown in Table 2.

- **Louvre**: defined as any similar arrangement of slats or fins attached in mechanical systems, often adjustable, used to control ventilation, light intensity and energy efficiency in general.
- **Window blind**: A lightweight system that permits control of light, privacy, and energy production. The window blind is retractable or movable and includes venetian blinds, roller blinds, vertical blinds or similar systems, which can be installed outdoor, indoor or embedded into the insulating glass unit (IGU).
- **Panel, or shading overhang**: roof projection, a story or a solid panel of a building beyond the building envelope of the lower part on which a module is integrated.
- **Fin**: little static wings that produce energy and are projected perpendicularly or not from the façade and used randomly across the façade, creating rhythm and scale on otherwise soulless cartesian curtain wall grids. Fins are used to control ventilation, light intensity and energy efficiency in general.
- **Egg-crate**: horizontal construction divided vertically into cell-like areas, used primarily to direct downward rays of overhead light and produce electricity.
- **Other systems**: shading system not included in the previous categories.
- **Composite systems**: SD combining multiple simple techniques.

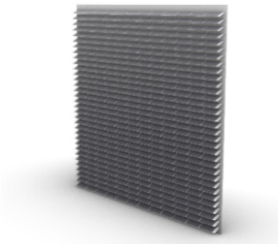
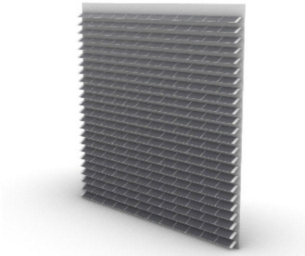
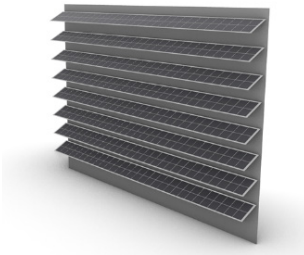
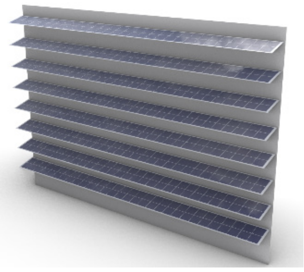
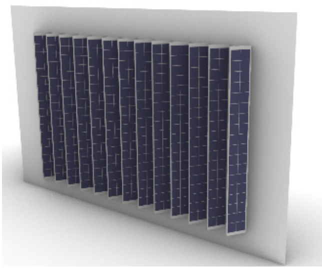
Table 2: Example of PVSD

PV Louver, vertical	PV louver, horizontal	PV Window Blind, external
		
PV Window Blind, embedded	**PV Panel, single**	**PV Panel, multiple**
		
PV Fins, single	**PV Fins, multiple**	**PV Eggcrate**
		
Other PV System	**PV Panel + Louver**	**PV Eggcrate + Louver**
		

3.2 Assessment of the photovoltaic potential of PVSD

Recently, PVSD systems are taking the attention of architects and engineers because of their multi-functionality. Indeed, they are envisioned as building elements capable of combining electricity generation with the typical advantages of external shading system devices, such as daylight and visual comfort improvement, as well as protection from summer overheating of large glass façades. **This activity focuses on different PVSD systems to investigate their potential energy production and compare them systematically**. The PVSD systems analysed in this activity consist of external dynamic venetian blinds, horizonal louvers (both dynamic and fixed) and dynamic vertical louvers. Moreover, these systems have been simulated in different climate conditions to provide energy production values needed to investigate their economic profitability in different locations (Berlin, Lugano and Rome). Even though PVSDs affect different aspects of the building envelope (e.g., thermal, daylight, etc.), this activity focuses on the energy generated by the different systems, which are presented in Table 3. The methodology is explained in 9.1 Annex A.

Table 3: Schematic illustration of the selected PVSD systems

T01: External PV venetian blind, d/l 4:3, dynamic system	**T02**: External PV venetian blind, d/l 1:1, dynamic system	**T03**: Horizontal PV louver, d/l 0.95, dynamic system
		
T04: Horizontal PV louver, d/l 0.95, fixed 15° and 50°	**T05**: Vertical PV louver, d/l 0.95, dynamic system	
		

The PVSD systems **T01** and **T02** have the lowest yield (in kWh/m^2 of shaded window area). This is mainly due to the self-shading effect between the slats and the control strategy. There is a slight yield increase when a small increase in the distance between the slat occurs (comparison between T01 and T02). The yield significantly increases when the self-shading is reduced, as in the system **T03**. However, the control strategy seems to have a greater impact. Indeed, it is important to highlight that **T01** with south orientation is often fixed in the horizontal position from April to September. The solar altitude is high during this period, and the cut-off angle is negative. Whereas when it is oriented toward the south-east or east is fixed in the horizontal position only in the afternoon. A similar behaviour is shown by systems **T02** and **T03**, even if the latter has higher PV production (+22% compared to T01, +10% compared to T02). These considerations indicate that there might be some shortcomings in using south-oriented thin slats with reduced interspaces to produce electricity. Moreover, in the abovementioned periods (April to September), the fixed positioning of the slat at 0° might not be sufficient to avoid glare or solar protection from overheating.

Instead, fixed systems represented by **T04** behave differently depending on the rotation angle. It can be noticed that the yield is higher when the angle is maintained at 50°, since the self-shading is very limited and the slats have better exposure to solar radiation. However, these systems cannot be inclined during the day to achieve higher visual comfort levels or avoid glare. Finally, the PVSD **T05** has the highest yield mainly because it is a sun-tracking system; thus, it allows benefiting from solar radiation throughout the day. However, a drawback of this system can be the visual comfort and daylight during the middle part of the day. The results are shown in Table 5.

3.3 Maximum investment for cost-effective PVSDs

The lack of concrete and documented cost analysis regarding PVSD applications is a missing gap for the sector. This research advances a cost-benefits study of the PVSDs presented in the previous chapters in the form of market available products and energy performance at different scenarios. **The goal of this task is to provide a methodology to assess the cost competitiveness of PVSDs by defining the maximum current investment (I_{Max}) in the purchase, installation and management of a PVSD to achieve a Net Present Value (NPV) equal to zero in 15 or in 30 years.** The analysis serves to define a cost benchmark for PVSDs to assess a potential cost.

The net present value) of an investment represents the total of all future cash flows over the project's lifespan, discounted to their present value. This financial metric serves as an objective criterion for determining whether a project is financially viable. The calculation methodology developed and presented below, has been published in [1], where the net present value is defined as follows:

$$NPV = -I_0 + \sum_{n=1}^{y} (C_I - C_O)(1 + D_R)^{-n}$$

Where:

- $\mathbf{I_0}$ is the initial investment in year 0. It represents the extra cost of the system compared to a conventional solution after accounting for subsidies.
- **y** is the life span period considered, in years, in which the NPV of the BIPV system is calculated. In this analysis 15 and 30 years.
- **Dr** is the discount rate.
- $\mathbf{CI_n}$ refers to the cash inflows in year *n* from self-consumed electricity and grid feed-in revenue.
- $\mathbf{CO_n}$ represents the cash outflows in year *n* for operating, maintenance, and replacement costs.

The maximum current investment, I_{Max}, is defined as the value that cancel the NPV (NPV=0):

$$I_{Max} = \sum_{n=1}^{y} (C_I - C_O)(1 + D_R)^{-n}$$

The cash inflows, C_I, during a reference year n, are defined according with the following formula:

$$C_{In} = T_{SC} \times E_{SCn} \times (1 + VEP)^n + T_{FB} \times E_{FBn} \times (1 + VEP)^n$$

T_{SC}, E_{SCn}, T_{FB}, E_{FBn}, and VEP are the withdrawn electricity price (CHF/kWh), the self-consumed electricity during the year n (kWh/yr), the fed-back electricity price (CHF/kWh), the fed-back electricity during the year n (kWh/year) and the linear variation of the electricity price respectively. The withdrawn electricity price is assumed as 0.26 CHF/kWh[1] while the fed-back electricity price is 0.11 CHF/kWh[2]. The linear variation of the electricity price is considered, in Switzerland, 0%[3].

The self-consumed electricity during a reference year (E_{SCn}) can be calculated as following:

---

[1] Median withdrawn electric tariff in Switzerland for an annual energy consumption of 30'000 kWh in 2023, VAT excluded. Elcom
[2] AET 2022
[3] SIA 480/2016

$$E_{SCn} = E_{n=1} \times (1-D)^n \times SC$$

E_n, D and SC are the electricity generated from the BIPV system during the first year (kWh/year), the PV power losses, namely the degradation rate of the PV module (%) and the ratio of the self-consumed electricity (%) respectively. The degradation rate is defined according to (2), and it corresponds to 0.7%/yr.

$E_{n=1}$ is calculated according to the following formula:

$$E_{n=1} = E_{y=1} \times PC$$

E_y and PC are the energy yield (kWh/kWp) and the capacity of the system (kWp). The following calculation assumes E_y and PC as pre-defined parameters for the different PVSD systems investigated in the 3.2. Table 4 shows the capacity of each system and the area of the active cells.

Table 4: Capacity of PVSDs and area of the active cells

PHOTOVOLTAIC SHADING SYSTEM	NOMINAL CAPACITY (kWp)	AREA OF ACTIVE CELLS (m^2)
T01 - External PV venetian blind d/l 4:3	0.80	3.87
T02 - External PV venetian blind d/l 1:1	0.58	2.87
T03 - Horizontal PV louver dynamic	1.97	9.79
T04 - Horizontal PV louver fixed	1.97	9.79
T05 - Vertical PV louver	2.17	10.78

The fed-back electricity during a reference year (E_{FBn}) can be calculated as following:

$$E_{FBn} = E_{n=1} \times (1-D)^n \times FB$$

Where FB represents the share of electricity generated from the BIPV system and fed-back in the electric grid (%). FB represents the amount of electricity produced from the BIPV system and not self-consumed:

$$FB_n = E_n - E_{SCn}$$

The cash outflows, C_O is the O&M cost of the solar system including the cost of the inverter replacement. In this case, the annual O&M costs are assumed to be the 0.03 CHF/kWh produced per year[4], subsidies are not included. The O&M costs include the annual inflation equal to 0.6%[5].

The maximum investment, which is normalised considering the shaded window area, is calculated considering the variables:

- variation of the energy potential for the PVSDs assessed within the previous chapter (Assessment of the photovoltaic potential of PVSD);

[4] O&M cost of a traditional rooftop PV system of 10.2 kWp installed on a single-family house. Costo di esercizio degli impianti fotovoltaici, Svizzera Energia, 2017
[5] https://www.newsd.admin.ch/newsd/message/attachments/57298.pdf

- variation of the self-consumption (60%, 80% and 100%);
- variation of the discount rate (4% and 7% [2]);
- Electricity tariff: withdrawn 0.26 CHF/kWh, injected 0.11 CHF/kWh.

PVSDs are systems that produce electricity and replace the functions of conventional shading devices. Hence, the maximum investment for PVSD can be considered an extra cost compared to a traditional conventional system. The extra cost approach is based on the idea that an investment in a PVSD, or any BIPV project, should only be assessed based on the extra cost that BIPV represents compared to a competing conventional solution. It is quantified by summing the cost of making the cladding "active" and the associated accessories such as cabling, inverters and/or optimiser.

When the investment (cost of purchase, installation and management) in a PVSD, under the calculation conditions, is below the maximum current investment, the investment can be considered favourable. The results are shown in Table 6 and Table 7.

The analysis serves to quantify an economic benchmark that allows stakeholders in the PVSD sector to orient themselves in defining a competitive product. At the same time, it can be useful for the end user to define the maximum possible investment to purchase a PVSD. The results show a maximum investment value (extra cost) calculated in 30 years of about 600 CHF per m^2 of active area for the horizontal PV louver (**T04**) with 4% WACC and maximum self-consumption and fixed slats at 50°, in Rome and Lugano, since the self-shading is very limited, and the slats have better exposure to the solar radiation. For the same system calculated with a self-consumption of 60% and a WACC of 7%, the maximum suggested investment is approximately 300 CHF per m^2 of active area calculated over 30 years and 250 CHF/m^2 over 15 years. For the vertical PV louvers (**T05**), the maximum suggested investment, considering a ROI of 15 and 30 years, is approximately 200-400 CHF/m^2 and 250-600 CHF/m^2, respectively, for a south-facing solar tracking installation depending on the boundary conditions. Considering the self-shading effect between the slats and the control strategy, the external PV venetian blind (**T01**) is the system that performs the worst economic output. Indeed, the suggested maximum investment in 15 years, considering installation, material and O&M, is defined between 80 and 200 CHF/m^2 and 90-300 CHF/m^2 calculated in 30 years for the solution **T01**. However, further optimisation of the PV cell design and an accurate shape of the slats could achieve considerable benefits in terms of energy performance, as demonstrated on the PV vertical louvers.

3.4 Discussion on Energy and economy assessment of PVSD

Literature review

The studio reveals that PVSDs require a customised design in each climate and environmental condition with regards to the tilt angle, the blind spacing, and width to maximise the benefits between energy production and energy savings. Indeed, the tilt angle that maximises the energy production of PVSD does not always guarantee the overall electricity benefits. The mutual shading effect between slats, in the case of louvres, window blinds and multiple repeated PVSD, increases by increasing the width of the slat. It influences the decrease in energy production. Significant shading effects are also registered by decreasing the tilt angle of PVSD. However, PVSDs are less sensitive to PV blind angle than PV blind spacing. Finally, implementing optimal control methods for PVSD increases PV efficiency, maintaining user comfort.

Energy potential of PVSD

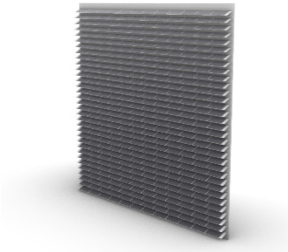
The external PV venetian blinds have the lowest yield in comparison with horizontal and vertical louvres: up to 39% lowest yield in comparison with south-oriented horizontal louvres and up to 41% lowest yield in comparison with south-oriented vertical louvres. This is mainly due to the self-shading effect between the slats and the control strategy. These considerations indicate that there might be some shortcomings in using south-oriented thin slats with reduced interspaces to produce electricity. The analysis also reveals that the yield of south-oriented horizontal PV louvres is about 35-38% higher when the angle is maintained at 50° instead of 15° since the self-shading is very limited and the slats have better exposure to solar radiation.

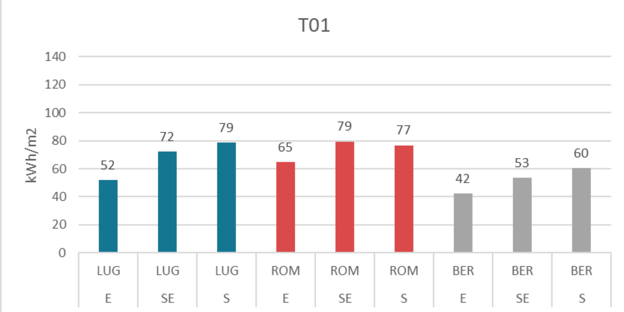
Maximum investment for cost-effective PVSD

The maximum present investment in purchasing, installing and operating a cost-effective vertical PV louvre, defined as a NPV after 15 years, is about 200-400 CHF/m^2 for a south-facing solar tracking installation depending on the boundary conditions. The maximum present investment of a cost-effective external PV venetian blind, defined as a NPV after 15 years, is about 80-200 CHF/m^2 and, after 30 years, 90-300 CHF/m^2. The maximum investment is considered an extra cost compared to a traditional conventional system.

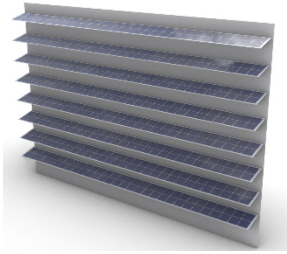
Table 5: Energy yield (kWh/m2) for different PVSD typologies. In the X axis, the different climate conditions (Lugano, Rome and Berlin) and orientations (east, south-east and south).

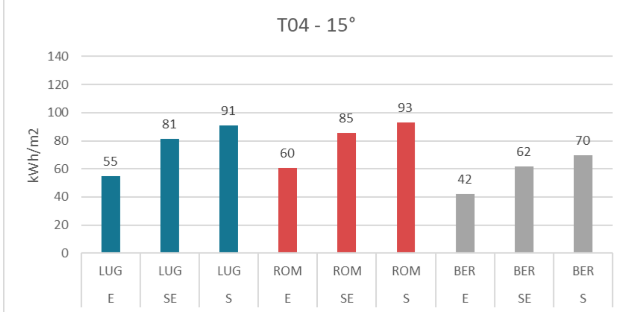
External PV venetian blind, d/l 4:3, dynamic system (T01)



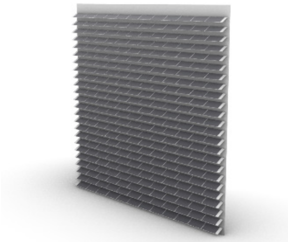


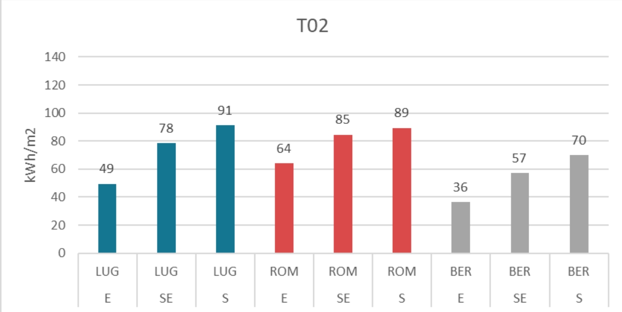
Horizontal PV louvre, d/l 0.95, fixed 15° (T04)



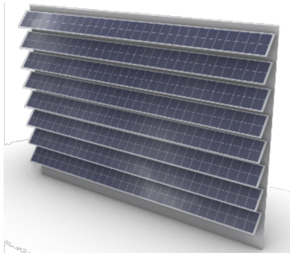


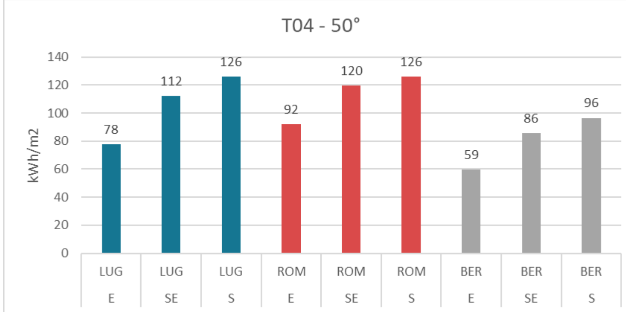
External PV venetian blind, d/l 1:1, dynamic system (T02)



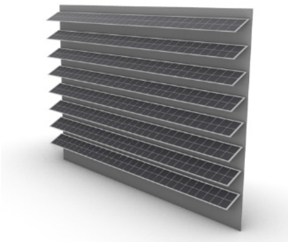


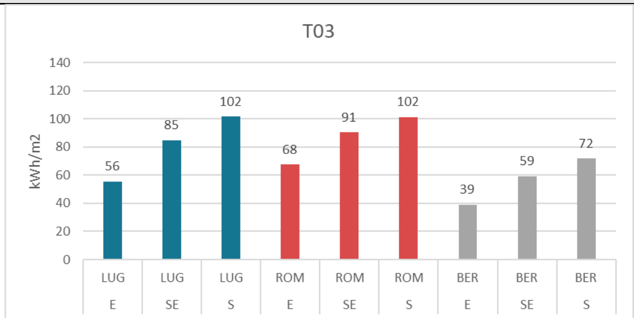
Horizontal PV louvre, d/l 0.95, fixed 50° (T04)



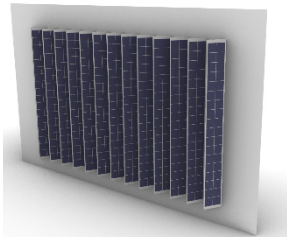


Horizontal PV louvre, d/l 0.95, dynamic system (T03)





Vertical PV louvre, d/l 0.95, dynamic system (T05)



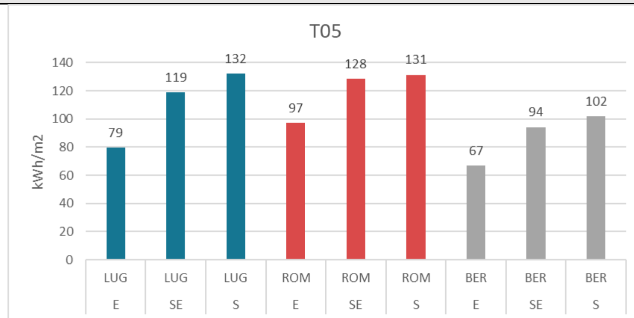
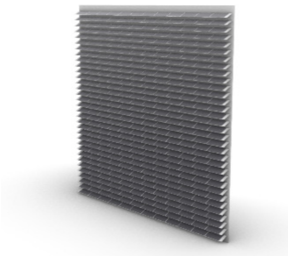
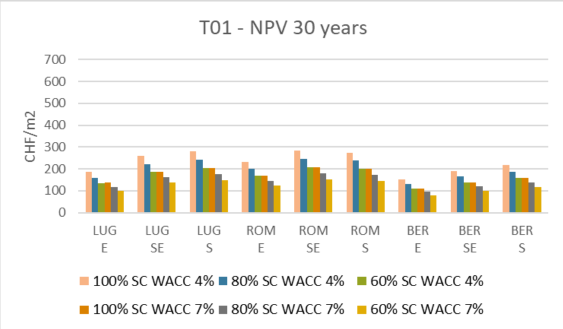


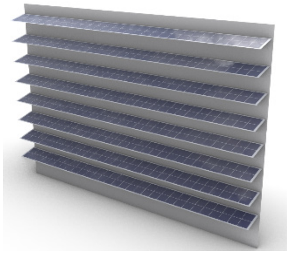
Table 6: Maximum investment for cost-effective PVSDd after 30 years.

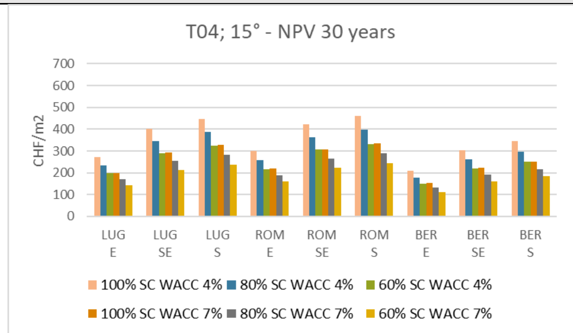
External PV venetian blind, d/l 4:3, dynamic system (T01) – 30 years



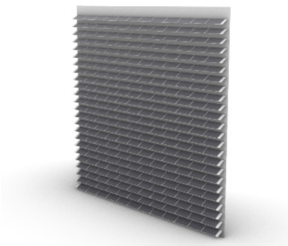


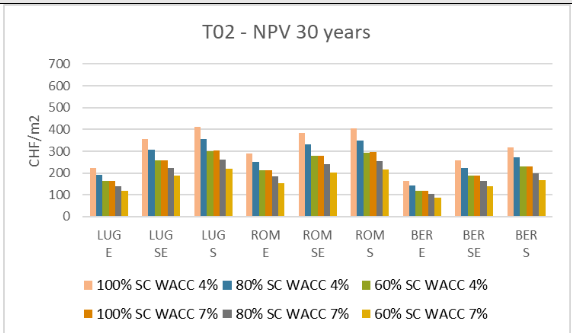
Horizontal PV louver, d/l 0.95, fixed 15° (T04) – 30 years



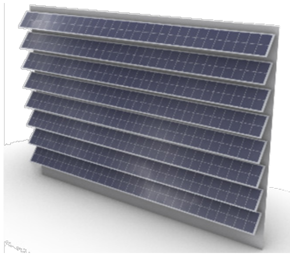


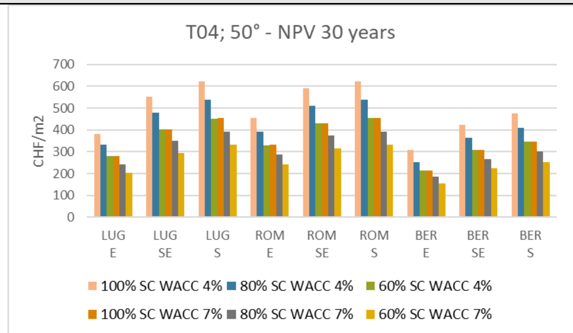
External PV venetian blind, d/l 1:1, dynamic system (T02) – 30 years



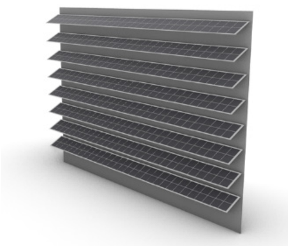


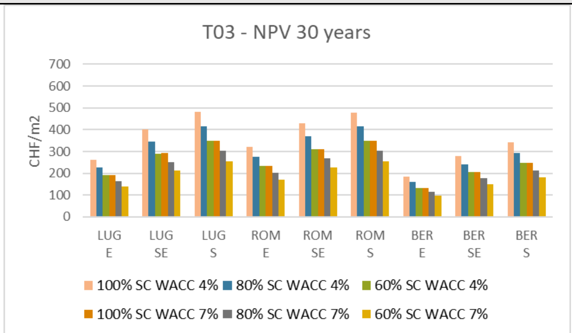
Horizontal PV louver, d/l 0.95, fixed 50° (T04) – 30 years



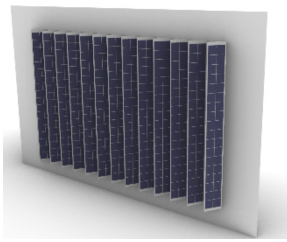


Horizontal PV louver, d/l 0.95, dynamic system (T03) – 30 years





Vertical PV louver, d/l 0.95, dynamic system (T05) – 30 years



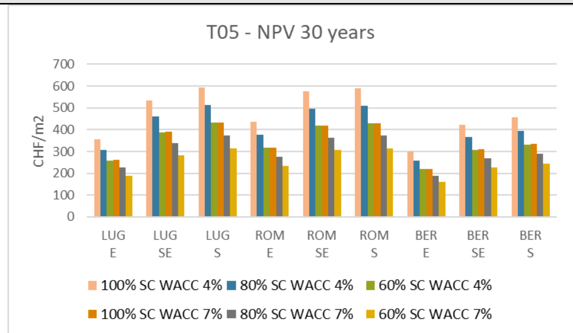
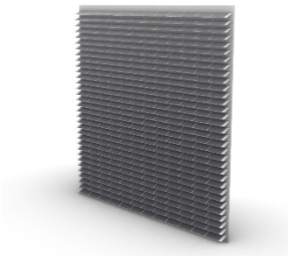
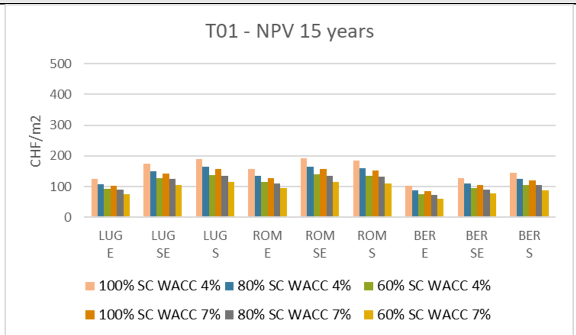


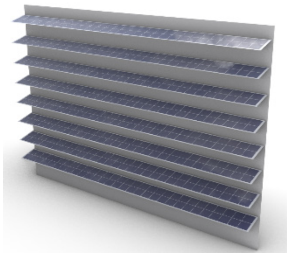
Table 7: Maximum investment for cost-effective PVSDd after 15 years.

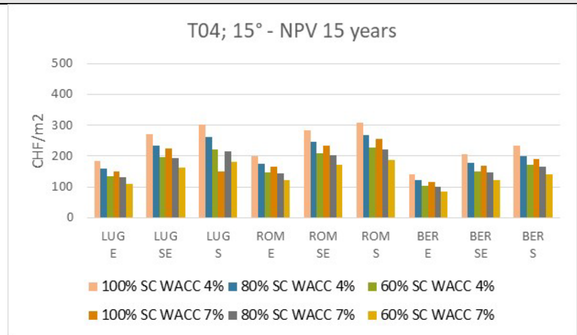
External PV venetian blind, d/l 4:3, dynamic system (T01) – 15 years



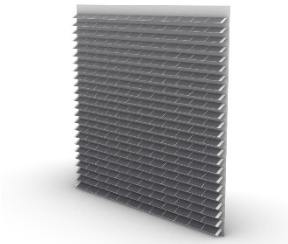


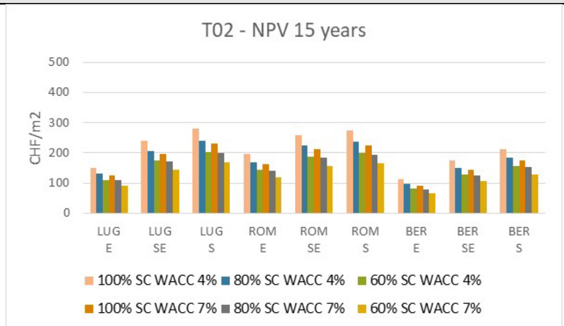
Horizontal PV louver, d/l 0.95, fixed 15° (T04) – 15 years



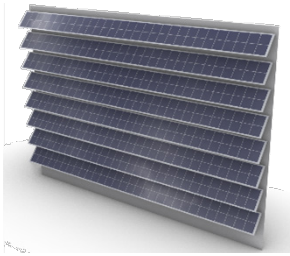


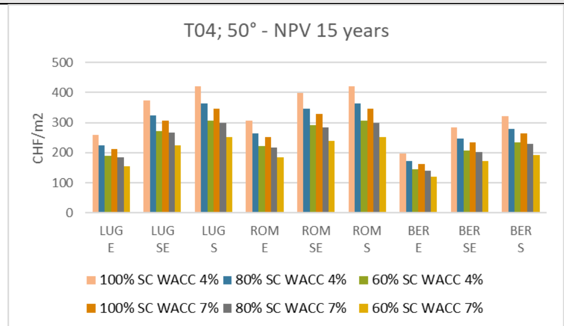
External PV venetian blind, d/l 1:1, dynamic system (T02) – 15 years



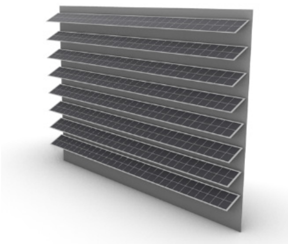


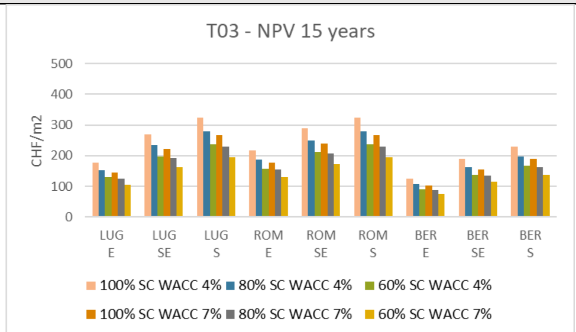
Horizontal PV louver, d/l 0.95, fixed 50° (T04) – 15 years



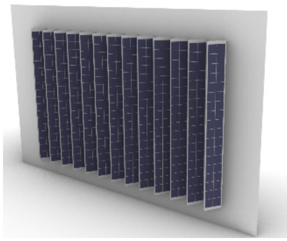


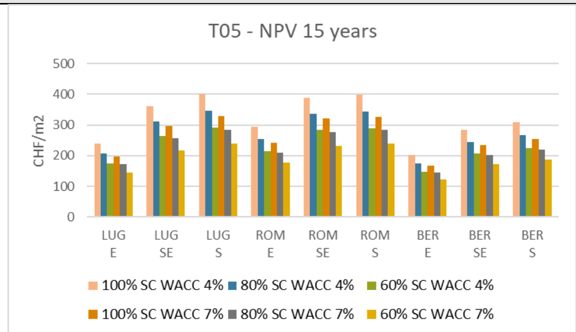
Horizontal PV louver, d/l 0.95, dynamic system (T03) – 15 years





Vertical PV louver, d/l 0.95, dynamic system (T05) – 15 years





4 Technology validation

To assess the outdoor performance of the innovative photovoltaic shading device (PVSD) tailored for the new FUS façade and specified in the Chapter 2, a mock-up was installed on the rooftop testing facility of SUPSI at Mendrisio. The mock-up allowed for comprehensive outdoor validation, ensuring the PVSD could perform effectively under real-world operational conditions.

This chapter reports the results of the one-year monitoring activities. Collected datasets, including temperature, humidity, and electrical measurements of PVSD, were analysed by first cleaning and filtering data to improve data quality, reduce distortions, and avoid misinterpreting results.

4.1 Mock-up installation

The multi-orientation of the building façade for PVSD installation and interaction with the shading from surrounding structures highlight the criticality of irradiation inhomogeneity on the PV slats and the importance of improving the electrical connection within the PV slats and wiring between the slats to maximise the electrical energy production without having to produce slats with different typologies.

Two PV module types (Table 8) have been manufactured to compare the energy performance: optimised and standard PV modules. The internal circuit of the optimised PV module was divided vertically into two electrically independent strings. Each optimised PV module’s vertical string (with six cells) is connected to a bypass diode. On the contrary, all cells of the standard design were connected in series and connected with a single bypass diode. The standard module's architectural design does not prioritise optimisation for enhanced shading tolerance – providing a baseline for quantitatively comparing shading tolerance.

The quantitative performance analysis and validation of optimised PV slats are based on two key performance indicators (KPIs). The KPIs were established based on the same preliminary studies to optimise PV module design:

- KPI1 PV module temperature reduction: temperature of optimised module < temperature of standard module[6]
- KPI2 Outdoor module energy yield: energy yield of optimised module > 20% energy yield of standard module[6]

[6] The standard module is a dynamic PV solar shading solution. The module's architectural design does not prioritise optimisation for enhanced shading tolerance.

Table 8: Features of PV modules

OBJECT	DESCRIPTION
Front glass	Float satin glass thickness 4mm uniform Suncol colour "Bianco Traffico"
Encapsulant	POE
Cell type	n°12 c-Si cells 158.75x158.75 mm; ribbon black; 2 strings of 6 cells
Back glass	Float clear thickness 4mm
Number of PV module	Optimised PV module: n°3 ¦ Standard PV module: n°3
Weight	23.75 Kg/m2
Thickness	9.5 mm (-0.5mm / +1.5mm)
Dimensions	1147 x 350 mm
Nominal power	34 Wp per module

Diode and PV module temperatures of mock-up slat L2 and L5 (Figure 4) were measured to compare the long-term outdoor measurements quantitatively with those of the indoor tests and assess the long-term thermal safety and reliability in outdoor and operational environments. The thermal safety and reliability of a new PVSD design are crucial for marketability, as required by all levels of government for BIPV installations. Temperature sensors were attached to diodes and on the rear-side glass of the left and right strings (approximately at the centre of the cells). Air gap temperature, i.e., air mass temperature between the module's rear side and aluminium enclosure, was also monitored to evaluate the impact of enclosing the PV module's rear side and restricting air flow on heat dissipation and corresponding PV module temperature.

Three EKO ML-02 silicon pyranometers (Figure 4, left) were attached to the L2 slat's front glass to measure plane-of-array (POA) irradiance incident on the left string, right string, and slat (at the vertical centre line of the slat). A meteorological station on the SUPSI rooftop provided irradiance, ambient temperature, and humidity data. Of six PV modules, only four are active. As shown in Figure 4, right, the left strings of optimised slats (L2 and L3) are connected in series to one maximum power point tracker (MPPT) and the right strings to the second MPPT. Two standard PV slats, L4 and L5, are connected in series to the third MPPT. The MPPT recorded the maximum voltage and current.

Figure 4: Left) mock-up installed at the rooftop test facility of SUPSI and right) maximum power point tracker (MPPT) connection for optimised and standard PV slats.

4.2 Temperature assessment

Indoor test

As part of the research activities for PVSD technology validation, electrical characterisation and indoor tests specified by IEC normative, for ensuring the safety and reliability of PV slats, were conducted by SUPSI PVLab. The PV slat's thermal safety and reliability tests include hot spot endurance, shading resistance, and bypass diode thermal tests. The indoor thermal test results from previous interim reports are highlighted in Table 9. Standard and optimised slats measured the same maximum temperature during indoor temperature tests under unshaded operation conditions. However, the optimised slat demonstrated higher shading tolerance with lower maximum temperatures in two shading tests: 2.0°C and 3.0°C lower in the shading resistance and hot spot endurance tests.

The indoor thermal tests were conducted to validate the safety and reliability of PV slats and to evaluate the temperature performance of optimised PV slats compared to standard design. The indoor test results were compared to one-year outdoor measurements, serving as the baseline for evaluating the long-term thermal safety and reliability under outdoor conditions [3]. The electrical schema and the configuration of the probe are shown in Figure 5.

Table 9: Temperature comparison at non-conventional shading scenarios.

PV module	Max. temperature 1000W/m2, Tamb = 40°C	Max. temperature Moving shadows (NTP-EL01)	Max. temperature Hot spot testing
Standard	60.0 °C	58.0 °C	76.0 °C
Optimised	59.9 °C	56.0 °C	73.0 °C

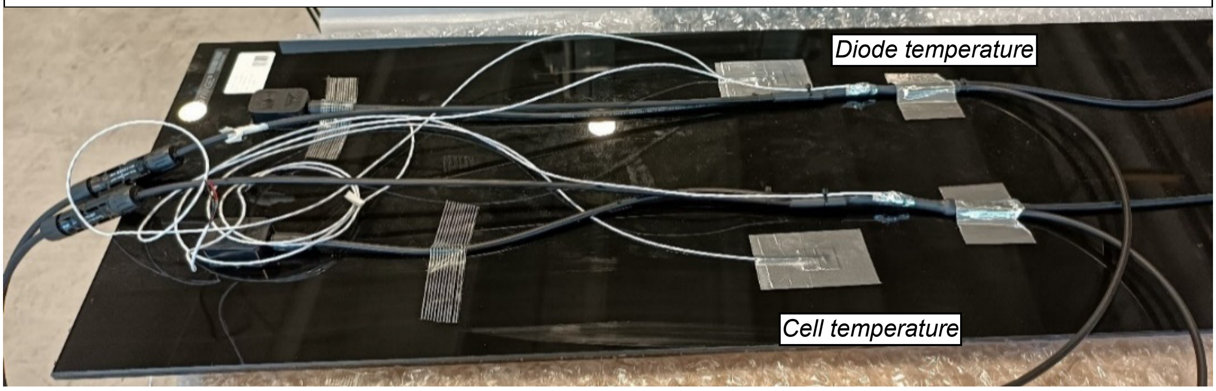


Figure 5: Back of an optimised PV module with probes (PT100). The air cavity temperature is measured with probes installed on the metal slat.

Outdoor test

PV module temperature

The temperatures of the outdoor PV modules align with the indoor tests, as shown in Figure 6. The optimised slat design (L2) consistently recorded lower maximum and mean temperatures for both the left and right strings compared to the standard design (L5). The outdoor maximum temperatures were also lower than those observed during shading resistance and hot spot endurance tests. These results meet the first KPI, confirming that the optimised PV design aligns with our expectations—derived from parametric analysis, simulations, prototyping, and indoor testing—to operate safely and reliably in outdoor conditions over an extended period, which is crucial for market success.

In the case of L5, the current generated by the unshaded string was limited due to the partial shading of one string, causing the excess power output from the unshaded string to be lost as heat in the shaded string, leading to elevated module temperatures. In contrast, the partially shaded string of L2 is not electrically linked to the unshaded string, preventing this heat accumulation. This design enhances shading and mismatch tolerance, resulting in improved energy performance, which will be discussed further. Moreover, the maximum and mean temperatures of the right string in L2 are higher than those of the left string, a phenomenon that will be clarified in the next section with daily temperature curves.

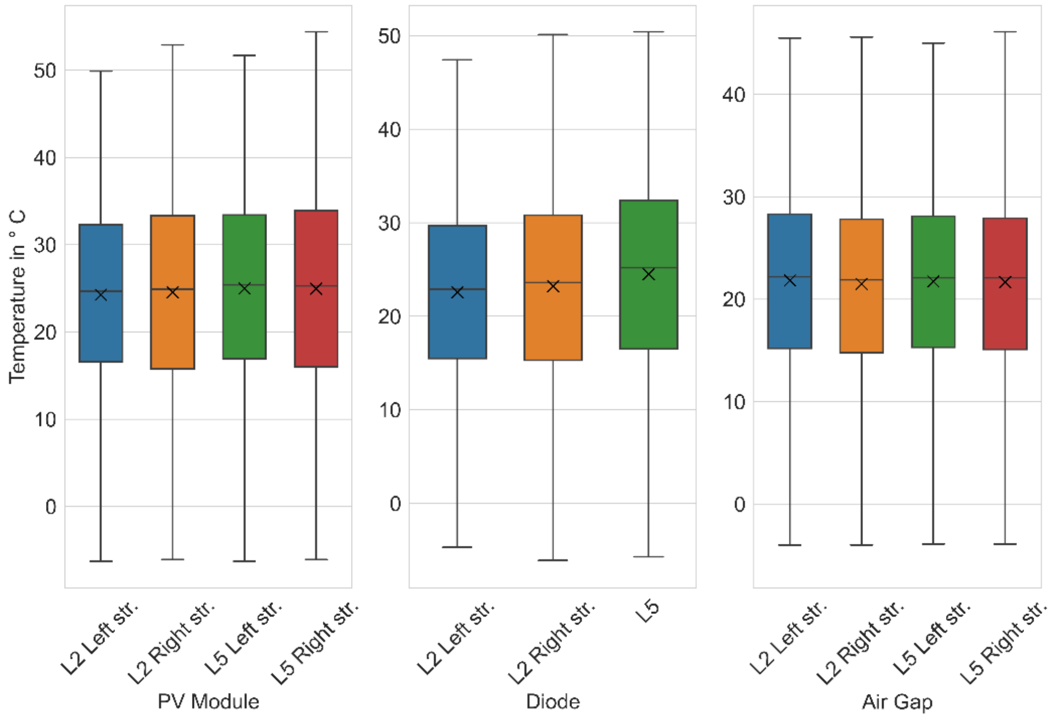


Figure 6 Comparison of module, diode, and air gap temperature between optimised and standard PV modules. The box's horizontal line and "X" mark denote median and mean values, respectively.

<u>Diode and air gap temperature</u>
No anomalies were detected in the diodes' temperatures during long-term outdoor operation, with maximum temperatures remaining lower than those of the PV modules, as illustrated in Figure 6. The same diode used in the pilot installation was also employed for the mock-up slats. This diode is rated for a maximum junction temperature of 200 °C, a maximum reverse bias voltage of 40 V, and a short-circuit current of 7.5 A. The electric current generated by the mock-up slats was relatively low, ranging from 3 A to 4 A, with voltage readings below 14 V. Consequently, the diode experienced only moderate heating when the lower current from the unshaded strings passed through the active diode. However, this scenario occurred only in L5, and repeated activation could increase the risk of early failure.

Overall, the maximum diode temperatures for both L2 and L5 were well below 140 °C, which is the highest diode temperature recorded during indoor thermal testing (conducted according to IEC 61215-2:2021, MQT 18.1). This indicates the thermal safety and long-term reliability of the bypass diodes in outdoor environments. Similarly, air gap temperatures showed no anomalies and were lower than those of the PV modules. The high thermal conductivity of thermo-lacquered aluminium facilitates efficient heat transfer, while the support structures within the air gap enhance the heat dissipation area.

4.3 Energy assessment

As illustrated in Figure 7, during the monitored period, the total energy yield for the optimised PV slats (L2 and L3) was 40.8 kWh, compared to 36.1 kWh for the standard PV slats (L4 and L5). This total for L2 and L3 was calculated by summing the energy yields of the left and right strings. Notably, the solar altitude is lower in winter than in summer, resulting in higher energy production for vertical PV slats during winter. The energy yields for July and December were relatively lower due to lower data availability at 55% and 45%, respectively. Moreover, all recorded days in July were cloudy.

The optimised PV slats achieved a yield gain of 20% or more for seven months, meeting KPI 2. However, the annual yield gain was 13%, as the yield gains from October to February ranged from 3% to 11%, with no observed gain in December. The unshaded strings of L4 and L5 had their current limited by the partially shaded strings, leading to reduced power output and energy yield, as shown in Figure 8.

In contrast, the optimised design consistently outperformed the standard design regarding temperature and energy performance, as indicated by the yellow region. The orange area shows that standard PV produced higher energy output at noon, which can be attributed to the optimised PVs' lower peak power and fill factor. While the exact reasons for this remain unconfirmed, it suggests that the energy gain for optimised PVs could be higher. By splitting the two strings, each equipped with a bypass diode, the impact of temperature due to shading mismatch is reduced, resulting in significant energy yield gains, especially during summer when solar altitude is at its highest.

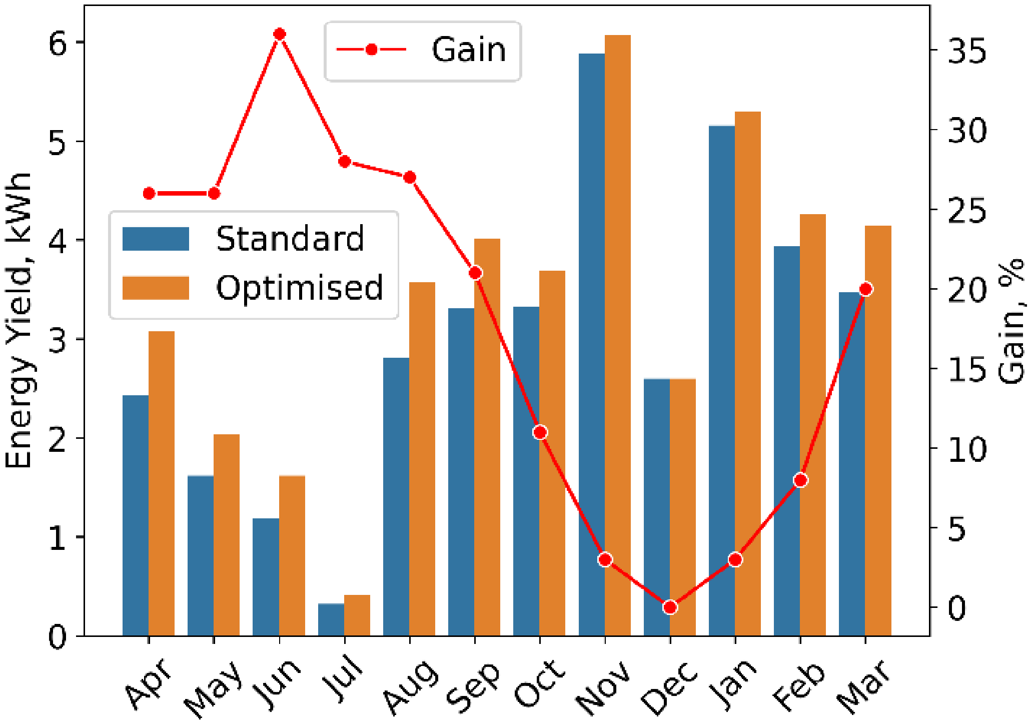


Figure 7: Monthly energy yield for mock-up

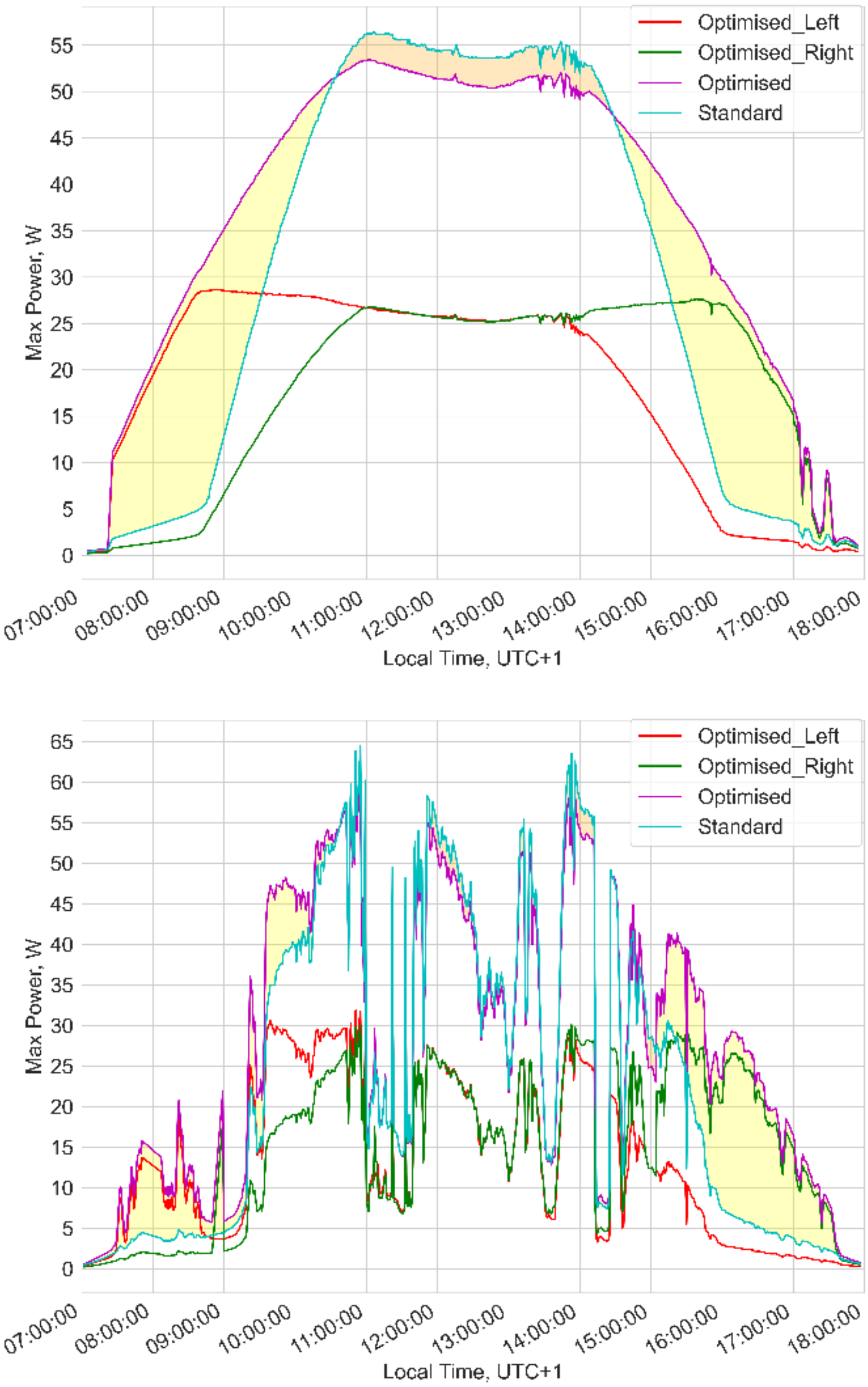


Figure 8: Time series of power yield for left) clear sky day (12th March) and right) cloudy day (11th March).

4.4 Discussion on technology validation

Highlights:

- The optimised PV slat, with two separate vertical strings, successfully enhanced tolerance to shading and minimising mismatch losses.
- The optimised PV slat achieved a gain of more than 20% during spring and summer, boosting the energy yield during months with higher solar altitude.
- For indoor and long-term outdoor test, module temperature of optimised PV slat was consistently lower than the standard design – ensuring the long-term thermal safety and reliability.

In conclusion, **the optimised PV slat's shading and mismatch tolerance are proven by reduced temperatures and improved energy performance.** The new innovative PVSD has gone through the whole design and test processes, including simulation, prototyping, and outdoor testing, to ensure long-term safety and reliability. It also improves energy yield compared to conventional products, eliminating the technical obstacles for market introduction. Detailed preliminary studies to analyse the irradiation distribution and the impact on energy yield facilitate the optimisation of the electrical interconnection by splitting the strings vertically. The design effectively reduces the mismatch effects between unshaded and shaded strings, by consistently measured lower temperatures than those of the standard design regardless of the sky conditions. It also enhances energy yield, particularly during spring and summer when solar elevation is higher. In contrast, partial or complete shading limits the current output of standard design due to the series connection of all cells.

5 Technology demonstration

A monitoring scheme was developed for the pilot installation of PVSDs on the FUS façade, located on the university complex's west side (Figure 9). The monitoring aims to showcase the system's progression from TRL6 to TRL7, indicating reliable and replicable technology with minimal process and maintenance costs in full-scale buildings. Activities involve tracking and comparing temperatures (diodes, air gap, and cells) of the PV slats (Figure 10) with those of the mock-up in Mendrisio. In the following subsections, the analysis of one-year temperature and energy measurements is presented.

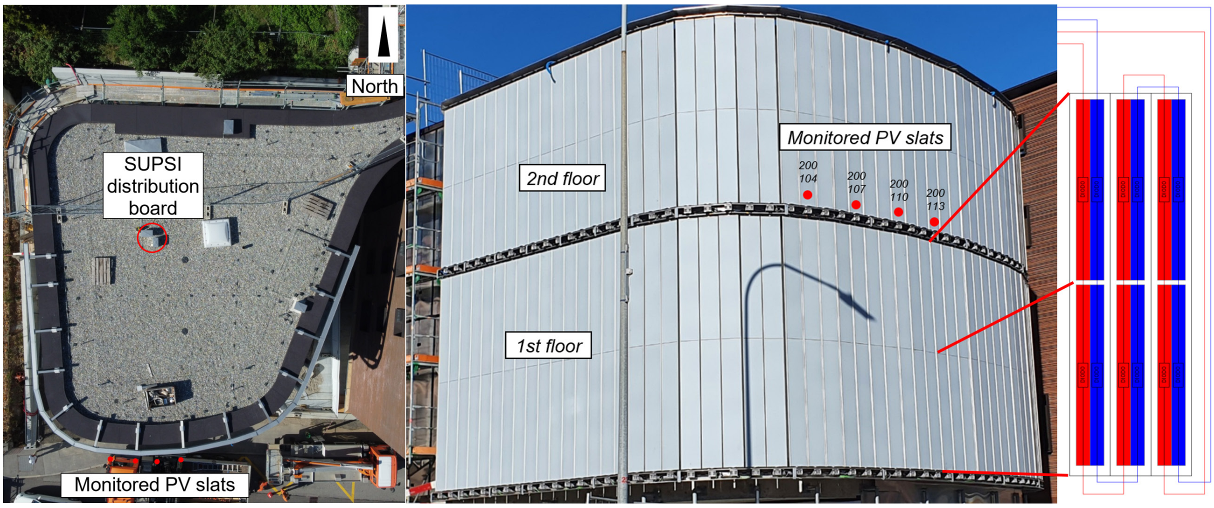


Figure 9 Left) ariel view of PVSD pilot installation, and right) modules on the left and right sides of the slats are separated, and each is connected to one optimiser.

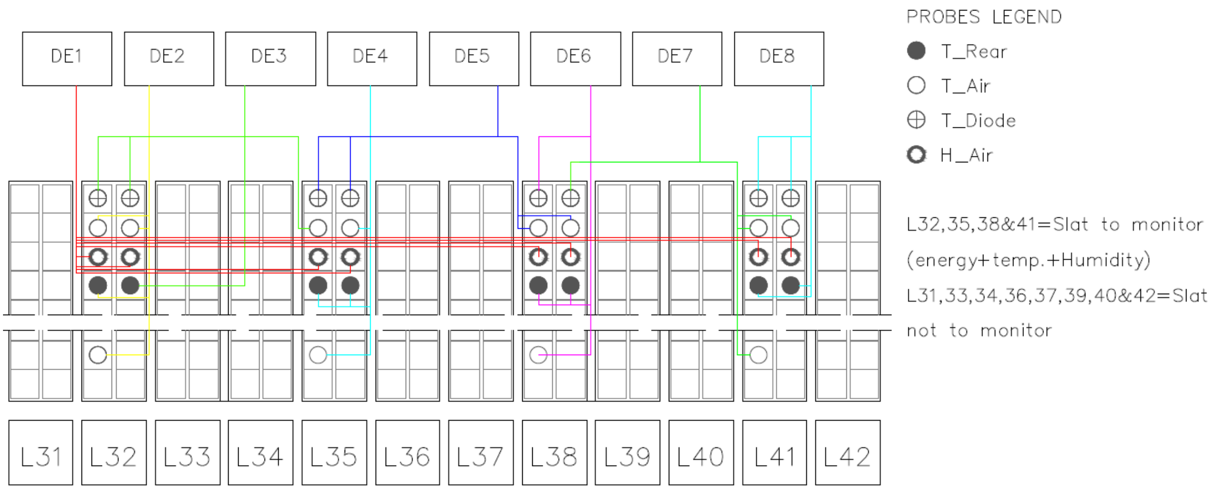


Figure 10 Schematic diagram for temperature probe positions.

5.1 Pilot installation

Demonstrating the technology in a real operation building environment ensures the TRL enhancement from TRL 6 to 7. Along with the manufacturing of the PV modules, the off-site assembly of the PVSD component and the on-site construction of the building skin were completed in the first reporting period, so that the next analysis will allow performing cross-referenced benchmarking between the controlled outdoor environment (mock-up) and the "as-built" condition in the real building (pilot installation) according to the project KPIs.

The PV slat manufacturing process involved the participation of a large group of stakeholders, which define the AIL consortium partners. The consortium developed the engineering, manufacturing and installation of the BIPV system at FUS. The PV modules were manufactured by the project partner Sunage according to the features shown in Table 10-top. The PV module has been optimised to increase the shading tolerance. The slats are realised with a loadbearing extrusion made of aluminium according to a specific shape which optimises the static resistance (Table 10-bottom, Figure 11). 126 PV modules of about 81 Wp have been installed on the first floor and 126 PV modules of 64 Wp on the second (Table 11).

Table 10: Features of PV modules (top) and slat (bottom).

PV MODULE (Partner: Sunage)	
Front glass	Float satin glass thickness 4mm uniform Suncol colour "Bianco Traffico"
Encapsulant	POE
Cell type	First floor: n°28 c-Si cells 158.75x158.75 mm; ribbon black; 2 strings of 14 cells Second floor: n°22 c-Si cells 158.75x158.75 mm; ribbon black; 2 strings of 11 cells
Back glass	Float clear thickness 4mm
Number of PV modules	First floor: 126 ¦ Second floor: 126
Weight	23.75 Kg/m2
Thickness	9.5 mm (-0.5mm / +1.5mm)
Dimensions	First floor: 2310x350mm2 ¦ Second floor: 1830x350mm2
Nominal power	First floor: 81.44 Wp per module ¦ Second floor: 64 Wp per module
SLAT (Partner: AIL consortium – Kummler+Matter, Poretti & Gaggini)	
Material	Aluminium EN AW-6060
Weight	5.46 Kg/m
Shape & thickness	See Figure 11
Dimensions	First floor: 4630x360mm ¦ Second floor: 3670x360mm

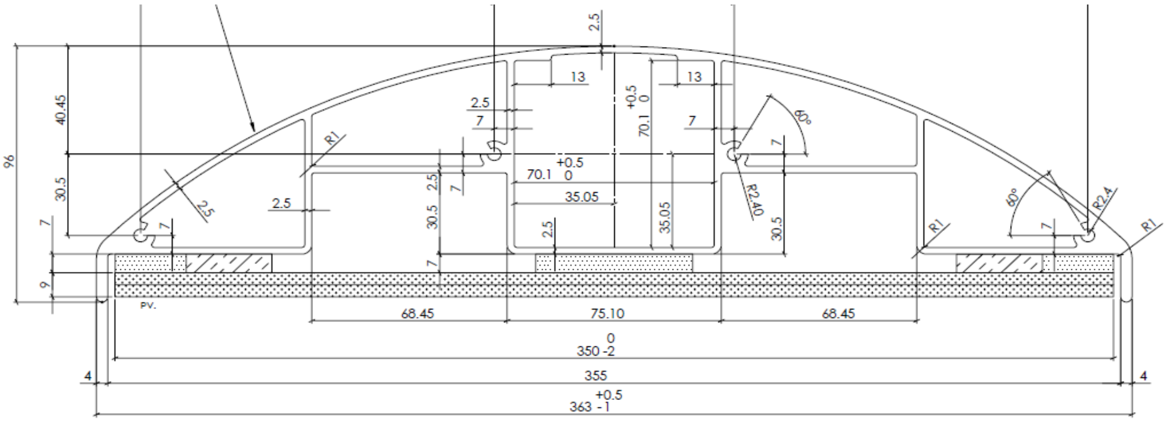


Figure 11: Shape and dimension PV slat.

Table 11: Specific of the BIPV system.

SECOND FLOOR	
N°1 inverter	SolarEdge SE7K
N°42 power optimisers	SolarEdge P404
N°63 PV slats, each made of 2 PV modules	Each string is composed of 6 PV modules in a series of 11 cells (66x2)
N°21 motors	N°1 motor manages three PV modules
N°63 reducers	
The string on the first floor (42 optimisers) has a power of 8.064 kWp with a safety voltage of 42 VDC	
FIRST FLOOR	
N°1 inverter	SolarEdge SE7K
N°42 power optimisers	SolarEdge P404
N°63 PV slats, each made of 2 PV modules	Each string is composed of 6 PV modules in a series of 14 cells (84x2)
N°21 motors	N°1 motor manages three PV modules
N°63 reducers	
The string on the second floor (42 optimisers) has a power of 10.261 kWp with a safety voltage of 42 VDC	

5.2 Temperature and humidity assessment

Figure 12 (left) presents the descriptive statistics for temperature measurements of slats “104” (Figure 9). The temperature components for Group 1—*air_1*, *module_1*, and *diode_1*—represent the air gap, rear-side PV module, and diode temperatures for the left string of the slat respectively, while Group 2 corresponds to the right string. Furthermore, Figure 12 (right) displays the descriptive statistics for relative humidity. Only results for slat “104” are presented here because temperature measurements across all monitored slats do not vary significantly: the mean and maximum PV temperature differences for slats “107”, “110”, and “113” are no more than 0.4 °C and 0.2 °C, respectively. For the diode and air gap temperatures of the other slats, the mean and maximum differences are within 0.8 °C and 2.8 °C, and 0.4 °C and 1.1 °C, respectively. The slight temperature variations among all slats suggest consistent manufacturing quality, with differences attributed to slat orientation and varying irradiance throughout the day. PV module, diode, and air gap temperatures show no anomalies; diode and PV module temperatures remain below the indoor thermal test values. Furthermore, the mean and maximum temperatures of the PV modules correspond with those of both the optimised and standard PV slats from the mock-up, indicating that the pilot installation's temperature performance aligns with the mock-up.

Figure 12 (left) also includes statistics for *air_1* and *air_1_bottom* for slat “104”, showing a maximum temperature difference of only 0.2 °C. However, this difference ranges from 1.0 °C to 2.3 °C for the other three slats. A notable increase in temperature difference was observed on August 22 (a clear-sky summer day), with the top portions of all slats recording higher temperatures than the bottoms. Lastly, the other slats' mean and maximum relative humidity show negligible differences compared to slat “104”, at approximately 0.7% and 2%, respectively. Overall, the statistics support the mock-up findings: the maximum module temperature is highest, followed by the diode and air gap temperatures, with the right string consistently showing higher maximum temperatures than the left.

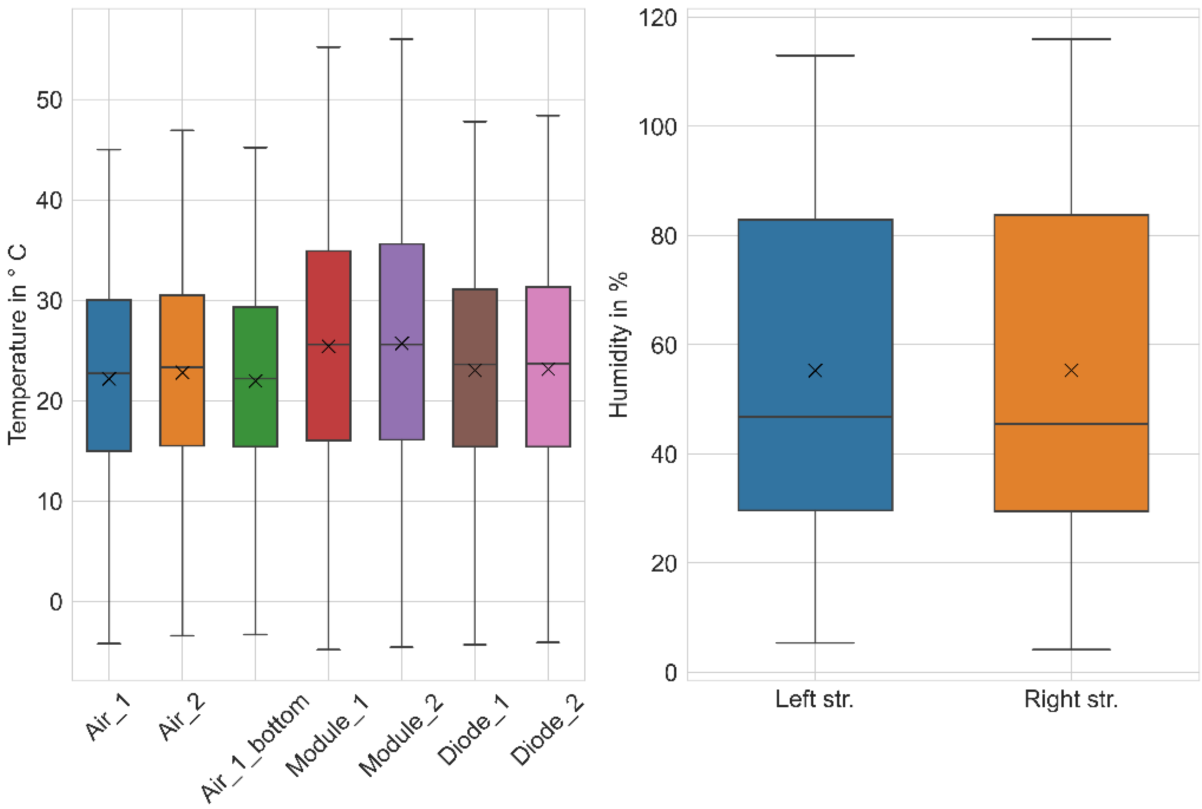


Figure 12 Descriptive statistics of left) temperature components and right) relative humidity measurements for slat 32 (or 104 in Figure 9).

5.3 Energy assessment

Figure 13 displays the energy and specific energy yield data from April 2023 to March 2024. The total energy yield for the PVSD system on the first and second floors is 4.85 MWh and 4.19 MWh, respectively. Notably, the system was non-operational in February due to maintenance. While the first-floor system consistently yields more energy than the second, its specific energy yield is lower. This discrepancy can be illustrated through an irradiance simulation example (Figure 14).

Figure 14 shows the irradiance received by selected slats at different façade orientations on June 21. As noted in the introduction, all selected slats face the same southwest orientation due to a shared tracking algorithm. With the solar altitude higher in June (and throughout summer), the upper parts of the second-floor slats capture more irradiance, resulting in a relatively higher specific energy yield. In contrast, the upper portions of the first-floor slats are often shaded and receive less exposure, particularly those oriented east-southeast and south-southwest.

Analysis of the mock-up results indicates that the effects of shading and mismatch on total energy yield could be exacerbated with a standard PV design, highlighting the necessity for BIPV-specific consultancy from the outset. Additionally, we observed that occupants frequently adjusted the slats manually, leaving them in non-optimal positions for energy production. To enhance performance, the control algorithm needs improvement, such as reverting to the original tracking position when the auditorium is unoccupied, which could be managed through motion sensors or computer vision techniques.

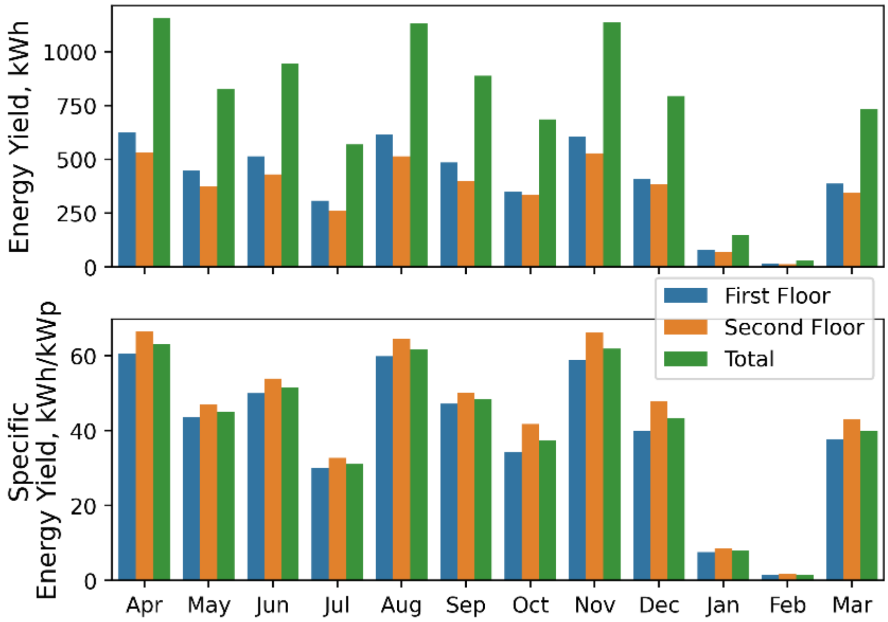


Figure 13: Monthly energy and specific energy yield for pilot installation.

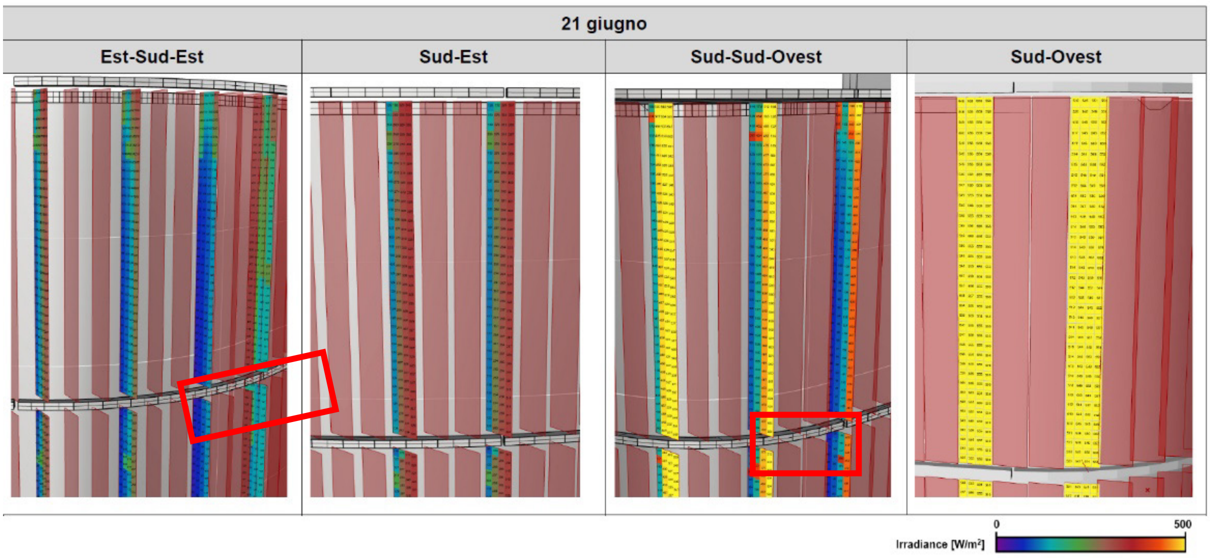


Figure 14: Red boxes indicate the shaded top portions of the first floor's PV slats.

5.4 Discussion on technology demonstration

Highlights:

- Long-term temperature measurements are in accord with those of the mock-up, achieving technology transition from TRL 6 to TRL 7.
- No extreme PV module, diode, and air gap temperatures were observed, indicating PVSDs' long-term thermal safety and reliability for real-building applications.
- BIPV-specific consultancy and design process are crucial, as can be seen from the energy yield reduction for first-floor due to shading, which could be worsen if standard PV design is used.

For complex technologies like dynamic PVSD installed on façades with various orientations and subjected to partial shading, it is essential during the design and planning phases to analyse irradiation inhomogeneity on the PV slats. This can be achieved through simulations of the building's 3D model, including detailed representations of the surroundings. Such analyses help optimise electrical interconnections, striking a balance between maximising energy production and minimising the need for diverse PV module typologies. This approach also reduces production and installation costs, enhancing marketability and promoting the widespread adoption of dynamic PVSD in various building projects.

Throughout the pilot installation, no extreme temperature or humidity measurements were recorded for the monitored slats, indicating that **there are no additional risks associated with the long-term application in real buildings**. The slight temperature variations among all monitored slats indicate consistent manufacturing quality. Furthermore, the temperature trends of the pilot installation are consistent with those observed in the mock-up, successfully demonstrating the technology readiness transition from 6 to 7.

The specific energy yield of the first-floor system is lower than that of the second floor, primarily due to shading of the upper parts of the first-floor slats during periods of high solar elevation. Utilising a standard PV design could further exacerbate energy yield issues. These results underscore the significance of research and development projects for achieving high technology readiness levels (TRL). **Both the mock-up and pilot installation reinforce the technological foundation for new PVSD designs, ensuring safety and reliability for long-term application—critical components for successful market introduction**.

Finally, the analysis in Chapter 4 and Chapter 5 have been published as EU PVSEC 2024 conference proceeding and scientific paper [4].

6 Construction site monitoring

6.1 Stakeholder map and cost breakdown

To illustrate the compelling value proposition of the PV shading device solution implemented at FUS, we conducted an extensive construction site monitoring initiative. This comprehensive endeavour spanned from the initial project conception through the culmination of building operations. Our undertaking encompassed an intricate examination of the multifaceted stakeholders involved in the entire process, meticulous time and procedural delineations, a comprehensive assessment of expenditures with thorough documentation, and an identification of challenges and opportunities that arose during construction.

Our primary objective is to foster robust collaboration between the PV sector and the building industry by presenting a resounding business case that underscores cost-effectiveness and the key drivers essential for the seamless integration of PV technology into buildings on a large scale. This report not only conducts a thorough analysis of the current landscape but also formulates a strategic roadmap geared towards streamlining the fragmented PV integration process. The objective is to pave the way for a more efficient and cost-effective future for the PV industry within the building sector while demonstrating our commitment to key performance indicators (KPIs) such as "Final User Cost" (KPI3) and "Installation and Dismantling Cost Reduction" (KPI4). These KPIs are validated as follows:

- KPI3: achieving a final user cost for the commercialized solution of less than[7]: <1'500 CHF/m^2
- KPI4: implementing a 10% reduction in installation and dismantling costs[8]

The research engendered a thorough and all-encompassing analysis of stakeholders and value chains within the realm of PV industry integration into the building sector. This rigorous approach lays the groundwork for the presentation of a compelling business case that not only underscores cost-effectiveness but also underscores the pivotal drivers for the seamless adoption of PV technology in large-scale building projects.

The Figure 15 and Table 14 (end of the chapter) provide an extensive roster of stakeholders' integral to the construction process and those directly engaged in the construction of the FUD PV shading devices. Within this broader group, we have further pinpointed and designated 37 stakeholders who play a pivotal role in the construction of the FUS PV shading system. The inclusion of both these stakeholder categories underscores the intricate nature of the project, highlighting the multitude of stakeholders involved in its execution. It is important to note that our analysis has strived to encompass the maximum number of stakeholders based on information provided by our partners. However, in certain instances, particularly in the case of raw material producers, it may not always be feasible to ascertain the company names or specific cost allocations for their activities.

The breakdown of the costs and timing incurred by each individual stakeholder within the project's value chain in Sorengo, displays that the total cost per square meter falls short of meeting the project's KPI3, which stipulates the attainment of a target cost of 1'500 CHF/m^2. As elaborated in the subsequent paragraphs, the achievement of KPI3 will be realized through a comprehensive cost reduction analysis. On the other side, the installation costs stand at 381 CHF/m^2, representing a 15% reduction compared to the KPI that we aim to demonstrate, which is KPI4. These estimates are based on two scenarios:

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[7] Final user costs include: PV coloured modules, extruded aluminium substructure, inverter, power optimizers and electrical cabling, PLC controller, monitoring system, fixing system on façades, KIT assembly, KIT transport and installation on site, design, project coordination and site supervision, PLC programming, plant commissioning
[8] In comparison with the cost assessed by the installer based on the traditional installation process of a non-prefab solar shading system (450 CHF/m^2).

- Scenario 0 (Pilot installation): End user cost of the FUS project
- Scenario 1 (SC1): End user cost projection envisioning the initiation of a new project under current conditions.
- Scenario 2 (SC1): End user cost projection anticipating the commencement of a new project with the maturation of technology and increased stakeholder expertise.

Scenario 0 primarily comprises research and development expenses, which will not be factored into the assumptions for future similar installations. In Scenario 1, we anticipate a reduction of approximately -20% for labour and 21% for material supply, resulting in a total cost of approximately 1'870 CHF/m². Conversely, in Scenario 2, we expect a reduction of -35% for material supply and -39% for labour, leading to a combined cost of approximately 1'480 CHF/m², representing a (small) reduction compared to the KPI that we aim to demonstrate, which is KPI3.

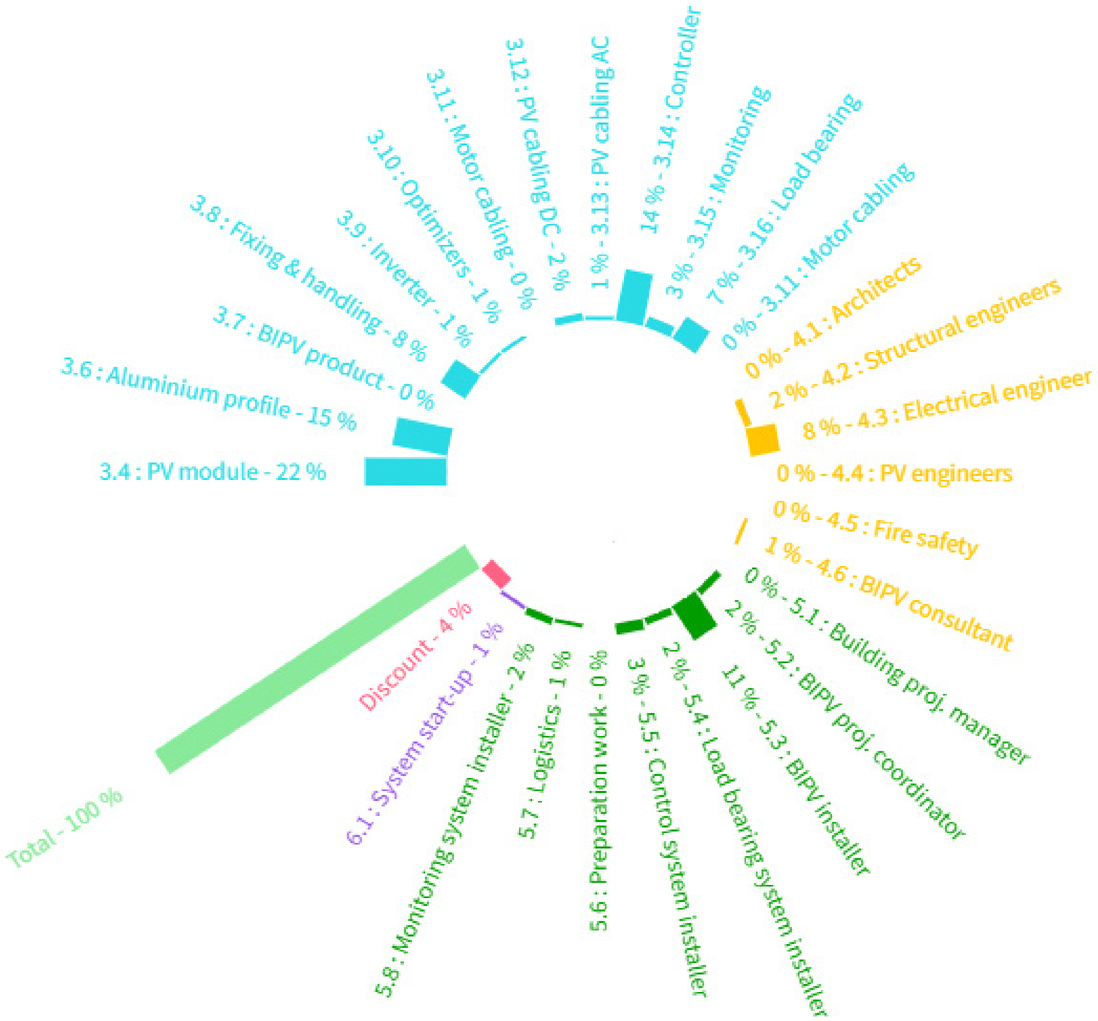


Figure 15: Construction process breakdown. The total (green) includes the discount. It doesn't include subsidies and unexpected costs. Raw material producers and product manufacturers (light blue), Design and engineering (yellow), Construction (dark green), O&M (purple).

Table 12 illustrates the project-specific reasons and motivations underpinning potential cost savings, as defined by the working group following a cost analysis assessment. Additionally, stakeholders have highlighted some key points for future projects, including:

- Architect/Designer project plans must be binding. Incorrect plans necessitated several supplementary surveys to accommodate the installation of horizontal beams with pre-existing fixtures.
- Incorporating diodes within the junction box of photovoltaic panels.
- Using longer photovoltaic panel connection cables (at least 3 meters).
- Direct cable pathways between technical rooms and external areas, avoiding routing through structural columns.
- Grouping all electrical components (control panel, power panel, inverter) within the same technical room.
- Revising the panel-to-blade attachment system, exploring the feasibility of a semi-fixed panel attachment without adhesive.
- The project timeline was affected by the pandemic and the political situation in Ukraine, impacting material supply and project timelines.

Table 12: Motivation for cost reduction roadmap.

Stakeholder	Reduction S1	Reduction S2	Motivation for the cost reduction
Supply			
PV module manufacturer	-25%	-45%	The reduction potential is probably even greater if one considers dimensions and colour closer to the standard (today's traffic white tempered glass). No other potential suppliers were sought for the FUS project (reduction effect due to competition).
PV module manufacturer	-25%	-45%	
Aluminium profile producers and BIPV manufacturers	-15%	-15%	The cost of producing the moulds (approx. CHF 15'000) was considered in the delivery cost. Future projects will not require
Aluminium profile producers and BIPV manufacturers	-15%	-15%	
Fixing & handling system manufacturer	-35%	-50%	The system is sub-optimal as the drive of each blade is regulated by a dedicated gearbox (extra cost for the drive part as well). Considering that the movements are very slow, a system with motor+gearbox+arm for a group of 5 blades would have been sufficient (see mock-up).
Controller supplier	-20%	-30%	
Optimizers supplier	-5%	-10%	Standard material (not much margin for optimisation). By buying in stock a certainly discounts can be negotiated (approx. -10%, at least)
Inverter supplier	-5%	-10%	
PV cabling supplier DC	-5%	-10%	
PV cabling supplier AC	-5%	-10%	
Load bearing system manufacture	-0%	-50%	Hypothesized 0%, however, if the façade had been continuous like the mock-up, the costs for these finishes could be reduced by 50%.
Monitoring supplier	-0%	-0%	-
Labour			
Structural engineers	-0%	-0%	-
Preparation work	-100%	-100%	These costs are usually part of the construction management services
BIPV project coordinator	-100%	-100%	
BIPV installer	-5%	-5%	The extras for diodes and bonding were not added because they were implementation errors not originally planned
Control system installer	-40%	-50%	The FUS project also includes the costs of designing and developing the code. On future projects there will not be included.
Logistic	-0%	-0%	-
System start-up	-0%	-0%	-
Load bearing system installer	-0%	-0%	-
Architects	-0%	-0%	-
BIPV consultant	-0%	-0%	-
Monitoring system installer	-0%	-0%	
Electrical engineer	-0%	-0%	

6.2 Set-up and monitoring of the demo installation

To evaluate the efficiency, monitoring, and cost optimization of BIPV shading systems throughout their operational lifespan, we have undertaken an approach that involves advanced system monitoring and management within its operational context. Specifically, this study encompasses the creation of a digital twin of the mock-up, achieved through the initial collection and meticulous control of data within a fully digitized framework, ensuring the implementation of an advanced data management system. Our objective is to validate the following KPI:

- KPI 5: Set-up of a monitoring platform for data monitoring and management.

The digital model has been crafted on a user-friendly platform, designed for efficient management, visualization, and interaction with both the digital model and sensor data. This platform encompasses a set of APIs that seamlessly link various components within the 3D model with what are informally termed 'extensions.' In the context of this project, the platform functions as a versatile 2D/3D viewer. Additionally, it offers a sophisticated environment for data visualization and the capability to perform data queries and excels in providing real-time updates on the status of individual components within the digital model. Sensor data is stored in a database, and the platform retrieves this data by querying the selected timeline chosen by the user. Subsequently, the platform processes the data internally and presents it in the extensions. The digital twin is readily accessible directly from a web browser and comprises four key elements Figure 16[9]:

- An asset selector that allows to choose the asset that might be visualized or uploaded.
- A timeline window selector for choosing the specific timeline window to query.
- An action toolbar that provides access to various interactions with the models and extensions.
- Interaction with dialogs that appear when an action in the toolbar is selected, such as the model tree browser that grants access to all the elements composing the digital twin model.

The capabilities of the Digital Twin go beyond mere visualization and interaction with the model and its constituent elements. The platform empowers a component to establish a connection with a data stream, enabling it to dynamically change the component's appearance using a customizable heatmap of colours. This functionality is complemented by a range of extensions:

- Sensor data presented in line charts.
- Sensor lists displayed in a tabular format.
- Rendering sensor positions using sprites.
- Utilization of heatmaps to represent the coloration of the 3D component based on specific sensor channels.

[9] The platform is not public available. Please refer to SUPSI to get access to the platform.

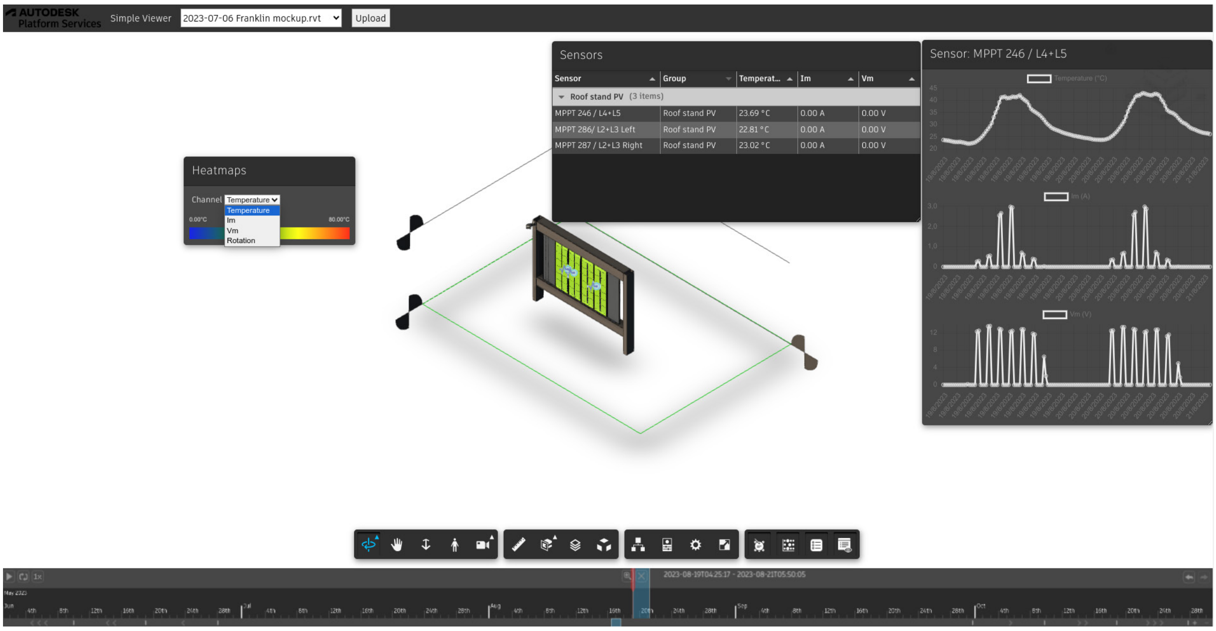


Figure 16: Digital Twin functionalities.

6.3 Maintenance cost reduction

Maintenance cost analysis for BIPV systems is essential for optimizing operational efficiency and ensuring long-term sustainability. Within the scope of this project, the analysis compares the initial operation and maintenance (O&M) cost estimates with the costs incurred after implementing the BIPV owner's O&M plan. This comparison aims to evaluate the plan's effectiveness in reducing maintenance costs and enhancing overall system performance.

- KPI 6: maintenance cost reduction by 5% compared to the initial O&M cost.

A 5% cost reduction would indicate a measurable improvement in the O&M strategy for BIPV systems. In the context of the project, the initial O&M costs have been evaluated based on the study conducted by Gholami et al. [5], which suggests that the annual O&M expenses for BIPV systems are approximately 0.5% of the initial investment cost. This assumption establishes a direct correlation between O&M costs and the initial investment, which can vary according to several factors, such as:

- Substructures: Variations in the support structures can influence overall project costs.
- Research and Development (R&D): Projects involving experimental or cutting-edge technologies typically incur higher investment costs.
- Aesthetic Modules: While the use of coloured or customized black photovoltaic modules may raise initial investment costs due to aesthetic demands, these factors do not directly affect maintenance costs.

It is important to note that maintenance costs are largely independent of investments in aesthetics, R&D, or specific design features. Therefore, evaluating maintenance cost reductions solely as a percentage of the initial investment may oversimplify the relationship between cost reduction and system performance. However, this assumption was necessary to establish a baseline for measuring the impact of different maintenance strategies.

Table 13 summarizes the key financial components of the project across the three analysed scenarios, including total investment costs (excluding VAT), initial O&M costs, and the fixed costs associated with the BIPV owner's O&M plan. A significant reduction in initial O&M costs is observed when comparing Scenarios 1 and 2 to the baseline (Scenario 0). This reduction is primarily attributed to lower initial investment costs, which directly influence O&M expenses, as O&M costs are calculated as a percentage of the total investment.

- Scenario 0: Current situation and associated costs considered for the pilot installation.
- Scenario 1: Cost projection envisioning the initiation of a new project under current conditions.
- Scenario 2: Cost projection anticipating the commencement of a new project with the maturation of technology and increased stakeholder expertise.

Table 13: Major financial components.

COMPONENT	UNIT	SCENARIO 0	SCENARIO 1	SCENARIO 2
		Pilot installation FUS	*Future scenarios*	
Total investment cost	CHF	545’253	430’004	340’621
Initial O&M cost	CHF/year	2’726	2’150	1’703
Planned O&M cost	CHF/year	1’679	1’679	1’679
O&M cost reduction	%	38.4%	21.9%	1.4%
KPI deviation	%	33.4%	16.9%	-3.6%

Two key parameters are used to evaluate the effectiveness of the O&M strategy:

- O&M cost reduction: Represents the percentage decrease in maintenance costs relative to the initial O&M cost estimates for each scenario when the BIPV owner's O&M plan is implemented.
- KPI Deviation: Quantifies the difference between the achieved O&M cost reduction and the target 5% reduction specified by the project's KPI.

As shown in Table 13, both Scenario 0 and Scenario 1 successfully meet the 5% cost reduction target, highlighting the effectiveness of the BIPV owner's O&M plan. However, Scenario 2 does not meet the 5% reduction target, indicating room for improvement driven by increased competence. The 5% reduction target was initially set under the assumption that a predictive maintenance model based on a digital twin would be implemented. This model aims to enhance maintenance efficiency by:

- Preventing unnecessary maintenance actions.
- Accelerating fault detection and resolution.
- Optimizing overall system performance.

Had this predictive maintenance model been fully operational, the planned O&M costs would have fallen below the CHF 1,679 benchmark used for comparison. This reduction would have further decreased O&M expenses, increasing the probability of Scenario 2 achieving the 5% KPI target while closing the remaining gap of 3.6%.

6.4 Discussion on construction site monitoring

Highlights:

- 37 stakeholders who play a pivotal role in the construction of the PV shading system at Franklin University have been pinpointed and designated.
- In Scenario 1, a 20% reduction in labour costs and a 21% reduction in material costs were anticipated, resulting in a price of 1’870 CHF/m². In Scenario 2, projected reductions of 35% in material costs and 39% in labour costs lower the price to 1’480 CHF/m².
- A preliminary monitoring platform was set up, enabling advanced data visualization, querying, and real-time updates on component status.
- A targeted 5% reduction in maintenance costs has been successfully achieved through the Scenario 0 (Pilot installation) and Scenario 1.

A comprehensive analysis of the construction site at Franklin University identified 37 key stakeholders involved in its construction. It serves to highlight first the project-specific reasons and motivations underpinning potential cost savings, and to define the project prices. The total project prices (pilot installation) were calculated with a price of 2’160 CHF/m². This dropped to 1’870 CHF/m² in Scenario 1 and 1’480 CHF/m² in Scenario 2, reflecting price reductions of up to 39% in labour and 35% in materials. The project's timeline was intensive, with 18 out of 21 activities completed between March 2022 and March 2023, spanning a total of one year. The preliminary monitoring platform served as a practical testbed to assess the functionality and explore the untapped potential of the Digital Twin. Future implementation of the Digital Twin may encompass a variety of actions, including setting alarms, integrating derivative data like power, configuring or adding new sensors.

A targeted 5% reduction in maintenance costs has been successfully achieved through the scenario 0 and Scenario 1, facilitated by the implementation of the BIPV owner O&M plan. This improvement underscores the importance of strategically managed maintenance practices, as evidenced by the substantial cost reductions observed in both scenarios. Despite this, the analysis identifies challenges in achieving similar cost reductions in the Scenario 2. However, it is important to note that the 5% cost reduction target was established with the assumption of implementing a predictive maintenance model based on a digital twin. This model aims to optimize production by preventing unnecessary actions, accelerating issue detection, and enhancing overall maintenance efficiency, thereby providing the additional 3.6% reduction needed to meet the 5% KPI target as for in the Scenario 2.

Table 14: Stakeholder map for BIPV construction process. The stakeholders engaged in the implementation of the Franklin project have been identified as “P+D Stakeholders”.

Clients and End users	**Government and Regulation bodies**	**Finance and investors**	**Raw material producers Product manufacturers**	**Design and engineering**	**Construction**	**Operation and Maintenance**	**Demolition processes**	**Renovation processes**
Building owners (P+D Stakeholder)	Politicians	Insurers	Polymer companies (P+D Stakeholder)	Architects (P+D Stakeholder)	Architects (execution supervisor)	Maintenance companies (facade)	Regulatory bodies (safety, permits, processes)	Facade renovation companies
Purchasers in construction or energy industry	Lobby groups	Financing organizations (banks)	Aluminium producers (P+D Stakeholder)	Structural engineers (P+D Stakeholder)	Engineers (site supervisor)	Maintenance companies (building operation)	Facade demolition companies	Renovation permits
BIPV system owner (P+D Stakeholder)	Central governments	Financing organizations (third party invertors) (P+D Stakeholder)	PV cell producers (P+D Stakeholder)	Facade engineers	General project managers (P+D Stakeholder)	Occupants (building mangers)	General demolition companies	Electricians
	Local authorities	Investors in real estate	Glass producers (P+D Stakeholder)	Sustainability engineers	BIPV project coordinator (P+D Stakeholder)	Occupants (residents)	PV plant decommissioning and demolition	General contractors
	Licensing bodies	Project sponsors	Aluminium producers (P+D Stakeholder)	Electrical engineers (P+D Stakeholder)	BIPV installer (P+D Stakeholder)	Occupants (office personnel)	Recycling companies	
	Regional and federal regulators		PV module manufacturer (P+D Stakeholder)	PV engineers (P+D Stakeholder)	Load bearing system installer (P+D Stakeholder)	System start-up (P+D Stakeholder)	Containers and dumping grounds	
	Certification companies		Aluminium profile producers (P+D Stakeholder)	Energy system designers	Control system installers (P+D Stakeholder)		Storage of used PV panels and other construction materials	
	Regulatory organizations for structural safety		BIPV module manufacturers (P+D Stakeholder)	PV and BIPV engineers	Electrical installers			
	Regulatory organizations for sustainability		Fixing and handling system manufacturer (P+D Stakeholder)	Embodied energy and carbon footprint evaluators	Project managers façade			
	Regulatory authorities: permits (P+D Stakeholder)		Inverter suppliers (P+D Stakeholder)	Experts in fire safety (P+D Stakeholder)	Preparation work (P+D Stakeholder)			
	Regulatory authorities: electrical integration permits		Optimizer suppliers (P+D Stakeholder)	BIPV consultants (P+D Stakeholder)	Project manager electrical			
	Regulatory authorities: incentives (P+D Stakeholder)		Motor cabling suppliers (P+D Stakeholder)	Sustainability consultants	Contractors PV			
			DC PV cabling suppliers (P+D Stakeholder)		Site supervision			
			AC PV cabling suppliers (P+D Stakeholder)		Logistic (P+D Stakeholder)			
			Controller suppliers (P+D Stakeholder)		Monitoring system installers			
			Monitoring & probes suppliers (P+D Stakeholder)		(P+D Stakeholder)			
			Load bearing system manufacturers (P+D Stakeholder)					

7 Replicability and market exploitation strategies

7.1 Market analysis

The information regarding market-available products has been collected in conferences, datasheets, exhibitions and previous projects. Market-available products are considered PVSDs manufactured by a registered company to reduce the number of products. For each of the PVSDs selected, a description of the products has been provided, when possible and according to the data available, to identify the technical, economic and energy parameters.

In the Table 15 and Table 16 is shown an overview of the PVSD available on the market and their features, combined with a simplified representation and technical data.

Table 15: (PV)SD: classification. The price is derived from market research conducted in 2022, based on publicly available pricing of products at that time. However, it may not fully reflect current pricing for this system category, as it does not account for advancements in recent years.

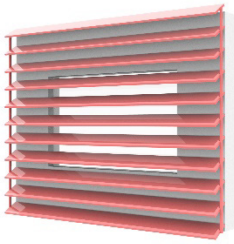
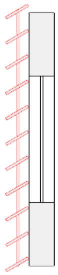
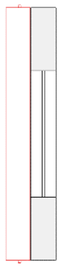
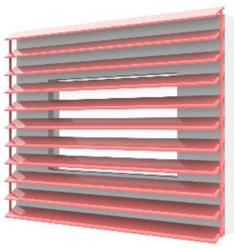
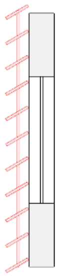
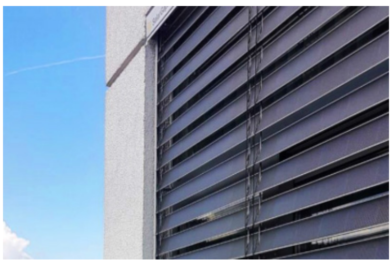
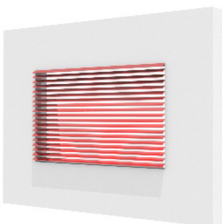
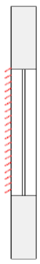
(PV)SD	POSITION			CUSTOMISATION		PRICE ('22)
System category	Outside	In be-tween	Internal	Colour	Size	CHF/m²
1. PV Louver	x			x	x	1'500
2. PV Louver	x				x	900
3. PV Window Blind	x				x	380
4. PV Window Blind			x	x	x	680
5. PV fins	x			x	x	N.A.
6. Louver	x			x	x	1'000

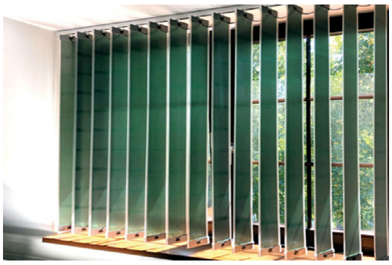
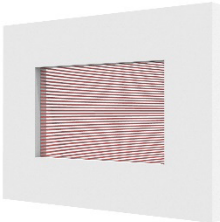
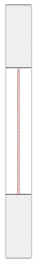
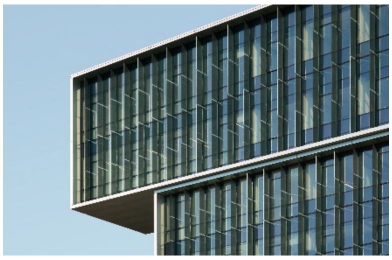
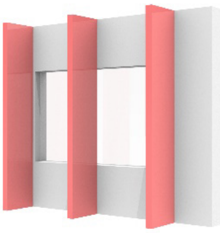
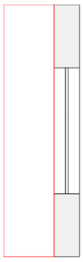
Few PVSDs have been considered as market available and thus reported within the following paragraphs. Large-size PVSDs, including PV louvers, are represented by a high level of customisation in terms of size, colour, and shape due to the own peculiarities of each project. On the other side, small-size PVSDs, such as window blinds, are defined as standard components with a low level of customisation. Here is reported a sample of the most representative PVSD market available. In the Table 16 is shown an overview of the PVSDs available on the market and their features, combined with a simplified representation and technical data. This research is a preliminary approach to the PVSD market sector, which aims to present a framework of affirmed or well-known PVSD companies to define a benchmark for other potential PVSD manufacturers. However, other manufacturers or consortiums of manufacturers are available on the market (e.g. City Hall of Freiburg, Die Mobiliaer in Bern, London Kingsgate House, etc.). The analysis of the PVSDs available on the market reveals two potential clusters of PVSDs:

- Landmark PVSDs, which include PV fins and PV louvres;
- Mass market PVSDs, which include PV window blinds.

PV louvres and fins are landmarks that require economic efforts in building design, installation, investment and maintenance. PV louvers should be offered as fully customised solutions in size, colour, shape, PV technology, etc. An easy manufacturing and installation process can considerably reduce overall costs and increase the appeal and the market volume of PV louvers and PV fins. On the other side, the PV window blinds analysed represent solutions suitable for integration in administrative and residential buildings. The industry of PV window blind still has a large margin of growing in technology implementation and product optimisation. Indeed, PV window blinds analysed are manufactured by SME or start-ups and thus are market available for a few years. Customised PV cells and an accurate slats design are crucial to obtain favourable results in energy production, savings and price. Not by chance, the PV window blind manufacturers are often small companies or start-ups.

Table 16: (PV)SD: representation (SUPSI 2022)

PV Louver, horizontal			
			Technology: c-Si Material: glass Dimension max: 4x0.6 m^2 Nominal power: NA Orientation: tracker, fixed, movable
PV Louver, vertical			
			Technology: c-Si Material: glass Dimension max: 4x0.6 m^2 Nominal power: NA Orientation: tracker, fixed, movable
PV Louver, horizontal			
			Technology: CdTe, CIS, a-Si Material: glass Dimension max: 1.3x0.7 m^2 Nominal power: up to 100W/m^2 Orientation: tracker, fixed, movable
PV Window Blind, external			
			Technology: c-Si Material: metal/polymer Dimension max*: 4x2.6m^2 Nominal power: up to 100 W/m^2 Orientation: tracker, fixed, movable *max window size

PV Window Blind, internal			
			Technology: OPV Material: polymer Dimension max*: NA Nominal power: up to 40 W/m^2 Orientation: fixed *max window size
PV Fins			
			Technology: a-Si Material: glass Dimension max: NA Nominal power: up to 60 W/m^2 Orientation: fixed

7.2 Cost competitiveness analysis

BIPV competitiveness could be defined as the fact of being able for a BIPV system to compete successfully with other traditional construction systems. It consists in an analysis of all cash-flows generated by a specific project, allowing to obtain an estimation of all costs but also all revenues associated with the BIPV systems on their operational lifetime.

The goal of this activity is to target a 10% reduction in system costs compared to a similar PV dynamic solar shading solution without optimized PV module architecture. Table 17 highlights the key differences in terms of extra costs, maintenance costs, and annual energy production between the baseline state of the art system, used as a benchmark to assess the KPI, and the Scenario 2, which reflects the advancements in technology and increase stakeholder expertise:

- KPI 7: cost competitiveness of the system reduced by 10%

The state-of-the-art benchmark, distinct from Scenario 0 outlined in chapter 6.3, provides reference values based on the data presented in Table 15, which reflects dynamic shading solutions available as of 2022. In this case, louvres systems have been considered with a specific price of 1'500CHF/m^2 and 1'000CHF/m^2 for the photovoltaic solutions and non-photovoltaic respectively. The extra cost corresponds with 500CHF/m^2. The O&M costs amounts to approximately 0.5% of the initial investment cost [5].

Scenario 2 indicates the cost projection anticipating the commencement of a new project with the maturation of technology and increased stakeholder expertise. The O&M costs for Scenario 2 were calculated based on the implementation of the operation and maintenance plan provided by the BIPV system owner.

Table 17: Comparative parameters between the State of the art and the Scenario 2.

COMPONENT	UNIT	STATE OF THE ART	SCENARIO 2
Extra cost	CHF/m^2	500	274
O&M cost	CHF/m^2/year	7.5	7.30
Annual energy production	kWh/year	15’600	10’415

This analysis is based on an adapted methodology outlined in chapter 3.3 (NPV formula). The cost plan includes expenses associated with system surveillance, cleaning, internal costs, and insurance. Additionally, the plan accounts for costs related to inverter replacement and spare parts (electromechanical components). These operations are scheduled to be performed every 10 years. A risk percentage on costs of 1% has been considered for the first 20 years, while a 2.5% risk has been applied for the remaining 10 years, based on consultations with the BIPV system owner. Given the impact of inflation, total cash outflows are expected to increase over time. To avoid overestimating the project’s profitability, these expenses have been adjusted for inflation. Table 18 provides a comprehensive overview of all input variables used in the NPV calculation, along with detailed references for the data sources.

Table 18: Parameters for the NPV calculation for Scenario 2

PARAMETER	VALUE	SOURCE
Active Area	230 m²	Technical Design
Initial Performance Loss Rate	3.00% (in year 0)	SUNAGE SA
Annual Performance Loss Rate	0.68%	SUNAGE SA
Discount Rate (WACC)	3.00%	BIPV system owner
Inflation Rate	2.10%	Admin.ch
Electricity Export Price	0.28 CHF/kWh	BIPV system owner
Extra Cost	274 CHF/m²	Construction monitoring
Investment in terms of Extra Cost	62’932 CHF	Construction monitoring
Subsidies (Year 0)	9’000 CHF	BIPV system owner
Self-Consumption Percentage	100%	BIPV system owner
Annual Energy Production AC side (2023)[10]	10’415 kWh/year	Monitoring/Simulation

Moving from energy to economic consideration, the calculation of the electricity price considers energy costs, grid charges, as well as taxes and fees. Table 19 presents all costs used in the calculation of electricity prices from 2023 to 2028. A contract defined by the electric utility specifies the energy component rates for the periods 2023-2025 and 2026-2028, with a reduction in costs expected in the latter period due to the price of electricity returning to normal levels after the significant spike caused by the war in Ukraine and the resolution of the maintenance problems of the French nuclear power plants.

For the period 2023-2025, the costs associated with grid usage, taxes, and fees are provided by the electric utility, considering FUS as a low-voltage "free market customer." Specifically, the grid cost is calculated as an average of the daytime and night time transportation tariffs. Taxes and fees include items such as system service charges, contributions to renewable energy, ecological remediation, public

[10] For calculation method, see 9.2 Annex B.

property taxes, the cantonal fund for renewable energy, and the electricity reserve. Due to missing information for the period 2026-2028, grid usage costs, taxes and fees for this period are estimated through a linear interpolation of values from the previous period.

In the NPV calculation, given the 30-year lifespan of the project, it is important to consider the evolution of electricity prices. While price information is available up to 2028, beyond that year, it is currently unavailable. Therefore, in the NPV calculation the electricity price is adjusted using an estimated linear increase of 1.27%. Rather than a single interpolation from 2023 to 2028, the periods 2023-2025 and 2026-2028 are treated separately (Figure 18). Both periods show a similar linear increase; however, treating 2023-2028 as a whole would imply a reduction in electricity price rather than the necessary upward trend, which better reflects future projections.

Table 19: Breakdown of the electricity prices from 2023 to 2028 for Scenario 2.

		2023	2024	2025	2026	2027	2028
Energy component	CHF/kWh	0.155	0.155	0.155	0.086	0.086	0.086
Grid	CHF/kWh	0.069	0.076	0.082	0.088	0.095	0.101
Taxes and fees	CHF/kWh	0.090	0.131	0.103	0.120	0.127	0.133
Total per kWh	CHF/kWh	0.314	0.362	0.339	0.294	0.307	0.320

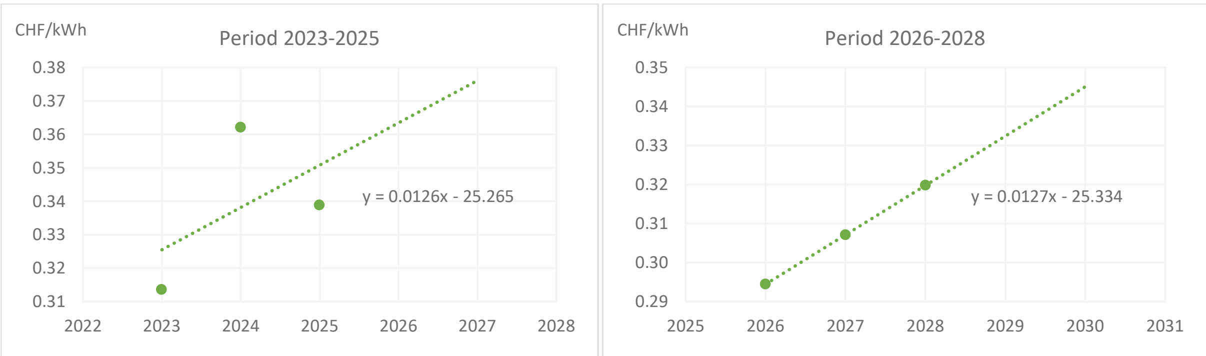


Figure 18: Total electricity prices evolution

Figure 19 illustrates the annual cash flow for the state of the art and the Scenario 2. According to the data presented, the net present values at year 30 for the two considered solutions are -47'270 CHF and -28'092 CHF, respectively for both solutions. The linear decline in the state-of-the-art solution reflects a consistent allocation of O&M costs over time, whereas, for Scenario 2, these costs are allocated more precisely, accounting for inverter replacements, spare part replacements, and system cleaning in the years when these operations are actually performed.

Scenario 2 demonstrates a 41% reduction of the NPV (year 30) compared to the state-of-the-art solution, achieved through reduced investment and O&M costs, effectively validating the project's initial KPIs. Despite this, the negative NPV suggests that the project or investment may still lack financial viability. Several factors likely contribute to this outcome, primarily the lower-than-expected energy production, as previously observed. This decrease may be related to recent changes in the surrounding landscape, including the construction of a new building adjacent to the BIPV system. Furthermore, the system's energy production is limited by the architectural choice of a light colour, "bianco traffico," selected for aesthetic reasons. A darker colour might have reduced the power loss, enhancing energy yield.

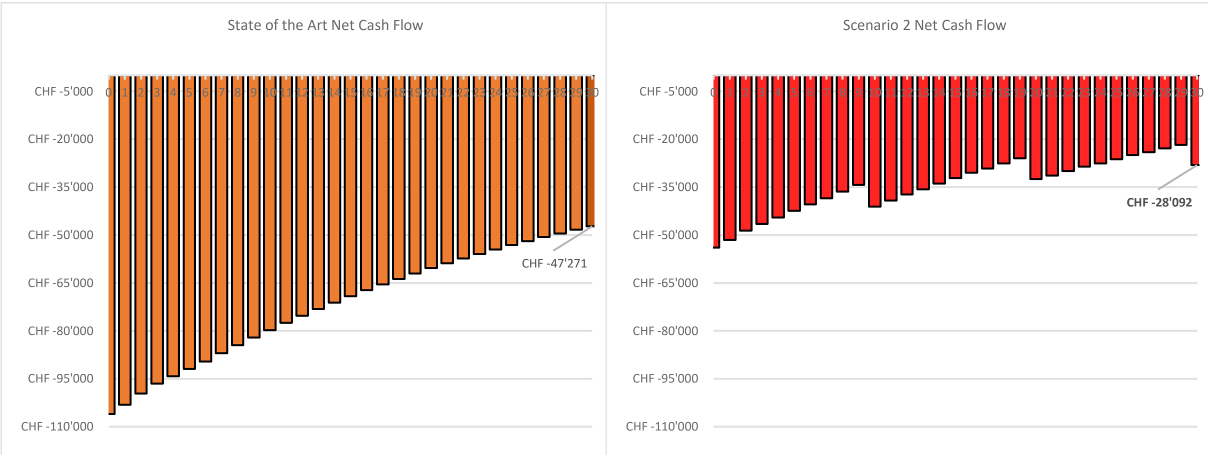


Figure 19: annual cash flow for State of the art and Scenario 2.

7.3 Discussion on Replicability and market exploitation strategies

For KPI7, the objective of a 10% reduction in system cost competitiveness compared to similar solutions has been significantly surpassed, with the Scenario 2 demonstrating a 41% reduction. This achievement is primarily driven by lower initial and maintenance costs. Nevertheless, the negative net present value (NPV) at year 30 raises concerns regarding the project's overall financial viability. Factors such as lower-than-expected energy production—arising from recent changes in the surrounding landscape and architectural choices—underscore the necessity of considering external variables when evaluating project outcomes.

The competitive background and technology validation conducted in the project form the foundation for replication and market introduction strategies for PV dynamic solar shading systems. Through thorough analysis, validation, and demonstration, the BIPV manufacturing company SUNAGE SA has acquired the rights to globally commercialize market this innovative solution in Switzerland (excluding the canton of Ticino) and globally, this innovative solution, integrating it into their product catalogue.

AIL as project coordinator and specialist in Canton of Ticino, will be granted exclusive rights to this area.

In collaboration with SUPSI, SUNAGE is developing a comprehensive business plan, a critical step in the BIPV sector. A business plan is essential for navigating the complexities of this industry, including market positioning, cost optimization, regulatory compliance, and stakeholder engagement. It ensures a structured approach to scaling the technology and achieving financial viability. Before commercializing the solution, the following steps are necessary:

- Compiling and organizing all technical materials.
- Gathering detailed technical insights from the project consortium.
- Finalizing the business plan.

These steps will establish a robust foundation for a successful market launch, ensuring the solution meets both technical and commercial expectations.

8 Evaluation of results

In this project, an innovative dynamic photovoltaic shading device was engineered and manufactured, combining the functions of renewable electricity generation (PV modules) with solar protection (metal slats) in a unique element. Before evaluating the technology, a thorough assessment of PV shading devices establishes the foundation for developing a methodology to conduct energy-economic evaluations of the shading system. This methodology will support the analysis of replicability and inform strategies for market exploitation.

The PV modules have been engineered to increase the shading tolerance and avoid mismatching due to the slats' self-shading. Before being integrated into the facade system, small-size samples of PV modules were tested in SUPSI PVLab and a small-size mock-up installation was monitored for one year to assess the technology's outdoor performance. The tests showed a **temperature reduction of up to 3 °C at non-conventional shading scenarios** compared to traditional PV modules, both in indoor and on the outdoor mock-up. In addition, it was monitored that the optimised PV slat's shading and mismatch tolerance are proven by reduced temperatures and improved energy performance. **The optimised PV slat achieved a gain of more than 20% during spring and summer**, boosting the energy yield during months with higher solar altitude

The solar tracking photovoltaic shading device was installed in the building façade of the FUS new pavilion, resulting a flagship example of highly aesthetic photovoltaic shading systems realised in Switzerland. Throughout the pilot installation, no extreme temperature or humidity measurements were recorded for the monitored slats, indicating that **there are no additional risks associated with the long-term application in real buildings**. The slight temperature variations among all monitored slats indicate consistent manufacturing quality. Furthermore, the temperature trends of the pilot installation are consistent with those observed in the mock-up, successfully demonstrating the technology readiness transition from 6 to 7.

An extensive construction site monitoring has effectively demonstrated the compelling value proposition of the PV shading device solution implemented. The comprehensive analysis of FUS PVSD end user and O&M costs reveals the financial contributions of each stakeholder in the project's value chain. The total costs amount to 545’253 CHF, 471’004 CHF, and 381’621 CHF for the Scenario 0 (pilot installation), Scenario 1, and Scenario 2, respectively. **This breakdown demonstrates a reduction in costs**, with a decrease of approximately -20% for labour and 21% for material supply in Scenario 1. In Scenario 2, there is a substantial reduction of -35% for material supply and -39% for labour. **A targeted 5% reduction in maintenance costs has been successfully achieved** through the Scenario 0 and Scenario 1.

The objective of a **10% reduction in system cost competitiveness compared to similar solutions** has been significantly surpassed, with the Scenario 2 demonstrating a 41% reduction.

Considering the successful outcomes achieved throughout the project, SUNAGE will be broadening its product portfolio with the introduction of this innovative system.

SUNAGE will offer a lamella photovoltaic system for any project where this type of system is required or can be integrated.

SUNAGE is working with SUPSI to develop a business plan that will identify the optimal product placement on the Swiss and global markets.

SUNAGE will be exhibiting at the BAU international trade fair in Munich from 13 to 17 January 2025.

In addition to showcasing its own product range, the photovoltaic lamella system developed within the project will also be exhibited and publicised for the first time.

This event will provide an excellent opportunity for the international launch of this new product.

9 Annex

9.1 Annex A: Methodology of the photovoltaic potential assessment of PVSD

Important factors when assessing different PVSDs are the simulation tools and calculation algorithms used. In this case, a specific workflow has been implemented within the Rhino+Grasshopper environment Figure 20.

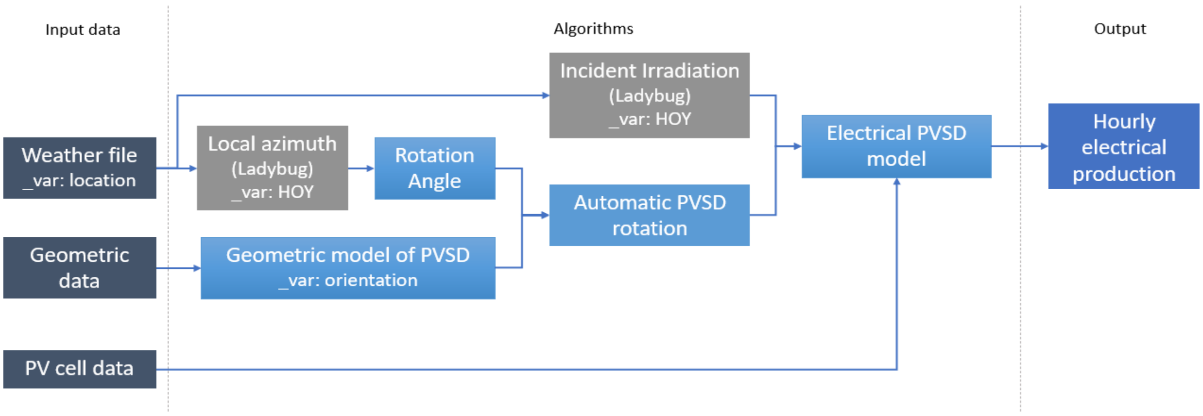


Figure 20: Schematic representation of the model developed for the assessment of the hourly electrical production of the PVSDs.

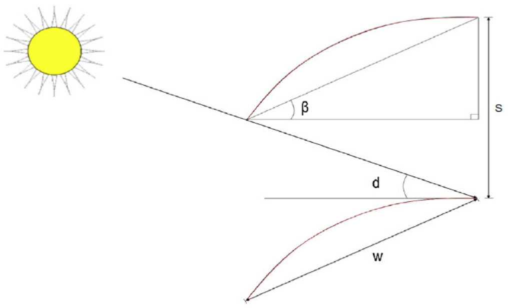
The input data used for the calculation of the hourly electrical production of the different PVSDs are the followings:

- Weather file: the TMY of three locations (Berlin - D, Lugano - CH, Rome - I) have been retrieved.
- Geometric data for the five PVSD systems: dimensions of the shading devices and the PV cell location have been defined.
- PV cell data: all the PVSDs have been characterised by PV cells made of monocrystalline silicon that are supposed to be integrated into the shading device as glass/cell/polymer layer. Electrical data about cells have been collected from PV cell datasheets.

Table 20: PV cells data.

PVSD	PV CELL	VOC (V)	ISC (A)	VMP (V)	IMP (A)	PM (W)	B (%/°C)	A (%/°C)
T01 T02	Mono-Si half-cut cell (158x79mm)	0.66	4.772	0.561	4.486	2.51	-0.36	0.07
T03 T04 T05	Mono-Si cell (158x158mm)	0.66	9.544	0.561	8.971	5.03	-0.36	0.07

Different algorithms were combined to calculate the hourly energy production. The model of the PVSD has been implemented, including the option to vary the orientation. Three different orientations have been considered (east, southeast, and south), whereas west and southwest have been assumed to be similar to east and southeast. The cut-off angle approach typically characterises PVSDs with horizontal rotation angles for automated venetian blinds Figure 21. However, from state of the art, automated shading systems are activated when the vertical irradiation exceeds the 200 Wh/m² threshold. Therefore, when the solar irradiance is below this threshold, the rotation angle is maintained at 0° in the horizontal position to allow maximum daylight. When vertical irradiation exceeds 200 Wh/m², the cut-off angle is used as the rotation angle. It is important to note that when the cut-off angle is negative (due to high solar altitude), the PVSD is fixed in the horizontal position to gain as much solar radiation over the PV cell to produce electricity. In the case of the fixed PVSDs, the angle of the slats is maintained at fixed values (15° and 50°). Regarding the PVSD with a vertical axis, the sun-tracking approach has been adopted and activated when the vertical irradiation is higher than the threshold value of 200 kWh/m².



$$\beta_{\text{cut-off}} = \sin^{-1}(\cos(d) \cdot s/w) - d$$
$$d = \tan^{-1}[\tan \alpha / \cos(\gamma)]$$

Figure 21: Definition of the cut-off angle [6].

In order to compare the results of the different PVSD systems for the different locations and orientations, the energy production results have been normalised considering the shaded window area.

The local azimuth was calculated for each location and for each hour-of-the-year (HOY) grounding on the "Azimuth" component of the Ladybug tool. Specifically, the local azimuth has been used to define the rotation angle of the dynamic PVSDs Table 21. This angle has been set accordingly to different criteria.

Table 21: Rotation angle definition of the dynamic PVSD.

PVSD	ROTATION AXIS	APPROACH	VERTICAL IRRADIATION		ROTATION ANGLE
T01 T02 T03	Horizontal	Cut-off	< 200 Wh/m²	-	0°
			> 200 Wh/m²	Cut off < 0°	0°
				Cut off > 0°	Cut-off angle
T04	-	Fixed	-	-	15°
					50°
T05	Vertical	Sun-tracking	< 200 Wh/m²	-	0°
			> 200 Wh/m²	-	Azimuth ± 90°

Once the rotation angle has been defined, the next step is the hourly computation of the solar irradiation over the PV cells by means of the "Incident Irradiation" of the Ladybug tool Figure 22. This data has been used to calculate the hourly power of the PV cells. Specifically, from the solar irradiation analysis, it arose that PV cells where irradiated with different level of irradiance depending on the shading produced by the above slat (see figure below).

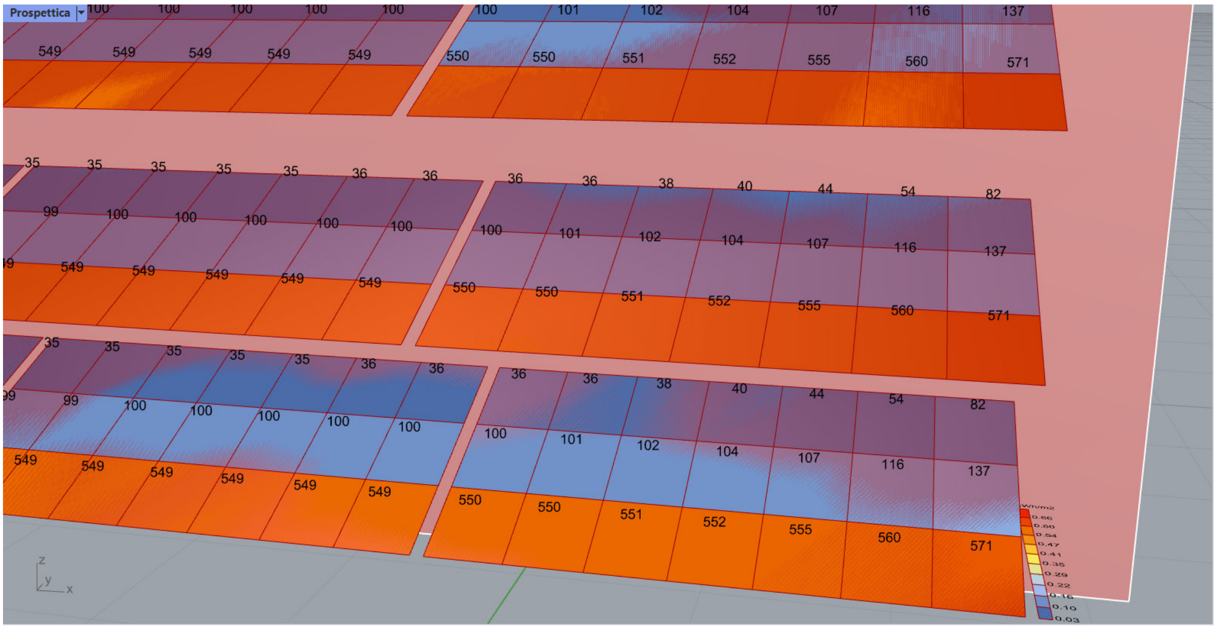


Figure 22: Hourly computation of the solar irradiation over the PV cells.

This shading effect has been taken into account in the model for the hourly calculation of the PV power of each cell considering causes a reduction of the PV cell sub-areas as they are in parallel and thus summing their current. Since shadings are also produced on the short side of the slat but often with heterogenous distribution, PV cells located in such areas are not considered.

Therefore, the hourly power of each PV cell has been calculated implementing the SAPM model, which also considers the PV cell temperature effect. The developed algorithm has been automated for each PVSD type to obtain the annual energy production.

9.2 Annex B: Annual energy production definition

For the calculation of the NPV, the yearly energy production from the AC side is a key parameter. However, during the first two months of 2023, the system did not deliver any energy. Coupling the first two months of 2024 with the remaining ten months of 2023 could be a potential option to provide an initial insight into the yearly energy production of the system for that year. Unfortunately, due to technical issues, the system was also non-operational during those months. Therefore, using simulated data becomes the only viable option in this case. However, rather than conducting a new energy simulation, the results delivered during the early design stage of the project have been implemented.

It is important to note that during the design phase, a planned size of 14.8 kWp was considered, while the current system size is approximately 18.36 kWp. Figure 23 presents the simulated DC energy production values from the system, estimating an annual energy production of about 16,120 kWh/year, along with the corresponding DC energy production for the currently installed system.

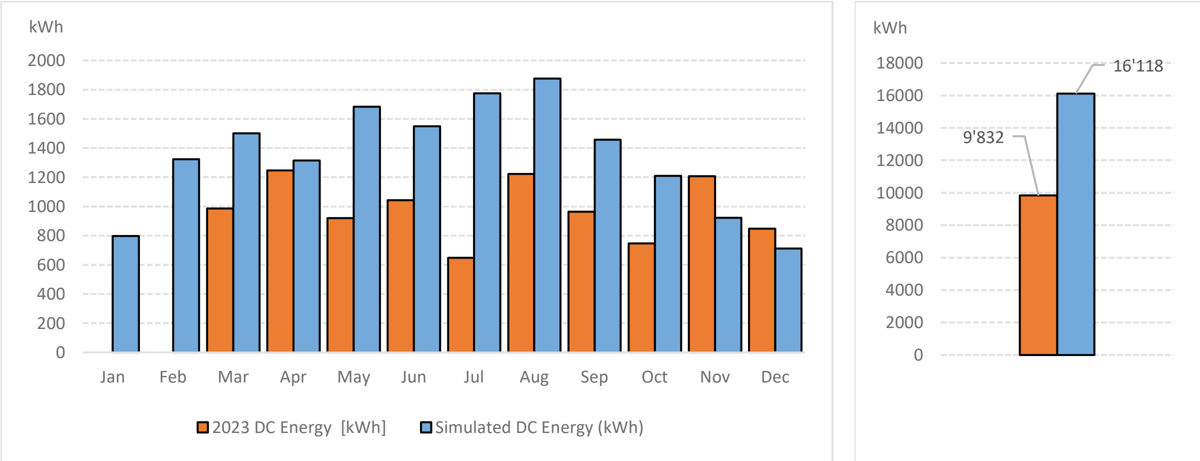


Figure 23: Simulated vs. actual DC energy production

To compare the two energy values, the simulated values have been normalized in terms of installed capacity. However, as shown in Figure 24 (top), the differences between the actual DC energy and the normalized values are significant, characterized by a Mean Absolute Error (MAE) of approximately 765 kWh and a Root Mean Square Error (RMSE) of about 892 kWh. Based on this, a second normalization has been performed. Therefore, the normalized DC energy values have been further adjusted, this time in terms of energy. The calibrated values, Figure 24 (bottom), now show smaller discrepancies compared to the actual DC values, with a MAE of approximately 245 kWh and an RMSE of about 314 kWh, which makes it possible for us to extrapolate the first two months and consider them for the NPV calculation.

A final conversion is performed. The selected energy values have been converted into AC by multiplying them by the AC/DC efficiency (0.92). This efficiency value has been calculated by dividing the monitored AC energy production of the system from March to December by the corresponding monitored DC energy production. Figure 25 shows the monthly trend of the AC energy used in the calculation of the NPV.

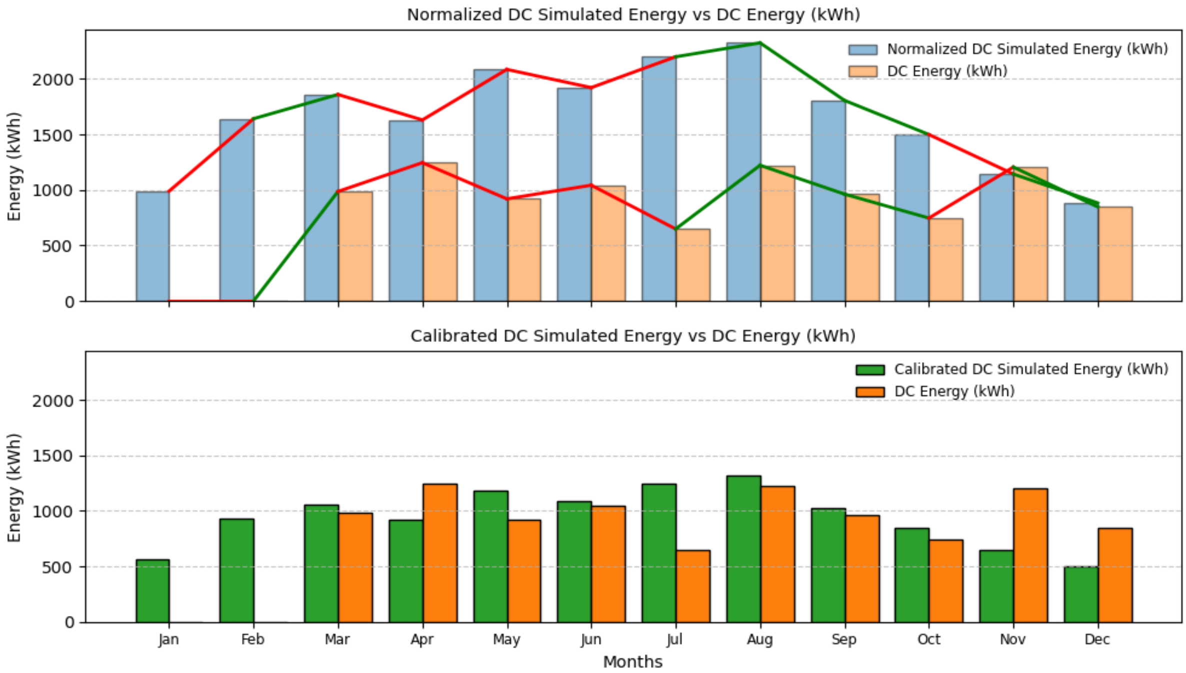


Figure 24: Normalized DC simulated and monitored energy (top); Calibrated DC simulated and monitored energy (bottom).

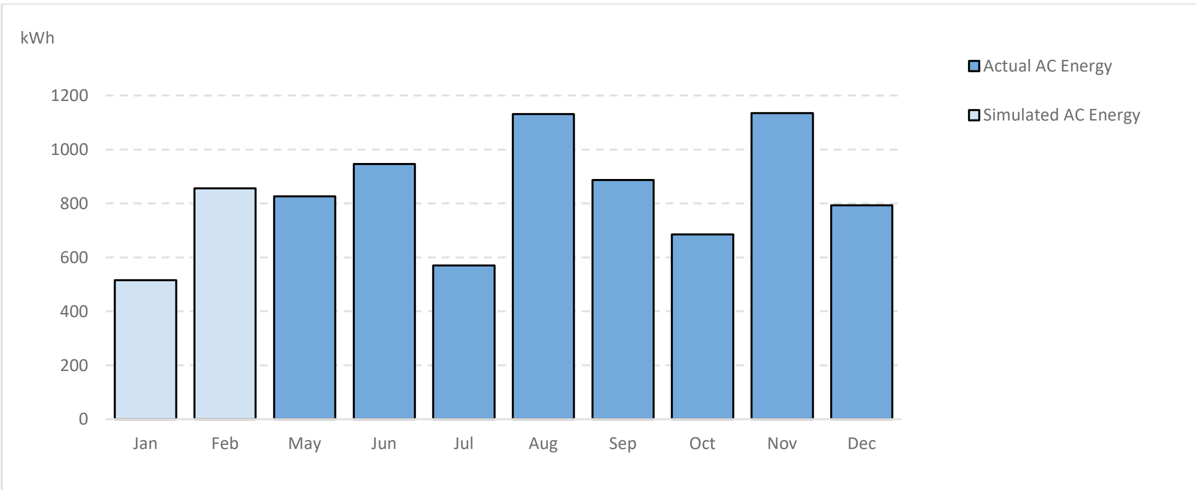


Figure 25: Monthly trend of AC energy used in the NPV calculation.

10 Reference

[1] P. Corti, A. Follo, and P. Bonomo, “Workflow to support cost-benefits comparison and sensitivity analysis of BIPV case studies: Three examples of BIPV facades in the south of Switzerland,” *Energy Build.*, vol. 322, no. February, p. 114732, 2024, doi: 10.1016/j.enbuild.2024.114732.

[2] E. Vartiainen, G. Masson, C. Breyer, D. Moser, and E. Román Medina, “Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity,” *Prog. Photovoltaics Res. Appl.*, vol. 28, no. 6, pp. 439–453, 2020, doi: 10.1002/pip.3189.

[3] P. Bonomo, F. Parolini, G. Bellenda, D. Valencia, Boddaert S, and J. M. Vega De Seoane, “BIPVBOOST Deliverable Report D5.2 ‘Report on the project developments of specific performance-based laboratory testing procedures for BIPV products,’” 2022.

[4] T. S. Liang, P. Corti, P. Bonomo, and F. Frontini, “Performance Analysis of Dynamic Building-Integrated Photovoltaic Shading System for High Technology Readiness Level Validation,” vol. 2400465, pp. 1–13, 2024, doi: 10.1002/solr.202400465.

[5] H. Gholami, H. Nils Røstvik, N. Manoj Kumar, and S. S. Chopra, “Lifecycle cost analysis (LCCA) of tailor-made building integrated photovoltaics (BIPV) façade: Solsmaragden case study in Norway,” *Sol. Energy*, vol. 211, no. October, pp. 488–502, 2020, doi: 10.1016/j.solener.2020.09.087.

[6] L. Karlsen, P. Heiselberg, and I. Bryn, “Occupant satisfaction with two blind control strategies: Slats closed and slats in cut-off position,” *Sol. Energy*, vol. 115, pp. 166–179, 2015, doi: 10.1016/j.solener.2015.02.031.