Monitoring the Operating Temperatures of Modules in Open-Rack and Typical BIPV Configurations

Ebrar Özkalay[1,2], Gabi Friesen[1], Andrew Fairbrother[2], Christophe Ballif[2,3], Alessandro Virtuani[2]

1 – University of Applied Sciences and Arts of Southern Switzerland (SUPSI-PVLab), Via Francesco Catenazzi 23, 6850 Mendrisio, Switzerland
2 – École Polytechnique Fédérale de Lausanne (EPFL), Institute of Microengineering (IMT), Photovoltaics and Thin Film Electronics Laboratory, Rue de la Maladière 71b, 2002 Neuchâtel, Switzerland
3 – CSEM PV-Center, Rue de Jaquet-Droz 1, 2002 Neuchâtel, Switzerland

***Abstract*—Elevated operating temperatures are expected in BIPV systems due to restricted or reduced rear-side ventilation, which impacts their performance and reliability. This work reports operating temperatures and diurnal (day-night) temperature variations of the modules in open-rack and BIPV mounting configurations (BIPV-ventilated and BIPV-insulated) monitored over a period of 2-5 years in southern Switzerland. The modules in BIPV configurations operated at 20-30˚C higher temperatures than the same modules in open-rack. The suitability of the indoor qualification and safety tests in IEC 61215 and IEC 61730 were evaluated according to the 98th percentile real-life operating module temperature as defined in IEC TS 63126 guideline for qualifying PV modules operating at elevated temperatures. The study shows that according to IEC TS 63126, BIPV modules on a tilted surface in southern Switzerland could need to be tested at harsher conditions (e.g. higher temperatures) in a selection of indoor qualification and safety tests.**

Keywords—BIPV, temperature, IEC TS 63126, T$_{98}$.

I. INTRODUCTION

Building integrated photovoltaics (BIPV) is one of the rapidly growing areas in photovoltaic (PV) applications in order to achieve nearly Zero Energy Buildings (nZEB) and reduce greenhouse emissions [1]. Despite the growth and increasing attention on BIPV applications, several barriers and constraints still exist. Unlike conventional field installations, BIPV modules are generally not installed at an optimal orientation or under optimal conditions. A common concern is the elevated operating temperature of BIPV modules relative to field installed PV due to due to reduced or restricted rear-side ventilation [2, 3]. This is a critical factor potentially impacting both the short- and long-term performance of BIPV modules [4, 5, 6]. Elevated temperatures reduce the instantaneous power output of modules, and may accelerate the degradation of polymeric and other materials. Recently, the International Electrotechnical Commission (IEC) published a technical specification (TS) called IEC TS 63126 “Guidelines for qualifying PV modules, components and materials for operation at high temperatures” [7] as modules in hot climates or in BIPV configurations may operate at temperatures higher than those used in the qualification and safety tests of IEC 61215 and IEC 61730 [8, 9]. The TS suggests that a module deployed under these specific conditions should be subjected to accelerated-aging tests at harsher conditions (e.g. increase in testing temperature or applied current). Testing conditions of a set of indoor qualification and safety tests (e.g. the upper-temperature limit of the thermal cycling test) depend on the 98th percentile operating module temperature (T_{98}) (Level 1 Test Condition for 70˚C < T_{98} ≤ 80˚C and Level 2 Test Condition for 80˚C < T_{98} ≤ 90˚C). T_{98} represents a combination of a cumulative exposure of 175.2 hours/year at or above the stated temperature. However, there is still lack of detailed analysis on measured operating module temperature and T_{98} in BIPV mounting configurations (BIPV-ventilated and BIPV-insulated).

This work reports operating temperatures including T_{98} of modules in open-rack and BIPV configurations (BIPV-ventilated and BIPV-insulated) obtained from three BIPV outdoor test stands located on the outdoor test facility of SUPSI in Canobbio, Switzerland. The suitability of the selected indoor qualification and safety tests in IEC 61215 and IEC 61730 are evaluated depending on T_{98} as defined in IEC TS 63126.

II. BIPV TEST STANDS

Three BIPV outdoor test stands were monitored at SUPSI in Canobbio, Switzerland, which according to the Köppen-Geiger is classified as having a Cfb climate (temperate and humid climate, and warm summers) [10]. The modules on the test stands were installed in open-rack and BIPV configurations as summarized in Fig. 1 and Table I.

The **open-rack** configuration, provisioned with full rear-side ventilation, is the most common and conventional PV module installation configuration used in ground-mounted and utility-scale PV systems. Due to free ventilation on the rear-side, open-rack modules are expected to operate at lower temperatures compared to BIPV modules. The most common BIPV solutions are full-roof, in-roof and cold-façade solutions [11]. These solutions can have a ventilation chamber between the module and insulation layer, which ensures partial ventilation on the rear-side of the module, as shown in Fig. 1. The modules in this configuration are here referred to as **ventilated** or **BIPV-ventilated** modules. The other BIPV mounting configuration is the insulated configuration without a gap between the module and insulation layer. Hence, the rear-

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side ventilation is restricted. The full-roof and in-roof solutions can be installed in a BIPV-insulated configuration. The modules in this configuration are here referred to as **insulated** or **BIPV-insulated** modules.

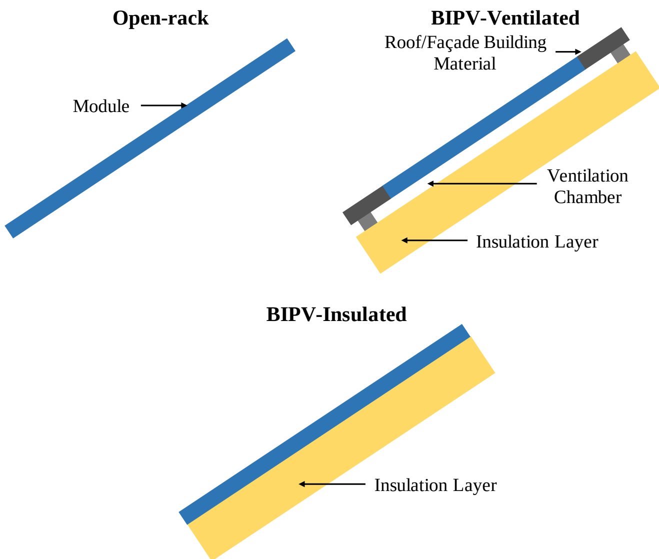

Fig. 1. Summary of installation configurations on the BIPV test stands.

As shown in Table I, **Test Stand-1** consisted of two module types, including aluminum back surface field (Al-BSF) glass/ethylene-vinyl acetate/backsheet (G/EVA/BS) and glass/polyvinyl-butyral/glass (G/PVB/G) modules. These were installed in open-rack and insulated configurations. The module performances and the related meteorological parameters were monitored for 51 months. The modules were installed at a tilt angle of 6˚ and azimuth of -4˚ from South. For the insulated configuration, 20 cm thick polyurethane foam was used to avoid rear-side air ventilation.

Test Stand-2 consisted of two module types: (1) heterojunction (HJT) solar cells in a glass/glass (G/G) configuration and passivated emitter and rear contact (PERC) cells in a G/EVA/BS configuration. The HJT modules were installed in open-rack and ventilated configurations while the PERC module was installed only in ventilated configuration. The modules and the related meteorological parameters were monitored for 53 months. The ventilated HJT and PERC modules had 6 cm and 12 cm wide ventilation chamber to ensure reduced rear-side ventilation, respectively. The modules were installed at a tilt angle of 20˚ and azimuth of -4˚ from South.

In **Test Stand-3**, a PERC G/PVB/G module in ventilated configuration at 90˚ tilt (resembling installation in a façade) was monitored for 27 months. The ventilation chamber between the module and the insulation material was 8 cm wide.

The HJT modules on Test Stand-2 are prototype modules, while the other modules are commercial products. Modules were monitored using Pt100 attached on the rear-side of the modules, and electrical performance parameters of the modules were acquired using maximum power point (MPP) tracker at 1-minute intervals. The temperature measurements were performed between 5:00 AM and 9:00 PM local time (Coordinated Universal Time+1 (UTC+1)).

III. RESULTS AND DISCUSSION

Operating temperature distributions of the modules on the test stands for the duration of their monitoring periods are shown in Fig. 2 and summarized in Table II. T_{98} of each module was determined from the cumulative hours spent at temperatures since some of the nighttime temperature measurements (from 9:00 PM to 5:00 AM, UTC+1) were not recorded. T_{98} values in Table II represents cumulative exposure of 175.2 hours/year at or above stated temperature. Only full-year data were used in Fig. 2 and for the calculation of T_{98} to avoid bias due to seasonal variation in temperature of the modules. For Test Stand-1, Test Stand-2, and Test Stand-3, the distribution corresponds, respectively, to 48, 48 and 24 months of data acquisition.

The insulated modules in **Test Stand-1** operated at higher temperatures due to restricted rear-side ventilation (Fig. 2a). While the open-rack modules reached a maximum of 62˚C and 66˚C, respectively, the insulated modules exhibited a larger distribution, reaching temperatures slightly above 90˚C. T_{98} of the insulated modules in Test Stand-1 are 80˚C, while T_{98} of the open-rack G/BS and G/G modules are 57˚C and 53˚C, respectively (Table II). Interestingly, the insulated modules are exposed to lower temperatures (even below 0˚C) with respect to modules in open-rack conditions. This is due to the stronger radiative cooling at night [12, 13].

TABLE I. CHARACERISTICS OF THE THREE TEST STANDS, INCLUDING THE MODULES USED AND THE TOPOLOGY OF INSTALLATION. THE THICKNESSES OF THE VENTILATION CHAMBERS FOR THE MODULES IN BIPV-VENTILATED CONFIGURATION ARE STATED IN PARENTHESES.

Test Stand	Cell and Module Technologies	Installation Configuration	Azimuth (South = 0˚) / Tilt Angles	Duration	Monitored Parameters
1	Al-BSF - G/EVA/BS Commercial module	• Open-rack • BIPV-Insulated	-4˚ / 6˚ (Roof)	51 Months	• G_{POA} (every 1 minute) • Module Temperature (Pt100 on rear-side of the modules) (every 1 minute) • Electrical performance using MPP tracker (every 1 minute)
	Al-BSF - G/PVB/G Commercial module				
2	HJT - G/G Prototype module	• Open-rack • BIPV-Ventilated (6 cm)	-4˚ / 20˚ (Roof)	53 Months	
	PERC - G/EVA/BS Commercial module	• BIPV-Ventilated (12 cm)			
3	PERC - G/PVB/G Commercial module	• BIPV-Ventilated (8 cm)	-4˚ / 90˚ (Façade)	27 Months	

Al-BSF: Aluminum back surface field, HJT: Heterojunction Technology, PERC: Passivated Emitter and Rear Contact, G: Glass, BS: Backsheet, EVA: Ethylene-vinyl acetate, PVB: Polyvinyl-butyral, G_{POA}: Plane of array irradiance and MPP: Maximum power point.

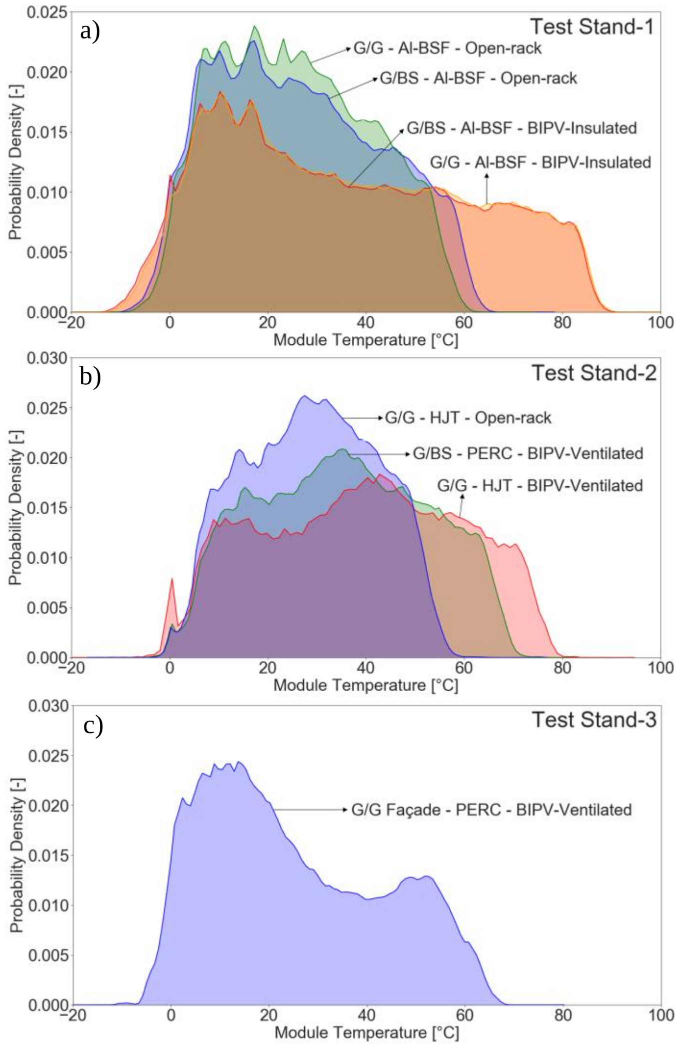

Fig. 2. Temperature distribution of the modules from (a) Test Stand-1, (b) 2 and (c) 3 during their outdoor deployment. Temperature measurements made between 5:00 AM and 9:00 PM local time (UTC+1) at 1-minute intervals. Only full-year data are used to prevent biases due to seasonal variations in module temperature. For Test Stand-1, Test Stand-2, and Test Stand-3 the distribution corresponds, respectively, to 48, 48 and 24 months of data acquisition. For each module, the integral of the temperature distribution corresponds to one.

There is a difference between the temperature distributions of the open-rack modules, whereas we observed no significant difference between the temperature distributions of the insulated modules (Fig. 2a). This is because the module temperatures measured on the rear-side of the open-rack modules may not represent the actual cell temperatures due to the thermal gradient through the module materials and the heat capacitance of the module materials [14].

In **Test Stand-2**, the ventilated HJT module reached higher operating temperatures than the same module type in open-rack configuration due to limited rear-side ventilation (Fig. 2b). T_{98} of the open-rack and the ventilated HJT modules are 50˚C and 71˚C, respectively (Table II). The ventilated PERC module has a T_{98} of 63˚C (maximum of 77˚C).

The ventilated G/G PERC BIPV module, installed as a façade module on **Test Stand-3**, operated at lower temperatures relative to the other modules in BIPV configurations (Fig. 2c). As expected, this is because there is usually a lower amount of irradiance on the vertical surface compared to the sloped surfaces, especially when solar altitude is high (e.g. in summer).

T_{98} of the two insulated BIPV modules on Test Stand-1 and the ventilated HJT module on Test Stand-2 are all higher than 70˚C, as shown in Table II. According to the IEC TS 63126, these modules should be tested at harsher testing conditions (Level 1 Test Condition) in a selection of indoor module qualification and safety tests defined in IEC 61215 and IEC 61730.

Table II shows that the BIPV modules installed in a mid-latitude country (Switzerland) with a reduced or restricted rear-side ventilation operated at temperatures 20-30˚C higher than the same modules installed in an open-rack configuration. As shown in various studies [15, 16], exposure of the modules to elevated operating temperatures may lead to higher degradation rates (e.g. higher rate of encapsulant discoloration, damaged interconnections and solder joints, etc.) and a faster occurrence of wear-out-failures that shorten the lifetime of a PV module.

IV. CONCLUSION

This work shows the operating temperatures of the modules in open-rack and BIPV mounting configurations during their monitoring of several years. Their operating temperatures including, T_{98} and diurnal (day-night) temperature variations depending on their mounting configurations, are compared. The maximum operating temperature of the insulated BIPV modules reached slightly above 90˚C in southern Switzerland. These modules have around 23-27˚C larger T_{98} compared to the same modules in open-rack due to restricted rear-side air ventilation.

TABLE II. MAXIMUM TEMPERATURE (T_{MAX}) AND T_{98} OF THE MODULES FROM TEST STAND-1, TEST STAND-2 AND TEST STAND-3. T_{98} VALUES IN BOLD ARE HIGH ENOUGH TO WARRANT HARSHER TESTING CONDITIONS FOR THE RELATED TESTS ACCORDING TO IEC TS 63126 [7].

Test Stand	Cell and Module Technologies	Tilt Angles	Open-Rack		BIPV-Ventilated		BIPV-Insulated		Temperature Difference (BIPV – Open-rack)	
			T_{98} [˚C]	*T_{max} [˚C]*	*T_{98} [˚C]*	*T_{max} [˚C]*	*T_{98} [˚C]*	*T_{max} [˚C]*	*T_{98} [˚C]*	*T_{max} [˚C]*
1	Al-BSF - G/EVA/BS	6˚	57	66	-	-	**80**	92	23	26
	Al-BSF - G/PVB/G	6˚	53	62	-	-	**80**	91	27	29
2	HJT - G/G	20˚	50	64	**71**	83	-	-	21	19
	PERC - G/EVA/BS	20˚	-	-	63	77	-	-	-	-
3	PERC - G/PVB/G	90˚	-	-	59	68	-	-	-	-

Similarly, the ventilated BIPV modules operated warmer than the open-rack modules (21˚C larger T_{98}).

The BIPV modules on a sloped roof surface were therefore exposed to larger thermal stresses than the modules in a conventional open-rack configuration. This stress could presumably accelerate the degradation of the polymeric materials in the module sandwich. This could later cause higher degradation rates and shorten the lifetime of BIPV modules. According to IEC TS 63126, two insulated Al-BSF and the ventilated HJT BIPV modules ($70˚C < T_{98} \leq 80˚C$) operated at temperatures above the typical temperature ranges used in the qualification and safety tests of IEC 61215 and IEC 61730. Hence, the selected module qualification and safety tests should be performed at harsher testing conditions as defined IEC TS 63126.

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