Validation process of a multifunctional and autonomous solar window block for residential buildings retrofit

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Abstract

In the framework of the EU H2020 project EnergyMatching, a catalogue of multifunctional and autonomous window renovation solutions was developed. Such catalogue is based on the Solar Window Block (SWB), which is a prefabricated window system that integrates a highly efficient window, a PV module, a shading system and a decentralized ventilation machine. The SWB aims at enhancing the energy performance and indoor comfort of existing residential buildings without adding electrical loads and simplifying the installation works. The development of the SWB was addressed through calculations, prototyping, testing campaign up to demo installation and monitoring. This paper focuses on the testing campaign validation process of this technology. Three main SWB configurations were designed and real scale prototypes manufactured, followed by dedicated tests to verify the operation of the system and its energy production-consumption matching performance. On the one hand, operational temperature tests showed a proper functioning of the electrical circuit of the system, as well as underlined the importance of the ventilative cooling of the electrical equipment. On the other hand, the energy matching performance tests showed the capability of the different SWB configurations to cover different demand profiles of the ventilation unit. Thanks to the holistic technology validation process, the executive SWB design has already implemented required modifications to assure safe functioning, easy installation and maintenance.

Keywords: energy efficiency, indoor comfort, BIPV, solar building, solar window block

1. Introduction

The retrofit of the existing building stock is being promoted by the EU Directives in terms of energy performance of buildings (2018/844/EU and 2012/27/EU) as one of the most relevant actions to reduce the building sector energy consumption, CO_2 emissions and therefore climate change risk. In a renovation intervention, windows are a crucial component due to their strong impact in the final achieved energy efficiency and comfort. Although their substitution is frequent, it is still a very delicate intervention because its correct installation influences significantly the building renovation final quality, that could be easily impoverished due to risk of wrong installation, of damages, of poor component performance as well as create excessive disturbance to occupants. To facilitate and secure the proper window installation, both in new and existing buildings, the use of a prefabricated insulating frame called “window block” is more and more used. Besides its decrease of thermal losses due to thermal bridges and increase of installation precision, it provides space for the integration of different components that could enhance energy efficiency and indoor comfort.

In the framework of the EU H2020 project EnergyMatching, a catalogue of multifunctional window blocks, called Solar Window Block (SWB) was developed for residential buildings retrofit (Andaloro, et al., 2018). The SWB is a prefabricated system composed by the following components: (i) an insulating frame; (ii) a highly efficient timber-frame window; (iii) photovoltaic modules; (iv) automated shading; (v) and a decentralized ventilation machine. The SWB solutions provide valuable opportunities for enhancing the energy performance of existing buildings and increasing building occupants comfort, in terms of enhanced indoor air quality and daylighting control, with a unique easy-to-install system, without adding electrical loads to the building. In addition, these systems allow for effective integration of BIPV modules to maximize renewable energy sources exploitation through self-consumption, with a low disturbance on building occupants.

Three main SWB configurations were identified based on a joint technical feasibility and performance-based assessment of the different possible solutions (Andaloro, et al., 2018). The development process was characterized by an iterative design through several steps with progressive increase of details and analysis, such as: (a) thermal performance, (b) daylighting analysis, (c) energy matching performance, (d) technical integration of components and PV sizing. This process led to the identification and detail design of a catalogue of SWB solutions. The three main configurations contained in the catalogue integrate the PV modules on the sill, as a shading overhang or vertically in the façade. Some of the most important barriers identified were the fire prevention requirements, operation and maintenance needs, components integration and interfaces. Consequently, the required modifications were implemented in the prototypes final design, resulting in the manufacturing of three real scale mock-ups (Fig. 1).

Fig. 1: Solar Window Block mock-ups in the outdoor lab (from left to right: BIPV vertical, BIPV sill, BIPV overhang)

After the executive design and real scale prototypes manufacturing, the SWB development was followed by the demonstration in real operational environments, both in testing infrastructures and in a real building. Hence, the work presented in this paper aims at validating the SWB design through a dedicated testing campaign. Specifically, the testing phase focused on operational temperature tests of the electrical components in their compartment, and energy production and consumption matching tests under real conditions. Finally, lesson learnt from the prototypes design, manufacturing and testing activities was implemented in the SWB design for a real demo case building.

2. Methods

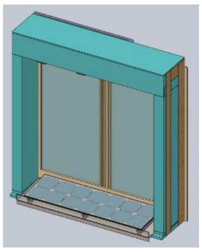
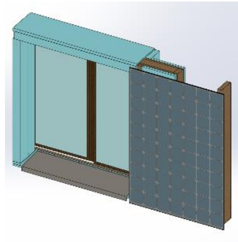
In order to validate the system before its installation in real buildings, an extensive testing campaign was performed. Initially, the manufacturing and assembly chain of the solution was validated through direct communication with the different component manufacturers and system integrator. Besides this, the functionality and robustness of the SWB and its components were verified through initial trials during the mock-ups commissioning. Once done the initial verifications, the testing campaign was focused on two main test types: operational temperature tests and system energy matching performance tests.

2.1. Summary of the SWB main features

The main features and components of the three tested SWB configurations are summarized in Tab. 1, and differ mainly by PV module positioning within the overall system: (i) in sill, (ii) in window overhang and (iii) vertical position next to window (Andaloro, et al., 2020). However, the position of the PV module impacts on other features of the system, such as the installed PV power (different PV cell technology and module size) and required electrical components. For example, the solution with the PV sill requires an additional electrical component (booster) increasing the output voltage to be able to charge the battery. Moreover, the PV position constraints the window position within the wall depth, which in turn has a significant effect in the SWB thermal bridges.

Apart from these differences, the concept behind the three SWB configurations is similar as well as its off-grid electrical connection scheme. As shown in Fig. 2, the energy produced by the PV module is used to charge the battery and to feed the ventilation machine. The circuit is controlled by the Maximum Power Point Tracker (MPPT), which controls the PV operation point, the battery charging process and the battery discharging process through the Ventilation Machine (VM).

Tab. 1: Summary of main features and installed components of the main SWB configurations

SOLAR WINDOW BLOCK / COMPONENTS		SWB 1 – BIPV SILL	SWB 2 – BIPV OVERHANG	SWB 3 – VERTICAL BIPV
				
GLAZING		Triple glazing of 52.8mm total thickness (U glazing = 0.6 W/m²K)		
SHADING		ScreenLine SL22W - V95 coated (reflective)		
WINDOW BLOCK	**WINDOW**	Versatile continental window (U frame = 0.91 W/m²K)		
	PV POSITION	On the sill	Overhang	Vertical
	VM POSITION	Above window		Next to window
VENTILATION MACHINE		Thesan Aircare ES (Max 20.6W)		
PV MODULE		c-Si (56 Wp)	a-Si (31 Wp)	c-Si (291 Wp)
PV CLICK&GO		Cosmos plug &play solution		
BATTERY		2x12V (Li-Fe-Po4)	1x24V (Lithium-ion)	2x12V (Li-Fe-Po4)
MPPT		-	Morningstar's SunSaver MPPT	
MPPT & BOOSTER		Genasun GVB-8-Li-28.4V	-	

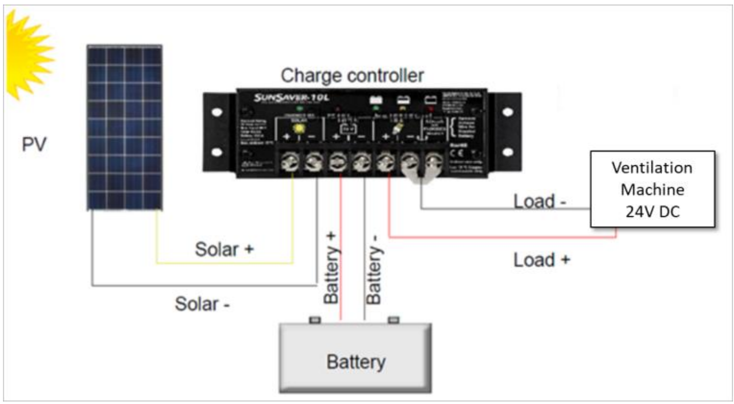


Fig. 2: Electrical connections scheme (without booster)

2.2. Operational temperature tests

The verification of the operation temperatures of the system was a first priority in the validation process, in order to identify the potential risk of fire due to the presence of electrical components within the window block. In fact, the VM, batteries and rest of electrical equipment are installed within a closed wooden compartment on top of the window block. A set of openings for the natural ventilation was designed and needed to be validated. In case of overheating of these components, besides the risk of fire, the system could not work properly if exceeding their maximum allowed operation temperatures (Tab. 3). Therefore, a dedicated test campaign was performed with the goal of verifying that the temperatures reached by the different components were acceptable and there was no risk of fire, malfunctioning of components.

These tests were performed in a prototype, containing the wood compartment with all the electrical equipment. The prototype represents the smallest wooden box design, representing thus the worst case in terms of overheating risk. This prototype was installed and tested in an indoor laboratory with an air temperature fixed to 25°C, in a set up that allowed air to flow naturally through the different ventilation grids foreseen in the system. All the electrical components, such as ventilation device, batteries, MPPT-controller and DC/DC controller, were installed. Normally, the real SWB is fed with the power generated by the PV module. However, in this indoor test, the lack of real PV power was substituted by a PV simulator Ametek ETS600X, which provides power in the same way as a PV module. This allows the MPPT-controller to work as it was connected to a PV panel in the different test scenarios.

During the tests, two air temperatures and four surface temperatures were monitored, together with the current and voltage of the battery and ventilation unit. In order to measure the temperatures five thermocouples were installed in the most representative positions, such as on the surfaces of battery, MPPT and DC/DC controller. The air temperature was measured next to the main electrical components and the air outlet ventilation holes, as shown in Fig. 3. The portable digital thermometer TM 947 SD with a resolution of 0.1°C and an accuracy of 0.5% of reading was used to monitor and record thermocouples data. However, the voltage and current measurements (1% and 2% of accuracy respectively), as well as the MPPT heat sink temperature measurement were done by the sensors embedded in the MPPT device. This data was monitored and gathered by the MSView software provided by SunSaver MPPT manufacturer. Both monitoring systems recorded data every 1 minute.

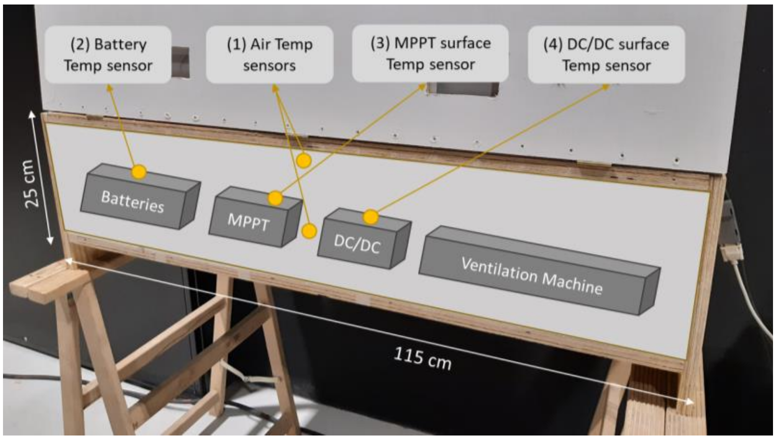


Fig. 3: Scheme of the operation temperature test mock-up and set-up

Besides the operation temperature verifications, these tests allowed to check the following aspects: (i) the real battery energy storage capacity and voltages related to different states of charge, (ii) battery charge and discharge strategy to be configured in the SunSaver MPPT and (iii) correct functioning of the MPP tracker. The implemented control strategy aimed at maximizing the PV power generation, while preventing the battery complete emptying and consequent system restart need. Fig. 4**Error! Reference source not found.** shows an example of evolution of the battery state of charge and the main control parameters: (i) upper battery capacity limit (95%), (ii) depth of discharge (80%), (iii) status of charge at which disconnect the load (20%) and (iv) reconnect the load again (80%).

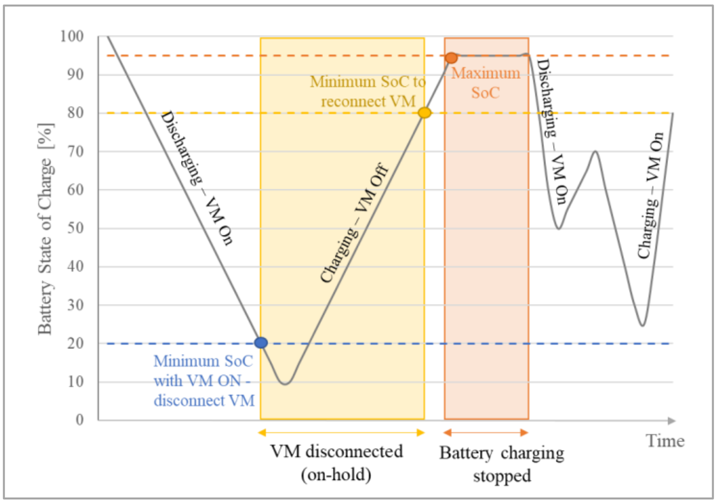


Fig. 4: Example of battery charging-discharging process along time and main control strategy parameters

When the battery reaches a minimum state of charge (20%), the system was programmed to disconnect the VM, aiming at being able to feed the inherent consumption of the system for certain time even if no power input from the PV modules occur. Once reached that minimum state, the VM continues disconnected until the battery is charged to 80%, with the goal of avoiding continuous VM switching on and off, and the consequent potential discomfort. Moreover, in order to define the battery charging strategy, such as the absorption and float voltage, the recommendations from the battery and MPPT manufacturers were considered.

The operation temperature tests were performed under the following different operation modes.

- Both open and closed box ventilation grids were considered (two configurations). Open configuration allowed natural ventilation through the electrical wooden compartment, as implemented in the SWB final design, while closed configuration represented the worst heat dissipation case.
- The power input from the PV simulator for charging the batteries was tested as per the following three configurations: (i) disabled, (ii) with constant maximum power supply equal to 300 Wp, which represents approximately the peak power of the largest PV module (configuration of SWB 3) and (iii) a more realistic variable power input generated by the largest PV module when receiving the highest irradiation daily profile in the year at the Italian demo case location and orientation.
- The consumption load that discharges the batteries, i.e. the ventilation machine, was tested both at the maximum fan speed and disactivated.

The prototype was tested in different operating modes resulting from the fully factorial combinations of the above described parameters, aiming at identifying the scenario that would lead to the highest temperatures. The number of tests amounts therefore to twelve (2x3x2).

2.3. Solar Window Block performance tests

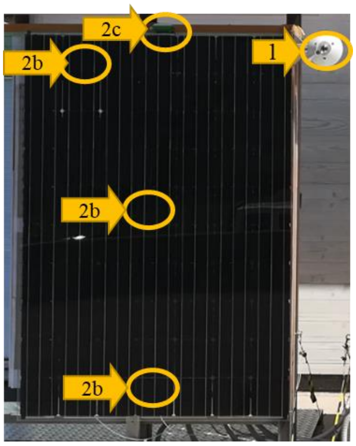
Once the adequate functioning of the electrical components was verified under indoor controlled conditions, the SWB electrical energy matching performance tests were conducted. The whole SWB system performance was tested in an outdoor laboratory with the following goals: (a) The verification of the energy matching KPIs among the BIPV production, the consumption profiles of the ventilation machine and the battery; (b) The measurement of the temperatures of the system during operation to check its correct and safe functioning; (c) The validation of the developed theoretical models; (d) The assessment of the durability and robustness of the electrical system and components.

The SWB performance tests were done on the manufactured real scale mock-ups shown in Fig. 1, which represent the three above described SWB configurations integrating all the components (section 2.1). Hence, each of them is in the off-grid setup. Therefore, the system performance was tested with the same operation mode as in the real conditions, i.e. the ventilation machine could be fed only by the energy produced by the PV modules and stored in the batteries. The prototypes were positioned facing South and are being monitored since mid-June 2020.

During these tests, the electrical parameters of the different components were monitored, i.e. voltage and current of PV module, batteries and ventilation machine. In addition, operation temperatures of the PV modules, batteries and MPPT controller, as well as solar irradiance were measured. For that purpose, a complete set of sensors were installed in the three prototypes, as reported in Tab. 2 for one of the prototypes. All the variables are measured every 1 min and gathered together in a database. The monitoring system is based on a NI LabView software reading and recording data from the Sun Saver MPPT and Seneca data acquisition system.

Different ventilation machine consumption profiles were applied to test the energy matching performance of each mock-up. Initially, occupancy profiles and related VM hourly profiles were generated for different room occupancies (1, 2 or 4 people), usage (bedroom or living room) and IAQ level (category II or III). These profiles were used as input to simulate the energy matching performance of the three mock-ups under the laboratory conditions. These simulations were done with an ad-hoc developed tool programmed in Phyton (Lovati, et al., 2017), that assesses the energy balance between the PV production and the consumption of the VM with a battery at hourly time steps. One of the outputs was the actual VM working hourly profile, considering that some moments the PV-battery system could not supply the required power to run the ventilation device. These profiles were used as inputs to a TRNSYS model to predict the indoor CO_2 concentrations reached by the actual VM working profiles and therefore the potential discomfort situations. Based on such simulation results, arbitrary threshold of discomfort hours of max 25% of occupied hours with CO_2 concentration above 1750 ppm, and VM Working Hours Rate (WHR), i.e. ratio between the actual VM working hours and the due ones as defined in the theoretical profiles, of min 80%, were used to select the VM profiles to be implemented for each mock-up. Fig. 5 shows the profiles chosen for each mock-up, as well as their main predicted KPIs. SWB with PV in sill and overhang were tested with a VM profile defined for a bedroom, so working only during the night at a constant medium speed. SWB with vertical PV was tested to cover a more demanding profile, i.e. for a living room. In this case, the VM is active during the day and disactivated at night, increasing its speed in the evening when the maximum occupancy is foreseen.

Tab. 2: SWB performance test measurements for mock-up 3 (BIPV vertical)

TARGET	MEASUREMENT	MEASURED BY		SENSOR POSITION
		SENSOR	DATA ACQUISITION	
1. Weather	Solar irradiance	Pyranometer Kipp & Zonen CMP11	Seneca Z-8TC-1	
2. PV	a) Electrical parameters: I, V	Built in MPPT	SunSaver MPPT 15L	
	b) Temp. PV (x3)	PT100	Seneca Z-4RTD2	
	c) Temp. air behind PV	EE16	Seneca Z-8AI	
3. Battery	a) Electrical parameters: I, V, Charge state	Built in MPPT	SunSaver MPPT 15L	
	b) Temp. battery	PT1000	SunSaver MPPT 15L	
4. VM	Electrical parameters: I, V, Load state	Built in MPPT	SunSaver MPPT 15L	
5. Air	Temp. air inside the box	EE16	Seneca Z-8AI	

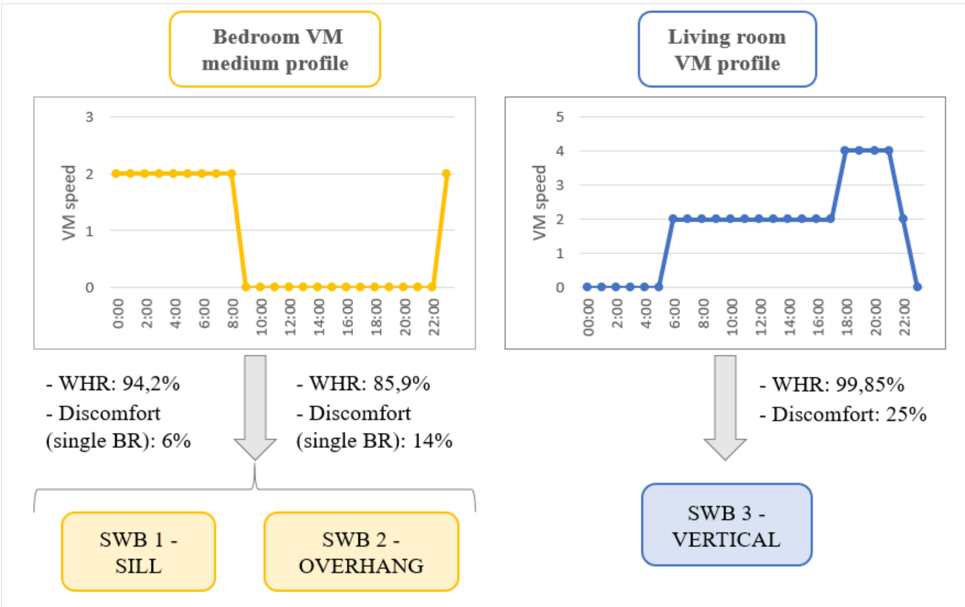


Fig. 5: Ventilation machine profiles applied to each Solar Window Block configuration and their corresponding predicted performance in terms of Working Hours Rate and Discomfort hours

2.4. Design adaptation

Often the development of a new technology sees continuous design correction and adaptation due to several problems and issues that comes up along the innovative development process. Hence, a further step in the SWB validation process was the design adaptation. Starting from the preliminary design output described in (Andaloro, et al., 2018), the SWB design adaptation process was carried out through the following phases.

(i) Executive design of components integration: the detailed drawings of the window block, the components, their dimensions and the main "boundary limits" were carefully analyzed. Specifically, the components' position into the wooden box was studied to define their interfaces.

(ii) Electrical design scheme and fire protection: these issues arose during the demo case design and deeply modified the components' position into the SWB wooden box, highlighting the need of the operational temperature test (section 2.2). In particular, the MPPT, protection fuses and batteries needed a "fire protected" area to decrease the fire risk working on the air ventilation flow scheme and non-combustible materials.

(iii) Operation & Maintenance analysis: the need for frequent maintenance on the VM, such as filter exchange or cleaning, and the possible system restart due to system stop or unexpected problems, was investigated and affected the internal wooden structure design.

(iv) Trial Window installation: A key aspect of the final SWB design validation was the installation of a "trial window". Just one complete SWB was manufactured and installed in the Italian demo carefully following all the installation steps, checking the interferences between the SWB and the existing wall and between each component. The demo implementation was done for a residential building in Florence (Italy), characterized by 12 apartments and 51 windows

Fig. 6 illustrates the overall design adaptation process with the timeline that starts from the concept idea till the executive design and manufacturing. The manufactured elements (in yellow), together with the test campaign and Demo design adaptation (light grey) were useful to collect valuable information and apply them in the design, since they were developed mostly in parallel.

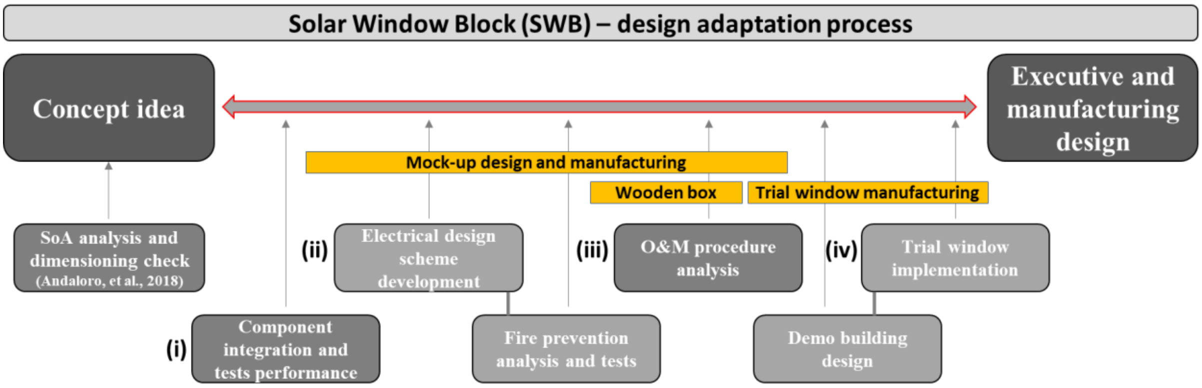


Fig. 6: SWB design adaptation process

3. Results and discussion

3.1. Operational temperature tests

Initially, the operational temperature tests served to verify the real battery capacity and define the optimal control strategy and its main parameters. Thanks to these tests, the battery voltage values corresponding to the main State of Charge points shown in Fig. 4 were identified as follows: 20% SoC = 25.4V, 80% SoC = 27.2V and 95% SoC = 28.6V.

With regard to the temperatures measured, Tab. 3 gathers the maximum registered temperatures in each component and the test scenario under which they occurred. As resulted from these data, batteries reached 31°C, while the MPPT and DC/DC converter are the most heated up components, (46.6°C and 44.3°C respectively). This demonstrated the crucial importance of the ventilation grids, as well as their positioning below and above these components to enhance their cooling through natural ventilation. The heat generated by the electrical equipment resulted in heating up the air inside the box. In the worst case, the box air temperature increased of around 6°C, with a room temperature of 25°C and ventilation grids closed.

Tab. 3: Maximum measured temperatures during operational temperature tests

Measurement	Internal Air – close to components	Internal Air – close to outlet grid	Battery	MPPT – surface	MPPT – Internal Heatsink	DC/DC
Max. measured temperature*	30.8°C	28.2°C	31°C	46.6°C	53°C	44.3°C
Max. allowed temperature**	-	-	~ 70°C	~ 60°C	~ 80°C	~ 70°C
Related test conditions	Max power Max load Closed holes	Max power No load Open holes	Max power No load Open holes	Max power Max load Closed holes	Max power Max load Closed holes	Max power Max load Closed holes

* Tests performed in a controlled environmental temperature of 25°C
** Information from data sheet of each component

As can be seen in Tab. 3, the operational temperature tests showed proper functioning and standard heating of the system, reaching temperatures in the wooden compartment within acceptable ranges in all scenarios. The maximum temperatures reached in all the electrical components were below the maximum allowed temperatures, even in the most demanding theoretical cases, with maximum power input, maximum ventilation fan speed and ventilation grids closed.

In order to see the effect of the different test scenarios in one of the measured temperatures, Fig. 7 gathers the internal air temperature evolution under the most representative and extreme test conditions. It shows that when testing the system in a more realistic scenario (section 2.2), such as variable power input profile and box ventilation grids open, the temperatures reached were lower than the maximum ones reported in Tab. 3.

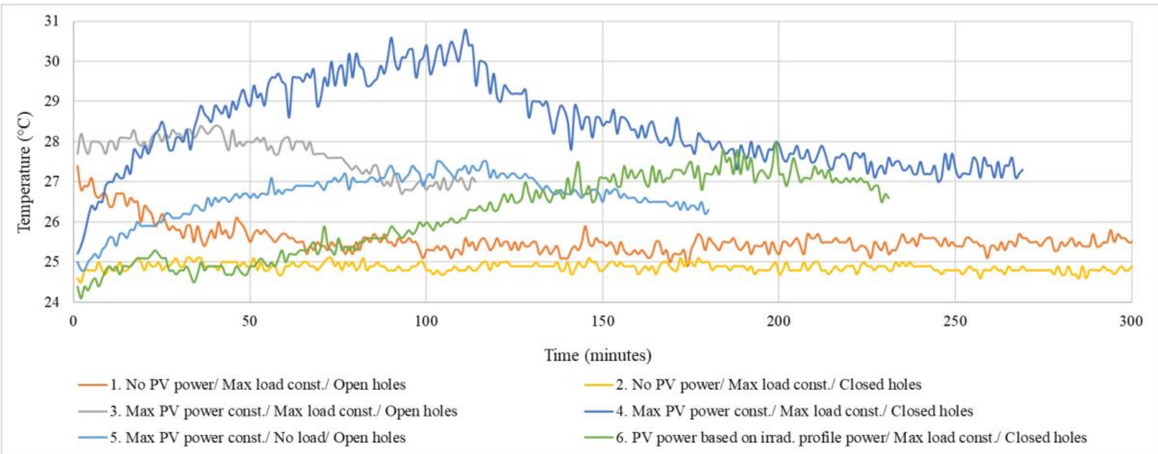


Fig. 7: Internal air temperature evolution during the different test scenarios

As can be seen in Fig. 7, the main condition affecting the heating is the power input. The highest temperatures are reached when the maximum constant PV power is applied during the complete charge of the battery, and load is demanding power at the same time (max air temp. 30.8°C). In a real case following the sun irradiance profile, where is not possible to have a constant PV maximum power, the charge of the batteries is performed in a slower pace generating less heat in the MPPT and thus in the surrounding air inside the box (max temp. 28°C). Besides, in these conditions, the cooling effect of the natural ventilation is significant, reducing the max air temp in more than 2°C. However, when the battery is only being discharged with the ventilation machine consumption, almost no heating occurs, and the effect of the natural ventilation is negligible.

3.2. Solar Window Block performance tests

The main result of the SWB performance tests is the capability of each SWB configuration to match the energy demand of the ventilation machine profile with the energy provided by the PV-battery system. This capability has been assessed based on the VM working time rate.

As shown in Tab. 4, throughout July and August, SWB configurations with PV in sill (1) and vertical (3) were able to cover the 100% of the time the VM demand. However, the SWB with PV in overhang position (2) covered the 91.7% of the time the load. The difference in the VM demand coverage between the different configurations is due to the PV-battery system design of each of them. The PV module of SWB 2 is made of amorphous silicon technology (Tab. 1), which has a lower efficiency (6%), while the other two configurations use crystalline silicone (eff. 15%). As seen in Tab. 4, the VM demand coverage rates are higher in the test results than in the simulations, although following the same trend (SWB 2 with the lowest value). This is reasonable taken into account that the simulated results covered the whole year performance, while the test results only covered 2 summer months.

Tab. 4: Summary of SWB performance results

KEY PERFORMANCE INDICATOR	SWB 1 – BIPV SILL	SWB 2 – BIPV OVERHANG	SWB 3 – VERTICAL BIPV
VM Working Rate (test result*)	100 %	91.7 %	100 %
VM Working Rate (simulation result**)	94.2 %	85.9 %	99.85 %
Efficiency of the system (total energy consumed by VM / total energy generated by PV)	57.6%	61.5%	84.7%
Max PV surface average temperature reached	78.3 °C	69.1 °C	67.8 °C
*Indicator calculated for July and August in minute time steps			
**Indicator calculated for the whole year in hour time steps			

Another interesting parameter reported in Tab. 4 is the ratio between the energy consumed by the VM and the energy generated by the PV, which allowed to understand the efficiency of the whole electric system. First of all, to better understand this value it is important to bear in mind that the MPPT adjusts the PV operation point in the I-V curve and therefore the generation, based on the demand of the VM and battery at each moment. Apart from that, this efficiency parameter takes into account the efficiency of the MPPT, battery charging and discharging and the partial self-consumption. That said, SWB 3 presents an efficiency of almost 85%, while SWB 2 configuration 62 % and SWB 1 configuration 58 %. SWB 3 higher efficiency can be explained because the load matches the generation in real time, so there is some direct self-consumption, avoiding the passage through the battery with the corresponding higher efficiency. Besides, the higher generation and consumption powers of this case fit better the MPPT optimal efficiency conditions. In the other two cases, with a bedroom VM profile, the efficiency is lower because the load does not match the generation, so the VM is always taking energy from the battery, working thus in a less efficient way. Finally, the booster required in SWB 1 to increase the voltage has a lower efficiency than the MPPT present in the other configurations, so making this version the less efficient one.

Tab. 4 also gathers the maximum temperatures reached in the rear surface of the PV modules. SWB with PV in sill was the one reaching the highest temperatures, around 78°C, due to its almost horizontal orientation and consequent reception of more direct irradiation during the summer months. SWB with vertical PV reached the lowest temperatures, around 68°C, due to its vertical position and consequent lack of reception of direct irradiation during the summer months. Besides, the VM working schedule of this latter case is demanding energy during the day, thus making the PV work while it is receiving the radiation and consequently dissipate part of the heat received when converting the radiation in electricity. In the cases with bedroom VM profile, the energy demand occurs at night, so during the day might be times in which the PV is not working if the battery already full, and consequently not dissipating part of that heat with the electricity generation.

Fig. 8 shows the evolution of the PV power generation, the VM power consumption and the battery voltage along a clear sky day. SWB 1 configuration shows a continuous discharging of battery during the night hours, when the VM is demanding energy. While during the day the PV is producing up to 47W (56Wp) and charging the battery. In the evening when the irradiance is lower, the battery starts to discharge at a slower pace due to the inherent consumption of the system, and in a higher pace once the VM is activated at night. SWB 2 covers the same VM profile as in the previous case, but two significant differences in its performance can be appreciated. Firstly, the maximum PV production hardly reaches 22W (31Wp). Secondly, the lower capacity battery of this system results in reaching the maximum charge around 15:00 and the consequent stop in the PV production followed by the battery voltage relaxation. SWB 3, instead, presents a completely different trend due to the different VM demand profile. During the night there is no load consumption, just the inherent one of the system. During the morning the PV is producing electricity up to 109W (291Wp), which is used to charge the battery and feed the VM. Around 13:00 the battery reaches its maximum state of charge and therefore the PV production is reduced to the same amount of power that the VM is demanding, occurring direct self-consumption. In the evening when the PV availability is low, the VM starts again taking the electricity from the battery until the night when is switched off.

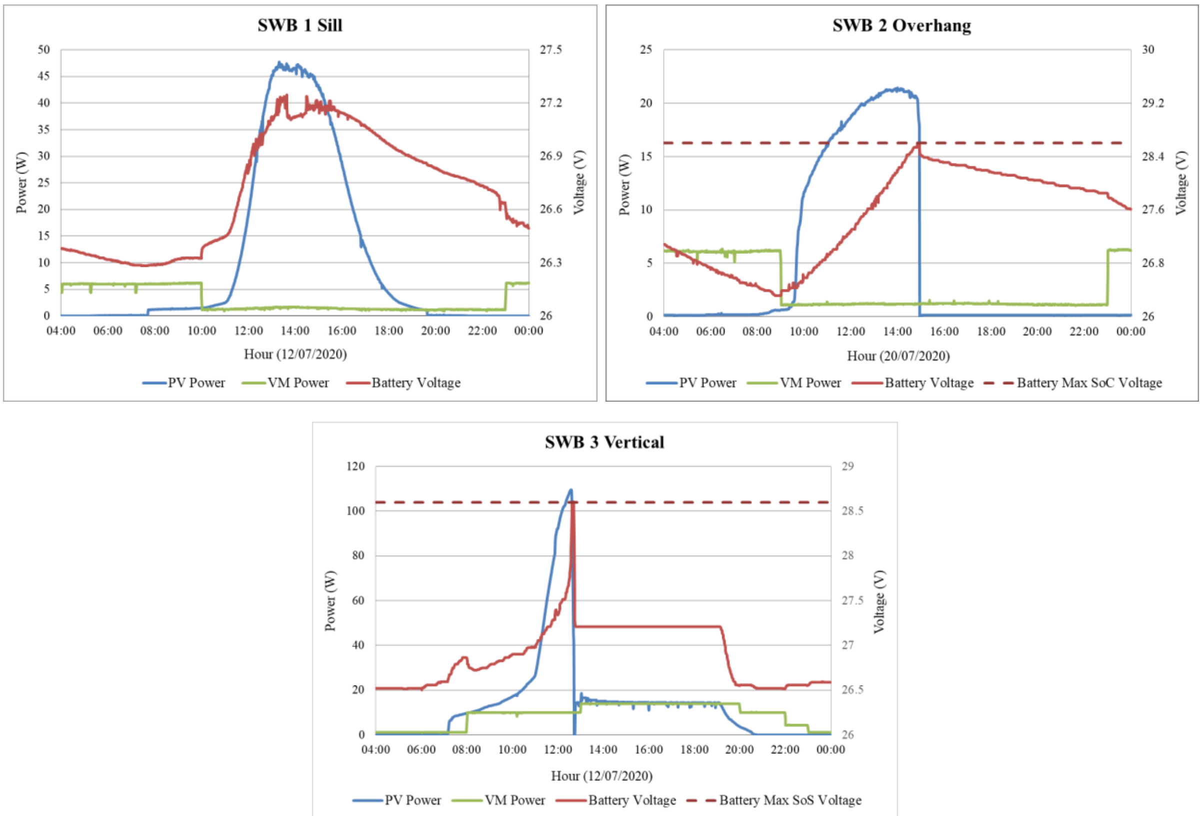


Fig. 8: Evolution of PV power, battery voltage and VM power along one day (a) SWB 1, (b) SWB 2, (c) SWB 3

3.3. Design adaptation

Thanks to the information collected from the mock-ups manufacturing and the testing campaign, together with the feedback from demo owners, the SWB design was adapted to answer to the arisen issues and allow its implementation in the real demo building. The main improvements resulting from the whole process (Fig. 6) are summarized below.

(i) Adaptation 1: Optimized SWB components integration and interfaces design. The VM, batteries, MPPT DC/DC converter and fuses were located in an optimized position based on a dedicated substructure, allowing a quick and safe connection among all the electrical components.

(ii) Adaptation 2: Fire resistant electrical compartment and natural air ventilation flow scheme. A specific fire resistance compartment for batteries was selected and installed in the wooden box. MPPT, DC/DC converter and fuses were located in the wooden box with further protection to avoid unexpected users touch or interferences. All the internal compartment was covered with non-flammable material and the holes for the natural ventilation were positioned in correspondence to the batteries, MPPT and the DC/DC converter (as explained in section 3.1) to allow an homogeneous and adequate natural ventilation.

(iii) Adaptation 3: Operation & Maintenance. The VM was positioned allowing an easy filter exchange without interfering with the electrical components foreseeing a series of openings and doors. The batteries' compartment, as well as all the rest of the electrical components were located in order to avoid final-user accidental interaction. Moreover, the rest of electrical components was positioned in a quick accessible part of the wooden box to allow a fast check from the electrician and a quick restart of the system. Every component was mechanically fixed avoiding glues to facilitate its removal.

(iv) Adaptation 4: Step-by-step installation procedure definition. As final step of the design and implementation phases, a detailed step-by-step installation procedure was elaborated easing all future installations by different companies (knowledge transfer), also providing some critical aspects and recommendation to avoid undesirable errors. The "trial window" concept was proposed as a further mandatory validation step to be introduced between the mock-up realization and the whole SWBs implementation. This new approach was positively evaluated from all the technology providers and the demo owner because it brought to light valuable feedback that allowed further improvement and optimization to the executive and detailed design of the system.

The whole design adaptation process, as described in Fig. 9, from the preliminary component integration to the executive design, sets the basis to validate the SWB design for its implementation in a real demo case building.

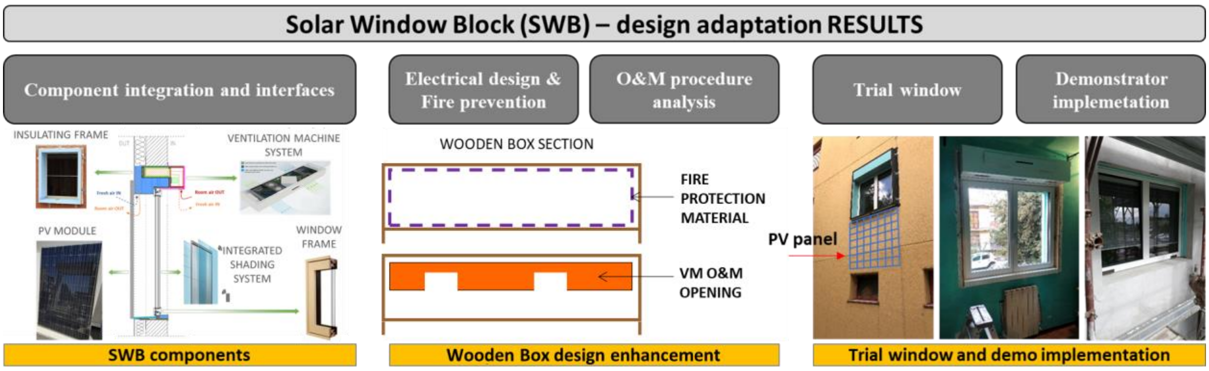


Fig. 9: SWB design adaptation results

4. Conclusions

The SWB testing and adaptation processes described in this paper allowed to validate the SWB design, focusing on its proper functioning and actual performance, as well as contributed to optimize the SWB detailed design.

Thanks to the operational temperature tests, the appropriate functioning of the electrical system of the SWB was verified under more demanding conditions than real ones. Although in all cases the temperatures reached were within the acceptable range, the importance of allowing a proper natural ventilation through the wooden box was demonstrated and therefore applied in the SWB design.

The energy matching performance tests verified the correct operation of the system in its off-grid setup and underlined the different performances achieved by each SWB configuration. The solution with the vertical BIPV showed higher efficiency, higher energy matching capability and consequent better autonomous functioning. This case also showed a proper coverage of the ventilation machine profile of a living room with 4 people, guaranteeing an acceptable indoor air exchange. The sill and overhang BIPV configurations could not guarantee the total ventilation machine working hours for a living room case, but could match appropriately a bedroom ventilation profile, specially the configuration with the PV in sill. However, a longer test data collection is required to get a better overview of the SWB performance along the year and, in fact, is already ongoing. Besides these testing, also the monitoring data from the implemented SWB in the demo site will contribute to better understand the actual performance of the system under real conditions.

Regarding the SWB design adaptation a new detailed SWB configuration was achieved, which integrated the meaningful inputs gathered during the different prototypes manufacturing process, testing campaign and trial window installation process. Thanks to that, the SWB design was validated as a valuable, flexible, and robust option for the building retrofit in terms of enhanced performance and comfort.

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6. References

Andaloro, A, Avesani, S, Belleri, A & Machado, M, 2018, ‘Adaptive window block for residential use: optimization of energy efficiency and user´s comfort’, *FACADE2018 Adaptive! Adaptive Facade Network Conference*, Luzern, Switzerland, 26-27 November.

Andaloro, A, Minguez, L & Avesani, S, 2020, ‘Active and energy autonomous window: renewable energy integration through design for manufacturing and assembly’, *Façade Tectonics 2020 World Congress*, Los Angeles, United States, 5-27 August.

DIRECTIVE (EU) 2018/844 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency

DIRECTIVE 2012/27/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC

Lovati, M, Albatici, R, Maturi, L & Moser, D, 2017, ‘Effect of module orientation and batteries on performance of building integrated photovoltaic systems’ *33rd European Photovoltaic Solar Energy Conference and Exhibition*, Amsterdam, Netherlands, 25-29 September.