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Prestazioni dei sistemi fotovoltaici in condizioni di ombreggiamento parziale

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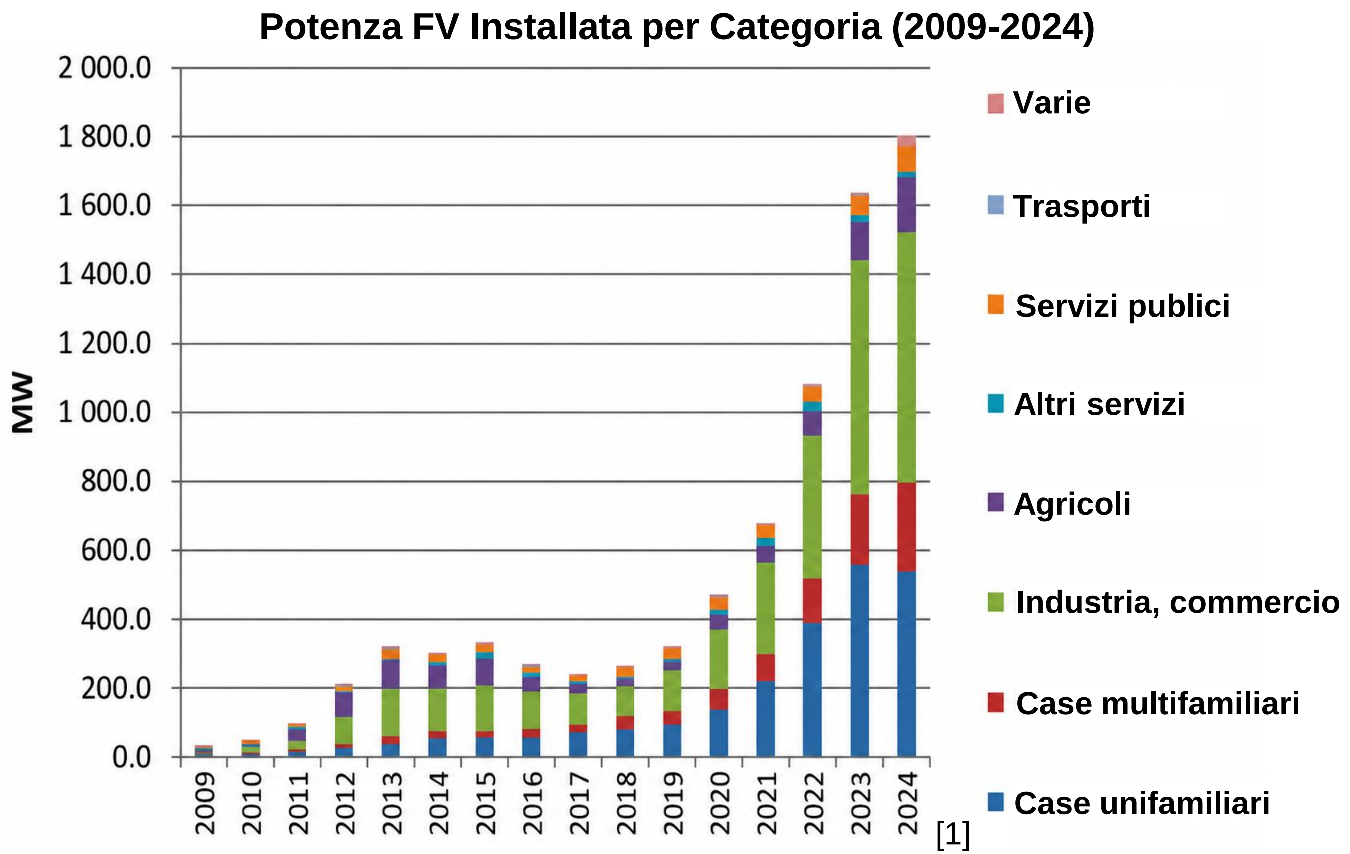
Introduzione

- In Svizzera, il terreno disponibile per installazioni fotovoltaiche su larga scala è limitato.
- I sistemi fotovoltaici sono installati principalmente su/in edifici e infrastrutture (non a terra!). [1]
- Le superfici degli edifici hanno un potenziale stimato di produzione annua di elettricità pari a 67 TWh in Svizzera. [2]
- Maggiore diffusione del fotovoltaico nelle aree urbane.



[1]

[1] Thomas Hostettler. Statistiques de l'énergie solaire - Année de référence 2024. OFEN, 10 July 2025.
[2] Bundesamt fur Energie, [Online]. Available: https://www.bfe.admin.ch/bfe/it/home/novita-e-media/comunicati-stampa/mm-test.msg-id-74641.html. [Accessed 2025]. 2019.

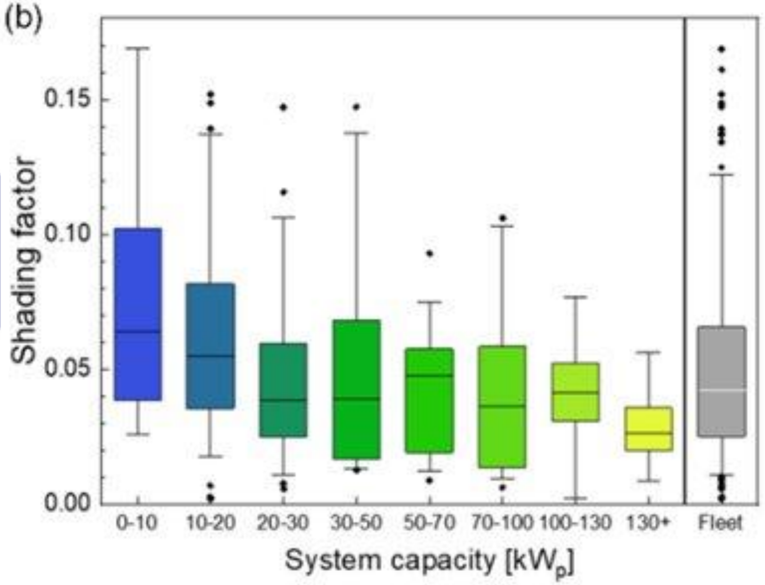
Motivazione

- Maggiore ombreggiamento nelle aree urbane: Gli ambienti urbani presentano numerose problematiche legate all’ombreggiamento.
- Camini, edifici vicini e alberi creano spesso ombre persistenti che possono ridurre l’efficienza e l’affidabilità dei sistemi fotovoltaici.
- I sistemi fotovoltaici di piccole dimensioni, in particolare le installazioni residenziali sui tetti, sono più frequentemente soggetti a ombreggiamento parziale rispetto ai sistemi più grandi installati su fienili, edifici commerciali o tetti industriali.

[1]

55 sistemi di tetti BIPV in Svizzera

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



[4]

[2]

[3]

[1] D. Chianese, M. Caccivio, “Investigations on the Main Causes for Reduced Performances during the Early Stage of Life of Rooftop PV Systems”, EUPVSEC, 2020.
[2] IEA Task 13, “Performance of Partially Shaded PV Generators Operated by Optimized Power Electronics”, 2024.
[3] F. Frontini, S. M. Bouziri, G. Corbellini, and V. Medici, “S.M.O Solution: An Innovative Design Approach to Optimize the Output of BIPV Systems Located in Dense Urban Environments,” in Energy Procedia, 2016. doi: 10.1016/j.egypro.2016.06.261
[4] A. Fairbrother, H. Quest, E. Özkalay, et al., “Long-Term Performance and Shade Detection in Building Integrated Photovoltaic Systems”, Solar RRL, vol. 6, no. 5, May 2022, DOI: 10.1002/solr.202100583.

Motivazione

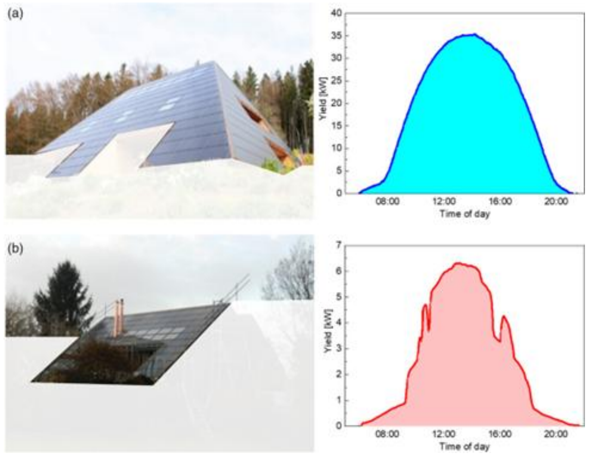
- **Progetto QUALITI finanziato dal FER: “Indagine sulle principali cause della riduzione delle prestazioni durante la fase iniziale di vita dei sistemi fotovoltaici su tetto”.**
  - Studio condotto su 30 sistemi fotovoltaici residenziali (203 stringhe) (statisticamente non significativo) in Ticino nel periodo 2018–2019.
  - Il 16,7% delle stringhe analizzate presenta un ombreggiamento parziale permanente.
  - Più del 50% è influenzato da ombreggiamento parziale temporaneo.

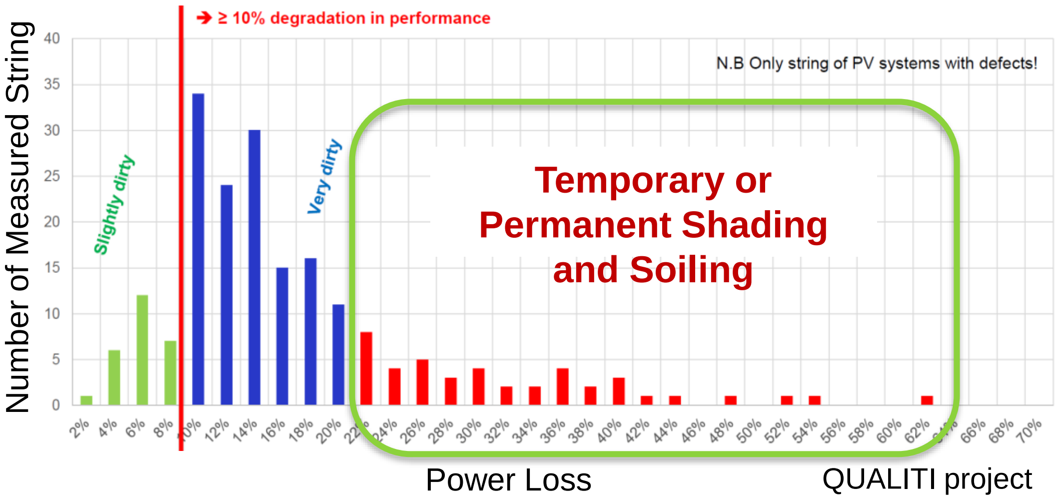
Percentuale delle stringhe con difetti riscontrati in 203 stringhe provenienti da 30 sistemi fotovoltaici in Ticino.

	Defects/Errors/Failures in strings	
1	Power Degradation (STC)	96.5 %
2	Soiling on modules	88.9 %
3	Partial shadows	53.3 %
4	Permanent partial shadows	16.7 %
5	Defects / dirt in the inverter	10.0 %
6	Broken glass	3 modules
7	Strings disconnected	1.4 %

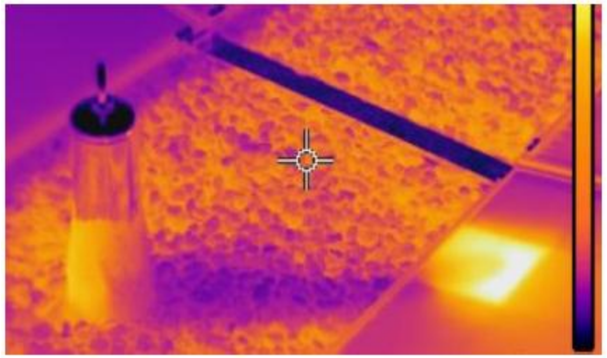
D. Chianese, M. Caccivio, “Investigations on the Main Causes for Reduced Performances during the Early Stage of Life of Rooftop PV Systems”, EUPVSEC, 2020.

Perdita di potenza istantanea (perdita temporanea rapida)



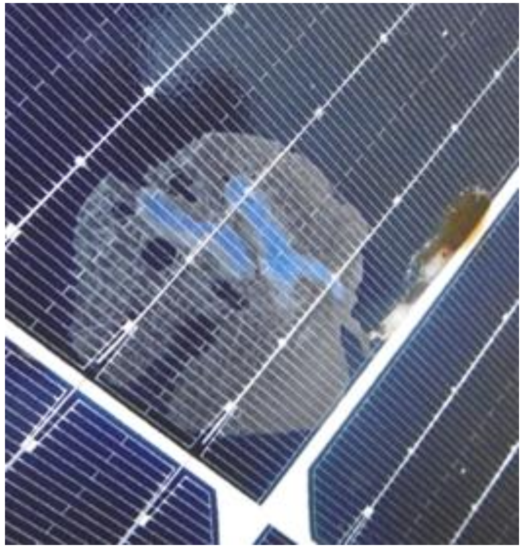


Formazione di hot spot (perdita lenta e permanente)

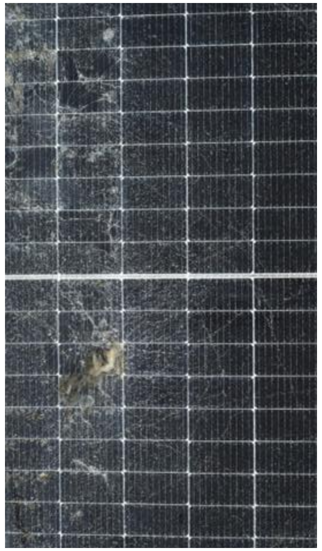


Discolouration

Delaminazione



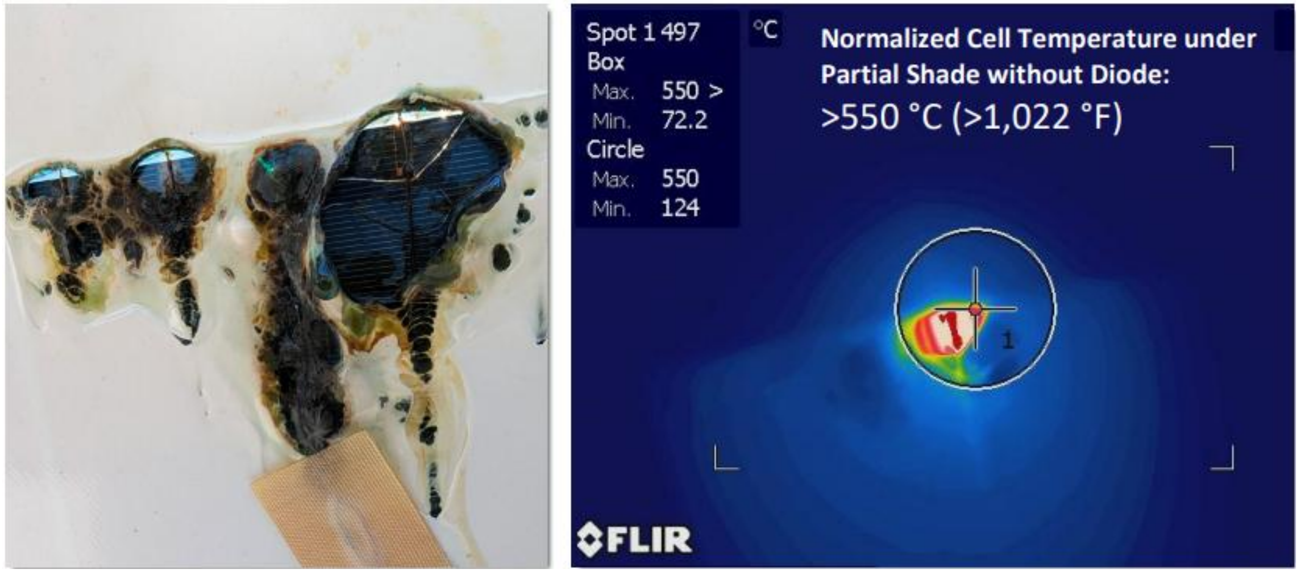
Rottura del Vetro



Impatto dell’ombreggiamento parziale – Affidabilità

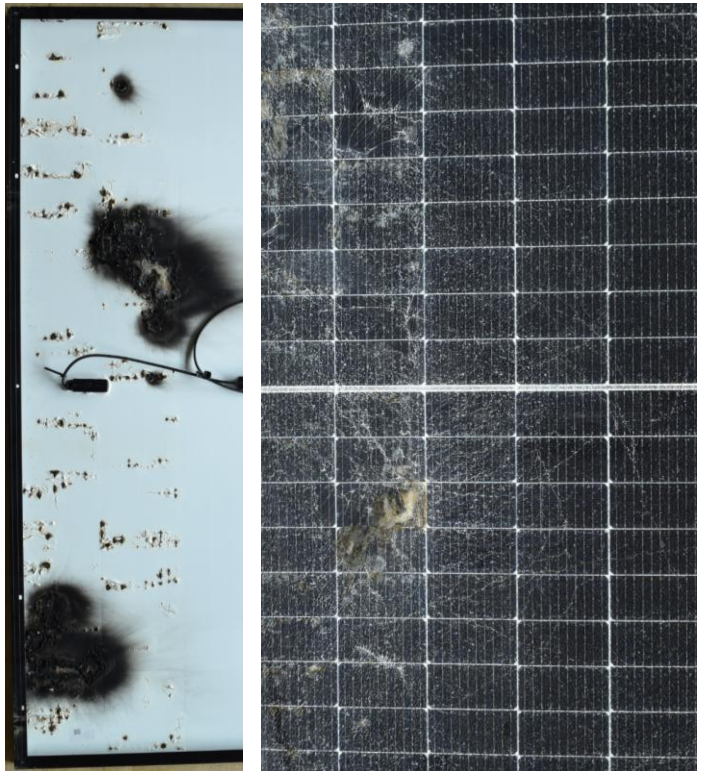
- Hot spot che raggiungono temperature fino a 130 – 150° C (o anche superiori), a seconda di vari parametri come la severità dell’ombreggiamento, il design del modulo e le condizioni operative. [1,2]

Test in caso di diodo di bypass guasto



Danno da hotspot visibile (a sinistra) insieme a un’immagine a infrarossi (a destra), alla temperatura massima dell’hotspot >550 ° C osservata nel pannello TOPCon entro 30 minuti dalla rimozione del diodo [3].

Un esempio dal Ticino



[1] E. Özkalay, F. Valoti, M. Caccivio, A. Virtuani, G. Friesen, and C. Ballif, “The effect of partial shading on the reliability of photovoltaic modules in the built-environment”, EPJ Photovoltaics, vol. 15, 2024, DOI: 10.1051/epjpv/2024001.
[2] Maxeon Solar Technologies, “Shading and Hotspot Resilience White Paper”, June 2024.

Strategie di Mitigazione

1) Diodi di bypass (BPD)

2) Celle solari a bassa tensione di breakdown

3) Celle solari half-cut (tagliate a metà)

4) Layout del modulo

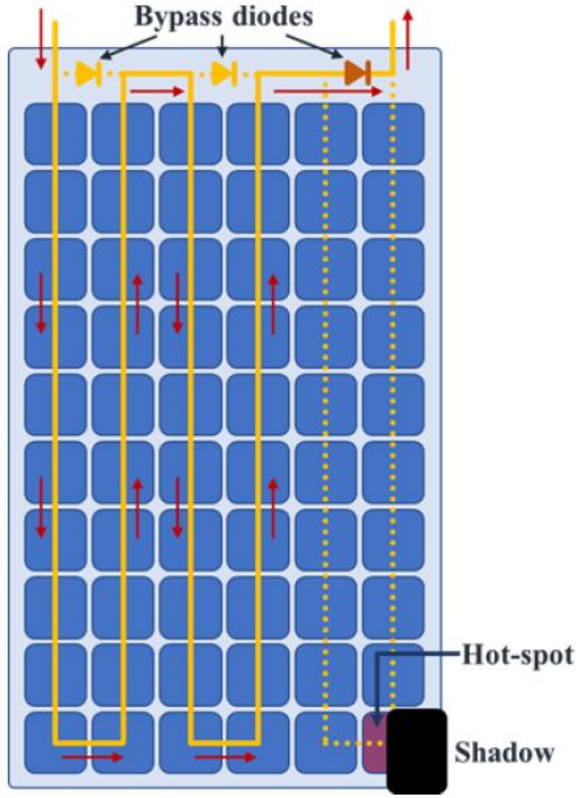
5) Ottimizzatori di potenza

6) Migliore progettazione del sistema fotovoltaico (strategie di cablaggio)

Strategie di Mitigazione e Limitazioni

1) Diodi di Bypass:

- Ridurre le perdite di prestazione, prevenire parzialmente la formazione di hotspot e mitigare i danni correlati.
- **I diodi di bypass (BPD) aiutano a ridurre l'impatto dell'ombreggiamento, ma non lo eliminano completamente [1].**



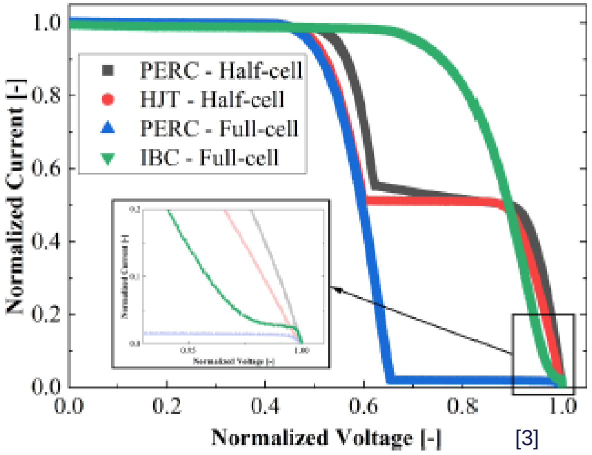
[1] R. Vieira, F. de Araújo, M. Dhimish, and M. Guerra, "A Comprehensive Review on Bypass Diode Application on Photovoltaic Modules", Energies, vol. 13, no. 10, May 2020, DOI: 10.3390/en13102472.

Strategie di Mitigazione e Limitazioni

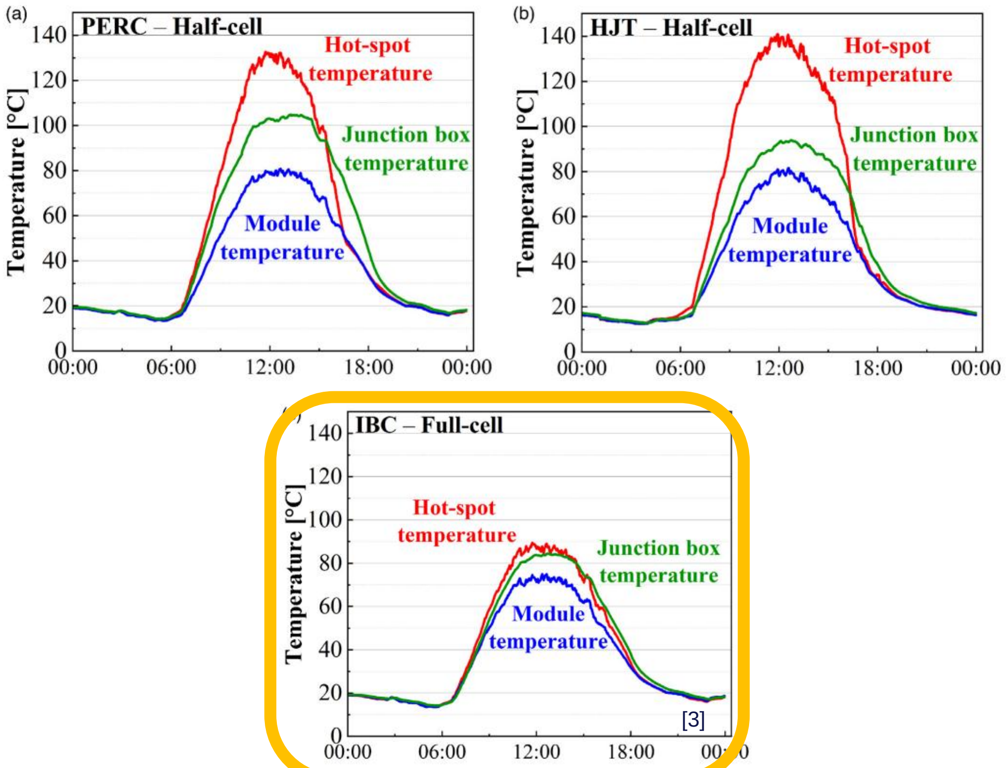
2) Celle solari a bassa tensione di breakdown:

- Tecnologie di celle Back Contact (BC) (ad es. Maxeon, Aiko, Longi, Zebra, ecc.).
- Diodo di bypass integrato che si attiva in condizioni di ombreggiamento tramite effetto tunnel (diodo Zener) → tensione di breakdown negativa inferiore (intorno a -5 V) [1,2]. TOPCon: intorno a -40/-50 V; HJT: intorno a -30 V; PERC: intorno a -20 V
- **Per una migliore risposta all'ombreggiamento, sono importanti la selezione delle celle, il layout del modulo e la progettazione del sistema [3].**

PERC, HJT and IBC – I-V characteristics (one cell shaded)



[3]



[3]

[1] H. Chu, L. J. Koduvelikulathu, V. D.Mihailetchi, G. Galbiati, A. Halm, and R. Kopecek, "Soft Breakdown Behavior of Interdigitated-back-contact Silicon Solar Cells", Energy Procedia, vol. 77, Aug. 2015, DOI: 10.1016/j.egypro.2015.07. 006.
[2] R.Müller, C. Reichel, J. Schrof, et al., "Analysis of n-type IBC solar cells with diffused boron emitter locally blocked by implanted phosphorus", Solar Energy Materials and Solar Cells, vol. 142, Nov. 2015, DOI: 10.1016/j.solmat.2015. 05.046.
[3] E. Özkalay, F. Valoti, M. Caccivio, A. Virtuani, G. Friesen, and C. Ballif, "The effect of partial shading on the reliability of photovoltaic modules in the built-environment", EPJ Photovoltaics, vol. 15, 2024, DOI: 10.1051/epjpv/2024001

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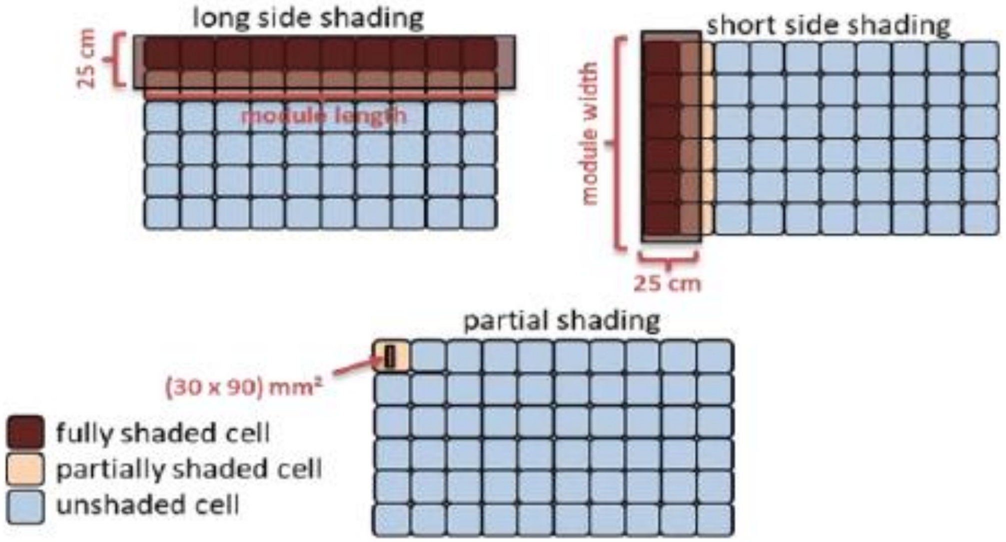
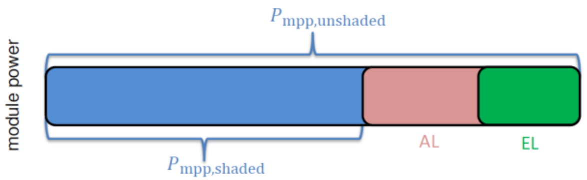


$$AL = \left(1 - \frac{P_{\text{mpp,shaded}}}{P_{\text{mpp,unshaded}}} - \frac{A_{\text{shaded}}}{A_{\text{total}}}\right) \cdot 100\ \%$$



better shade resistance ↑

class	long side	short side	partial
A	AL < 5 %	AL < 5 %	AL < 2 %
B	5 % ≤ AL < 25 %	5 % ≤ AL < 25 %	2 % ≤ AL < 5 %
C	25 % ≤ AL < 50 %	25 % ≤ AL < 50 %	5 % ≤ AL < 10 %
D	AL > 50 %	AL > 50 %	AL > 10 %

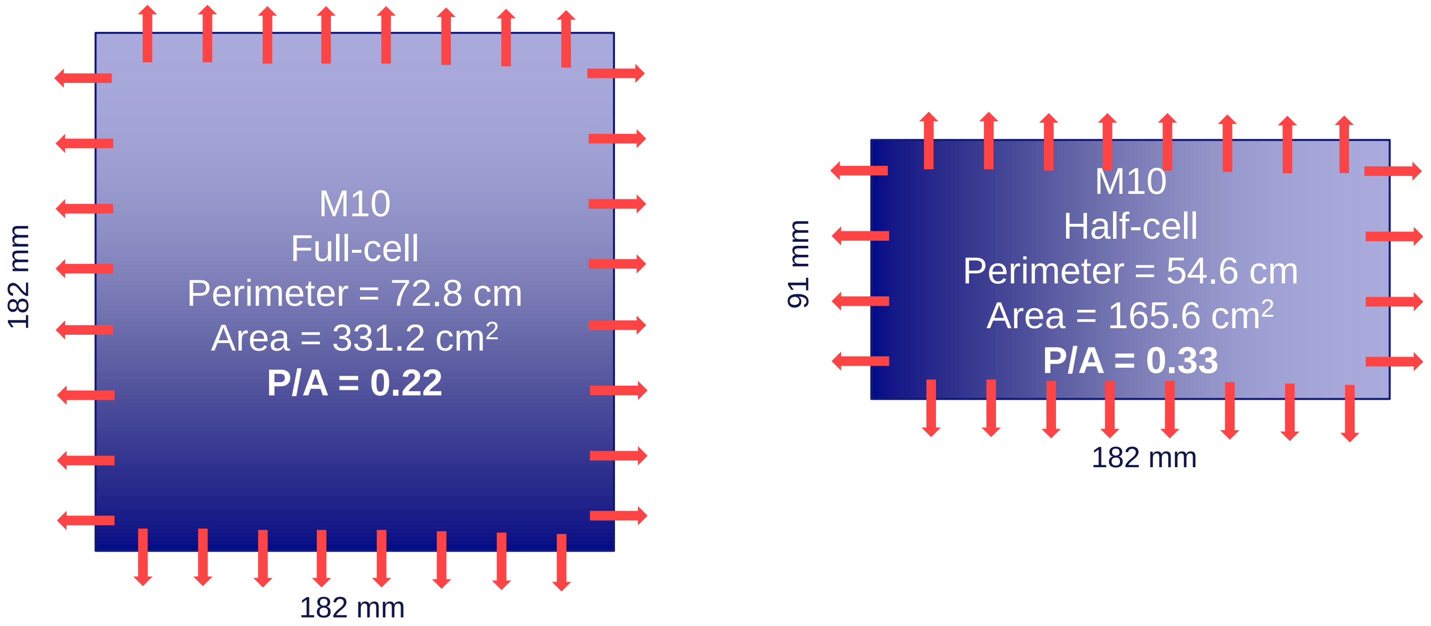
	Long edge	Short Edge	Partial	
Reference Standard Module	B	D	B	BDB
PERC Half-cut / two parallel sections	B	C	B	BCB
PERC Shingled /four sections	C	B	B	CBB
Integrated diode	B	B	B	BBB
TOPCon Half-cut	B	C	B	BCB
PERC 3cut	B	C	B	BCB
HJT Half-cut / two parallel sections	B	C	B	BCB
IBC full cell	A	D	B	ADB

[1] H. Chu, L. J. Koduvelikulathu, V. D.Mihailetchi, G. Galbiati, A. Halm, and R. Kopecek, "Soft Breakdown Behavior of Interdigitated-back-contact Silicon Solar Cells", Energy Procedia, vol. 77, Aug. 2015, DOI: 10.1016/j.egypro.2015.07. 006.
[2] R.Müller, C. Reichel, J. Schrof, et al., "Analysis of n-type IBC solar cells with diffused boron emitter locally blocked by implanted phosphorus", Solar Energy Materials and Solar Cells, vol. 142, Nov. 2015, DOI: 10.1016/j.solmat.2015. 05.046.
[3] E. Özkalay, F. Valoti, M. Caccivio, A. Virtuani, G. Friesen, and C. Ballif, "The effect of partial shading on the reliability of photovoltaic modules in the built-environment", EPJ Photovoltaics, vol. 15, 2024, DOI: 10.1051/epjpv/2024001

Strategie di Mitigazione e Limitazioni

3) Dimensioni delle celle:

- Le celle half-cut/più piccole generalmente presentano temperature di hotspot inferiori rispetto alle celle intere/più grandi, grazie al loro maggiore rapporto perimetro/superficie. Il perimetro più ampio migliora il trasferimento di calore per conduzione, con conseguente riduzione della temperatura degli hotspot [1].
- Tuttavia, per tecnologie PERC, HJT e TOPCon, la temperatura degli hotspot delle celle M6 (166 × 166 mm) è tipicamente solo 2–12 ° C inferiore rispetto a quella delle celle M12 (210 × 210 mm) [2,3].
- **Per una migliore risposta all'ombreggiamento, sono importanti la selezione delle celle, il layout del modulo e la progettazione del sistema.**



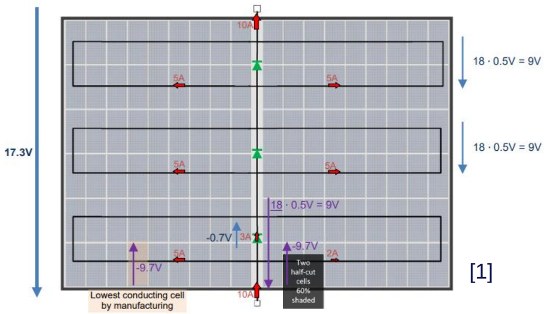
[1] R. Witteck, Hot cells in high-power photovoltaic modules with solar cells from larger siliconwafer formats (Eu-PVSEC, 2021), https://doi.org/10.4229/EUPVSEC20212021-4AV.1.25
[2] C. Reichel et al., "Design aspects in consideration of hotspot phenomena in high-performance photovoltaic modules featuring different silicon solar cell architectures," Solar Energy Materials & Solar Cells, vol. 276, art. 113058, 2024..
[3] T. Xu, S. Deng, G. Zhang, Z. Zhang, Sol. Energy 230 (2021) 583

Strategie di Mitigazione e Limitazioni

<u>4) Layout del Modulo:</u>

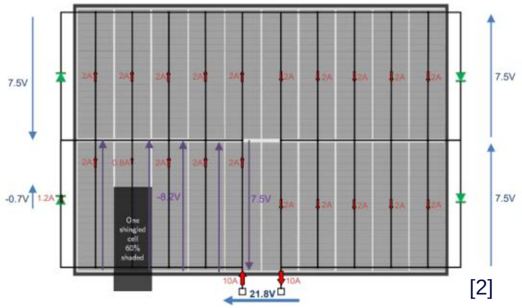
- Meno celle per diodo e più regioni in parallelo.
- **Non impedisce completamente la formazione di hotspot; l'aggiunta di più componenti aumenta i rischi di affidabilità e la selezione delle celle e la progettazione del sistema restano comunque importanti.**

Standard Half-cut Module



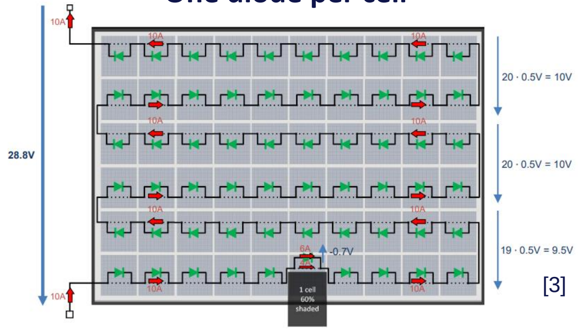
[1]

4-parallel parts

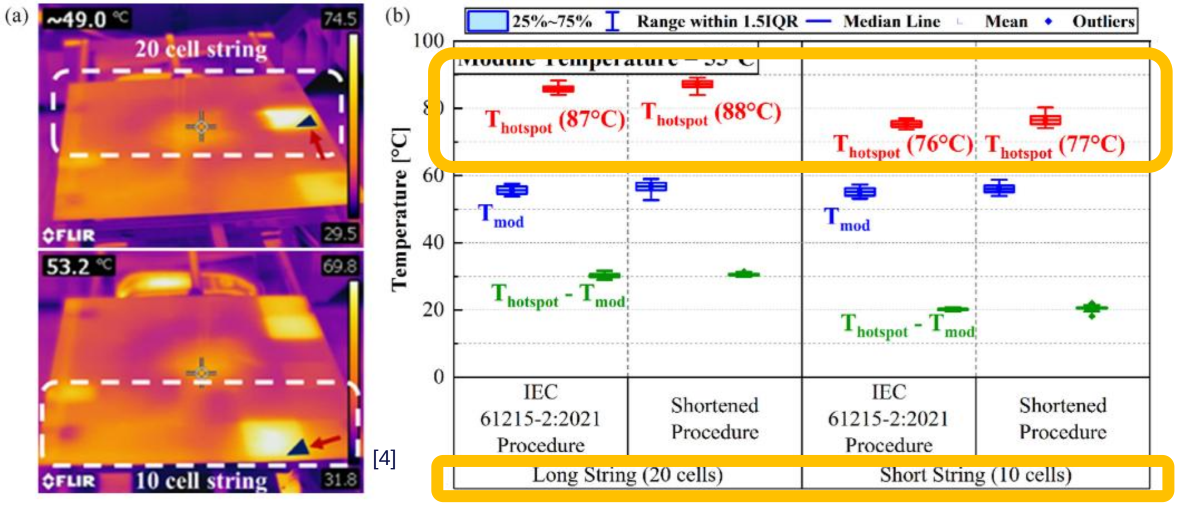


[2]

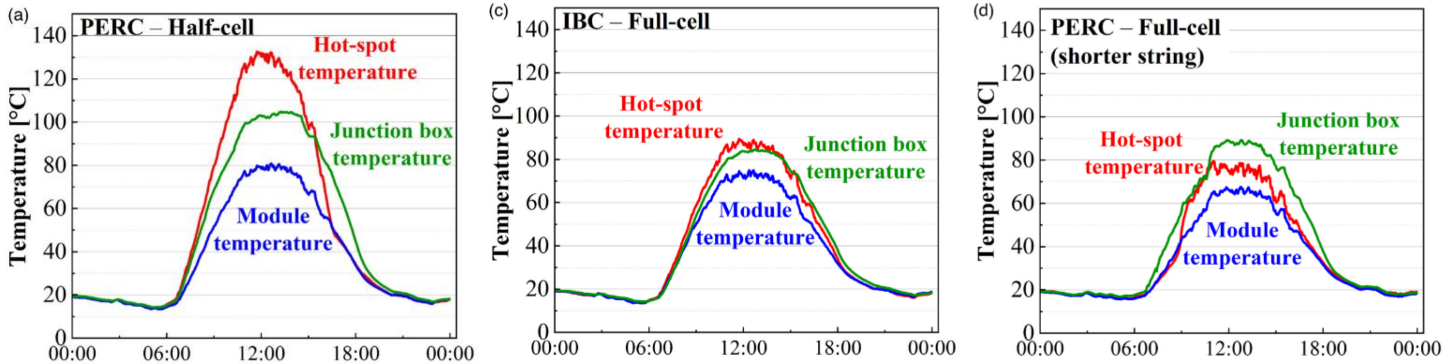
One diode per cell



[3]



[4]

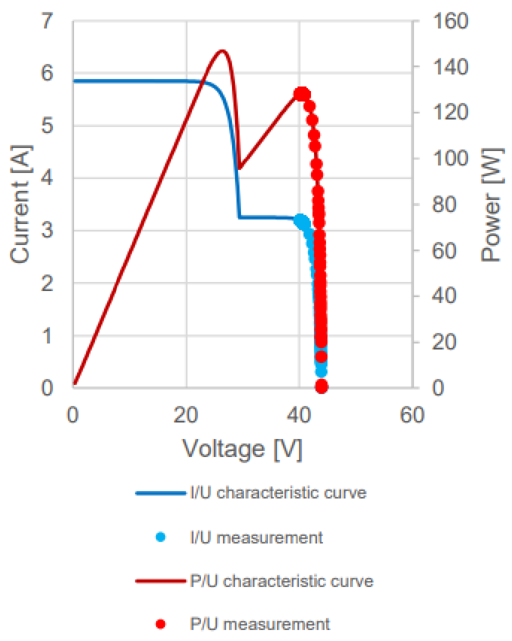


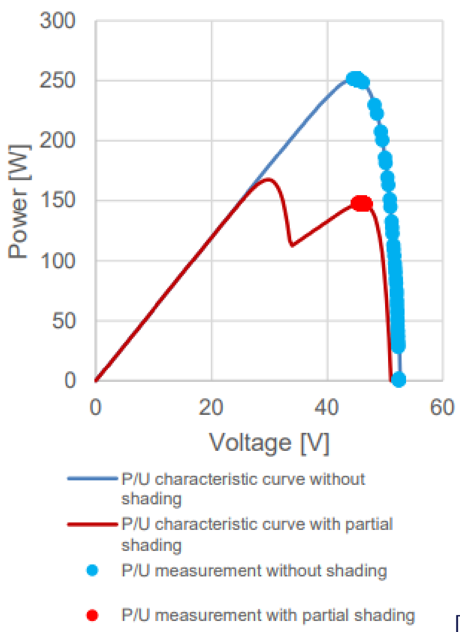
[1] F. Baumgartner, C. Allenspach, "Performance gain of shading tolerant PV modules in different electrical PV system setups" in 40st EUPVSEC, Lisbon
[2] IEA Task 13, "Performance of Partially Shaded PV Generators Operated by Optimized Power Electronics", 2024.
[3] manufactures websites of shading tolerant PV module; ShadeStar products AE400HM6-60 product with 60 by-pass diodes, https://www.ae-solar.com/
[4] E. Özkalay, F. Valoti, M. Caccivio, A. Virtuani, G. Friesen, and C. Ballif, "The effect of partial shading on the reliability of photovoltaic modules in the built-environment", EPJ Photovoltaics, vol. 15, 2024, DOI: 10.1051/epjpv/2024001

Strategie di Mitigazione e Limitazioni

5) Module Level Power Optimizers (MLPE):

- In condizioni specifiche di ombreggiamento parziale, gli MLPE ottimizzano la potenza di ciascun modulo separatamente e quindi riducono le perdite di potenza a livello di sistema.
- **Tuttavia, presentano una minore efficienza del sistema durante il funzionamento in condizioni non ombreggiate e ulteriori criticità di affidabilità (!).**





[1]

[1] F. Baumgartner,"Will PV optimiser lead to optimum solar output at light shading", presentation at the IEA side event in 8th World Conference on Photovoltaic Energy Conversion (WCPEC-8), Milano, Italy, 2022

Strategie di Mitigazione e Limitazioni

6) Migliore progettazione del sistema fotovoltaico:

- Progettazione delle stringhe e del cablaggio e posizionamento dei moduli, considerando l'ombreggiamento parziale durante l'anno.
- **Non sempre è possibile risolvere completamente il problema. Può essere necessario combinarlo con una o più strategie tecnologiche di mitigazione.**

Edificio residenziale a energia positiva in Seewadelstrasse – Affoltern am Albis (ZH–CH). Attraverso un cablaggio accurato è possibile controllare l'ombreggiamento dei moduli a partire dall'edificio stesso https://solarchitecture.ch/shading/. (Crediti fotografici: Viridén + Partner AG).

[1]

Esistono studi sufficienti sull'efficacia delle diverse strategie di ombreggiamento parziale?

Strategie di mitigazione per migliori prestazioni in condizioni di ombreggiamento parziale	Perdita di potenza istantanea (perdita temporanea rapida)		Formazione di hot spot (perdita lenta e permanente)	
	A livello di modulo	A livello di sistema	A livello di modulo	A livello di sistema
Progettazione del modulo (selezione delle celle e layout del modulo)				
Ottimizzatori di potenza a livello di modulo, microinverter				
Progettazione intelligente del sistema				

Esistono studi sufficienti sull’efficacia delle diverse strategie di ombreggiamento parziale?

Strategie di mitigazione per migliori prestazioni in condizioni di ombreggiamento parziale	Perdita di potenza istantanea (perdita temporanea rapida)		Formazione di hot spot (perdita lenta e permanente)	
	A livello di modulo	A livello di sistema	A livello di modulo	A livello di sistema
Progettazione del modulo (selezione delle celle e layout del modulo)	Y	Y	Y	*Y (only 1, cell selection)*
Ottimizzatori di potenza a livello di modulo, microinverter				
Progettazione intelligente del sistema				

Esistono studi sufficienti sull'efficacia delle diverse strategie di ombreggiamento parziale?

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	A livello di modulo	A livello di sistema	A livello di modulo	A livello di sistema
Progettazione del modulo (selezione delle celle e layout del modulo)	Y	Y	Y	*Y (only 1, cell selection)*
Ottimizzatori di potenza a livello di modulo, microinverter	NA	Y	NA	N
Progettazione intelligente del sistema	NA	Y	NA	N

Problem 1: There are not enough studies on the effect of these mitigation strategies on system-level hot spot formation.

Problema 1: Non ci sono abbastanza studi sull'effetto di queste strategie di mitigazione sulla formazione di hotspot a livello di sistema.

Esistono abbastanza studi su come le diverse strategie funzionano insieme?

Strategie di mitigazione per migliori prestazioni in condizioni di ombreggiamento parziale	Perdita di potenza istantanea (perdita temporanea rapida)		Formazione di hot spot (perdita lenta e permanente)	
	A livello di modulo	A livello di sistema	A livello di modulo	A livello di sistema
Progettazione del modulo + Ottimizzatori di potenza a livello di modulo, microinverter				
Progettazione del modulo + Progettazione intelligente del sistema				
Ottimizzatori di potenza a livello di modulo, microinverter + Progettazione intelligente del sistema				

Esistono abbastanza studi su come le diverse strategie funzionano insieme?

Strategie di mitigazione per migliori prestazioni in condizioni di ombreggiamento parziale	Perdita di potenza istantanea (perdita temporanea rapida)		Formazione di hot spot (perdita lenta e permanente)	
	A livello di modulo	A livello di sistema	A livello di modulo	A livello di sistema
Progettazione del modulo + Ottimizzatori di potenza a livello di modulo, microinverter	**NA**	***Y (solo 1)****	**NA**	**N**
Progettazione del modulo + Progettazione intelligente del sistema	**NA**	***Y (solo 1)****	**NA**	**N**
Ottimizzatori di potenza a livello di modulo, microinverter + Progettazione intelligente del sistema	**NA**	***Y (solo 1)****	**NA**	**N**

Problema 2: Non ci sono abbastanza studi sull'efficacia della combinazione di diverse strategie a livello di sistema in termini di resa energetica e formazione di hotspot.

*: *the work done by ZHAW. The work is not sufficiently comprehensive→ F. Baumgartner and C. Allenspach, doi: 10.4229/EUPVSEC2023/3DO.16.1.*

Conosciamo quali strategie (singole o combinate) siano ottimali per ciascun caso di ombreggiamento, considerando la resa energetica e l’affidabilità?

Strategie di mitigazione per migliori prestazioni in condizioni di ombreggiamento parziale	Case-1	Case-2	Case-3	Case-4
				
Progettazione del modulo (selezione delle celle e layout del modulo)				
Ottimizzatori di potenza a livello di modulo, microinverter				
Progettazione intelligente del sistema				
Progettazione del modulo + Ottimizzatori di potenza a livello di modulo, microinverter				
Progettazione del modulo + Progettazione intelligente del sistema				
Ottimizzatori di potenza a livello di modulo, microinverter + Progettazione intelligente del sistema				

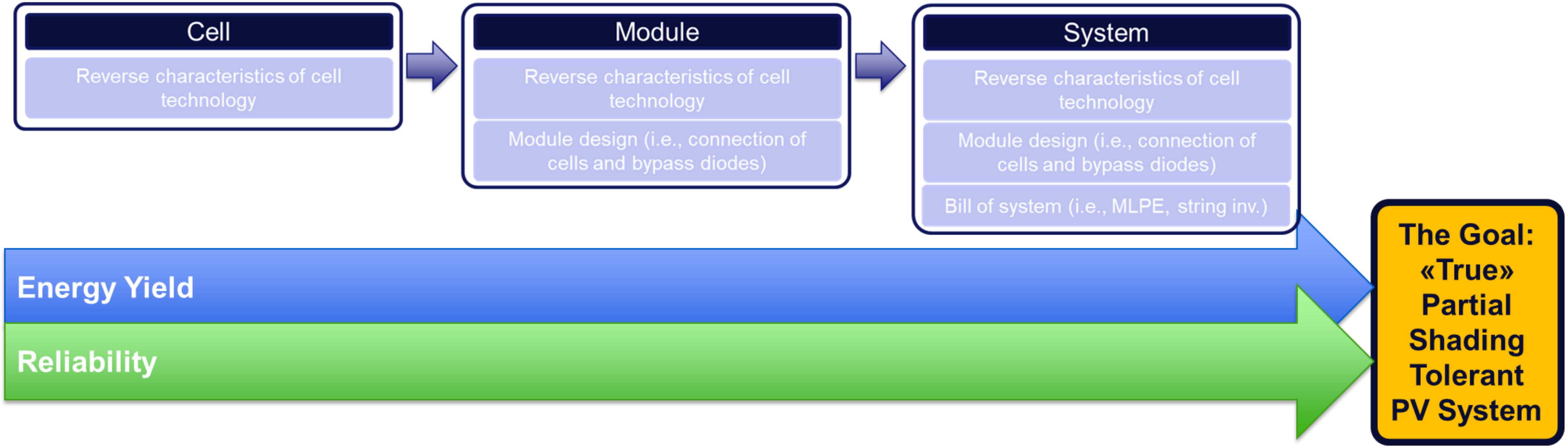
Conosciamo quali strategie (singole o combinate) siano ottimali per ciascun caso di ombreggiamento, considerando la resa energetica e l’affidabilità?

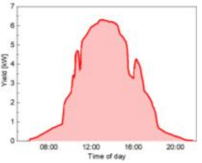
Strategie di mitigazione per migliori prestazioni in condizioni di ombreggiamento parziale	Case-1	Case-2	Case-3	Case-4
				
Progettazione del modulo (selezione delle celle e layout del modulo)				
Ottimizzatori di potenza a livello di modulo, microinverter				
Progettazione intelligente del sistema				
Progettazione del modulo + Ottimizzatori di potenza a livello di modulo, microinverter	?	?	?	?
Progettazione del modulo + Progettazione intelligente del sistema				
Ottimizzatori di potenza a livello di modulo, microinverter + Progettazione intelligente del sistema				

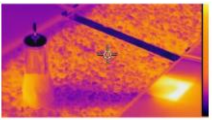
Problema 3: Non sappiamo come scegliere la migliore strategia di mitigazione per ciascun caso di ombreggiamento al fine di ottenere un sistema fotovoltaico realmente tollerante all’ombreggiamento parziale.

Progetti SHADYPV (finanziato da BFE) + SHADYPVTI (finanziato da FER)

- “Prestazioni dei sistemi fotovoltaici in condizioni di ombreggiamento parziale: dalla cella al sistema”
- 2026 – 2029 (appena iniziato)
- Strategie di progettazione (tipo di cella, layout dei moduli e MPPT a livello di modulo/stringa) per ridurre l’effetto dell’ombreggiamento parziale.
- Comprensione limitata di come i diversi elementi interagiscono tra loro in condizioni di ombreggiamento parziale.
- **Obiettivo: sviluppare una comprensione completa di come progettare un sistema fotovoltaico realmente “tollerante all’ombreggiamento”, integrando strategie a livello di modulo e di sistema, per garantire una resa energetica ottimale e un’elevata affidabilità a lungo termine in condizioni di ombreggiamento parziale.**







Progetti SHADYPV (finanziato da BFE) + SHADYPVTI (finanziato da FER)

- Analisi dei dati elettrici di sistemi fotovoltaici reali in Ticino per comprendere le condizioni operative in presenza di ombreggiamento parziale e il suo impatto sulle prestazioni del sistema.
- Valutazione in sito di sistemi selezionati (come QUALITI) per identificare eventuali problemi legati all’ombreggiamento parziale (e non solo).

SE DESIDERATE CHE ANALIZZIAMO I VOSTRI SISTEMI, VI PREGHIAMO DI FARCELO SAPERE.

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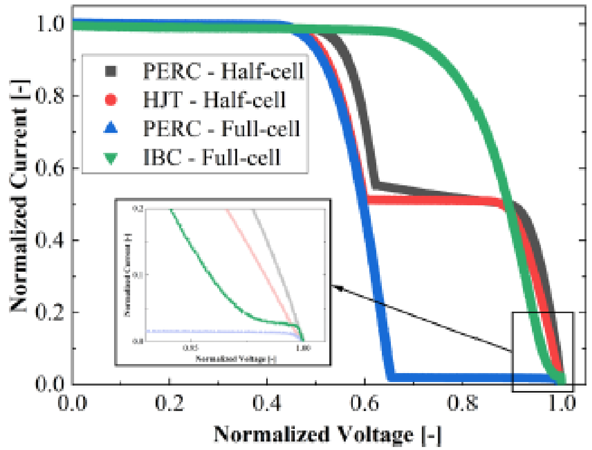
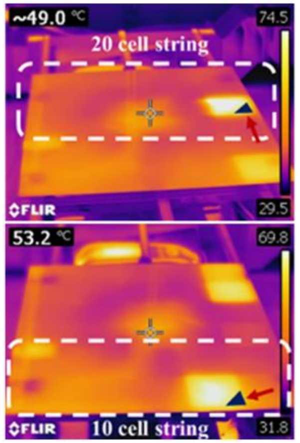
- Misure di caratterizzazione elettrica a livello di cella e di modulo e test di affidabilità (test di resistenza agli hotspot) di moduli fotovoltaici commerciali e personalizzati in diverse condizioni di ombreggiamento.
- Monitoraggio di mini-sistemi fotovoltaici considerando diverse strategie per l'ombreggiamento parziale in condizioni di ombreggiamento selezionate (confronto tra le strategie scelte in termini di resa energetica e rischio di hotspot).

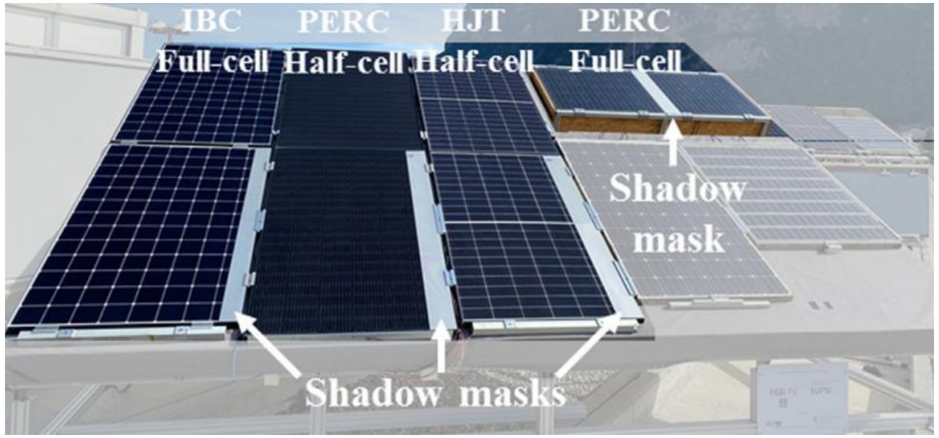
Caratterizzazione elettrica in ambiente indoor in diverse condizioni di ombreggiamento



Test di affidabilità in ambiente indoor in diverse condizioni di ombreggiamento



Monitoraggio di mini-sistemi fotovoltaici in ambiente outdoor in diverse condizioni di ombreggiamento



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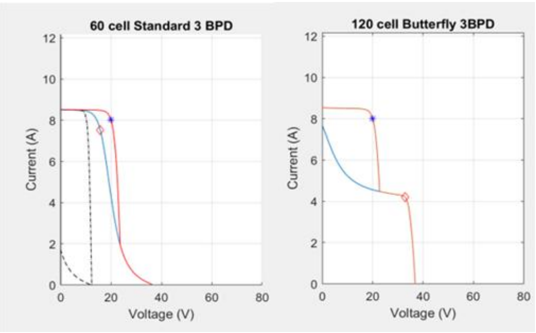
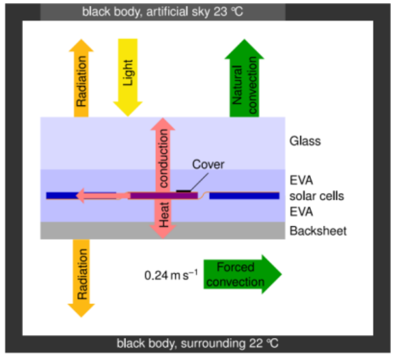
- Sviluppo di modelli elettrici e termici per diverse tecnologie fotovoltaiche in diverse condizioni di ombreggiamento.
- Estensione dello strumento di simulazione della ZHAW per l’ombreggiamento parziale (accesso pubblico)

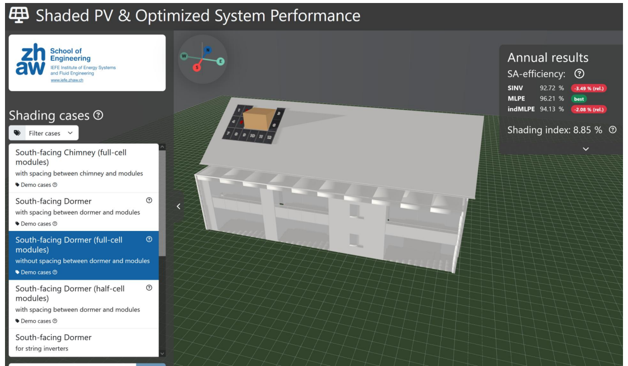
Modello elettrico



Modello termico



Strumento di simulazione per sistemi fotovoltaici in condizioni di ombreggiamento parziale



Progetti SHADYPV (funded by BFE) + SHADYPVTI (funded by FER)

- Analisi dei dati elettrici di sistemi fotovoltaici reali in Ticino per comprendere le condizioni operative in presenza di ombreggiamento parziale e il suo impatto sulle prestazioni del sistema.
- Valutazione in sito di sistemi selezionati (come QUALITI) per identificare eventuali problemi legati all'ombreggiamento parziale (e non solo).
- Misure di caratterizzazione elettrica a livello di cella e di modulo e test di affidabilità (test di resistenza agli hotspot) di moduli fotovoltaici commerciali e personalizzati in diverse condizioni di ombreggiamento.
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University of Applied Sciences and Arts of Southern Switzerland
Department for Environment Constructions and Design
Institute for Applied Sustainability to the Built Environment
SUPSI PVLab laboratory

SUPSI

Grazie!

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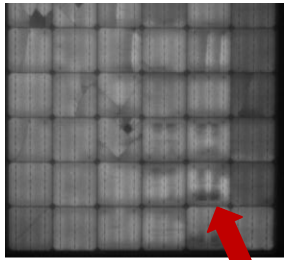
Impact of Partial Shading - Reliability

- <u>**Formation of Hot spots (Reliability)**</u>
  - **Hot spots** reaching temperatures as high as **130–150° C (or even more)** [1,2]

PV System – after 10 years

Electroluminescence



Corrosion of metallization due to degradation by products of encapsulant (larger thermal stress)

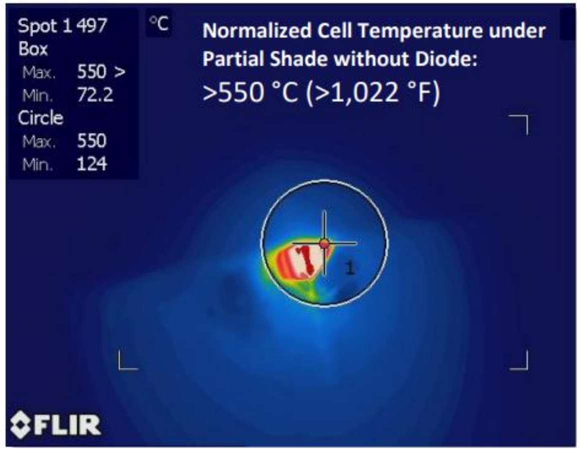
Visual Image

UV-flurescence

Brighter fluorescence effect due to faster degradation of encapsulant by larger thermal stress

Encapsulant discolouration due to larger thermal stress

Testing if bypass diode is failed



Visible hotspot damage (left) alongside an infrared image (right) at the maximum hotspot temperature of >550° C witnessed in the TOPCon panel within 30 minutes of diode removal [3].

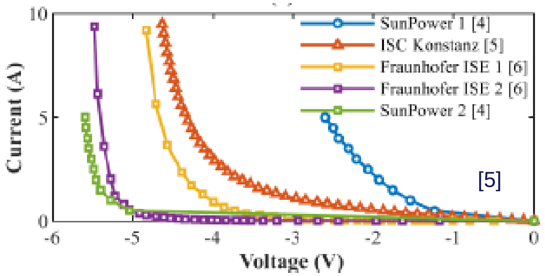
[1] E. Özkalay, F. Valoti, M. Caccivio, A. Virtuani, G. Friesen, and C. Ballif, "The effect of partial shading on the reliability of photovoltaic modules in the built-environment", EPJ Photovoltaics, vol. 15, 2024, DOI: 10.1051/epjpv/2024001.
[2] Maxeon Solar Technologies, "Shading and Hotspot Resilience White Paper", June 2024.

Motivation – Existing Mitigation Strategies and Limitations

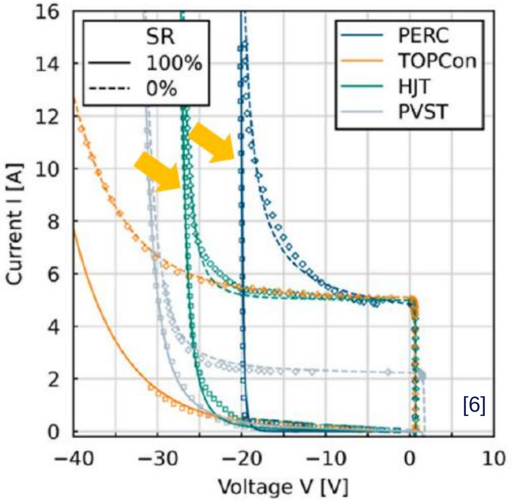
3) Cells with Low Breakdown Voltage:

- **BC** (Back Contact) cell technologies (e.g., Maxeon, Aiko, Longi, Zebra, etc.)
- **Integrated bypass diode** when shaded due to tunnelling (Zener diode) → **Less negative breakdown voltage (Vbr)** [1,2]
- **For a better shadow response, cell selection, module layout and system design are important** [3,metropv]

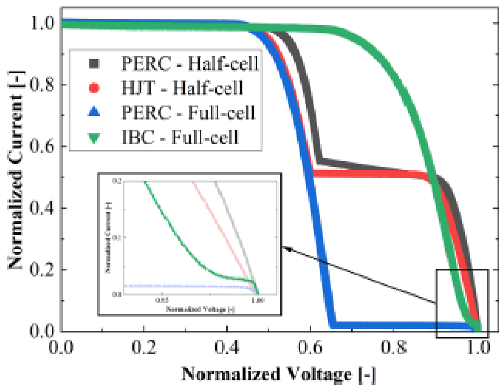
BC cell – reverse characteristics and breakdown voltage

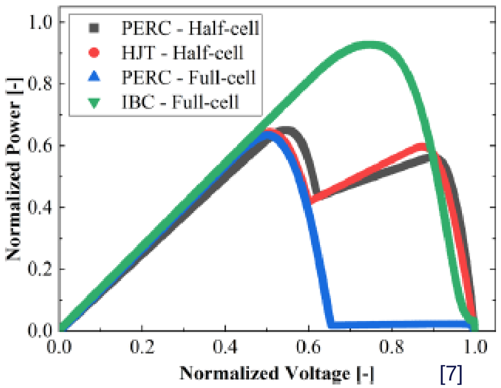


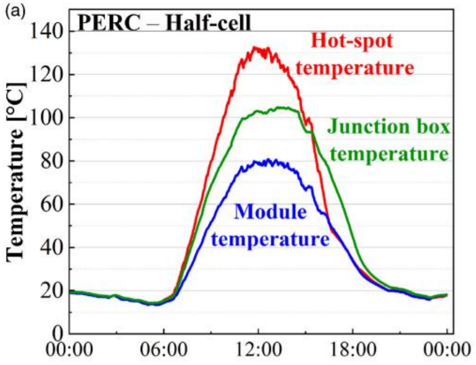
PERC, TOPCon, HJT and Perovskite – reverse characteristics and breakdown voltage

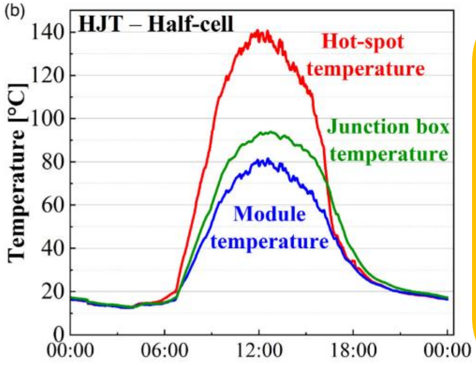


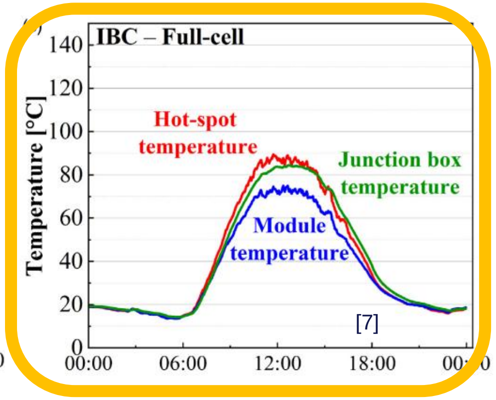
PERC, HJT and IBC – I-V and P-V characteristics (one cell shaded)











[1] H. Chu, L. J. Koduvelikulathu, V. D.Mihailetchi, G. Galbiati, A. Halm, and R. Kopecek, "Soft Breakdown Behavior of Interdigitated-back-contact Silicon Solar Cells", Energy Procedia, vol. 77, Aug. 2015, DOI: 10.1016/j.egypro.2015.07. 006.
[2] R.Müller, C. Reichel, J. Schrof, et al., "Analysis of n-type IBC solar cells with diffused boron emitter locally blocked by implanted phosphorus", Solar Energy Materials and Solar Cells, vol. 142, Nov. 2015, DOI: 10.1016/j.solmat.2015. 05.046.
[3] Internal SUPSI testing.
[5] A. Calcabrini, V. Kambhampati, P. Manganiello, M. Zeman and O. Isabella, "The Relevance of the Cell's Breakdown Voltage in the DC Yield of Partially Shaded PV Modules," 2021 IEEE PVSC, 2021, doi: 10.1109/PVSC43889.2021.9518842.
[6] C. Reichel, J. Forster, B. Artha, K. Ingwersen, A. Tummalieh, J. Weber, E. Fokuhl, L. C. Rendler, D. H. Neuhaus, "Design aspects in consideration of hotspot phenomena in high-performance photovoltaic modules featuring different silicon solar cell architectures", Sol. En. Mat. and Sol. Cells, 2024, https://doi.org/10.1016/j.solmat.2024.113058.
[7] E. Özkalay, F. Valoti, M. Caccivio, A. Virtuani, G. Friesen, and C. Ballif, "The effect of partial shading on the reliability of photovoltaic modules in the built-environment", EPJ Photovoltaics, vol. 15, 2024, DOI: 10.1051/epjpv/2024001

Motivation – Existing Mitigation Strategies and Limitations

1) Basic Mitigation-Cell Sorting:

- **Sorting PV cells by their current output**, and **screening cells for low shunt resistance**[1]
- **Only prevents hot spot formation due to cell mismatch and faulty cell, but do not eliminate the impact of shading**

[1] J. Appelbaum, A. Chait, and D. Thompson, “Parameter estimation and screening of solar cells”, Progress in Photovoltaics: Research and Applications, vol. 1, no. 2, Feb. 1993, DOI: 10.1002/pip.4670010202.

Is there enough study on how different strategies work together?

Strategies for Better Performance Under Partial Shading	Instantaneous Power Loss (Fast temporary loss)		Hot Spot Formation (Slow permanent loss, unless safety issue)	
	Module-level	System-level	Module-level	System-level
Module Design + Module level power optimizers, microinverters	NA	*Y (only 1)**	NA	N
Module Design + Smart system design	NA	*Y (only 1)**	NA	N
Module level power optimizers, microinverters + Smart system design				

**: the work done by ZHAW. The work still misses some points → F. Baumgartner and C. Allenspach, "Performance Gain of Shading Tolerant PV Modules in Different Electrical PV System Setups," in Proceedings of the 40th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC 2023), 2023, pp. 020254-001–020254-004, doi: 10.4229/EUPVSEC2023/3DO.16.1.*

Problems?

- **Problem 1:** Not enough study on the **effect of individual strategies on system-level reliability (hot spot formation)**
- **Problem 2:** Not enough study on the **effect of combination of more than one strategy on the syste,-level** (both energy yield and reliability)
- **Problem 3:** Not enough study on **which strategy or combination of strategies are optimal for each shading condition, considering energy yield and reliability**?

Strategies for Better Performance Under Partial Shading	Instantaneous Power Loss (Fast temporary loss)		Hot Spot Temperature (Slow permanent loss, unless safety issue)	
	Module-level	System-level	Module-level	System-level
Cell Selection	Y	Y	Y	*Y (only 1)*
Module layout	Y	Y	Y	N
Module level power optimizers, microinverters	NA	Y	NA	N
Smart system design	NA	Y	NA	N

Problem 1

Strategies for Better Performance Under Partial Shading	Instantaneous Power Loss (Fast temporary loss)		Hot Spot Temperature (Slow permanent loss, unless safety issue)	
	Module-level	System-level	Module-level	System-level
Cell Selection + Module layout	NA	*Y (only 1)**	NA	N
Cell Selection + Module layout + Module level power optimizers, microinverters	NA	*Y (only 1)**	NA	N
Cell Selection + Module layout + Smart system design	NA	*Y (only 1)**	NA	N

Problem 2

Strategies for Better Performance Under Partial Shading	Case-1	Case-2	Case-3	Case-4
				
Cell Selection				
Module layout				
Module level power optimizers, microinverters				
Smart system design				
Cell Selection + Module layout	?	?	?	?
Cell Selection + Module layout + Module level power optimizers, microinverters				
Cell Selection + Module layout + Smart system design				

Problem 3

Shading-Tolerant PV System Information Sheet
For System Planners and Installers

Generated Know-How for:
- PV System planners and installers
- Module manufacturers
- Software developers
- Standardization bodies
- Inverter and optimizer manufacturers

Outdoor System-level Monitoring (in WP2)
- Different shading scenarios will be tested
- Various mini system designs will be evaluated
- Collected data will be used to validate the PV system simulation tool in WP4

PV System Simulation & Validation (in WP4)
- Integration of a thermal model into ZHAW's existing simulation tool
- Validation of the PV system simulation tool using outdoor system-level monitoring data in WP2
- Simulation of different shading scenarios and system designs that cannot be physically realized within this project – The simulations will complement outdoor monitoring data and support the preparation of system design guidelines
- Cost and LCOE sensitivity analysis for different configurations and scenarios

STEP 3

Model Development & Validation (in WP3)
- Electrical model under partial shading conditions
- Thermal model (i.e. hot spot temperature) under partial shading
- Validation of the models using indoor measurements for different PV technologies and module designs using data in WP2

Indoor Module Testing (in WP2)
- I-V curve testing under various shading conditions I-V curve testing includes the reverse bias region, which is essential for thermal modelling
- Hot spot endurance testing – collecting hot spot temperature data is critical
- Data will be used to validate the electrical and thermal models developed in WP3

STEP 2

Preperation of Representative Custom Modules (in WP1)
- Cell technologies included: TOPCon, Back Contact (BC), Heterojunction (HJT), and PERC
- Different substring sizes will be tested for each cell technology

Module Procurement (in WP1)
- Procurement of reference and commercially available shading-tolerant PV modules

STEP 1

Shading-Tolerant PV System Information Sheet
For System Planners and Installers

Generated Know-How for:
- PV System planners and installers
- Module manufacturers
- Software developers
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STEP 3

Outdoor System-level Monitoring
- Extending the number of shading scenarios
- Extending the number of PV system design configurations

+

Outdoor System-level Monitoring (in WP2)
- Different shading scenarios will be tested
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- Data will be used to validate the electrical and thermal models developed in WP3

STEP 1

Field Data Analysis
- Electrical data analysis of real PV systems in Ticino to understand operating conditions under partial shading and its impact on system performance
    - Assessment of energy losses caused by partial shading
    - Analysis of the frequency and duration of partial shading events
    - Analysis of the frequency and duration of hot-spot formation
    - Evaluation of system degradation rates
- On-site evaluation of selected systems (like QUALITI) to identify any issues related to partial shading

+

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- Cell technologies included: TOPCon, Back Contact (BC), Heterojunction (HJT), and PERC
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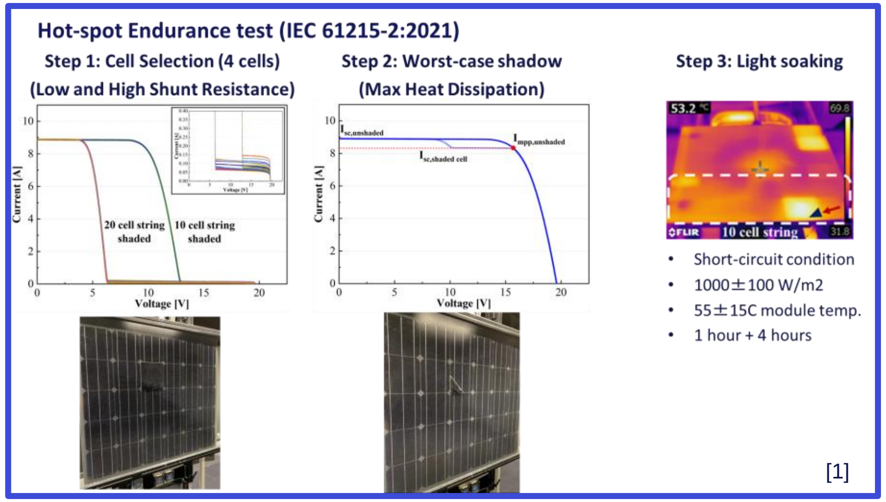
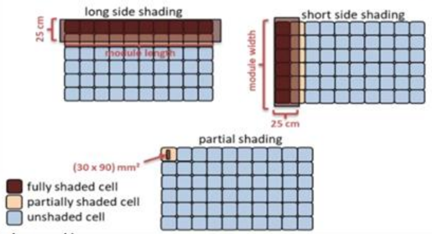
- Procurement of reference and commercially available shading-tolerant PV modules

Motivation – Shadow Related Testing and Limitations

- **Hot spot endurance test (IEC 61215-2:2021):**
  - Focuses on PV modules installed in open-field, rather than those subject to **frequent shading (duration is too short)**, **high temperatures (temperature is too low)[1]**, and **high irradiance (front side irradiance is too low)[2]**.
  - **The test does not fully address the specific stresses associated with modules exposed to persistent shading**
- **Shadow-tolerant module classification:**
  - Shade resistance is poorly defined – no reliable and universal way to compare different products
  - A few initiatives, such as METROPV, have attempted to address this gap, but they are still in development[3]
  - **Focus on evaluating the effect of shading on the I-V curve, without accounting for the potential impact on module reliability**



Shadow-tolerant module classification (metropv)



Class	long side shading / %	short side shading / %	spot shading / %
A	$AL < 5$	$AL < 5$	$AL < 2$
B	$5 \leq AL < 25$	$5 \leq AL < 25$	$2 \leq AL < 5$
C	$25 \leq AL < 50$	$25 \leq AL < 50$	$5 \leq AL < 10$
D	$AL \geq 50$	$AL \geq 50$	$AL \geq 10$

[3]

[1] E. Özkalay, F. Valoti, M. Caccivio, A. Virtuani, G. Friesen, and C. Ballif, "The effect of partial shading on the reliability of photovoltaic modules in the built-environment", EPJ Photovoltaics, vol. 15, 2024, DOI: 10.1051/epjpv/2024001.
[2] SUPSI, Interview with a Swiss Alpine PV installer, 2025.
[3] S. Riechelmann, H. Sträter, L. Stenzig, G. Bardizza, W. Herrmann, E. Ozkalay, G. Friesen, O. Bazkir, A. Schmid and S. Winter, "Laboratory Intercomparison on a Shading Resistance Classification of PV Modules", EUPVSEC, 2024.

Motivation – Lack of Clear Guideline

- **What is a shadow-tolerant PV module? Does it mean the same as a shadow-tolerant system?**
- **How can a shadow-tolerant module be identified? What tests can determine if a module is shadow-tolerant?**
- **Is a shadow-tolerant module sufficient on its own, or is MLPE necessary? Can MLPE alone provide enough shading tolerance?**
- **Should shadow-tolerant solutions be used for all types of applications?**
- **Should a system be optimized for energy yield or reliability under persistent shading, or both? If both, how can this be achieved?**

Project Goals / Research Questions

Project Goals / Research Questions

Component-level design and testing:

- What design strategies can installation companies implement to ensure optimal performance of PV systems under variable shading conditions for various applications (e.g. residential, commercial, industrial and alpine)?

System-level design and testing:

- How can the integration of shadow-tolerant modules and module/string-level MPPT optimize energy yield and system reliability under partial shading conditions across different PV applications?

Electrical and Thermal Modelling under Partial Shading:

- How can electrical and thermal models be integrated to simulate the performance of PV systems under partial shading conditions also considering reliability due to partial shading? And how can the developed tool help installers optimize the performance and reliability of PV systems by considering different shading scenarios?

Project Goals / Research Questions – How to Answer?

Component-level design and testing:

- What design strategies can installation companies implement to ensure optimal performance of PV systems under variable shading conditions for various applications (e.g. residential, commercial, industrial and alpine)?
  - Hot-spot endurance testing (module) (WP2)
  - Shading tolerance classification testing (module) (WP2)
  - MLPE testing: Dynamic performance of optimizers, mismatch under partial shading conditions (WP2)
  - Outdoor monitoring of different module-inverter combinations (system) (WP2)

System-level design and testing:

- How can the integration of shadow-tolerant modules and module/string-level MPPT optimize energy yield and system reliability under partial shading conditions across different PV applications?
  - Outdoor monitoring of different module-inverter combinations (system) (WP2)
  - Simulation (both energy yield and reliability aspects due to partial shading) tool (system) (WP4)

Electrical and Thermal Modelling under Partial Shading:

- How can electrical and thermal models be integrated to simulate the performance of PV systems under partial shading conditions also considering reliability due to partial shading? And how can the developed tool help installers optimize the performance and reliability of PV systems by considering different shading scenarios?
  - Electrical and thermal modelling (module) (WP3)
  - Simulation (both energy yield and reliability aspects due to partial shading) tool (system) (WP4)

Main Outcomes

- **Recommendation to installers on how to design shadow-resilient PV systems for various PV applications**
  - Development of PV system designs – considering shadow-tolerant modules and module/string-level MPPT – that optimize both energy yield and reliability under partial shading conditions for various PV applications.

- **Development/Improvement of a tool to simulate various shading conditions for different PV applications considering KPIs related to both performance and reliability (due to shadow)**
  - Enhanced performance simulations through the integration of electrical and thermal models, providing more accurate and comprehensive predictions for PV system performance and reliability under shading.

- **Feedbacks to module manufacturers on true shadow-tolerant PV module**

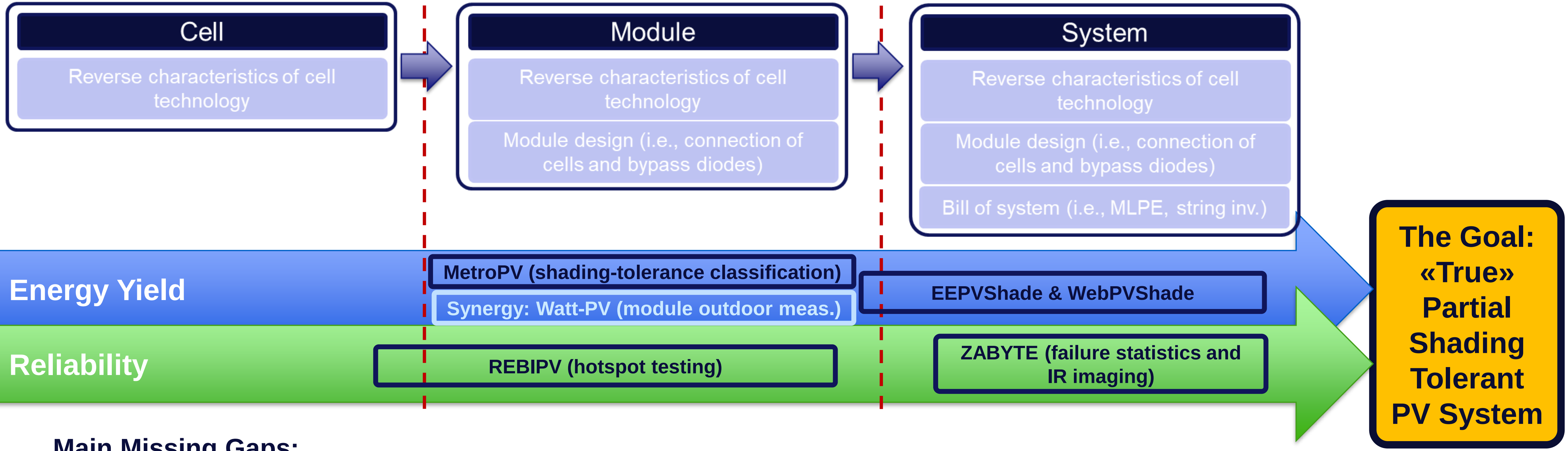
Minor Outcomes

- **Improved understanding of module performance and reliability under shading**
  - Enhanced knowledge of how shading impacts the reliability and performance of modules.
- **Improved understanding of the behavior of optimizers and module/string-level inverters in combination with standard and shading-tolerant modules under partial shading conditions**
- **Improved testing of hot-spot endurance (feedback to IEC)**
  - Representative testing of hot-spot endurance, considering real-world shading scenarios across various PV applications.
- **Enhanced shadow-tolerant module classification method (feedback to IEC)**
  - A more accurate shadow-tolerant classification method that considers both performance and reliability under shading conditions.

Our Previous Related Studies

Project	Cell / Module / System-Level	Worked on	Missing gap
EEPVShade (ZHAW)	Module & System	optimize energy yield under partially shading conditions by using module level power optimizers	Validation, reliability parameters (i.e. hot spot temperature), more complicated shade-tolerant modules, more variety of electronic components to the system, not so complex shading scenarious
WebPVshade (ZHAW)	System-Software	Software tool to compare the respective output: an openly accessible platform using example cases of varying complexity, optimizer vs string inverter	
REBI (SUPSI)	Module	Hot-spot testing of various module and cell technologies in indoor and outdoor conditions (reliability)	Effect of shadow on I-V curve is missing, realistic shadow conditions (temperature, duration, irradiance etc.)
METROPV (SUPSI)	Module	Shadow-tolerant module classification focussing on single I-V curves in indoor and outdoor conditions	Only module level, Hot-spot (reliability), moving shadow
WATT-PV (BFH+SUPSI)	Module	Development of an I-V curve tracer Software for outdoor module qualification	Partial shading questions not answered
Student Thesis (BFH)	Module	Partial Shading Resistant Photovoltaic Modules, Overview of Concepts and Challenges	Just literature study
ZABYTE (BFH)	Module & System	Zustandsanalyse von Bypassdioden in Teilverschatteten PV-Anlagen	Only failure statistics and IR imaging are in scope

Our Previous Related Studies



Main Missing Gaps:

- Behavior of a PV system with module/string level inverters and different shade-tolerant modules under partial shading
- Understanding of shadow-tolerant module in terms of both energy yield and reliability under partial shading
- Modelling electrical performance and thermal behaviour of shadow-tolerant PV modules under partial shading

Electrical and Thermal Modelling – Previous Works

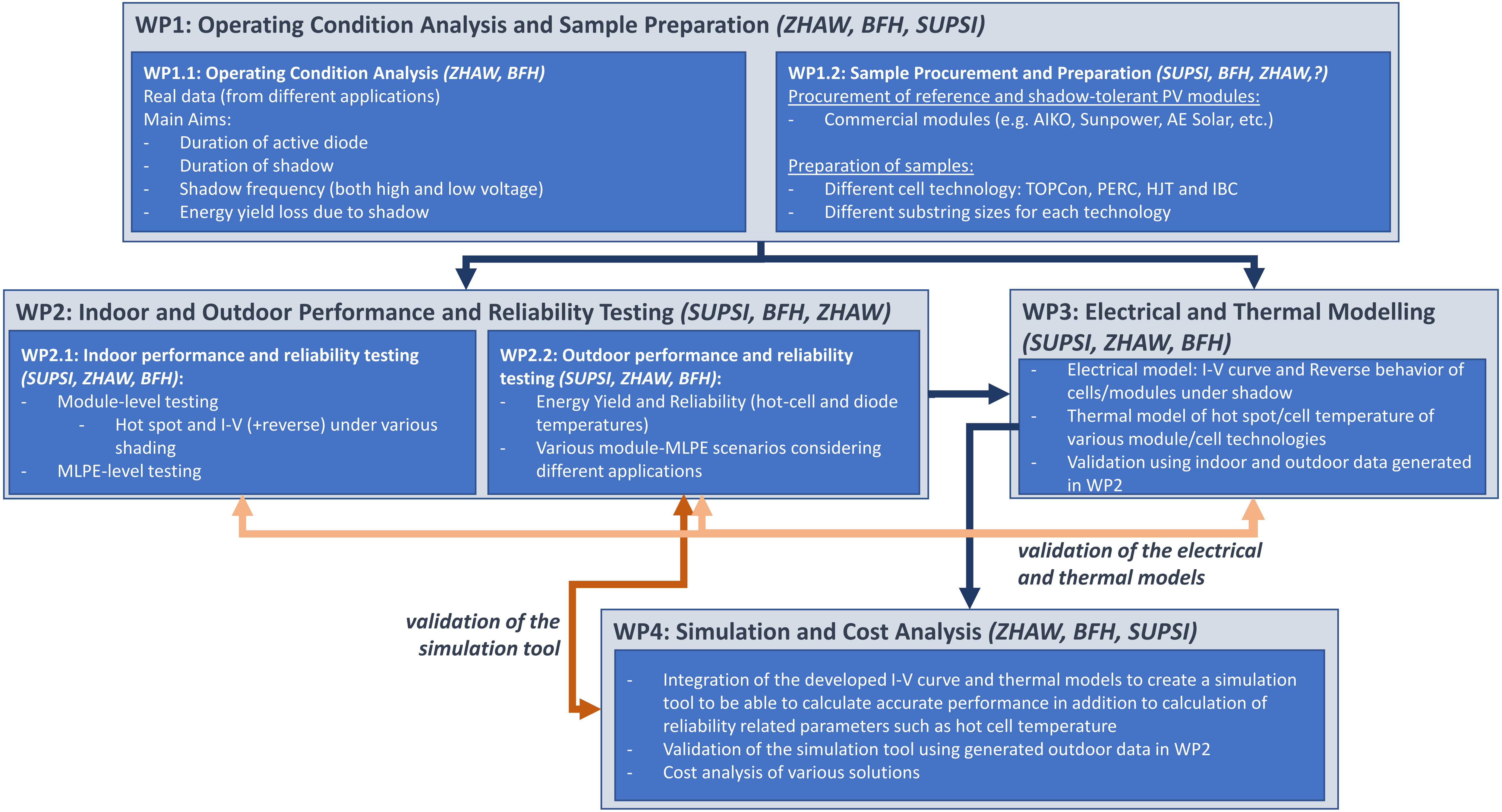
There are existing electrical[1,2,3,4] and thermal models[3,5] to simulate module behavior under partial shading. However, they have various limitations and gaps.

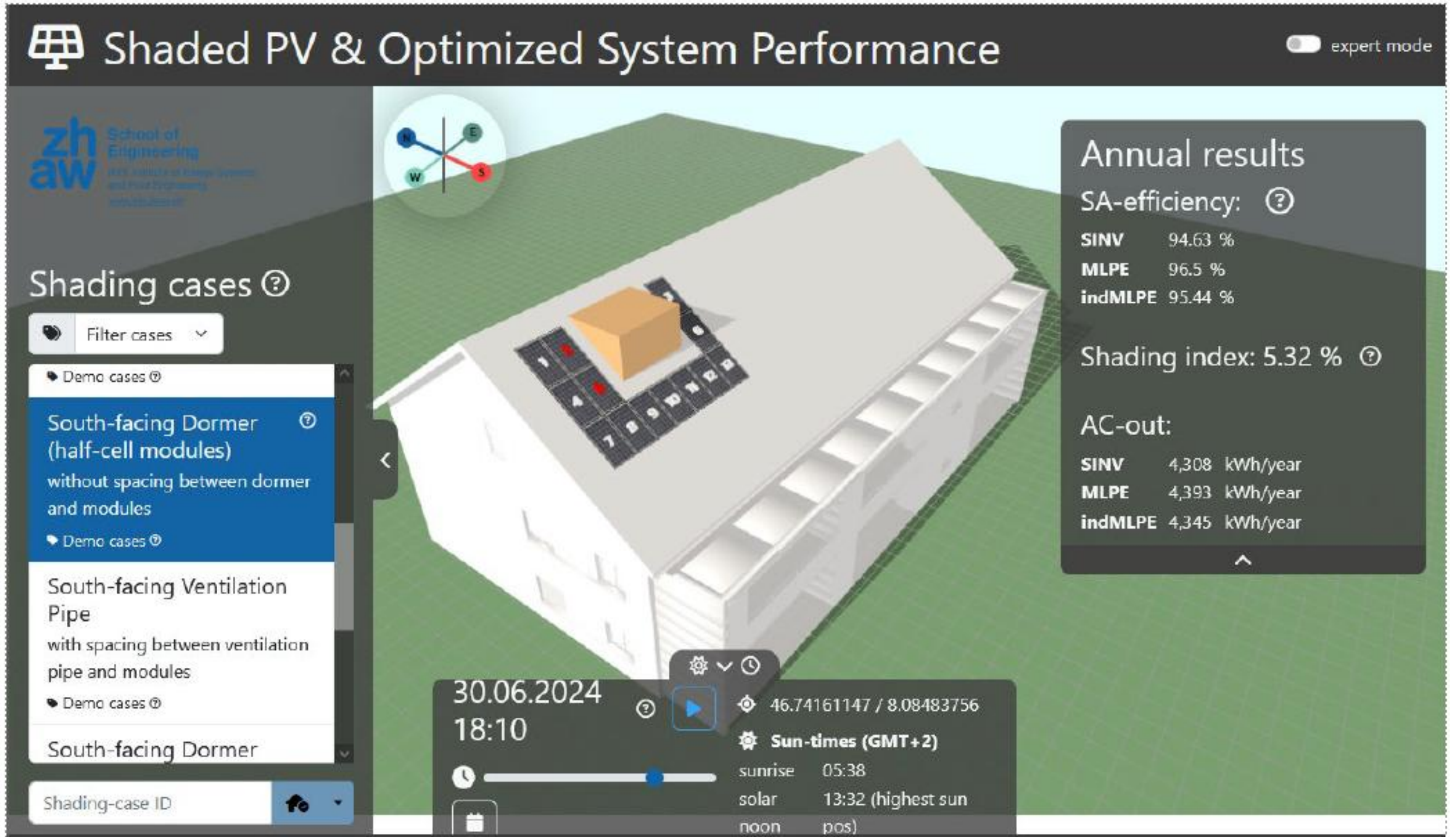
Main gaps:

- These studies are typically limited to a small set of technologies and does not cover a broad range of scenarios.
- They often assume indoor thermally equilibrium conditions and well-defined single-cell (not module shading) shading patterns.
- There is a lack of integration between electrical and thermal models (except one[3])
- They do not consider different PV applications

[1] Haifeng Chu, Andreas Halm, Valentin D. Mihailetchi, Giuseppe Galbiati, Radovan Kopecek, “Shade Performance of a Back-contact Module Assembled with Cells Featuring Soft Breakdown Characteristic”, Energy Procedia, Volume 92, 2016, https://doi.org/10.1016/j.egypro.2016.07.138.
[2] E.E. Bende, N.J.J. Dekker, M.J. Jansen, «Performance and Safety Aspects of PV Modules under Partial Shading: A Simulation Study», EUPVSEC, 2014, doi: 10.13140/2.1.1569.6640.
[3] A. Calcabrini, P. Procel Moya, B. Huang, V. Kambhampati, P. Manganiello, M. Muttillo, M. Zeman, O. Isabella, “Low-breakdown-voltage solar cells for shading-tolerant photovoltaic modules”, Cell Reports Physical Science, Volume 3, Issue 12, 2022, https://doi.org/10.1016/j.xcrp.2022.101155.
[4] A. D. Pettersen, “Simulation and experimental study of power losses due to shading and soiling on photovoltaic (PV)”, Norwegian University of Life Sciences, master thesis, 2015.
[5] R. Witteck, M. Siebert, S. Blankemeyer, H. Schulte-Huxel and M. Köntges, "Three Bypass Diodes Architecture at the Limit," in IEEE Journal of Photovoltaics, vol. 10, no. 6, Nov. 2020, doi: 10.1109/JPHOTOV.2020.3021348.

Project Approach


WP1: Operating Condition Analysis and Sample Preparation (ZHAW, BFH, SUPSI)
WP1.1: Operating Condition Analysis (ZHAW, BFH)
Real data (from different applications)
Main Aims:
- Duration of active diode
- Duration of shadow
- Shadow frequency (both high and low voltage)
- Energy yield loss due to shadow
WP1.2: Sample Procurement and Preparation (SUPSI, BFH, ZHAW,?)
Procurement of reference and shadow-tolerant PV modules:
- Commercial modules (e.g. AIKO, Sunpower, AE Solar, etc.)
Preparation of samples:
- Different cell technology: TOPCon, PERC, HJT and IBC
- Different substring sizes for each technology
WP2: Indoor and Outdoor Performance and Reliability Testing (SUPSI, BFH, ZHAW)
WP2.1: Indoor performance and reliability testing (SUPSI, ZHAW, BFH):
- Module-level testing
- Hot spot and I-V (+reverse) under various shading
- MLPE-level testing
WP2.2: Outdoor performance and reliability testing (SUPSI, ZHAW, BFH):
- Energy Yield and Reliability (hot-cell and diode temperatures)
- Various module-MLPE scenarios considering different applications
WP3: Electrical and Thermal Modelling (SUPSI, ZHAW, BFH)
- Electrical model: I-V curve and Reverse behavior of cells/modules under shadow
- Thermal model of hot spot/cell temperature of various module/cell technologies
- Validation using indoor and outdoor data generated in WP2
validation of the electrical and thermal models
validation of the simulation tool
WP4: Simulation and Cost Analysis (ZHAW, BFH, SUPSI)
- Integration of the developed I-V curve and thermal models to create a simulation tool to be able to calculate accurate performance in addition to calculation of reliability related parameters such as hot cell temperature
- Validation of the simulation tool using generated outdoor data in WP2
- Cost analysis of various solutions



Reliability due to partial shading:

- Hot spot/cell Temperature
- Module Temperate
- 98th percentile (175.2 hours/year) (tbc)

Will be upgraded:

- Extension of commercial shading tolerant modules (i.e. various reverse characteristics)
- Higher complexity of shading scenarios
- New electronic components
- Various PV applications
- Validation

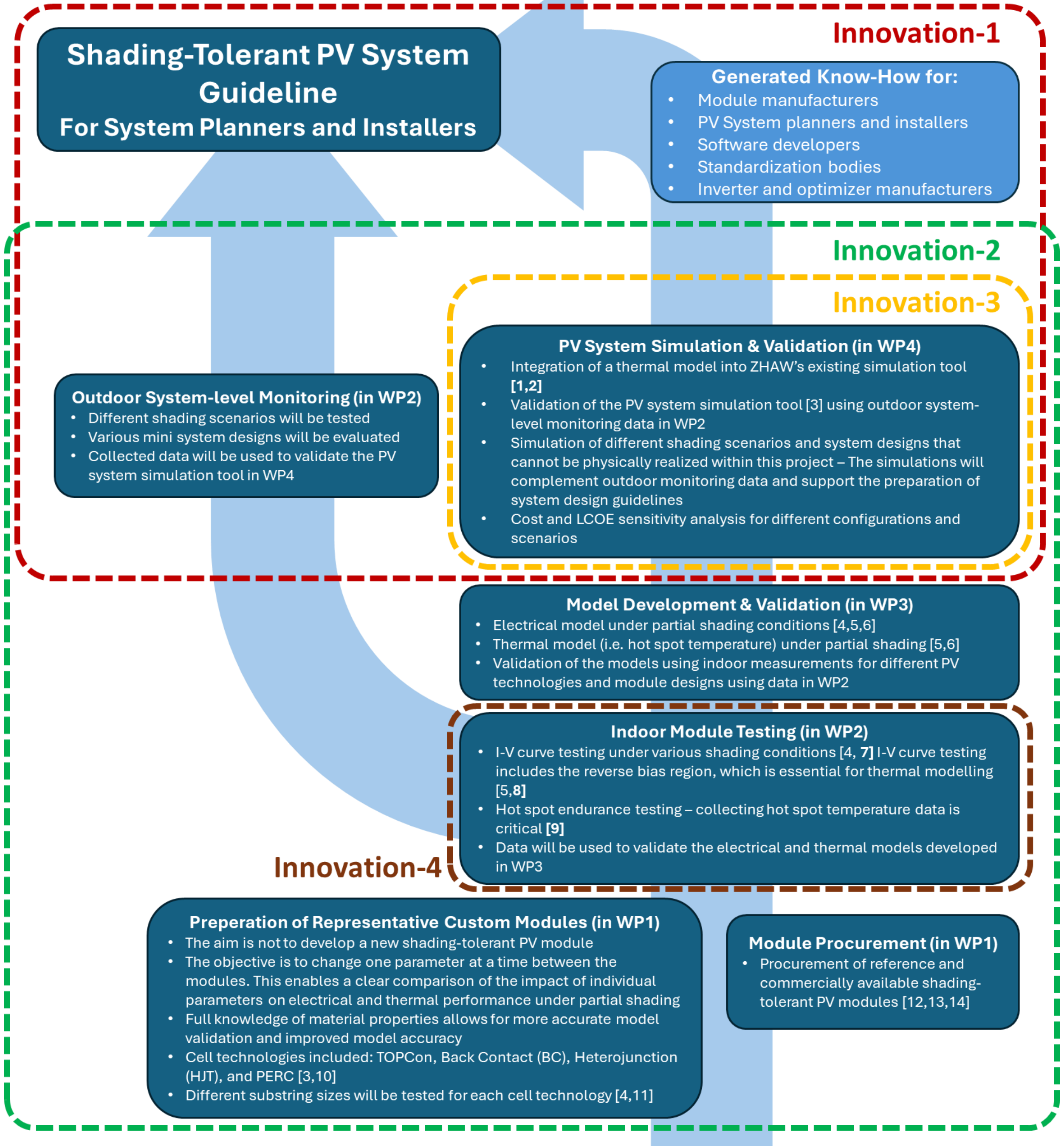
Discussion

- 3 years of project
- Starting in Autumn 2025
- Rough estimated budget range of 600k to 900k CHF

Next Steps?

Thank you for your attention!

WP Details



Main innovations:

Innovation-1 (primary): A practical guideline for installers/planners that integrates energy-yield and reliability aspects for partially shaded PV systems.

Innovation-2 (primary): A multi-level, holistic analysis linking cell behaviour → module design → system-level performance (including MLPE and inverter interactions) under partial shading.

Innovation-3 (primary): An enhanced PV system rating tool (ZHAW PVShade extension) that integrates thermal modelling to predict hot spot temperatures and power losses at the system level under partially shaded conditions. The tool will be used to develop the guideline, as it is not feasible to test all possible mitigation strategies and relevant shading scenarios under real-world conditions. Additionally, it will serve as an educational tool for PV system designers and installers.

Innovation-4 (minor): A robust shading-tolerance classification method that integrates instantaneous power loss and hot spot stress, plus recommendations to adapt hot spot endurance testing to relevant operating conditions.

WP-1: Operating Condition Analysis and Sample Preparation (ZHAW, BFH, SUPSI)

Operating Condition Analysis

In order to get some idea about the real-life situation, below topics can be investigated through data analysis of monitored residential PV data:

- Duration of active diode
- Duration of shadow
- Shadow frequency (both high and low voltage)
- Energy yield loss due to shadow
- Effect of shadow on long-term performance

WP-1: Operating Condition Analysis and Sample Preparation (ZHAW, BFH, SUPSI)

Sample Procurement and Preparation

Procurement of commercially available shade-tolerant PV modules will be carried out. Additionally, to gain a deeper understanding of cell and module behavior under shading, samples with different cell technologies and module-substring sizes will be prepared. The selection of MLPEs for the project will also be made.

Procurement of reference and shadow-tolerant PV modules:

- Commercial modules (e.g. AIKO, Sunpower, AE Solar, Half-cut, etc.)
- Main samples of the project

Preparation of samples:

- Different cell technology: TOPCon, PERC, HJT and IBC
- Different substring sizes for each technology
- This will also allow us to compare cell technologies independently, without the influence of different BOMs and module manufacturing processes

MLPEs

WP-2: Indoor and Outdoor Performance and Reliability Testing (SUPSI, BFH, ZHAW)

Module testing:

To provide accurate recommendations to installers, we must test the modules accurately for their specific application type.

- **Hot-spot endurance test**
  - Longer duration to consider more frequent shadow in residential systems (need results from WP1 here)
  - At higher temperatures, to realistically consider the BIPV operating conditions (already have some relevant data from REBIPV)
  - Different PV applications (e.g., Alpine)?
- **I-V indoor testing under various shading scenarios**
  - Under METROPV, a shadow tolerant module classification method was started to be developed. This method can be improved and applied on various module technologies prepared in WP1.
  - Reverse I-V behaviour of the various cell and module technologies prepared in WP1

MLPE testing:

- ZHAW will use the indoor laboratory to the various MLPEs for specific partly shading scenarios in combination with standard and shading tolerant modules. Dynamic performance of optimizers, mismatch under partial shading conditions.

WP-2: Indoor and Outdoor Performance and Reliability Testing (SUPSI, BFH, ZHAW)

The potential of using existing outdoor test facilities at SUPSI and ZHAW, which feature shadow-tolerant modules, will be evaluated. The goal is to monitor the most relevant module and module/string-level MPPT combinations. The primary focus of the monitoring will be on performance and reliability parameters, such as **energy yield**, **hot spot/cell** and **junction box temperatures**, under various application-relevant partial shading conditions.

New outdoor test stands will include:

Various module concepts and module/string-level MPPT combinations.

- Reference module + module/string-level MPPT
- Selected shadow tolerant module/s + module/string-level MPPT

Under various shading conditions for short/mid-term monitoring periods considering different applications

- BAPV roof
- BIPV roof
- Façade
- Row to row shading
- Rear side shading (in case of bifaciality)

The combination that has the lowest energy loss and the lowest maximum hot spot/cell temperature will be the better choice for shading tolerance.

WP-3: I-V curve and Thermal Modelling (SUPSI, ZHAW)

Work in WP2 will help us understand the behavior of various technologies under shading, both in indoor and outdoor conditions. However, we cannot test every possible combination for each module, module/string-level inverter, and application. Therefore, it is crucial to have a reliable tool that allows us to simulate different scenarios and combinations. By developing and validating these models, the goal is to evaluate new technologies that emerge after this project, without the need to install an outdoor test stand for monitoring these new technologies.

Preliminary study to assess the potential for building upon the PVShade tool from ZHAW will be conducted.

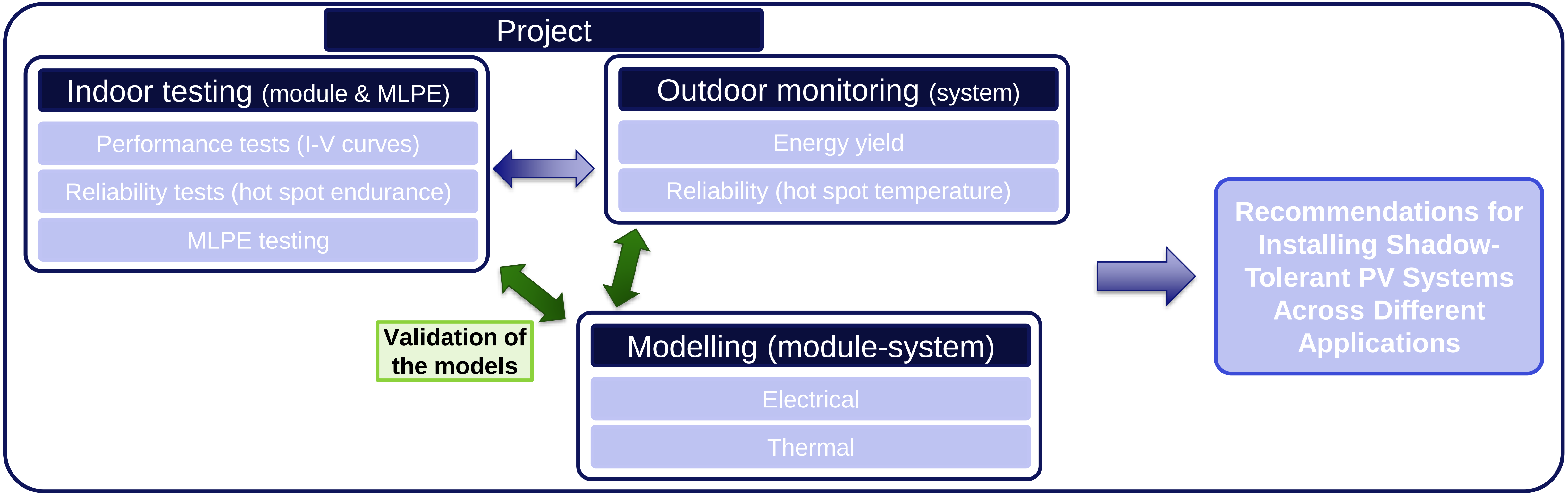
- **Modelling of I-V curve and reverse behaviour** of various module technologies under partial shading
- **Modelling of thermal aspects** (including hot spot/cell temperature) of various module technologies under partial shading

Both modeling will be validated using data from indoor and outdoor testing in WP2.

The developed models will then be integrated in WP4.

Support of BFH on diode characteristics for electrical modelling

WP-2 & WP-3: Indoor and Outdoor Testing and Modelling



- Not possible to perform outdoor monitoring of all possible module-inverter combinations for all different shading scenarios and PV applications. We need modelling.

- After the project ends, the modelling tool could be updated for new module and components after performing their necessary indoor tests (to create input for the model)

WP-4: Simulation and Cost Analysis (ZHAW, BFH, SUPSI)

Possibility to use ZHAW's PVShade tool will be assessed in WP3.

The developed models in WP3 will be integrated. Calculated parameters will be:

- Electrical performance (build-on ZHAW's tool?)
- Hot spot/cell temperature due to partial shading in addition of module temperature (T98 and/or probability distribution)

Simulations of various module concepts and module/string-level MPPT combinations (will go beyond outdoor monitoring in WP2)

- Reference module + module/string-level MPPT
- Selected shadow tolerant module/s + module/string-level MPPT

Under various shading conditions considering different applications (will beyond outdoor monitoring in WP2) (e.g., BAPV, BIPV roof, façade, row to row shading, rear side shading, etc.)

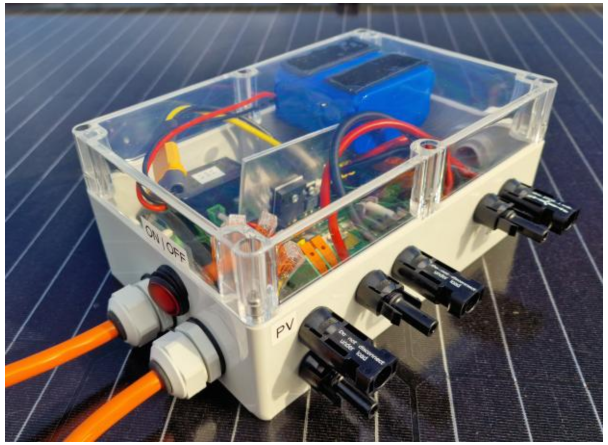
Cost Analysis of various solutions (cost of MLPEs and modules)

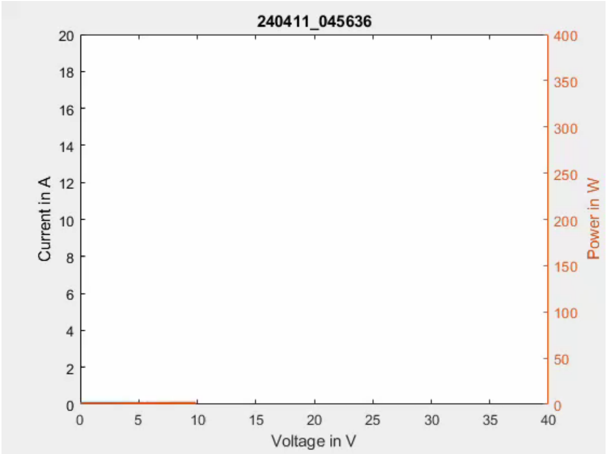
Sensitivity analysis of LCOE

Synergies with Current Projects

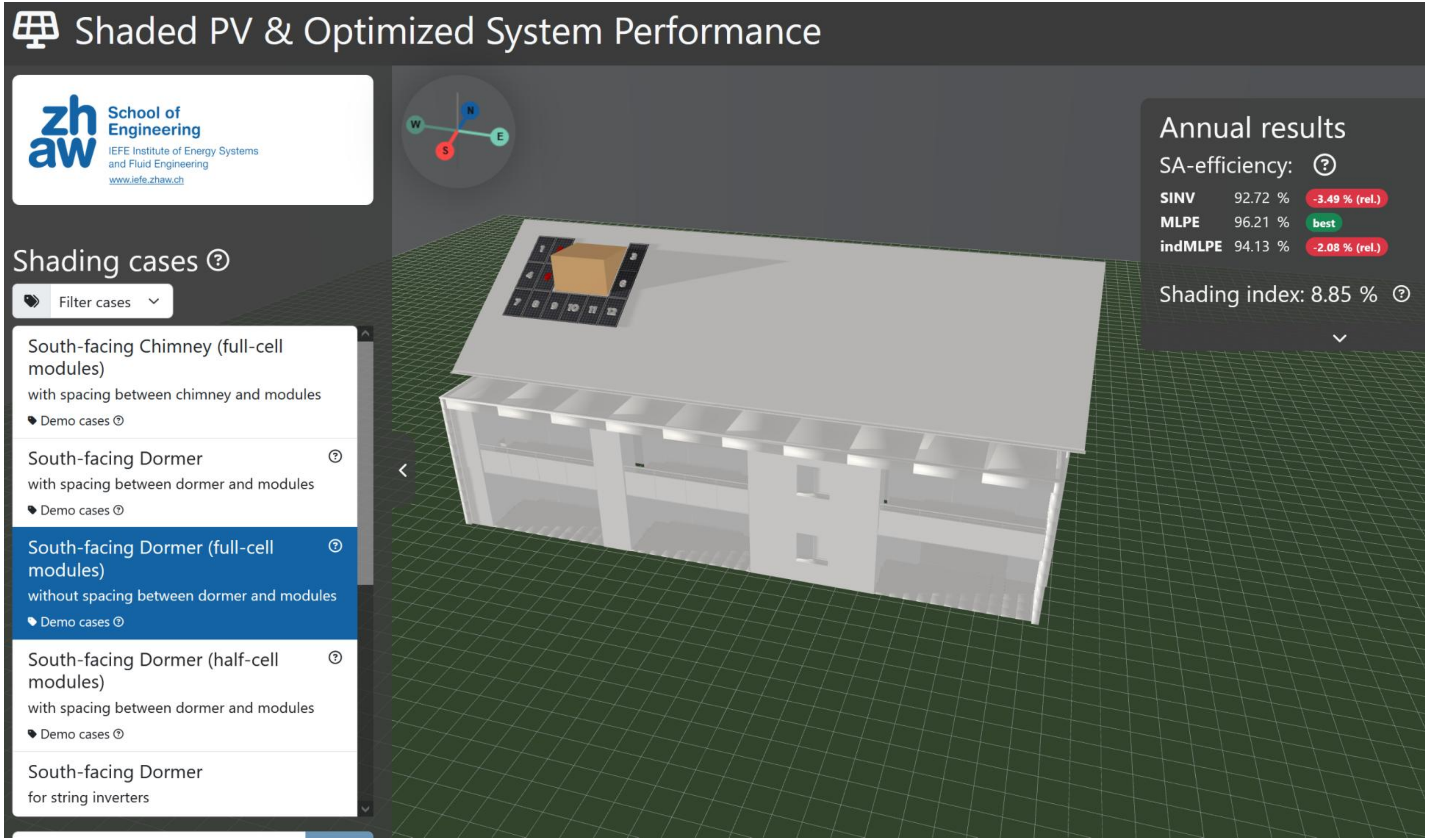
Energy Loss Measurements and Visualisation of Partially Shaded Modules (BFH, SUPSI)

- Outdoor module-level I-V curve tracing of partially shaded modules in a system in WP2
- Quantify partial shading losses due to lower fill factor
- Quantify MPPT efficiency losses due to missed MPP by inverter / mismatch
- Measure peak temperatures which occure in this situation
- Compare between different modules, compare maximum temperatures





WebPVshade


Shaded PV & Optimized System Performance
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Shading cases
Filter cases
South-facing Chimney (full-cell modules)
with spacing between chimney and modules
Demo cases
South-facing Dormer
with spacing between dormer and modules
Demo cases
South-facing Dormer (full-cell modules)
without spacing between dormer and modules
Demo cases
South-facing Dormer (half-cell modules)
with spacing between dormer and modules
Demo cases
South-facing Dormer
for string inverters
Annual results
SA-efficiency:
SINV 92.72 % -3.49 % (rel.)
MLPE 96.21 % best
indMLPE 94.13 % -2.08 % (rel.)
Shading index: 8.85 %

Electrical and Thermal Modelling – Previous Works

Simulation tools of I/V characteristic of standard module types