Higher Thermal and Thermomechanical Stresses in BIPV Modules

Ebrar Özkalay, SUPSI PVLab

Hasselt, 25.04.2024, 2:00pm – 3:30pm (CET)

What is BIPV?

Building Attached/Added PV (BAPV):

1. Generate electricity
2. Reduce CO_2 emissions

P. Heinstein et al., De Gruyter (2013)

Building Integrated PV (BIPV):

1. Generate electricity
2. Reduce CO_2 emissions
3. Serve as building material
   - Weather protection
   - Thermal insulation
   - Noise protection etc.

Solaris, Solararchitecture

P. Heinstein et al., De Gruyter (2013)

Multifunctional Active Building Element

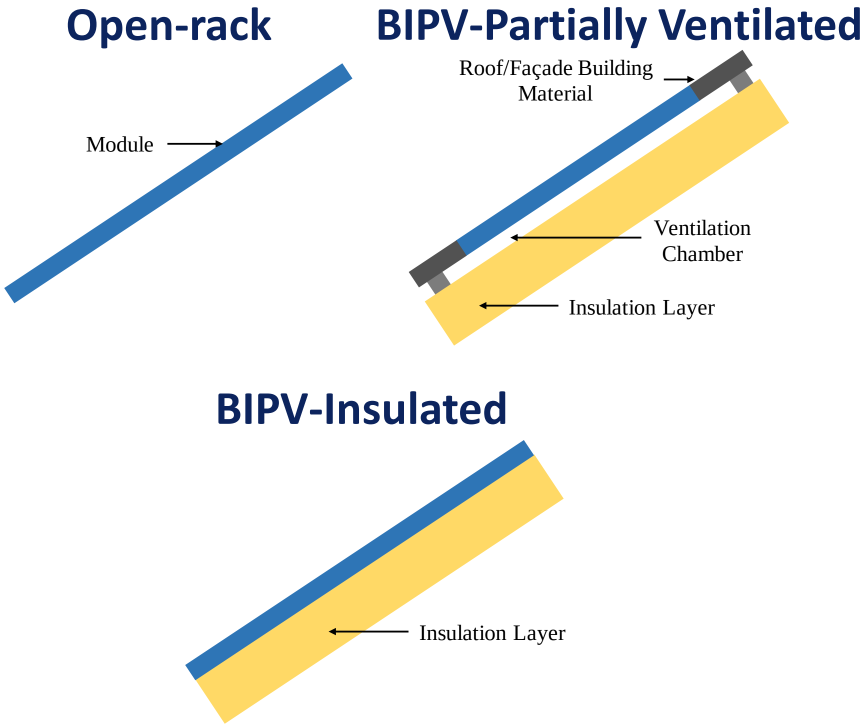
Motivation

Open-rack and BIPV Mounting Configurations:

- **Open-rack**
  - Free rear-side air ventilation
- **BIPV-Partially Ventilated**
  - Reduced rear-side air ventilation
- **BIPV-Insulated**
  - No rear-side air ventilation

BIPV modules operate at harsher conditions:

1. Elevated operating temperatures [1,2]
2. Larger diurnal (day-night) temperature changes [3]
3. More frequent partial shadow [4]



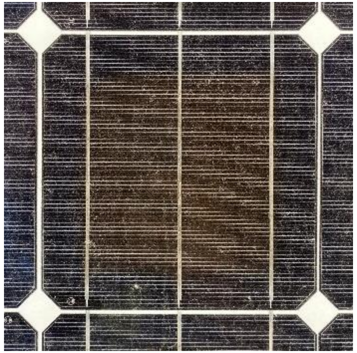
Long-term performance of BIPV modules?

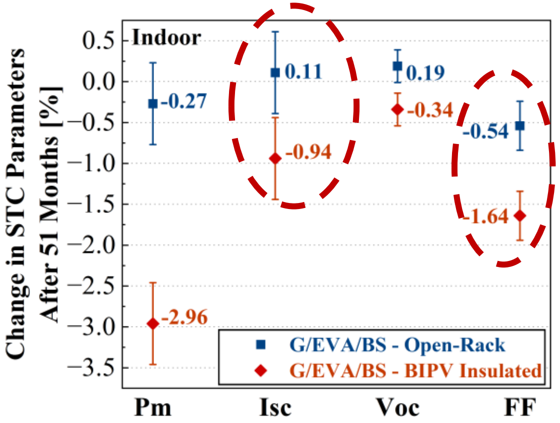
[1] T. Nordmann et al., WCPEC (2003)
[2] T. Sample and A. Virtuani, EUPVSEC (2009)
[3] H. Hongjie et al., EUPVSEC (2018)
[4] A. Fairbrother et al. Solar RRL (2021)

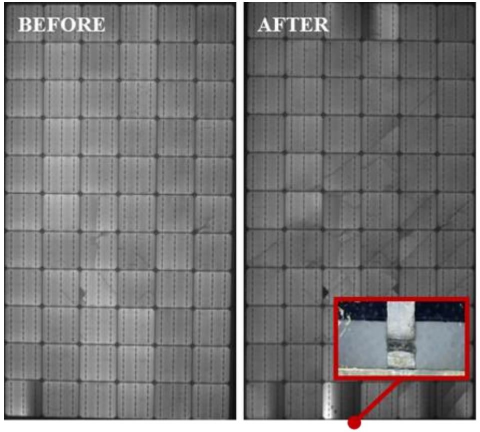
Motivation

Two degradation processes found in BIPV configuration[1]:

- **Faster photothermal degradation of the encapsulants** (discolouration) due to the **higher operating temperature (higher thermal stress)** in BIPV configurations, resulting in **I_{sc} loss**.
- **Formation of damaged cells and metallisation** due to **larger diurnal temperature changes (higher thermomechanical stresses)** in BIPV conditions, resulting in **FF loss**.







How should BIPV modules be tested?

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[1] E. Özkalay et al., submitted to Energy & Buildings

Outline

1. **Elevated Operating Temperatures**
2. **Larger Diurnal (day-night) Temperature Changes**
   - Operating Temperature Analysis (IEC TS 63126 & IEC 62892)
   - Extended and Accelerated Thermal Cycling Test
3. **More Frequent Partial Shading**
   - Hot-spot Test and its sufficiency for BIPV testing?

Stress 1: Elevated Operating Temperatures

IEC TS 63126 (2020): “Guidelines for qualifying PV modules, components and materials for operation at high temperature”

- 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
- **T_{98}** (98th percentile of real-life temperatures, **175.2 hours/year**): reasonable combination of **high temperature** and **time-spent at the high temperature**

Standard	Test Reference	Test Name	Original Requirement $T_{98} \leq 70°C$	Proposal – Level 1 $70°C < T_{98} \leq 80°C$	Proposal – Level 2 $80°C < T_{98} \leq 90°C$
IEC 61215	MQT 09	Hot-spot endurance test	(50±10)°C	**+10°C**, (60±10)°C	**+20°C**, (70±10)°C
	MQT 10	UV preconditioning	(60±5)°C	**+10°C**, (70±5)°C	**+20°C**, (80±5)°C
	MQT 11	Thermal cycling test	(85±2)°C	**+10°C**, (95±2)°C	**+20°C**, (105±2)°C
	MQT 18	Bypass diode testing chamber – Part 1	(75±2)°C I_{sc}	**+15°C**, (90±2)°C **1.15** x I_{sc} for diode T	**+25°C**, (100±2)°C **1.15** x I_{sc} for diode T
		Bypass diode testing chamber – Part 2	(75±2)°C 1.25 x I_{sc}	**+15°C**, (90±2)°C **1.4** x I_{sc} for stress	**+25°C**, (100±2)°C **1.4** x I_{sc} for stress

- **Lack of detailed analysis on measured operating module temperature and T_{98} in BIPV mounting configurations**

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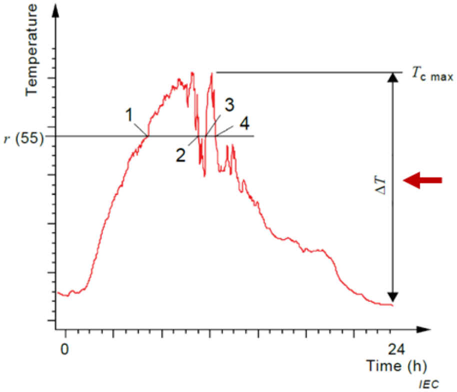
Stress 2: Larger Diurnal (Day-Night) Temperature Changes

IEC 62892 (2019): "Extended Thermal Cycling of PV Modules – Test Procedure"

- Increased **loss of FF (failing solder bond)** in hot climates with respect to cooler climates [1,2]
- **Thermal Cycling Test →** to determine the ability of the PV modules to withstand thermal mismatch, fatigue, and other stresses caused by rapid, non-uniform or repeated changes of temperature
- **IEC 62892:** to evaluate modules for deployment in locations most susceptible to thermal cycling type stress

STEP 1

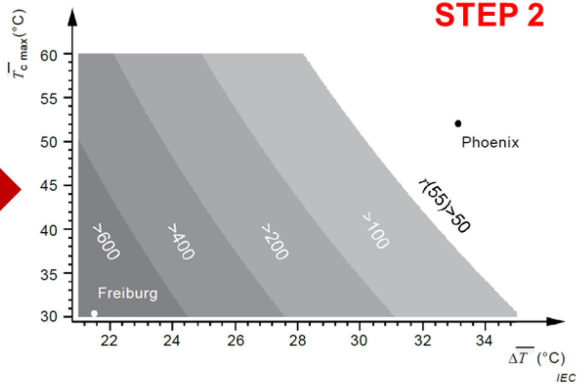
r(55˚C): Temperature reversal term →



Mean $T_{c\ max}$: Mean maximum temperature

Mean ΔT_D: Mean diurnal temperature change

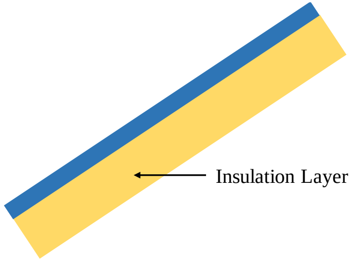
STEP 2



- **Lack of detailed analysis in BIPV mounting configurations**

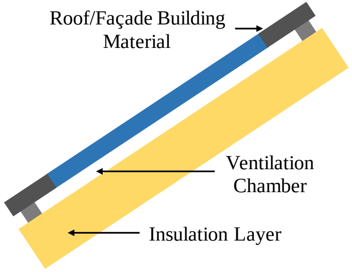
[1] D. C. Jordan, J. Wohlgemuth and S. Kurtz, "Technology and climate trends in PV module degradation", doi: 10.4229/27thEUPVSEC2012-4DO.5.1.
[2] N. Bosco, T. J. Silverman and S. Kurtz, "Climate specific thermomechanical fatigue of flat plate photovoltaic module solder joints", doi: 10.1016/j.microrel.2016.03.024.

BIPV Test Stands and Buildings



BIPV Insulated Roof:

- Test Stand-1*
- Test Stand-4*



BIPV Partially Ventilated Roof

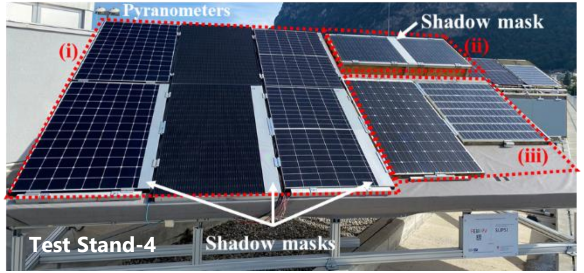
- Test Stand-2*

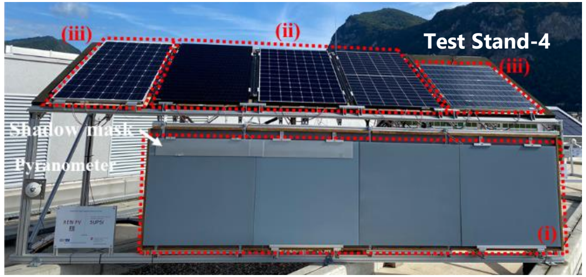
BIPV Partially Ventilated Façade

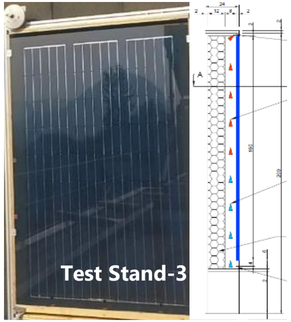
- Test Stand-3
- Test Stand-4
- BIPV Building-1
- BIPV Building-2

**: Same module types in open-rack as well*

© SUPSI (stands built in the framework of ConstructPV project)







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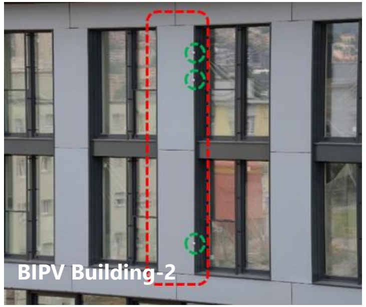
BIPV Building-1



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Operating Temperature Analysis
(IEC TS 63126 & IEC 62892)

Operating Temperature Analysis (IEC TS 63126 & IEC 62892)

Mounting Configuration	IEC TS 63126:2020 (thermal)			IEC 62892:2019 (thermomechanical)	
	Standard ($T_{98} \leq 70˚C$)	Level-1 ($70˚C < T_{98} \leq 80˚C$)	Level-2 ($80˚C < T_{98} \leq 90˚C$)	Extended TC is not advised	Extended TC is advised
Open-rack – Roof	12	-	-	9	3 (same type)

- All **open-rack modules** have $T_{98} \leq 70˚C$ and extended TC not necessary (except 3 modules which are same type)

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Operating Temperature Analysis (IEC TS 63126 & IEC 62892)

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Open-rack – Roof	12	-	-	9	3 (same type)
BIPV Insulated – Roof	-	5	-	-	5

- All **open-rack modules** have $T_{98} \leq 70$˚C and extended TC not necessary (except 3 modules which are same type)
- All **BIPV Insulated Roof modules** have $T_{98} > 70$˚C and extended TC is necessary

Operating Temperature Analysis (IEC TS 63126 & IEC 62892)

Mounting Configuration	IEC TS 63126:2020 (thermal)			IEC 62892:2019 (thermomechanical)	
	Standard ($T_{98} \leq 70$˚C)	Level-1 (70˚C < $T_{98} \leq 80$˚C)	Level-2 (80˚C < $T_{98} \leq 90$˚C)	Extended TC is not advised	Extended TC is advised
Open-rack – Roof	12	-	-	9	3 (same type)
BIPV Insulated – Roof	-	5	-	-	5
BIPV Partially Ventilated – Roof	1	1	-	-	2

- All **open-rack modules** have $T_{98} \leq 70$˚C and extended TC not necessary (except 3 modules which are same type)
- All **BIPV Insulated Roof modules** have $T_{98} > 70$˚C and extended TC is necessary
- All **BIPV Partially Ventilated Roof modules** need extended TC but their T_{98} strongly depends on their ventilation chamber design

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Operating Temperature Analysis (IEC TS 63126 & IEC 62892)

Mounting Configuration	IEC TS 63126:2020 (thermal)			IEC 62892:2019 (thermomechanical)	
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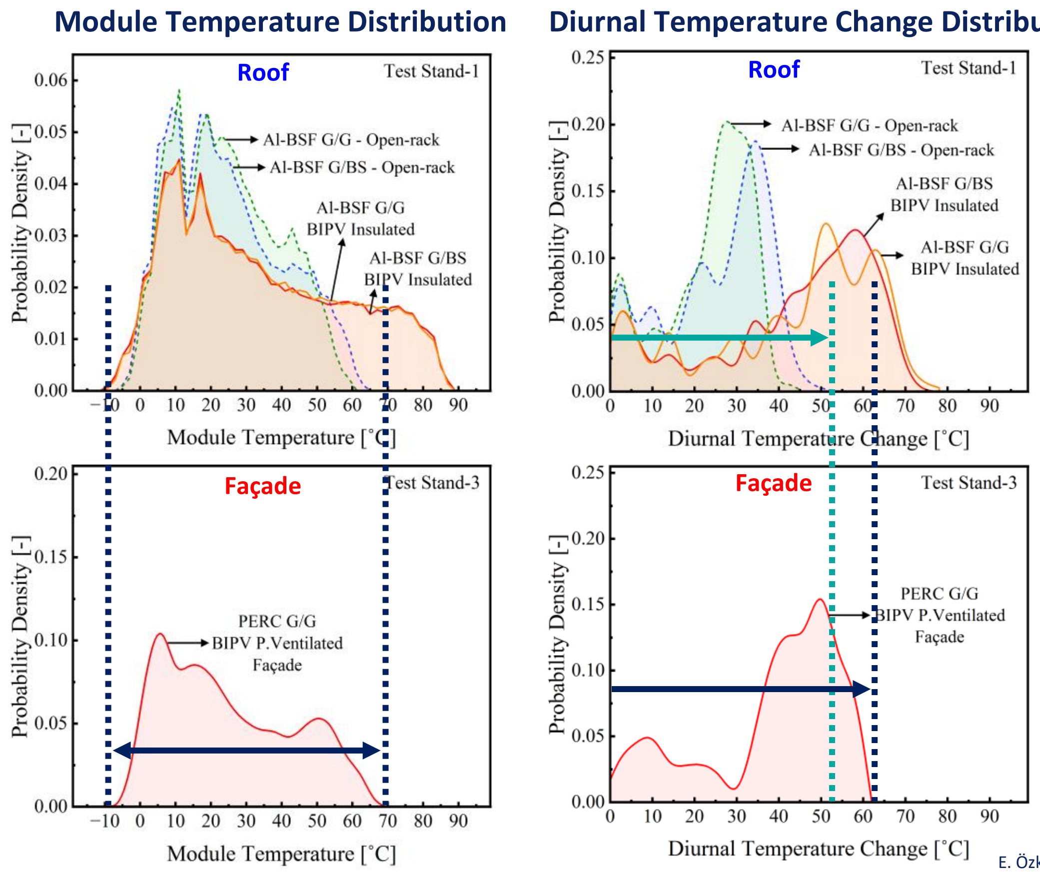
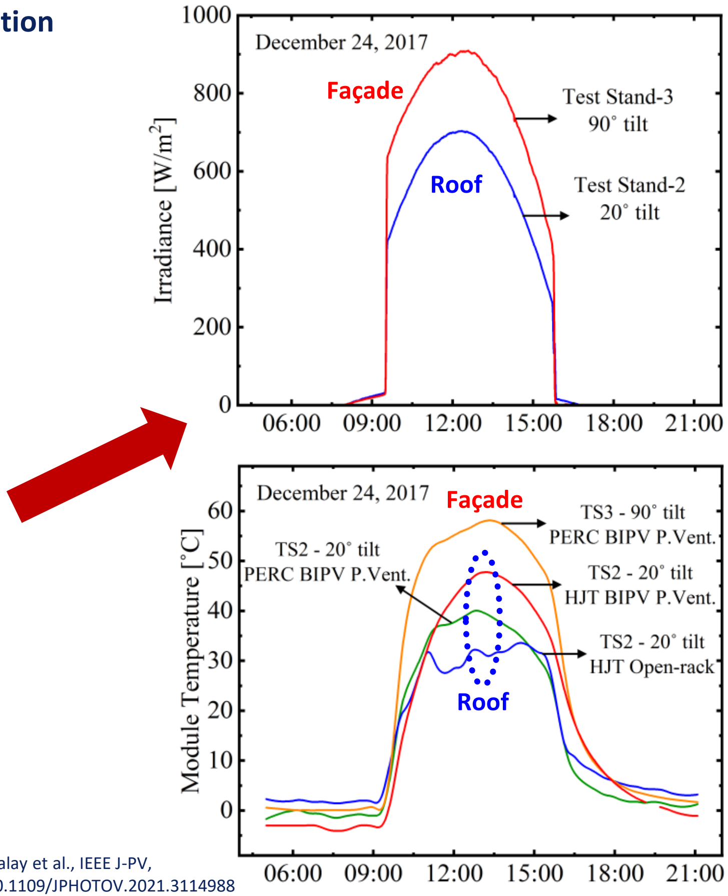
Open-rack – Roof	12	-	-	9	3 (same type)
BIPV Insulated – Roof	-	5	-	-	5
BIPV Partially Ventilated – Roof	1	1	-	-	2
BIPV Partially Ventilated – Façade	6	-	-	-	6

- All **open-rack modules** have $T_{98} \leq 70^\circ C$ and extended TC not necessary (except 3 modules which are same type)
- All **BIPV Insulated Roof modules** have $T_{98} > 70^\circ C$ and extended TC is necessary
- All **BIPV Partially Ventilated Roof modules** need extended TC but their T_{98} strongly depends on their ventilation chamber design
- All **BIPV Partially Ventilated Façade modules** have $T_{98} \leq 70^\circ C$ but they need extended TC

Operating Temperature Analysis
BIPV P.Ventilated Façade





E. Özkalay et al., IEEE J-PV,
doi: 10.1109/JPHOTOV.2021.3114988

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Operating Temperature Analysis (IEC TS 63126 & IEC 62892)

Mounting Configuration	IEC TS 63126:2020 (thermal)			IEC 62892:2019 (thermomechanical)	
	Standard ($T_{98} \leq 70^{\circ}C$)	Level-1 ($70^{\circ}C < T_{98} \leq 80^{\circ}C$)	Level-2 ($80^{\circ}C < T_{98} \leq 90^{\circ}C$)	Extended TC is not advised	Extended TC is advised
Open-rack – Roof	12	-	-	9	3 (same type)
BIPV Insulated – Roof	-	5	-	-	5
BIPV Partially Ventilated – Roof	1	1	-	-	2
BIPV Partially Ventilated – Façade	6	-	-	-	6

Main takeaways:

- T_{98} (IEC TS 63126) highly depends on the type of BIPV configuration and orientation
  - All **BIPV Insulated roof modules** have **$T_{98} > 70^{\circ}C$**
  - All **BIPV Partially Ventilated façade modules** have **$T_{98} \leq 70^{\circ}C$**
- **All BIPV modules need extended thermal cycling test** according to IEC 62892.

Extended and Accelerated Thermal Cycling Test

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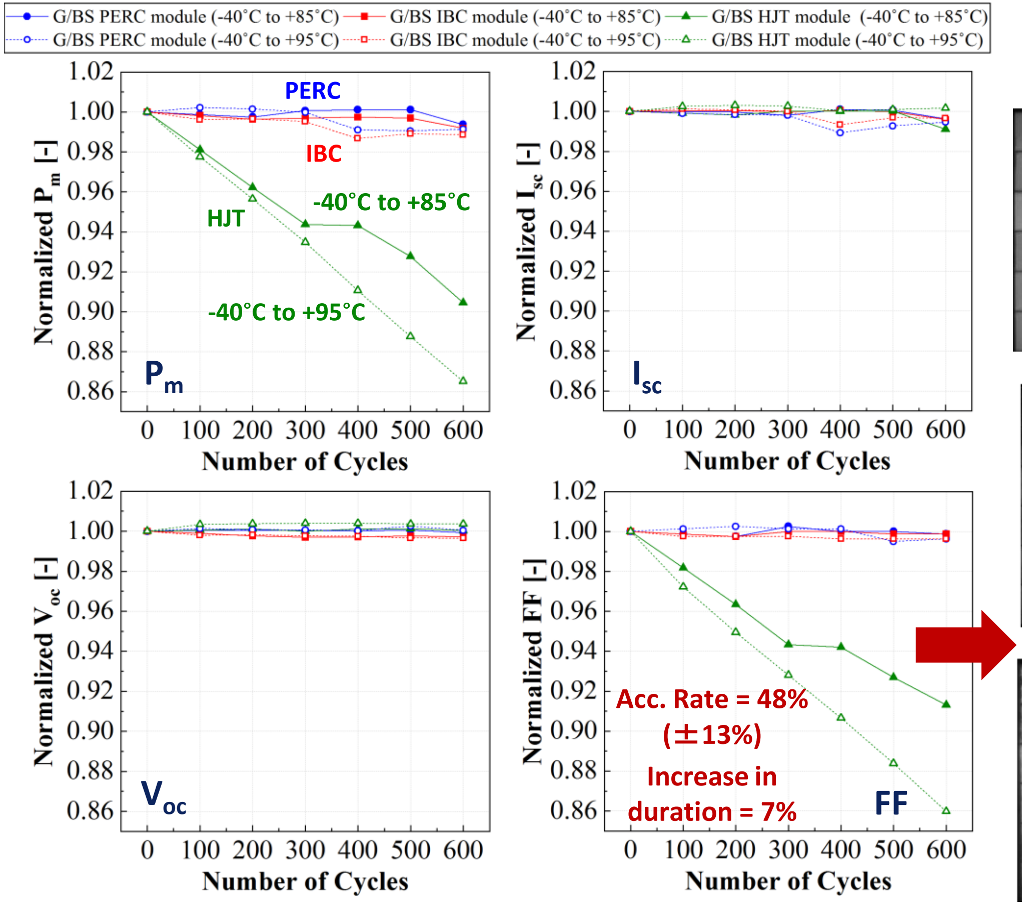
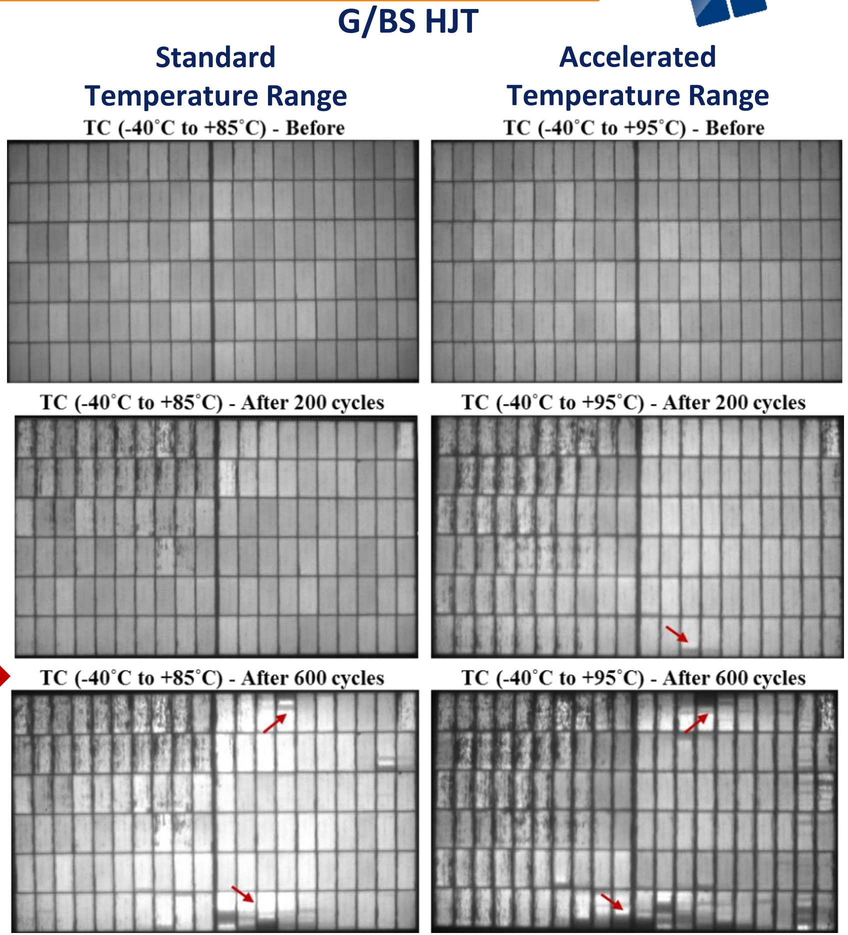
Extended and Accelerated Thermal Cycling (TC) Test

- **IEC 62892: Larger thermomechanical stress** in BIPV configuration → **Extended TC test**
- **IEC TS 63126:** If **70°C < T_{98} ≤ 80°C** (larger thermal stress), **maximum temperature of TC is 95°C**

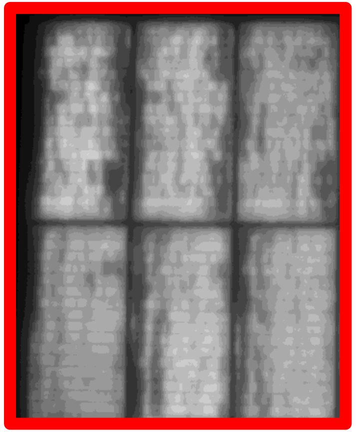
	Temperature Range	Number of Cycles
Thermal Cycling (Extended)	-40°C to +85°C (Standard range according to IEC 61215)	600 cycles (Measurements every 100 cycles)
Accelerated Thermal Cycling (Extended)	-40°C to **+95°C**	600 cycles (Measurements every 100 cycles)

Extended and Accelerated Thermal Cycling (TC) Test

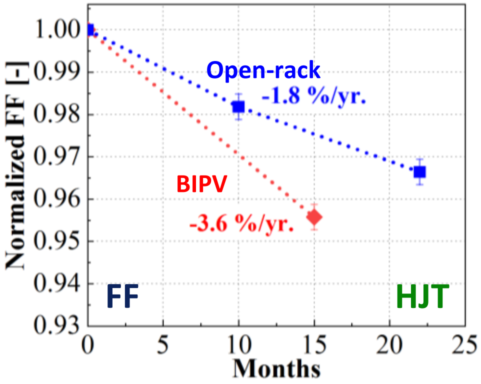




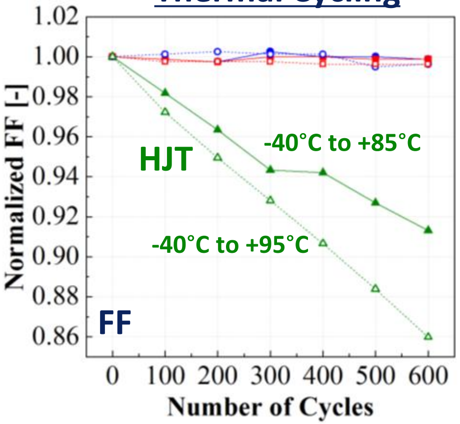
Extended and Accelerated Thermal Cycling (TC) Test Suitable for BIPV?



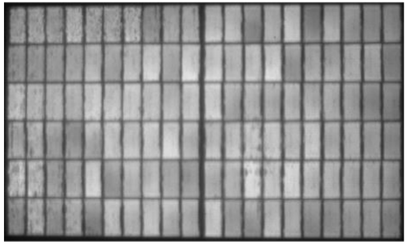
Outdoor Exposed



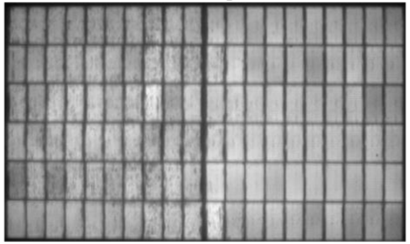
Thermal Cycling



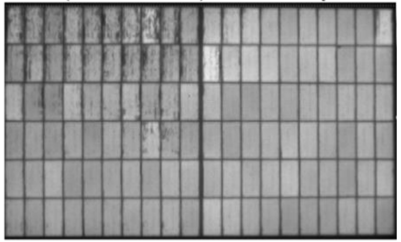
Open-rack – After 22 Months of Outdoor Exposure



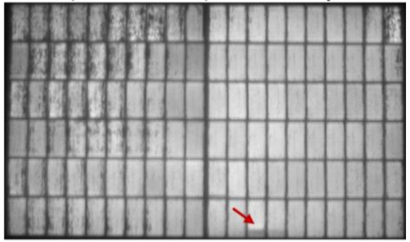
BIPV Insulated – After 15 Months of Outdoor Exposure



TC (-40°C to +85°C) - After 200 cycles



TC (-40°C to +95°C) - After 200 cycles



- **Field representative results** (IV and EL)
- More time necessary to see how the issues of the outdoor exposed module evolves
- More samples need to be tested

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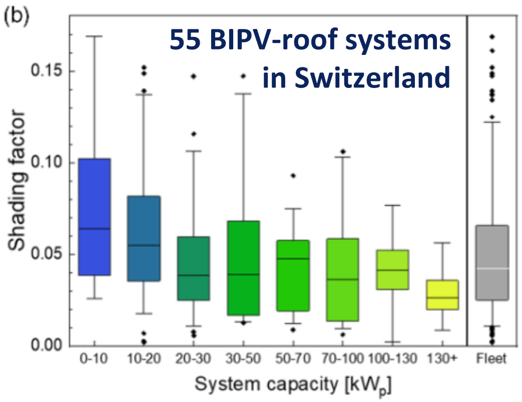
Stress 3: More Frequent Partial Shading

More Frequent Partial Shading

D. Chianese et al., EUPVSEC (2020)

$$\text{Shading factor} = \frac{\text{Time in shading fault}}{\text{Time in operation}}$$



A. Fairbrother et al. Solar RRL (2021)

Hot spot endurance test (IEC61215-2:2021, MQT9)

- To assess module's ability to resist local-point/cell heating under partial shading
- **IEC TS 63126:2020** Guidelines for qualifying PV modules, components and materials for operation at high temperatures → **T_{98} (175.2hour/year)**

Module Temperature	IEC 61215:2021 (T_{98} ≤ 70°C)	Level 1 (70°C < T_{98} ≤ 80°C)	Level 2 (80°C < T_{98} ≤ 90°C)
IEC TS 63126:2020	55±15°C (50±10°C*) *IEC 61215:2016	60±10°C	70±10°C

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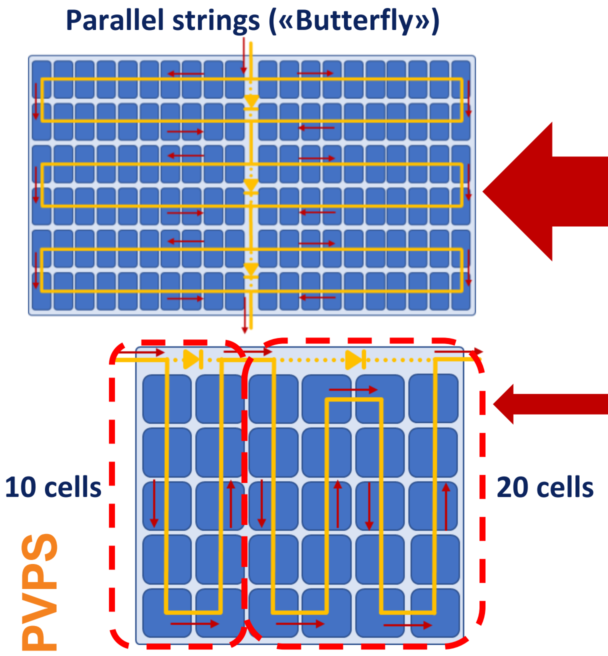
More Frequent Partial Shading

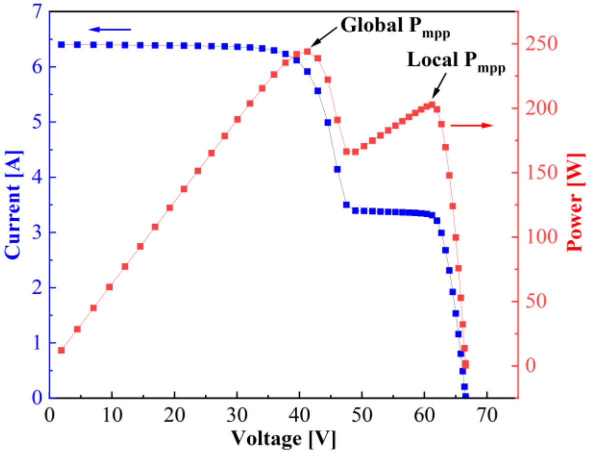
- Effect of **cell technology** and **string length** on hot-spot temperature
- **Sufficiency of HS test for BIPV** in terms of **testing temperature**

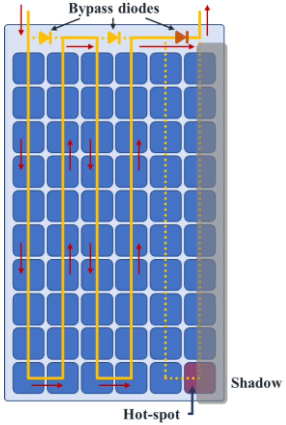


Module Technology	Indoor Hot-spot Endurance Tests	
	IEC 61215-2:2021 (55°C, max 5h) *+ 5h*	IEC TS 63126:2020 Level-2 (75°C, max 5h) *+ 5h*
1 - PERC Half-Cell (20 cells/diode)	1	1
2 - HJT Half-Cell (20 cells/diode)	1	1
3 - IBC Full-Cell (104 cells, 3 diodes)	1	1
4 - PERC Full-cell (Short + Long String) (10 cells/diode + 20 cells/diode)	1	-

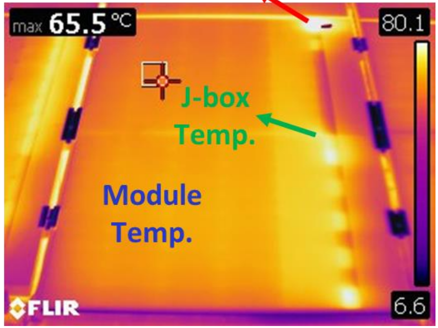
E Özkalay, et. al, "The effect of partial shading on the reliability of photovoltaic modules in the built-environment", EPJ Photovoltaics, 2024

Outdoor Accelerated Ageing using Shadow Masks



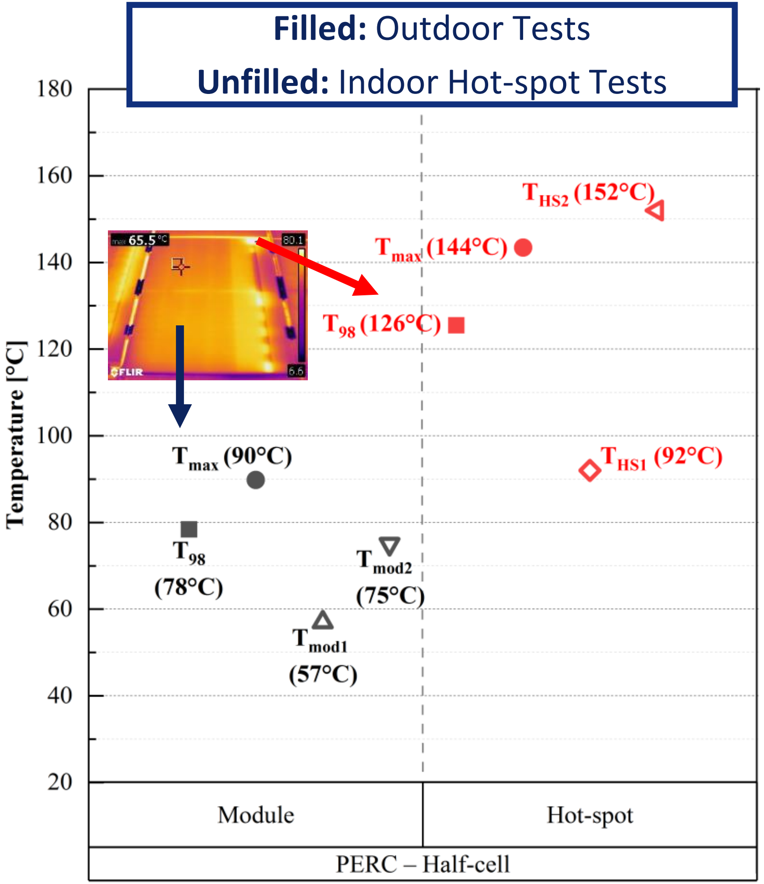


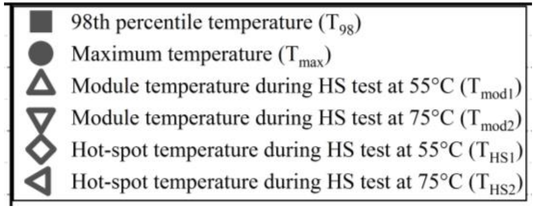
- Stress on **bypass diode** and **module materials**
- Difference between **Global P_{mpp} and Local P_{mpp} is 10±5%**
- Shadow mask **36% transmittance**
- 13 months of monitoring
- **Module**, **hot-spot** and **junction box temperatures** every minute
- IV curves every minute



E Özkalay, et. al, "The effect of partial shading on the reliability of photovoltaic modules in the built-environment", EPJ Photovoltaics, 2024

Sufficieny of HS test for BIPV?





Hot-spot Endurance Test	IEC 61215-2:2021 (2016)	Level 1 (70°C < T_{98} ≤ 80°C)	Level 2 (80°C < T_{98} ≤ 90°C)
IEC TS 63126:2020	55±15°C (50±10°C)	60±10°C	70±10°C
Proposal of this study	55±15°C	*75±15°C*	*85±15°C*

HS test should be performed at higher module temperatures for BIPV testing!

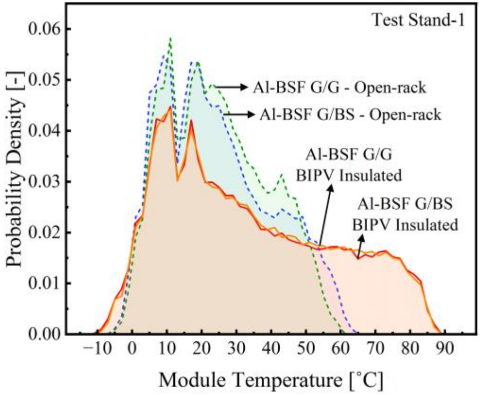
E Özkalay, et. al, “The effect of partial shading on the reliability of photovoltaic modules in the built-environment”, EPJ Photovoltaics, 2024

Summary and Conclusion – 1

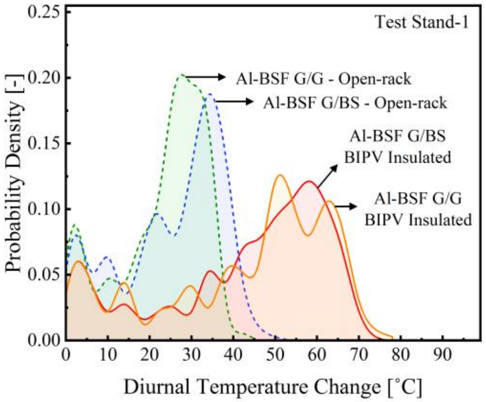
- **Thermal stress:** T_{98} (IEC TS 63126) highly depends on the type of BIPV configuration and orientation
  - All **BIPV Insulated roof modules** have **T_{98} > 70˚C**
  - For **BIPV Partially Ventilated roof modules**, T_{98} depends on the ventilation chamber design
  - All **BIPV Partially Ventilated façade modules** have **T_{98} ≤ 70˚C**

- **Thermomechanical stress: All BIPV modules need extended thermal cycling test** (IEC 62892)

Module Temperature Distribution



Diurnal Temperature Change Distribution



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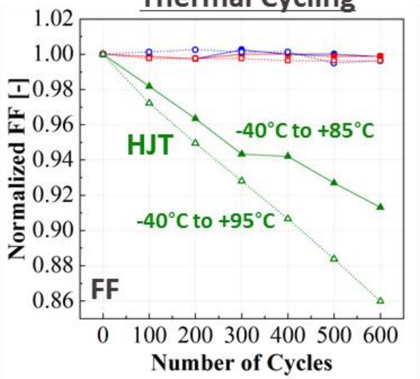
Summary and Conclusion – 2

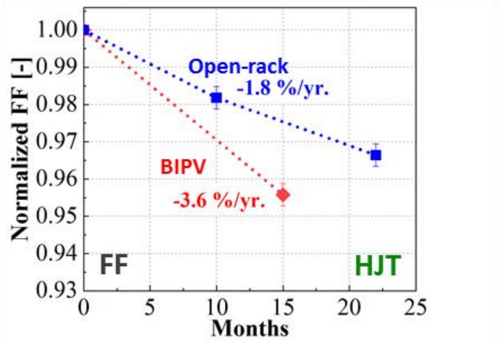
Extended and Accelerated Thermal Cycling:

- Increasing the maximum temperature of the TC test and extending the test can be representative for BIPV testing, but more samples need to be tested

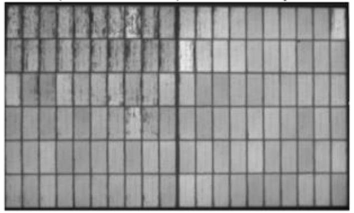
Thermal Cycling



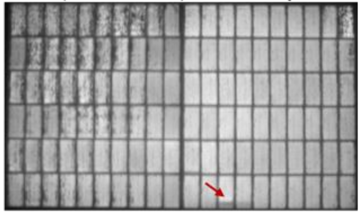
Outdoor Exposed



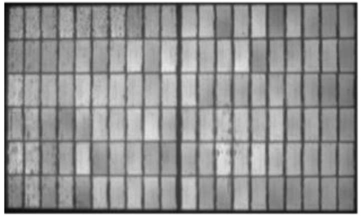
TC (-40°C to +85°C) - After 200 cycles



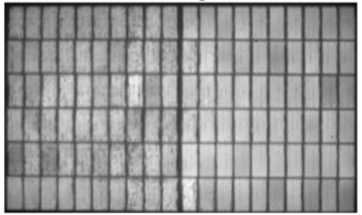
TC (-40°C to +95°C) - After 200 cycles



Open-rack – After 22 Months of Outdoor Exposure



BIPV Insulated – After 15 Months of Outdoor Exposure



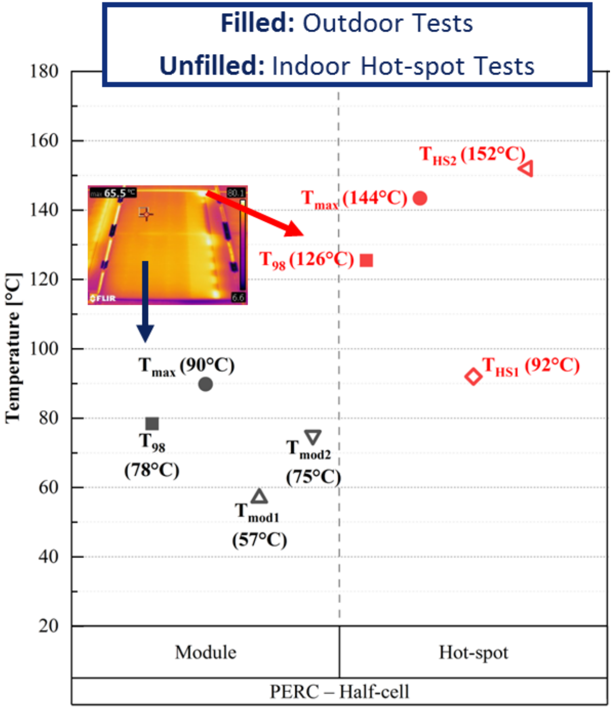
PVPS

Summary and Conclusion – 3

Sufficiency of HS test for BIPV in terms of testing temperature

- 15°C higher module temperature for Level 1 & 2 in IEC TS 63126:2020

Hot-spot Endurance Test	IEC 61215-2:2021 (2016)	Level 1 (70°C < T_{98} ≤ 80°C)	Level 2 (80°C < T_{98} ≤ 90°C)
IEC TS 63126:2020	55±15°C (50±10°C)	60±10°C	70±10°C
Proposal of this study	55±15°C	*75±15°C*	*85±15°C*



PVPS

Thank you!

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IEA PVPS

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