Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Interim report dated 11 December 2023

BIPVdSHADING

Source: Franklin University Switzerland

Date: 11 December 2023

Location: Bern

Publisher:
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech
CH-3003 Bern
www.bfe.admin.ch

Subsidy recipients:
Aziende Industriali di Lugano (AIL) SA
CP 5131, 6901 Lugano
www.ail.ch

SUPSI, ISAAC
Via Flora Ruchat-Roncati 15, 6850 Mendrisio
www.supsi.ch/isaac

Sunage SA
Via Pian Faloppia 11, 6828 Balerna
www.sunage.ch

Authors:
Paolo, Corti, SUPSI, paolo.corti@supsi.ch
Erika, Saretta, SUPSI
Pierluigi, Bonomo, SUPSI
Tian Shen Liang, SUPSI
Alberto Follo, SUPSI
Mohamed Boutaleb, SUPSI
Giovanni, Bellenda, SUPSI
Francesco, Frontini, SUPSI
Giovanna, Bevilacqua, AIL, gbevilacqua@ail.ch
Luca Trapani, AIL, ltrapani@ail.ch
Gazmend, Luzi, Sunage, luzi@sunage.ch

SFOE project coordinators:
Men Wirtz, men.wirz@bfe.admin.ch
Stefan Oberholzer, stefan.oberholzer@bfe.admin.ch
Karin Söderström, karin.soederstroem@bfe.admin.ch

SFOE contract number: SI/502267-01

Summary

The project goal is to demonstrate 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.

Contents

Abbreviations

PV: photovoltaics

BIPV: building integrated photovoltaics

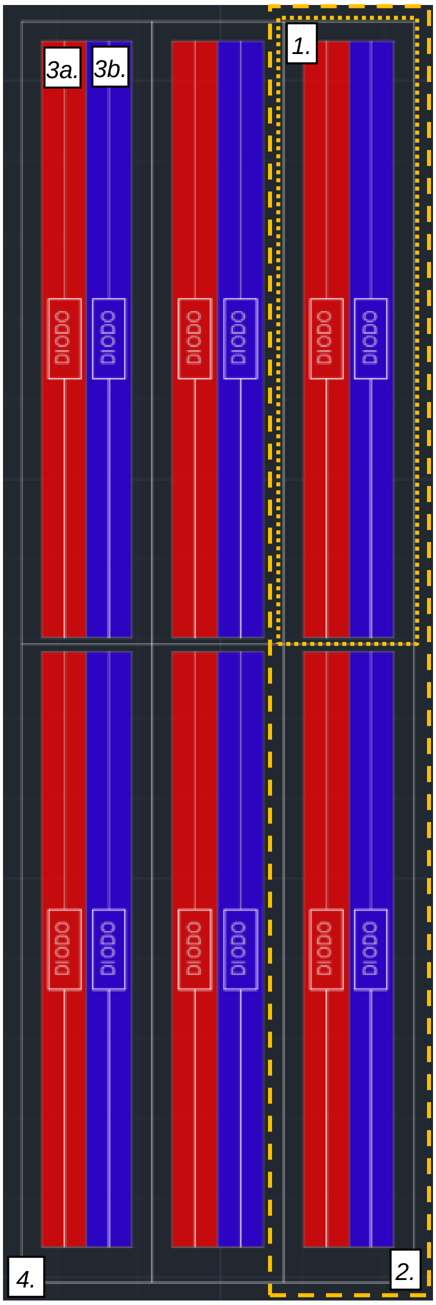
PVSD: photovoltaic shading device

TRL: technology readiness level

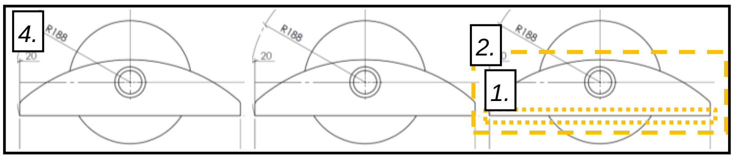
nZEB: nearly zero energy building

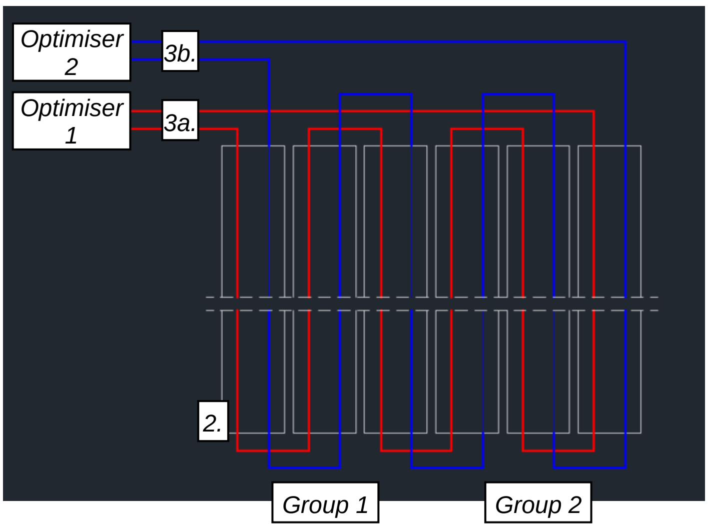
NPV: net present value

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 CO2 emissions globally. Without changes to current trends, global CO2 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 interim report 2023 presents the results achieved in the intermediate phase (during the year 2022 and 2023). Further analysis and results will be shown in the following reports. The final report is expected to be published in November 2024.

2 Description of the demonstration facility

2.1 Context

The photovoltaic generation system of Franklin University 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 facade. 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 (credits: AIL).

2.2 BIPV system for the new auditorium of Franklin University 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 2).

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 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 the 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.

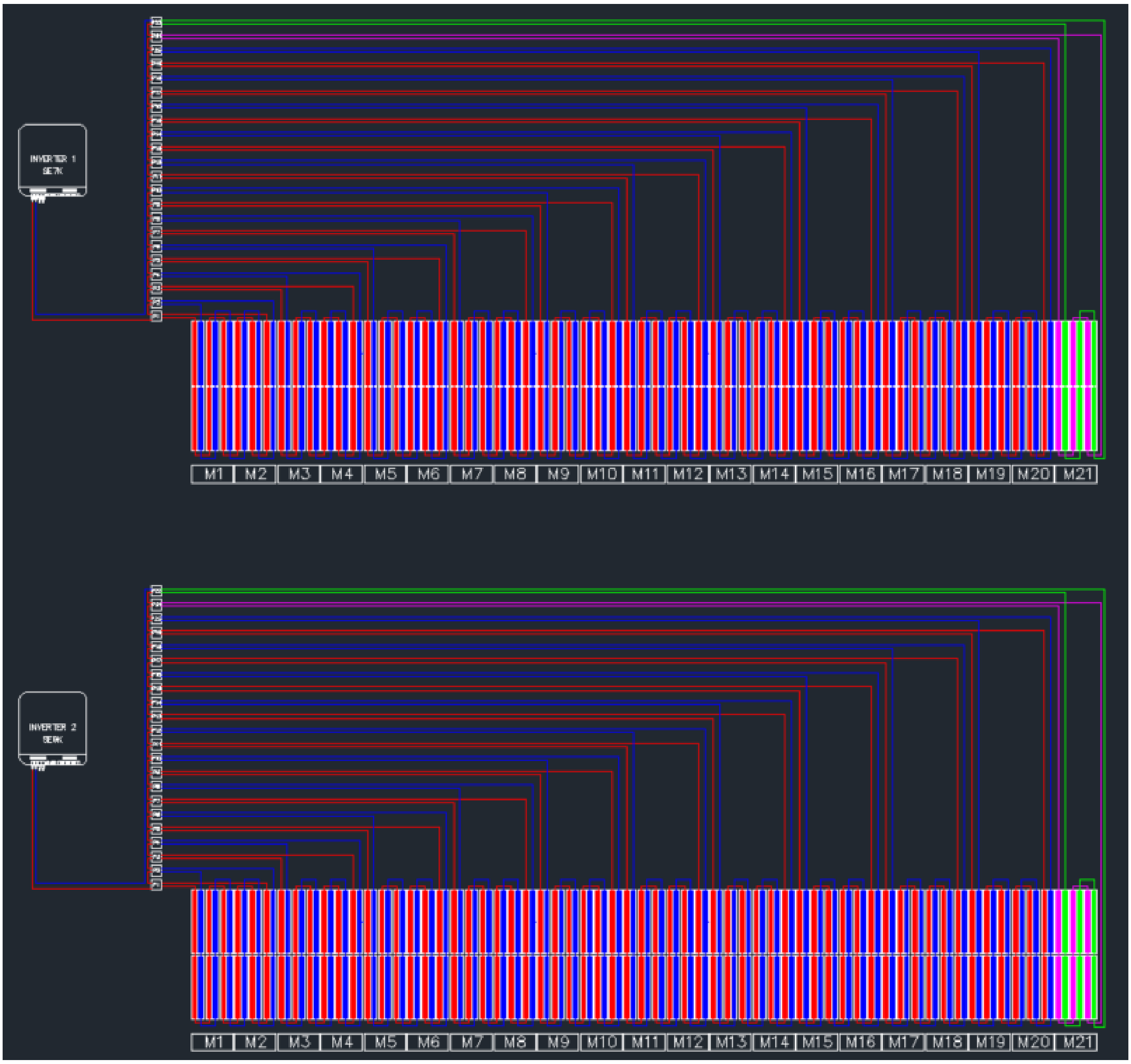


Figure 2 Electric layout of the BIPV installation. Up: first floor; down: ground floor. Mn represents the group which is managed by a motor (credits: AIL).

3 Holistic technology assessment

This study identifies under which energy and economic conditions a 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 net present value (NPV) equal to zero in 15 or 30 years. This activity assesses cost competitiveness scenarios in relevant architectonic situations and at different conditions (climate conditions, control system, orientation, technological systems), 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 holistic technological assessment identifies the status of PVSD technologies and builds up a benchmark for cost-reduction activities. The study is structured in three sections: i) the market analysis, 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. The study aims to assess only the energy performance of PVSD in terms of PV generation. Even though PVSDs affect different aspects of the building envelope (e.g., thermal, daylight, etc.), this activity focuses on the energy generated. In this report a brief extract of the whole methodology and study results is reported. From this research has been published a paper review aiming 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[1].

3.1 Market analysis

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 1 and Table 2 is shown an overview of the PVSD 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, Franklin University in Lugano, 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.

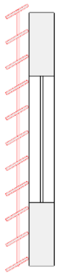
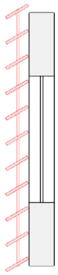
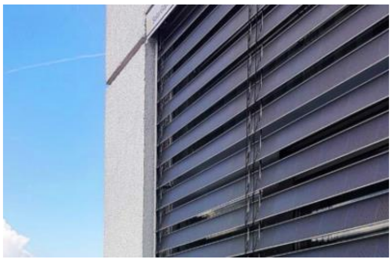
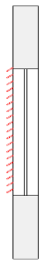
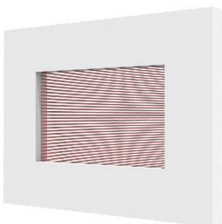
The data reported in table 1 are intended for only indicative purposes in the framework of this project and are not intended to provide reference for design or other market analysis or calculations.

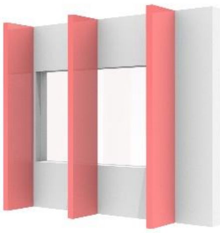
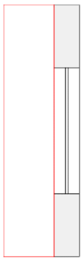
Table 1 PVSD: classification (credits: SUPSI 2022)

PVSD	POSITION			CUSTOMISATION		POSSIBLE MANUFACTURER	PRICE
System category	Outside	In between	Internal	Colour	Size	-	CHF/m²
1. PV Louver	x			x	x	Colt	1500
2. PV Louver	x				x	Merlo	900
3. PV Window Blind	x				x	SolarGaps	380
4. PV Window Blind			x	x	x	SunCurtain	680
5. PV fins	x			x	x	Onyx Solar	?

[1] Corti, P.; Bonomo, P.; Frontini, F. Paper Review of External Integrated Systems as Photovoltaic Shading Devices. Energies 2023, 16

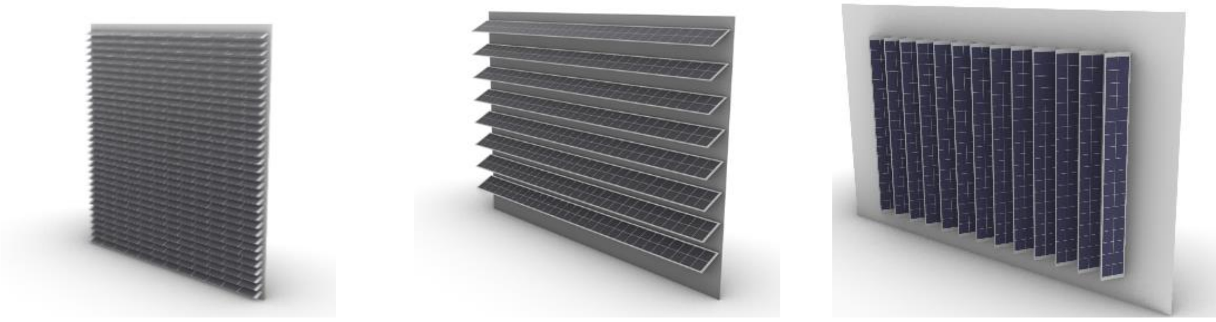
Table 2 PVSD: representation (credits: SUPSI 2022)

PV Louver, horizontal			
			Manufacturer: Colt Technology: c-Si Material: glass Dimension max: 4x0.6 m^2 Nominal power: NA Orientation: tracker, fixed, movable
PV Louver, vertical			
			Manufacturer: Colt Technology: c-Si Material: glass Dimension max: 4x0.6 m^2 Nominal power: NA Orientation: tracker, fixed, movable
PV Louver, horizontal			
			Manufacturer: Merlo 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			
			Manufacturer: SolarGaps Technology: c-Si Material: metal/polymer Dimension max*: 4x2.6m^2 Nominal power: 100 W/m^2 Orientation: tracker, fixed, movable *max window size
PV Window Blind, internal			
			Manufacturer: SunCurtain Technology: OPV Material: polymer Dimension max*: NA Nominal power: 40 W/m^2 Orientation: fixed *max window size

PV Fins			
			Manufacturer: Onyx Solar Technology: a-Si Material: glass Dimension max: NA Nominal power: 30 W/m^2 Orientation: fixed

3.2 Assessment of the photovoltaic energy potential of PVSD

PVSDs 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 study focuses on different PVSDs (Figure 3**Errore. L'origine riferimento non è stata trovata.**) with the goal to investigate their potential energy production and compare them systematically. The PVSDs analysed in this activity consist of external dynamic venetian blinds, horizontal louvres (both dynamic and fixed) and dynamic vertical louvres. Moreover, these systems have been simulated in different climate conditions to provide energy production values needed to investigate their economic profitability in different locations (Table 3).



External PV venetian blind | Horizontal PV louvre | Vertical PV louvre

Figure 3 Schematic illustration of PVSDs selected for the energy analysis.

3.3 Maximum investment for cost-effective PVSDs

This activity advances a cost-benefit study of the PVSDs in the form of market-available products and energy performance in different scenarios. This task's goal is to define the maximum present investment in the purchase, installation and management of a PVSD to achieve a NPV equal to zero in 15 or 30 years. The analysis defines a cost benchmark for PVSDs to assess a potential cost. 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;
- variation of the self-consumption ratio (60%, 70% and 100%);
- variation of the discount rate (4% and 7%[2]);
- electricity tariff: withdrawn 0.2631 CHF/kWh, injected 0.11 CHF/kWh.

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 4 and Table 5. PVSDs are systems that produce electricity and replace the functions

[2] Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity, 2019, E. Vartiainen et Al.

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 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, etc. The method of the additional charge (extra cost) has been discussed within the BIPV Status Report 2020[3] and within the report Integrierte Solaranlagen[4] promoted by Energie Schweiz. It is the basis from which the economic effectiveness of BIPV systems is calculated.

3.4 Consideration of the holistic technology assessment

3.4.1 Market analysis

PV louvres and fins are defined as landmarks PVSDs 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 (e.g., SolarGaps, SunCurtain).

3.4.2 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.

3.4.3 Maximum investment for cost-effective PVSD

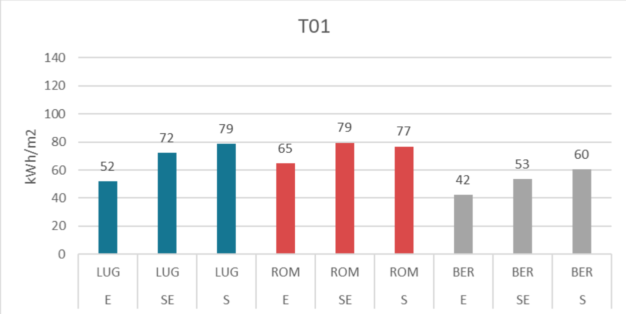
The maximum present investment in purchasing, installing and operating a cost-effective vertical PV louvre, defined as a NPV after 15 years, is about 250-400 CHF/m2 for a south-facing solar tracking installation depending on the boundary conditions. The maximum present investment of a cost-effective external PV venetian blind, defined as a NPV after 15 years, is about 80-200 CHF/m2 and, after 30 years, 100-300 CHF/m2. The maximum investment is considered an extra cost compared to a traditional conventional system[2].

[3] Building Integrated Photovoltaics: A practical handbook for solar buildings' stakeholders, 2020, P. Corti et Al.

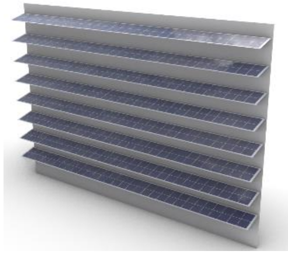
[4] Integrierte Solaranlagen Handlungsanleitung zur energetischen wirtschaftlichen Bewertung, 2020, C. Renken et. Al.

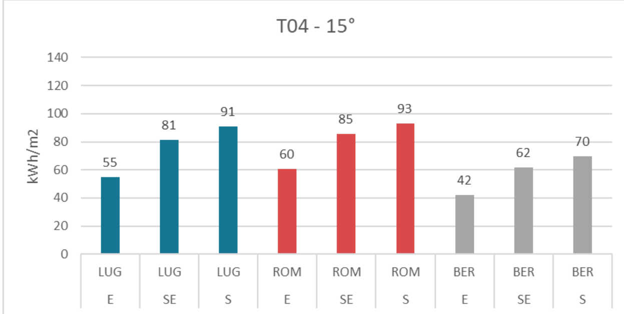
Table 3 Energy yield (kWh/m2) for different PVSD typologies. In the X axis, the different climate conditions (Lugano, Rome and Berlin) and orientations (east, south-east and south).

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

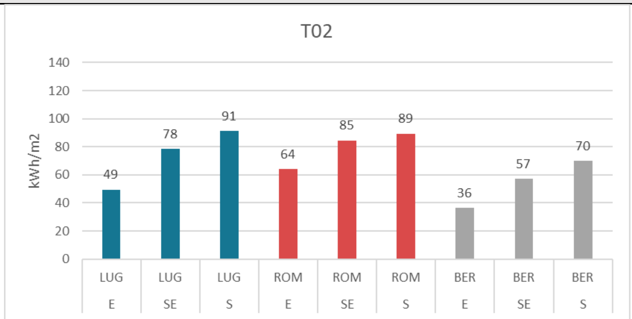


Horizontal PV louvre, d/l 0.95, fixed 15° (T04)

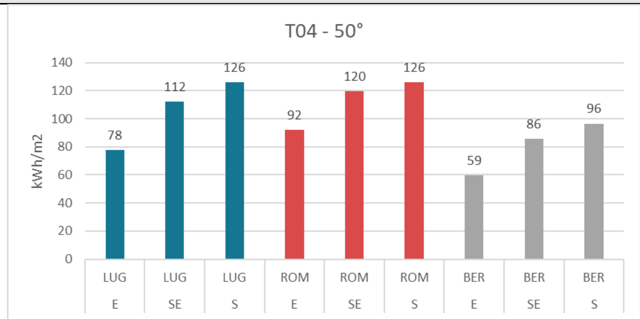




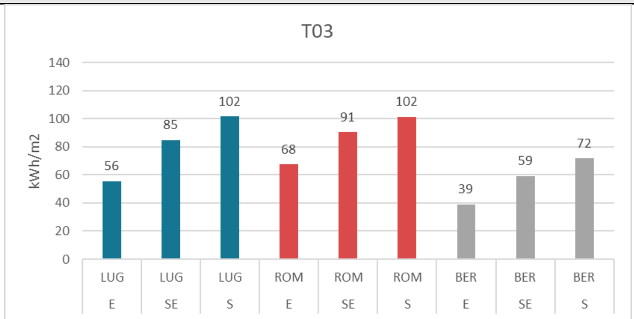
External PV venetian blind, d/l 1:1, dynamic system (T02)



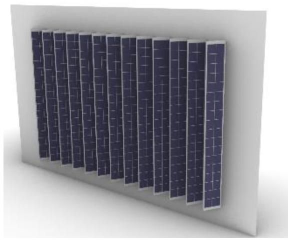
Horizontal PV louvre, d/l 0.95, fixed 50° (T04)



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



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



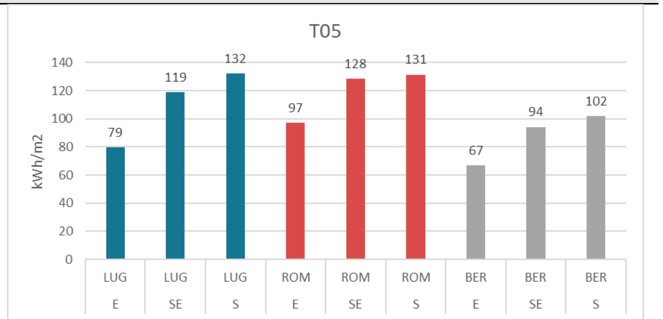
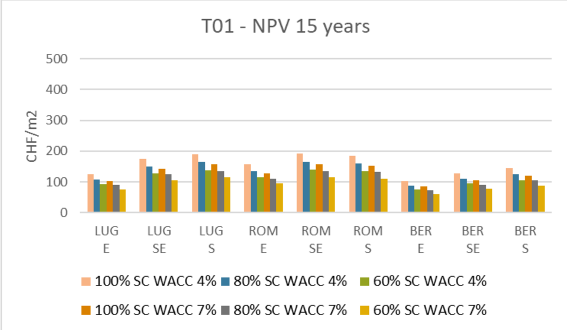
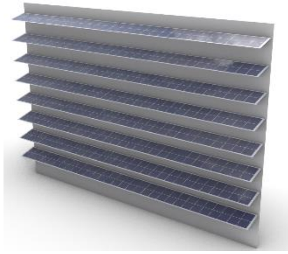


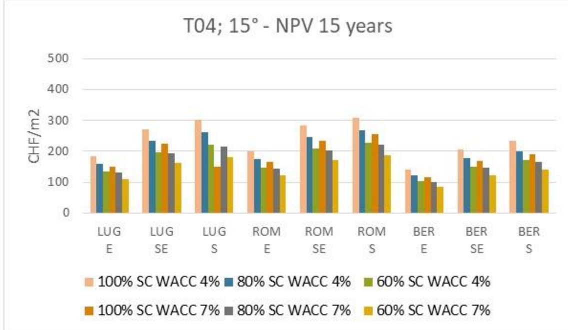
Table 4 Maximum investment (CHF/m2) for cost-effective PVSD to achieve an ROI in 15 years. In the X axis, the different climate conditions (Lugano, Rome and Berlin) and orientations (east, south-east and south).

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

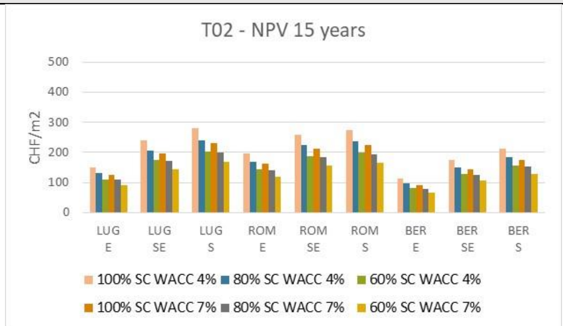


Horizontal PV louvre, d/l 0.95, fixed 15° (T04) – 15 years

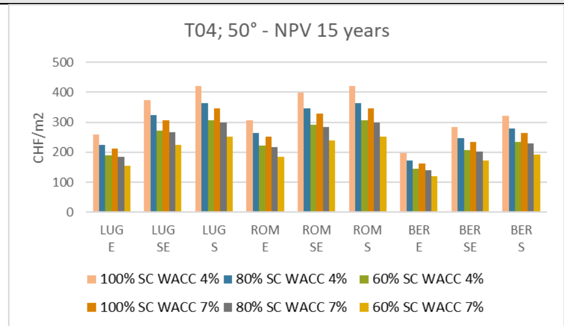




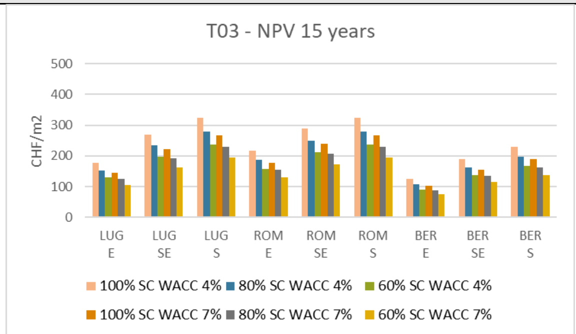
External PV venetian blind, d/l 1:1, dynamic system (T02) – 15 years



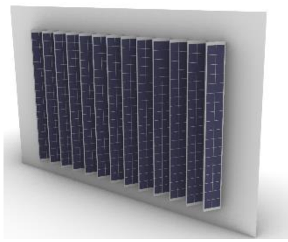
Horizontal PV louvre, d/l 0.95, fixed 50° (T04) – 15 years



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



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



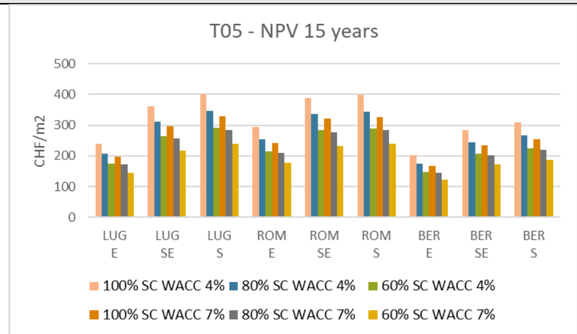
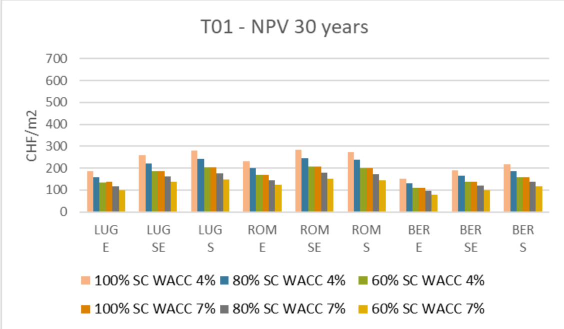
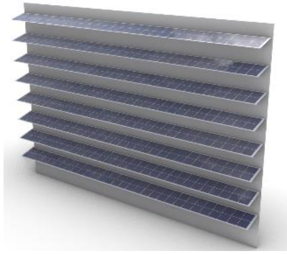


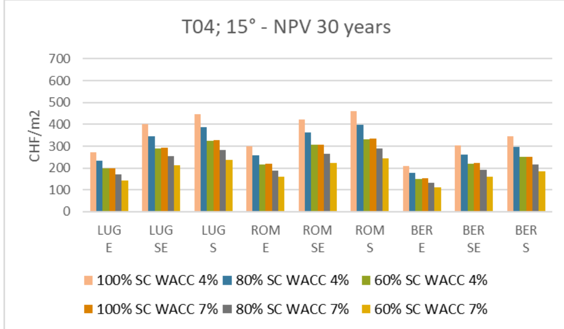
Table 5 Maximum investment (CHF/m2) for cost-effective PVSD to achieve an ROI in 30 years. In the X axis, the different climate conditions (Lugano, Rome and Berlin) and orientations (east, south-east and south).

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

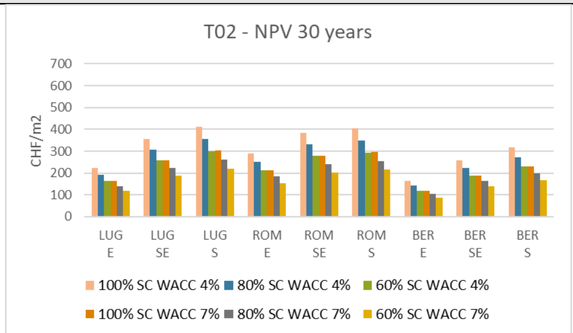


Horizontal PV louvre, d/l 0.95, fixed 15° (T04) – 30 years

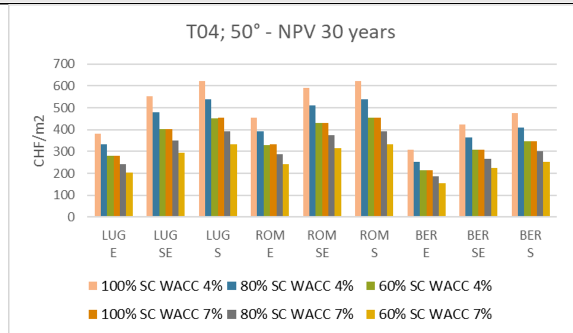




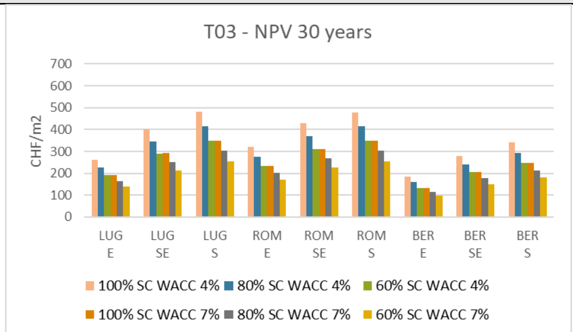
External PV venetian blind, d/l 1:1, dynamic system (T02) – 30 years



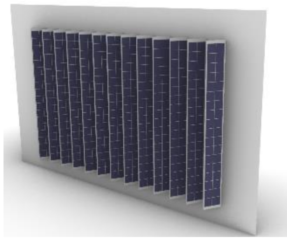
Horizontal PV louvre, d/l 0.95, fixed 50° (T04) – 30 years

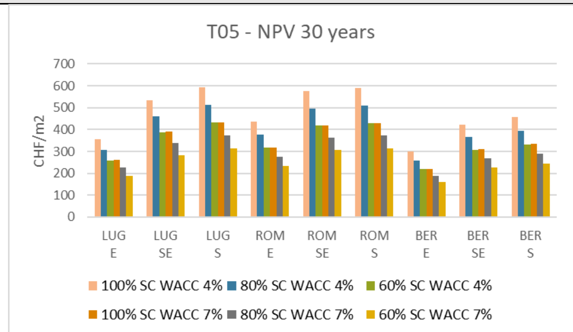


Horizontal PV louvre, d/l 0.95, dynamic system (T03) – 30 years



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





4 Technology validation: monitoring of the mock-up installation for one year

4.1 Mock-up installation

Small-scale samples of PV modules have been manufactured to replicate the large-size pilot system installed at Franklin University in Sorengo. The manufacturing of the PV modules was carried out by the project partner Sunage. Two PV module types have been manufactured to compare the energy performance: optimised and standard PV modules. The optimised PV module, also used on the pilot installation, has been engineered to increase the shading tolerance and avoid mismatching into the PV modules due to the slats' self-shading. Indeed, the internal electrical circuit of each optimized PV module has been subdivided vertically into two electrically independent "columns". The standard PV module is not engineered to increase the shading tolerance and the internal circuit of the module has not been divided into electrically independent columns. Both modules have the same mechanical structure, as shown in Table 6.
The analysis performed in this chapter validates the energy performance of a small-scale PVSD in a relevant environment to achieve a reliable and cost-effective product solution according to the predefined KPIs:

- KPI1 PV module temperature reduction: temperature of optimised module < temperature of standard module[5]
- KPI2 Outdoor module energy yield: energy yield of optimised module > 20% energy yield of standard module[4]

Table 6 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

4.2 Temperature assessment

Indoor test
The PV modules have been tested in SUPSI PVLab to ensure reliability for typical operating conditions of PVSD. The tests were aimed at detecting BIPV maximum temperatures in non-conventional scenarios by combination of the temperature test (IEC61730-2 MST21) with shading scenarios (IEC TS 63140 “Partial shade endurance testing”)[6]. Results showed an operation temperature reduction of up to 3 °C at non-conventional shading scenarios for the optimised PV module against the standard PV module (Table 7). The electrical schema and the configuration of the probe are shown in Figure 4.

[5] The standard module is a dynamic PV solar shading solution. The module's architectural design does not prioritise optimisation for enhanced shading tolerance.
[6] The test methodology is described in BIPVBOOST H2020 project. D5.2 Report on specific performance-based laboratory testing procedures for BIPV products (www.bipvboost.eu)

Table 7 Temperature comparison at non-conventional shading scenarios.

PV module	Max. temperature 1000W/m2	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

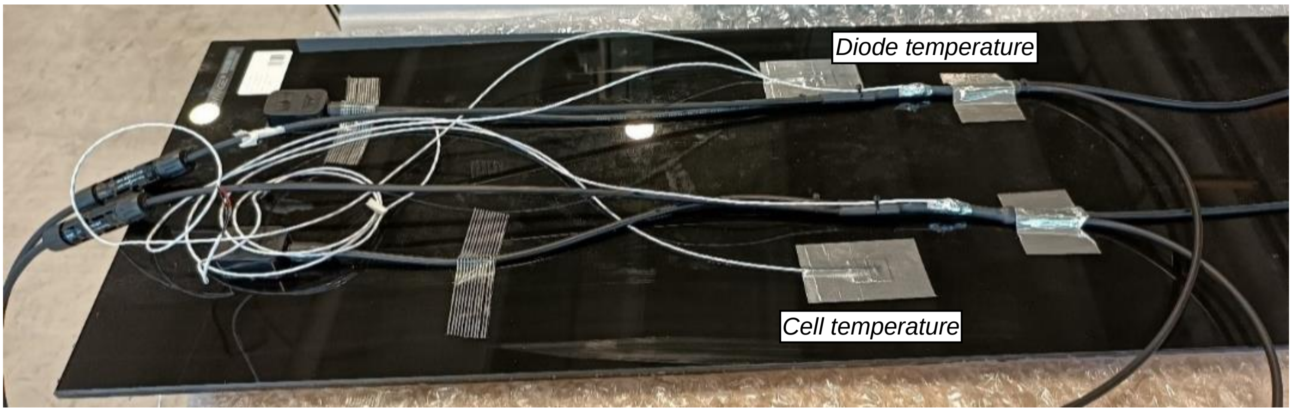


Figure 4 Back of an optimised PV module with probes (PT100). The air cavity temperature is measured with probes installed on the metal slat.

Outdoor test

PV module temperature

The outdoor test (in Figure 5 the mock-up installation in Mendrisio) showed comparable results with the indoor test. The optimised module, L2, measured a lower maximum module temperature than the standard module, L5, albeit with a similar mean module temperature (Table 8). **The temperature for the optimised PV slats (PV modules' temperature) is lower when compared to the standard configuration, successfully achieving the target established for KPI 1.** The PV design evaluation based on maximum temperature is more relevant because it reveals the effectiveness of the optimised module in shading tolerance and reduction of self-shading mismatch. It was when modules were under high irradiance, and the shading constituted bypass diode activation and module heat-up that led to the higher module and diode temperature. Due to the partial or complete shading of one string, the current generated by the unshaded string of L5 was limited to the level of the shaded string. The lost power output of the unshaded string was dissipated as heat in the shaded string, resulting in a higher module temperature.

Table 8 Descriptive statistics of PV modules' temperature monitored (source: SUPSI).

	L2 Left str.	L2 Right str.	L5 Left str.	L5 Right str.
Mean	25.1°C	25.1°C	25.8°C	25.5°C
Median	25.6°C	25.4°C	26.3°C	25.7°C
Max.	49.9°C	52.9°C	51.7°C	54.4°C
Min.	-3.8°C	-4.0°C	-3.9°C	-4.0°C

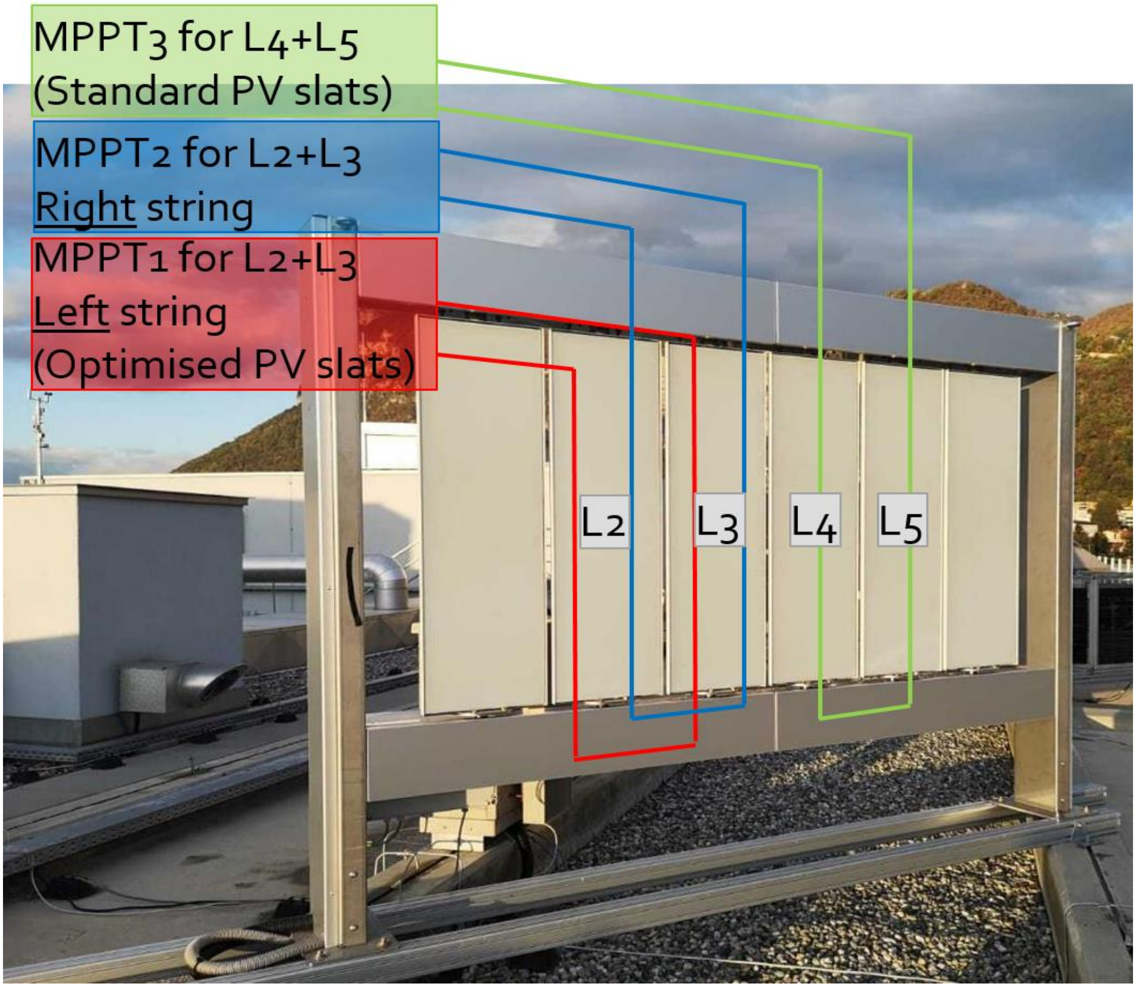


Figure 5 Mock-up installed at the rooftop test facility of SUPSI.

<u>Diode and air gap temperature</u>
The mean and maximum diode temperatures of the L2 left string are also lower by approximately 2.0°C (Table 9Table 9). Nevertheless, the L2 right string has a slightly higher diode temperature than that of the L5. The left strings for L2 and L5 have a lower maximum temperature than the right strings, by about 3.0°C. A time series analysis is required to explain this phenomenon. On the contrary, the difference in mean and maximum air gap temperature for both types of PV modules are insignificant, which is merely 0.2°C and 1.1°C. It indicates an adequate aluminium enclosure design even for the standard module: a high thermal conductivity of thermo-lacquered aluminium in white that enhances conductive heat transfer and the support structures within the air gap that increase the heat dissipation area.

Table 9 Descriptive statistics of diode and air gap temperature monitored (source: SUPSI).

	Diode Temperature			Air Gap Temperature			
	L2 Left str.	L2 Right str.	L5	L2 Left str.	L2 Right str.	L5 Left str.	L5 Right str.
	Optimised PV module		Stand. PV	Optimised PV module		Standard PV module	
Mean	23.3°C	24.1°C	25.1°C	23.1°C	22.7°C	23.0°C	22.9°C
Median	23.8°C	24.6°C	25.9°C	23.6°C	23.3°C	23.5°C	23.4°C
Max.	47.4°C	50.1°C	49.5°C	45.5°C	45.6°C	45.0°C	46.1°C
Min.	-4.1°C	-4.1°C	-3.8°C	-3.6°C	-3.6°C	-3.5°C	-3.4°C

4.3 Energy assessment

The total energy yield, monitored from November 2022 to September 2023 for the optimised PV slats and the standard PV slats are 23.8 kWh and 19.7 kWh, respectively (Table 10). The total energy yield of the optimized PV slats was calculated by summing the energy yield of left and right strings. The energy yield for the optimised PV slats represents a significant gain of 19.8% when compared to the standard configuration, successfully achieving the target established for KPI 2. The actual gain could be higher with higher data availability.

Due to the partial or complete shading, the current generated by the unshaded strings of the standard PV slats was limited to the level of the shaded strings. It resulted in lower power output and energy yield. On the contrary, with strings on separate electrical routings and two bypass diodes, the impact of the shaded strings on the unshaded ones was minimised.

Table 10 Energy evaluation of optimised and standard PV modules monitored (source: SUPSI).

	Optimised Left	Optimised Right	Optimised total	Standard total
Total Energy Yield	11.8 kWh	12.0 kWh	23.8 kWh	19.7 kWh
Specific Energy Yield	87.2 Wh/W_p	88.6 Wh/W_p	175.8 Wh/W_p	145.2 Wh/W_p

4.4 Discussion

In conclusion, splitting two strings, each with a bypass diode, reduced the mismatch effect between unshaded and shaded strings. The optimised design achieved a better temperature and energy performance, fulfilling the KPI1 and KPI2 of this section: lower module temperature and 20% energy yield gain, respectively. The optimised module has consistently lower module temperatures throughout the day than the standard module, regardless of the sky conditions; the monthly energy yield is also higher. The optimised design demonstrated resiliency under shading conditions. The maximum module temperature is below that of the standard module by a minimum of 2.0°C for indoor tests. Similarly, for the outdoor test, the optimized module also achieved an approximately 2.0°C lower module temperature. The heat generated by the modules was dissipated efficiently, given that no extreme air gap temperatures were observed. Three conditions: oversized diode, indirect contact between temperature probe and diode surface, and low current passing through diode resulted in lower diode temperature. These observations will be compared while analysing the demonstration building’s temperature data.

5 Technology demonstration: monitoring of the pilot installation for two years

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 Franklin University. The PV modules were manufactured by the project partner Sunage according to the features shown in Table 11-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 11-bottom, Figure 6). 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 12).

Table 11 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 6
Dimensions	First floor: 4630x360mm ¦ Second floor: 3670x360mm

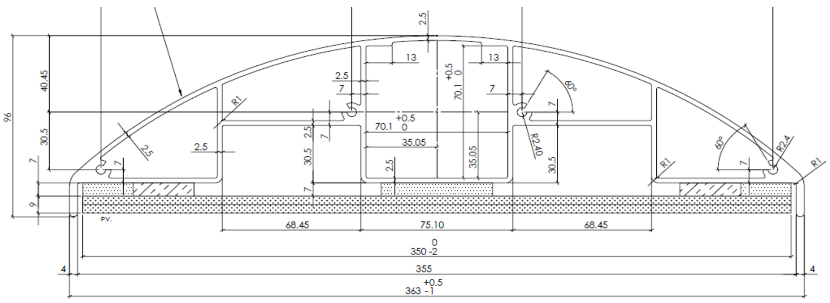


Figure 6 Shape and dimension PV slat.

Table 12 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 monitoring

A monitoring scheme was developed for the pilot installation of PVSD on the façade of a new Franklin University auditorium located on the west side of the university complex. The monitoring activity aims to demonstrate the system readiness from TRL6 to TRL7, representing the technology reliability with low process and maintenance costs in actual full-scale buildings. Activities include monitoring and comparing the temperature (diodes, air cavity and cells) of the PV slats against the mock-up in Mendrisio and indoor measured values. As the monitoring is ongoing, we present only the pilot installation's six-month temperature and energy data in the subsequent sub-sections.
The position and label of temperature probes are shown in Figure 7. The slats under monitoring (32, 35, 38, and 41) are on the second floor. Figure 8, left, shows the descriptive statistics for temperature measurements of slat 32. Group 1 temperature components: air1, cell1, and diode1 refer to the air cavity, rear-side PV cell, and diode temperature measurements for the slat's left side; group 2 refer to the right side. Descriptive statistics of relative humidity are shown in Figure 8, right. Only the results of slat 32 are presented since the temperature measurements of all slats under monitoring do not differ significantly. The difference is described in the following paragraphs.

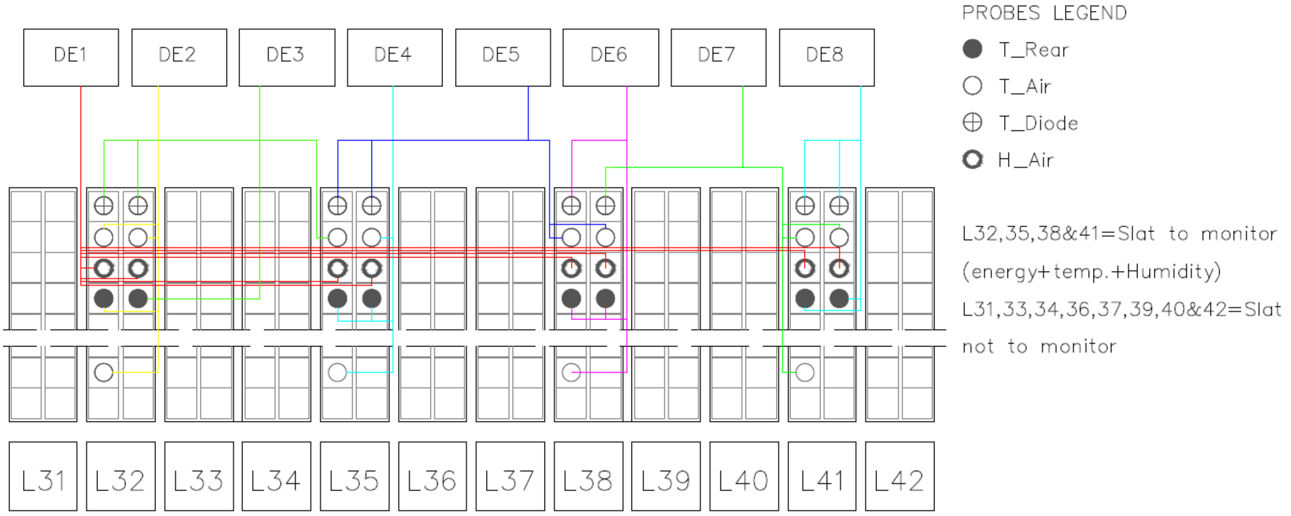


Figure 7 Schematic diagram for temperature probe positions (source: SUPSI.)

As shown in Figure 8, left, the mean and maximum temperatures for the left and right sides of slat 32 do not differ significantly. PV cells' mean and maximum temperatures are around 28°C and 54°C, respectively. The air cavity temperatures for all positions are also similar: 26°C and 45°C for mean and maximum. The mean and maximum diode temperatures are between that of the PV cell and air cavity: 26°C and 48°C. Mean and maximum relative humidity for positions 1 and 2 are similar: around 44% and 113%, respectively.
Compared to slat 32, the mean and maximum cell temperature ranges for other slats (35, 38, and 41) are not more than 2.5°C and 8.9°C, respectively. For air cavity and diode temperatures of other slats, the mean and maximum are not more than 1.5°C and 4.4°C, and 1.4°C and 1.9°C, respectively, from that of the slat 32. Moreover, the mean and maximum relative humidity for other slats show insignificant differences from the that of the slat 32: around 1.3% and 2%, respectively.

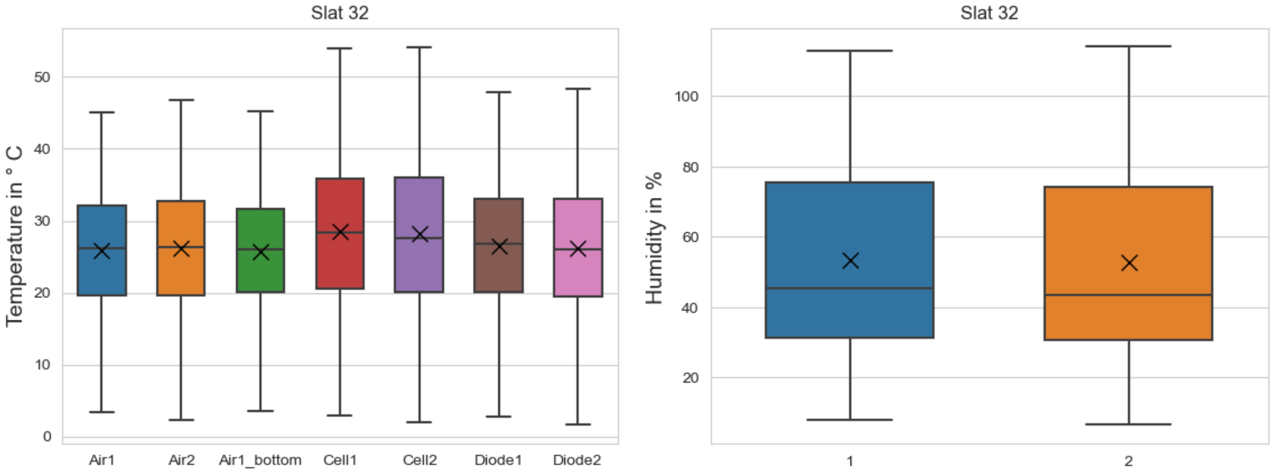


Figure 8 Descriptive statistics of left) temperature components and right) relative humidity measurements for slat 32 (source: SUPSI).

5.3 Energy assessment

Six-month energy and specific energy yield data are shown in Figure 9. The total energy yield for the PVSD system on the first and second floors is 2.9 MWh and 2.5 MWh, respectively. The monthly energy yield of the first-floor system is higher than the second floor, but the specific energy yield is lower. According to preliminary simulations, the first-floor experienced shading on parts of the slats, shown in Figure 10. On the 21st of June, the simulation indicates that the top parts of the first floor's slats have received lower irradiance than the second floor due to the shading: it is more noticeable on the slats on the south-southeast and south-southwest orientations.

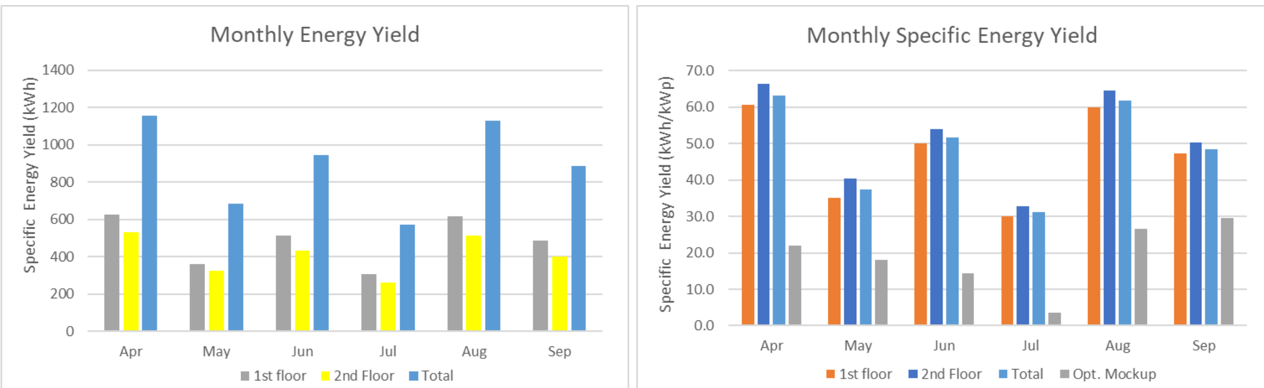


Figure 9 Monthly left) energy and right) specific energy yield (source: SUPSI).

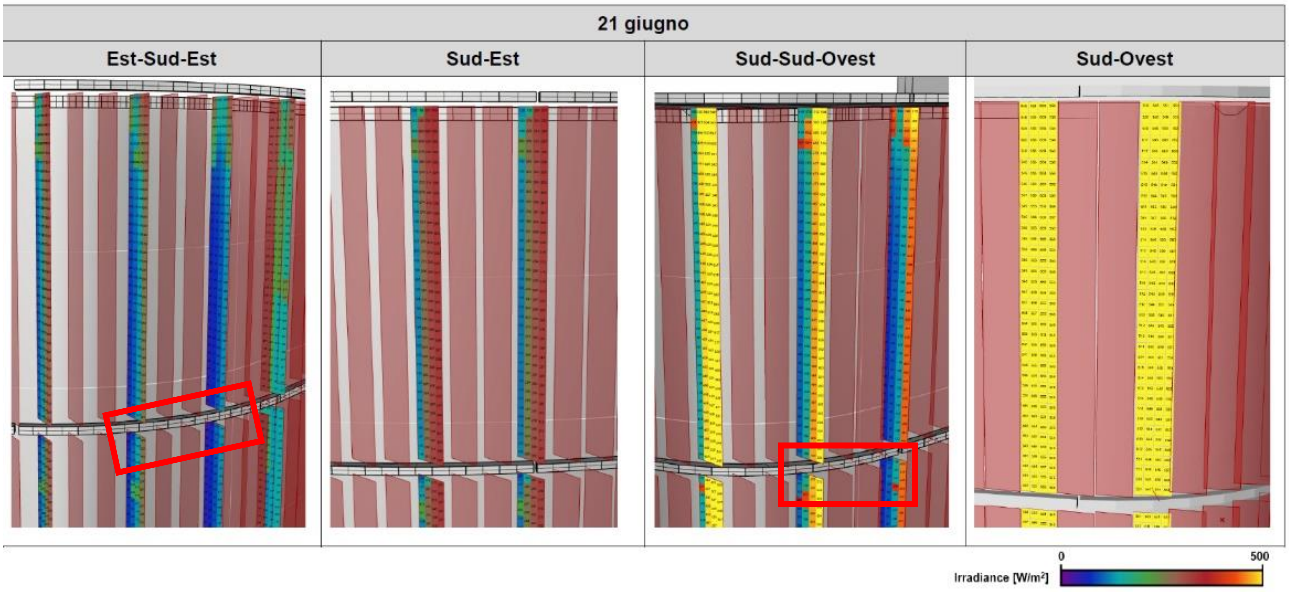


Figure 10 The Top parts of the first floor's slats are shaded, resulting in lower exposure to irradiance (source: SUPSI).

5.4 Discussion

This chapter presented a preliminary six-month temperature and energy yield results analysis. No extreme temperature and humidity measurements were observed for all slats. The mean and maximum are around 28°C and 54°C, respectively. The descriptive statistics of temperature measurements for slat 32 also agree with those of other slats. The variations were observed on the daily temperature profiles due to the Sun-tracking and slats' shading. Overall, the temperature measurements of the pilot installation are consistent with that of the mock-up system. Furthermore, the six-month total energy yield of the pilot installation is 5.4 MWh. It is important to note that the specific energy yield of the first floor's system is lower than that of the second floor due to the shading of the top parts of the slats for the first floor. Annual energy yield analysis will be performed after a complete one-year data collection.

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 Franklin University, 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. Our 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]: <1500 CHF/m2
- 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 11 and Table 14 provide an extensive roster of stakeholders integral to the construction process and those directly engaged in the construction of PV shading devices for the Franklin University project (identified with a reference number). Within this broader group, we have further pinpointed and designated 37 stakeholders who play a pivotal role in the construction of the PV shading system at Franklin University. 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/m2. 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/m2, representing a 15% reduction compared to the KPI that we aim to demonstrate, which is KPI4. These estimates are based on two scenarios:

- Cost projection for 2023, envisioning the initiation of a new project under current conditions.
- Cost projection for 2025, anticipating the commencement of a new project with the maturation of technology and increased stakeholder expertise.

[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/m2).

Scenario 1 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 1% reduction compared to the KPI that we aim to demonstrate, which is KPI3.

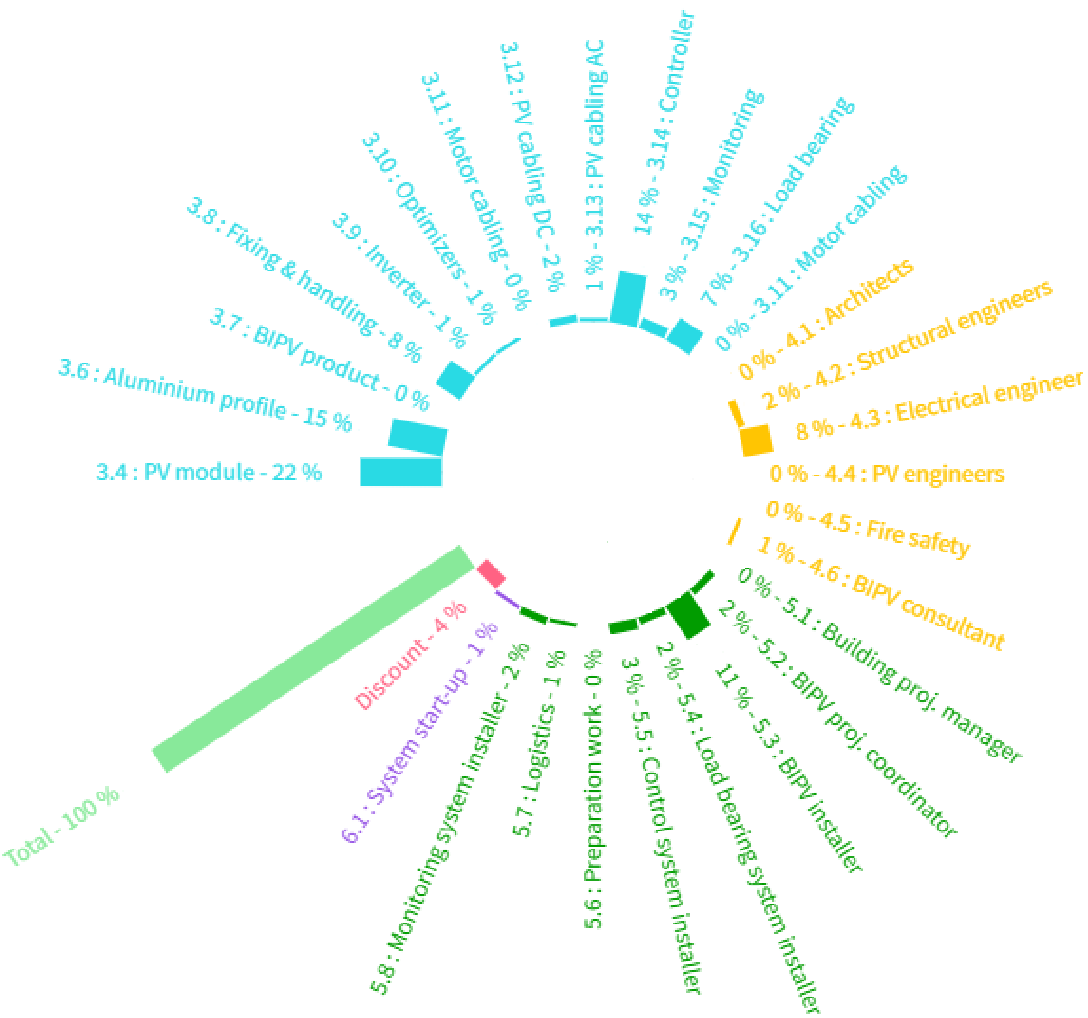


Figure 11 Construction process breakdown. The total (green) includes the discount. It doesn't include subsidies and unexpected costs. Raw material producers and product manufacturers (light blue), Design and engineering (yellow), Construction (dark green), O&M (purple).

Table 13 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 13 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 Discussion

The following points have been highlighted:

- 37 stakeholders who play a pivotal role in the construction of the PV shading system at Franklin University have been pinpointed and designated.
- The detailed breakdown of the PVSD costs at the Franklin University installation incurred by each individual stakeholder within the project's value chain displays a total cost of 545'253 CHF, 471'004CHF and 381'621 CHF for the state of art, the Scenario 1 (2023) and Scenario 2 (2025) respectively.
- In Scenario 1 (2023) it was anticipated a reduction of approximately -20% for labour and 21% for material supply; conversely, in Scenario 2 (2025), it was expected a reduction of -35% for material supply and -39% for labour.
- 18 out of the 21 project activities were concentrated between March 2022 and March 2023, spanning a total duration of one year.

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 (P+D Stakeholder)			
			Monitoring & probes suppliers (P+D Stakeholder)					
			Load bearing system manufacturers (P+D Stakeholder)					

7 Set-up of a monitoring platform

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. The subsequent analyses encompass:

- Real-Time Monitoring of PV System Parameters: continuous tracking of the system's temperature, voltage, current and rotation parameters, enabling real-time insights into its performance.
- Operational Data Recording: data recording system to capture and store operation results, facilitating comprehensive performance analysis over time.
- Slat Handling: examination of the slat position to understand their impact on the overall system operation and shading efficiency.
- Alarm Management: development of a temperature alarm to ensure a preliminary reliability and safety of the BIPV shading system.

By addressing these key aspects, we aim to provide in the future preliminary insights and strategies for enhancing the operational performance, efficiency, and cost-effectiveness of BIPV shading systems throughout their operational lifespan. This activity presents the results of our investigation and highlights the significance of monitoring and management approaches in the context of renewable energy systems.

7.1 Preliminary monitoring platform for a BIPV shading system

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 13)[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 (Figure 13 and Figure 14):

- Sensor data presented in line charts.

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

- 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.

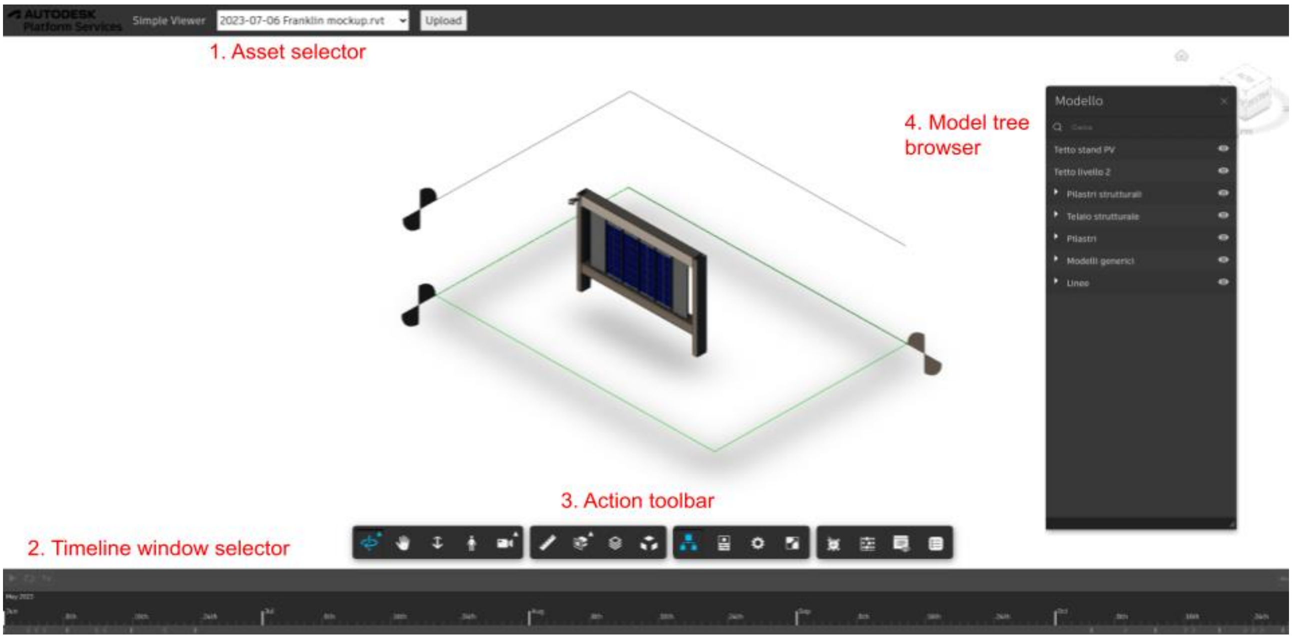


Figure 13 Monitoring platform elements (source: SUPSI).

Figure 14 Digital Twin functionalities (source: SUPSI).

This demonstration serves 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. It's worth noting that, at present, these configurations require coding skills for implementation. However, our next logical step involves simplifying this process to make it more accessible to a wider user base.

8 Evaluation of results and next steps

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. 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, the optimised design achieved a better energy performance by increase the energy yield of about 20% in comparison with the standard PV modules.

To assess the efficiency, monitoring, and cost optimization of BIPV shading systems throughout their operational lifespan, it was undertaken an approach that involves 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. This demonstration serves as a practical testbed to assess the functionality and explore the untapped potential of the Digital Twin.

The solar tracking photovoltaic shading device was installed in the building façade of the new pavilion of Franklin University, resulting a flagship example of highly aesthetic photovoltaic shading systems realised in Switzerland. The installation, testing and monitoring of the technology in real operating conditions represents a pilot installation for achieving new information, assessing KPIs and performance to increase the TRL and ensure the system market penetration. As the monitoring is ongoing, in this interim report are presented only the pilot installation's six-month results.

To illustrate the compelling value proposition of the PV shading device solution implemented at Franklin University, it was conducted an extensive construction site monitoring initiative. The extensive construction site monitoring has effectively demonstrated the compelling value proposition of the PV shading device solution implemented at Franklin University. This comprehensive endeavour, which involved a stakeholder analysis, time and procedural delineations, expenditure assessment, and the identification of challenges and opportunities, serves to fostering collaboration between the photovoltaic sector and the building and infrastructure industry. The comprehensive analysis of PVSD costs at the Franklin University installation 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 state-of-the-art, Scenario 1 (2023), and Scenario 2 (2025), respectively. This breakdown demonstrates a noteworthy reduction in costs, with a decrease of approximately -20% for labor and 21% for material supply in Scenario 1 (2023). In Scenario 2 (2025), there is a substantial reduction of -35% for material supply and -39% for labor.

The holistic technology assessment for PV shading devices lays the foundations for developing a methodology of energy-economic evaluation for the shading system which will be used to build the analysis of replicability and market exploitation strategies.

The final report is expected to be published in November 2024. The activities which are planned to be included are the followings:

- Final results of pilot building monitoring to achieve the TRL 7 by demonstrating the technology in a relevant environment (one year);
- Replicability and market exploitation strategies definition.