FOUR-TERMINAL BIFACIAL PEROVSKITE ON SILICON TANDEM DEVICES: CONCEPT, DEVICES, ENERGY YIELD AND OUTDOOR RESULTS

Gianluca Coletti

SOLLIANCE
SOLAR RESEARCH

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ACKNOWLEDGEMENTS

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TKI Urban Energy

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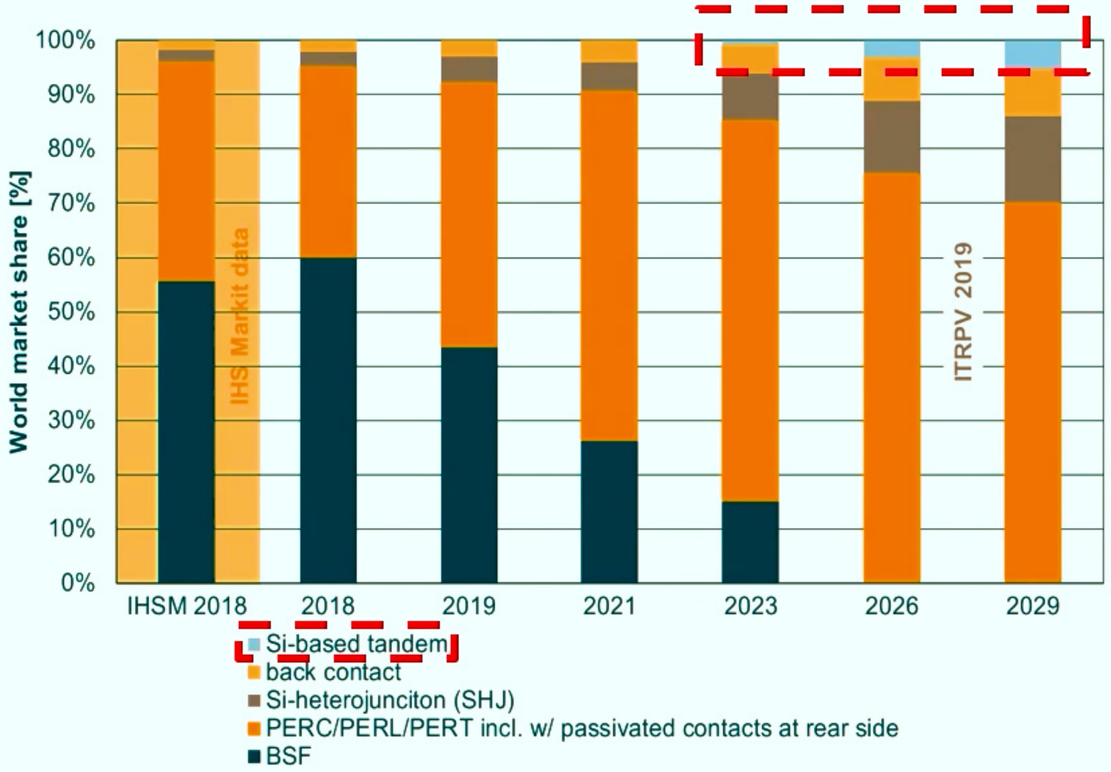
OUTLINE

- Towards cost competitive tandem modules
  - Bifacial 4T tandem
  - Comparison bifacial versus monofacial tandem
  - Tandem energy yield simulations
  - Outdoor measurements
  - Scale up to larger area
  - Conclusions

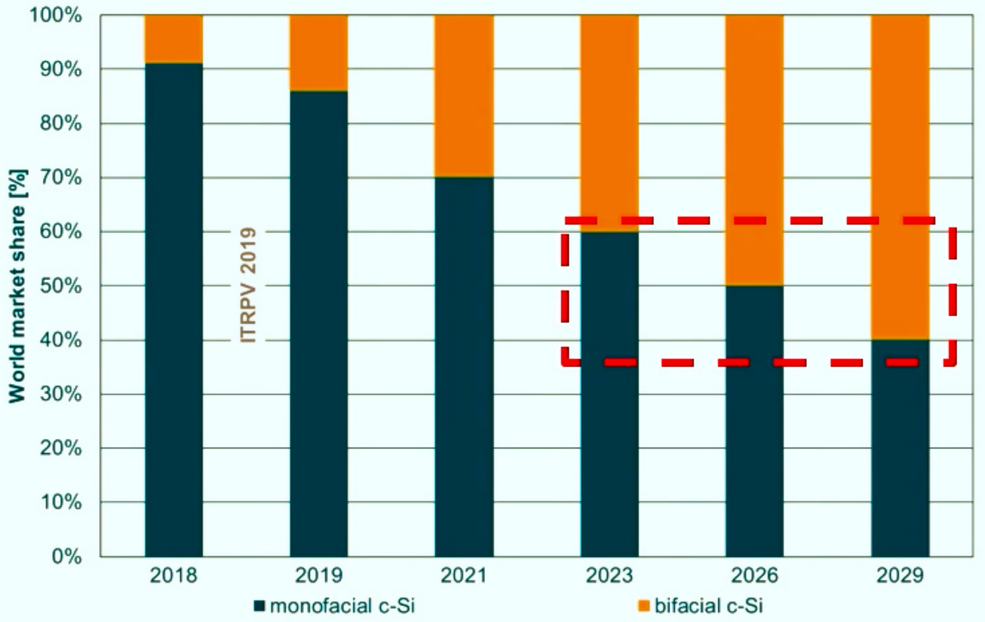
IN WHICH MARKET TANDEM HAS TO COMPETE?

c-Si based tandem



- Mass production after 2021
- Tandem market share starts in 2023

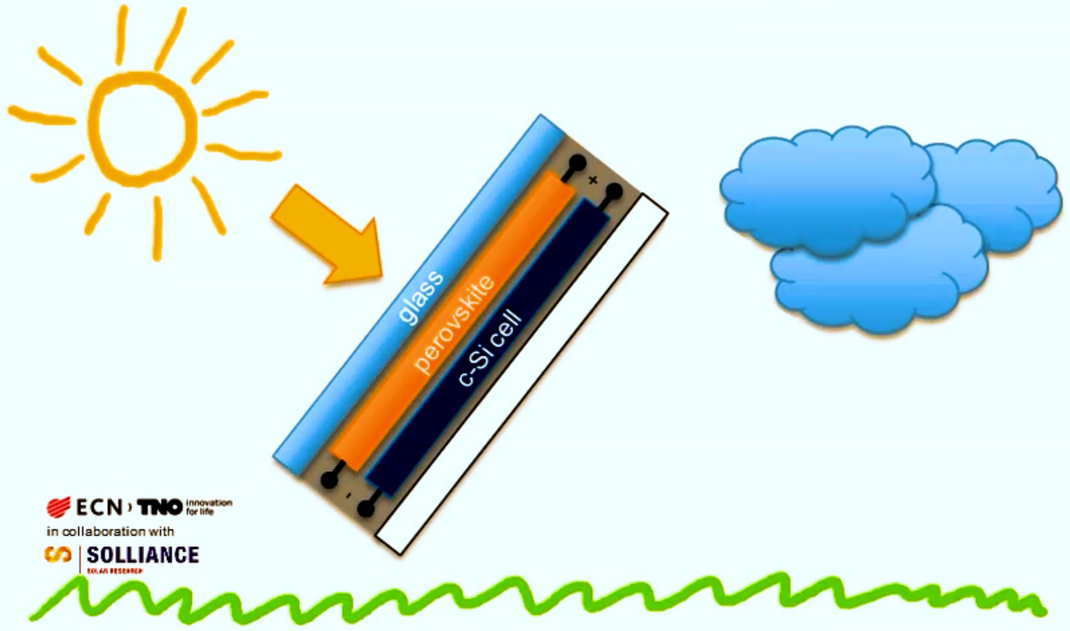
c-Si bifacial cells



- Bifacial cells ~50% of the market
- Market segment:
  ground PV and commercial roof top

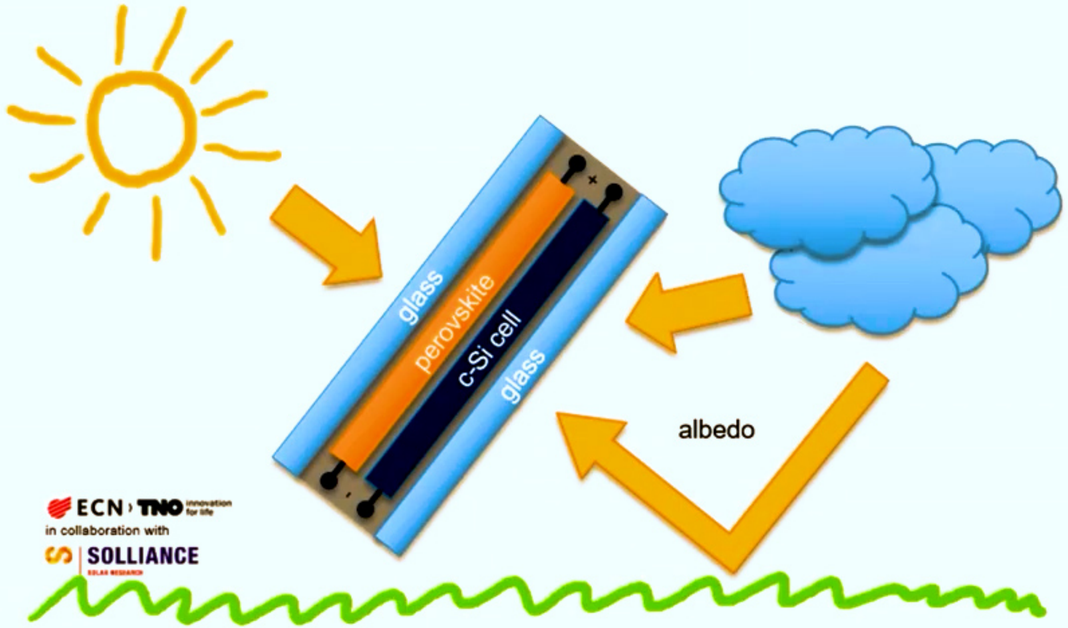
WHY DON'T MAKE USE OF BIFACIAL TANDEM?

Monofacial 4T tandem



If we can do this?

Bifacial 4T tandem



then we can also do this

NEW 4T Tandem record with PERC!

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BIFACIAL PEROVSKITE/c-Si 4T TANDEM CELLS

Cell	Description	Voc (mV)	Jsc (mA/cm2)	FF	Eff (%)	4T tandem efficiency	Bifaciality
ST-PSC 3x3 mm2	Backward scan	1046	21.0	78.6	17.3		
	Forward scan	1041	21.0	78.0	17.0		
	Top cell – 5min MPP tracking	-	-	-	**17.0**		96%
						+4.2%$_{abs}$	
PERC+ 6 inch	Front single junction	682	39.7	81.2	22.0		73%
	Filtered bottom cell	660	16.9	82.4	**9.2**	**26.2%**	61%

TU/e

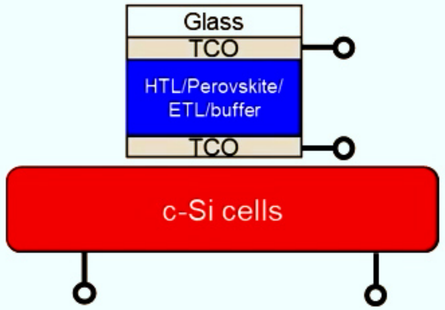
imec

JÜLICH

CIC

LONGi

Aikosolar



4-terminal tandem measurements
J. Werner et al, *ACS Energy Letters* 1, 474 (2016)
Z. Yu, et al., Nat. Energy 1 (2016) 16137
S.L. Luxembourg, et al. 33rd EUPVSEC (2017) 1176-1180

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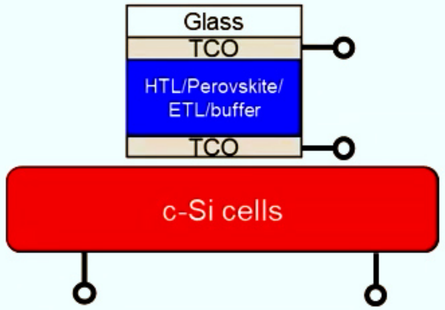
	Top cell – 5min MPP tracking	-	-	-	**17.0**		96%
MWT-SHJ Bifacial 6 inch	Front single junction	730	39.4	79.4	22.8	+3.7%$_{abs}$	84%
	Filtered bottom cell	710	16.8	79.9	**9.5**	**26.5%**	72%



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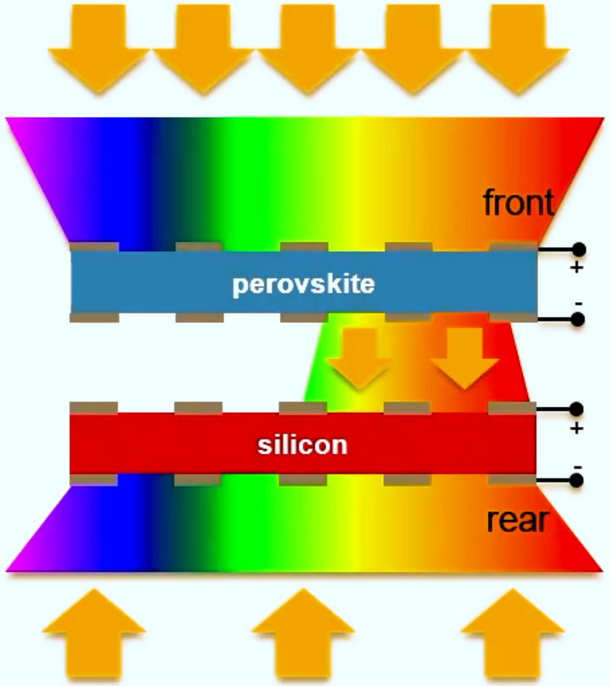
DEVICE STRUCTURE AND CHARACTERISATION

Metric: Power density



100 mW/cm^2

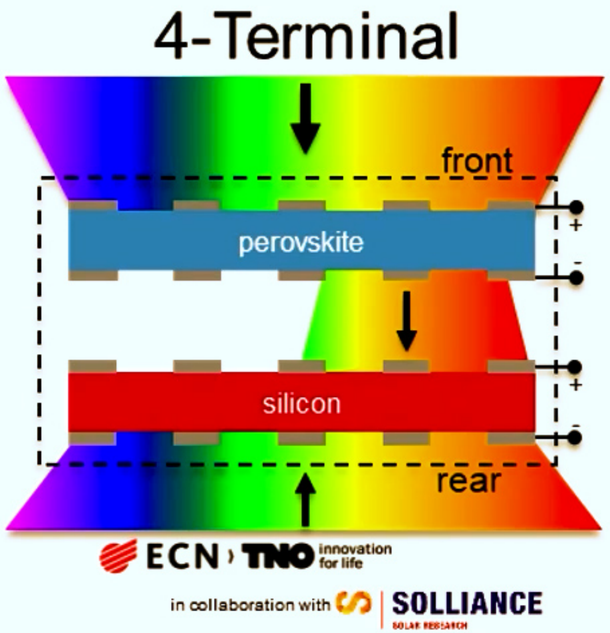
$P_{maxBiFi200*}$ / cm^2

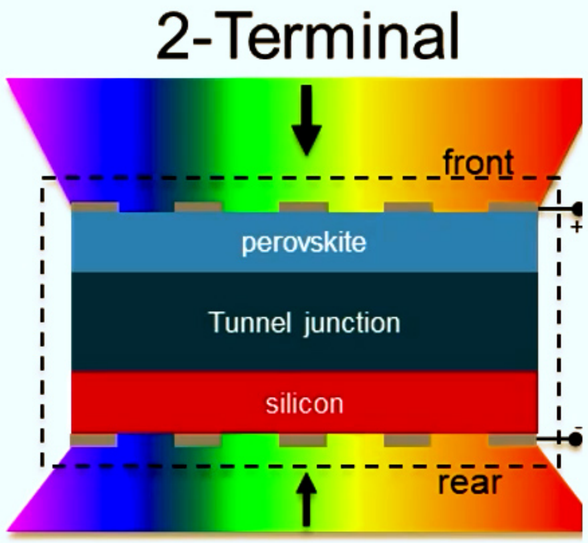
e.g. 20 mW/cm^2

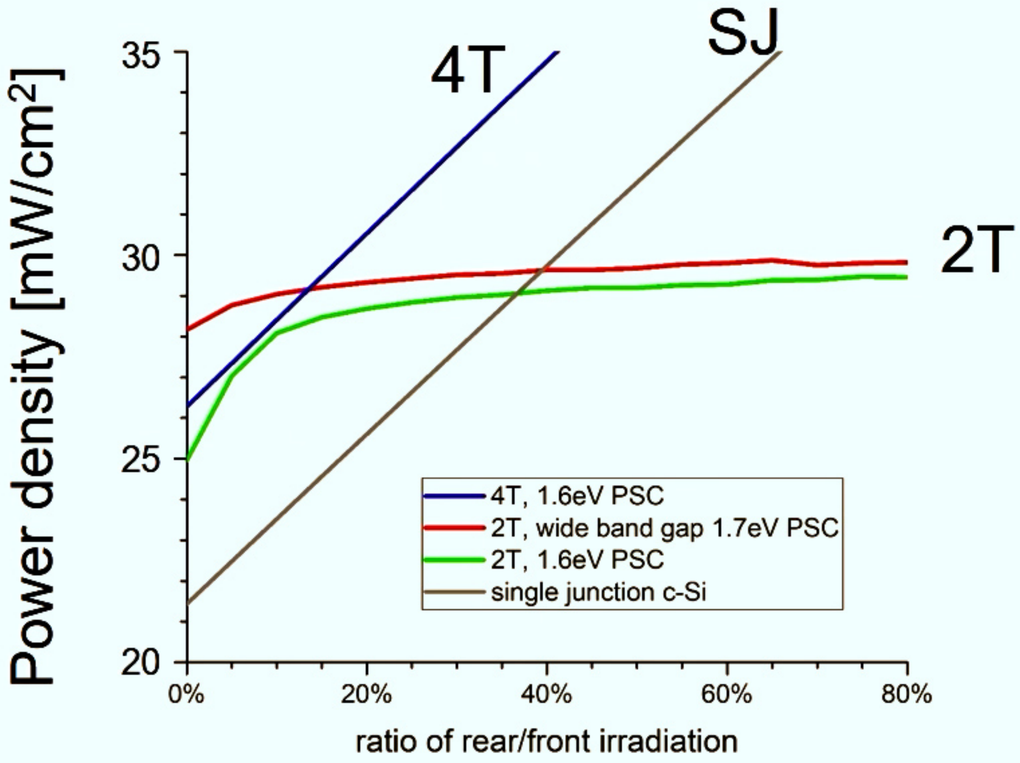
In bifacial tandem the bottom device receive full light spectrum in the rear

* Norm IEC TS60904-1-2:2019 Photovoltaic devices - Part 1-2: Measurement of current-voltage characteristics of bifacial photovoltaic (PV) devices

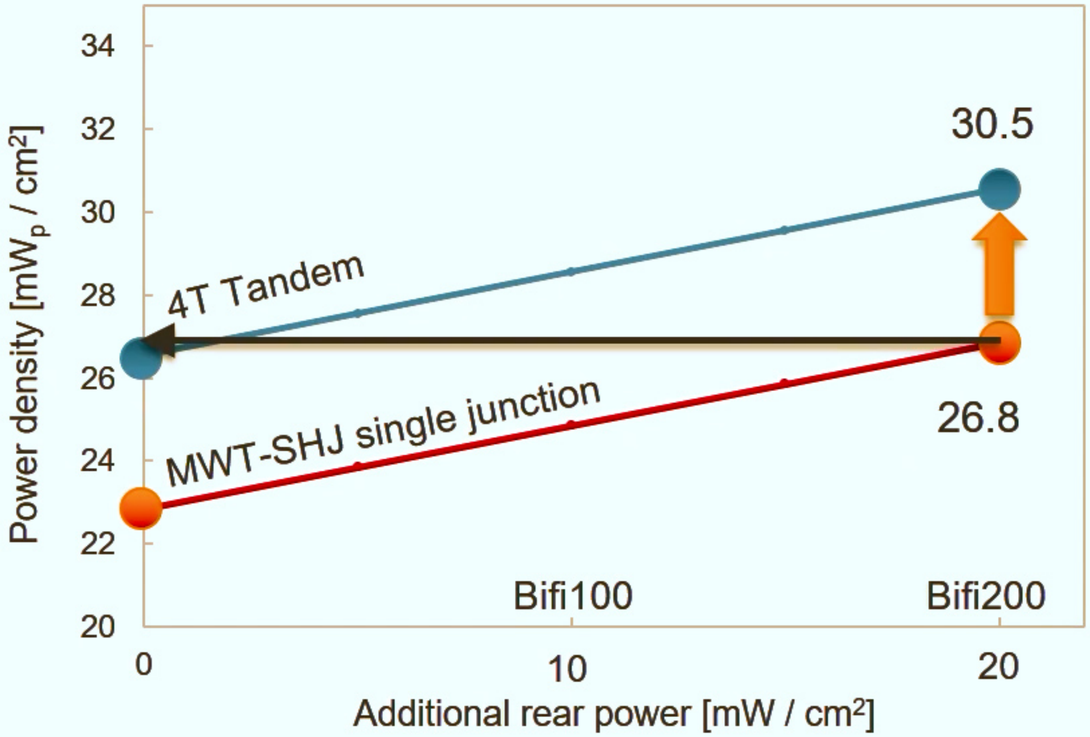
HOW TO COMPARE 4T WITH 2T?







HOW DO THESE DEVICES BEHAVE IN BIFACIAL CONDITIONS?

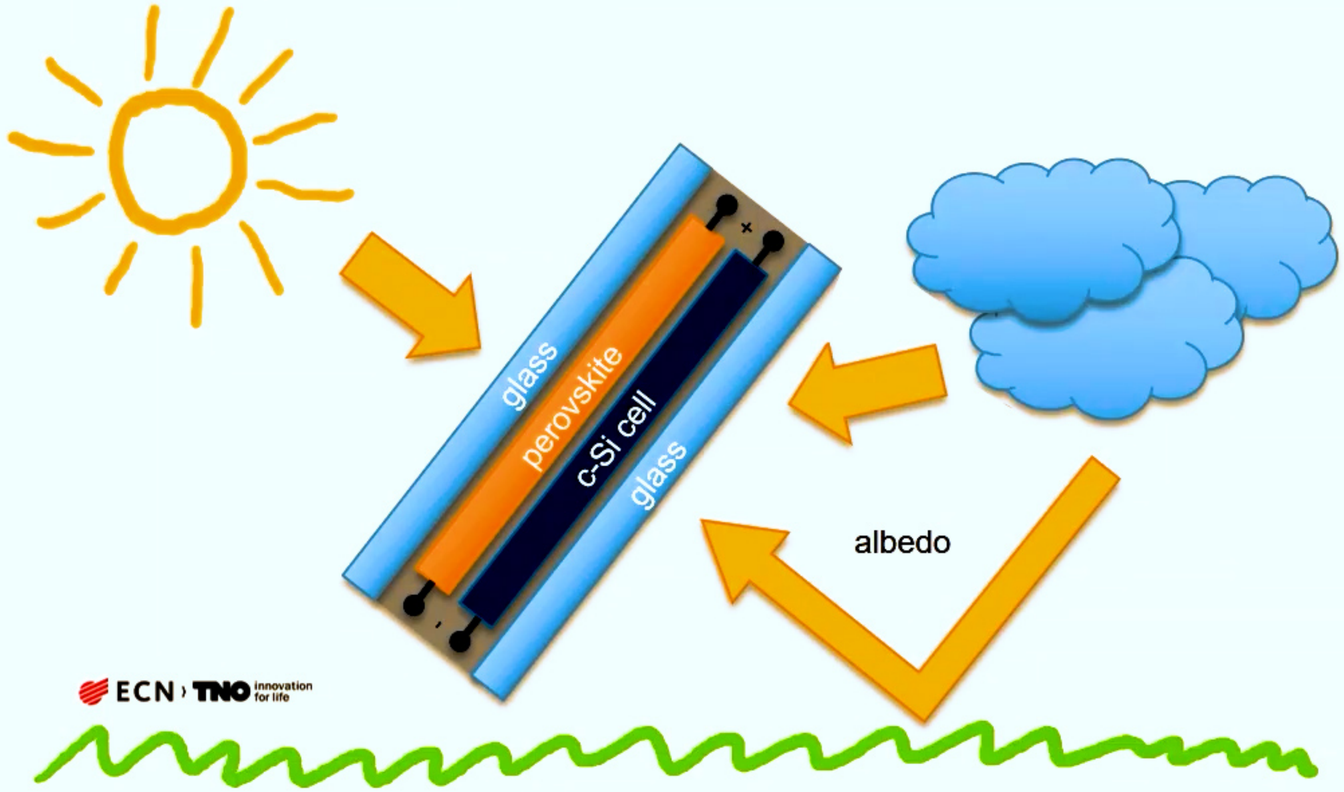


Bifacial MWT-SHJ SJ (BiFi200) and 4T tandem have similar power density

Bifacial 4T tandem power density of 30.5 mW_p/cm^2

* Based on IEC TS60904-1-2:2019 Photovoltaic devices - Part 1-2: Measurement of current-voltage characteristics of bifacial photovoltaic (PV) devices

HOW TO COMPARE BIFACIAL WITH MONOFACIAL IN REAL OUTDOOR ENVIRONMENT?



Use an equivalent efficiency:
the efficiency of a monofacial device required to generate the same (annual) amount of energy as the bifacial device, [installed at the same site], under the same operating conditions

N. Eisenberg et al. BIFI Workshop, Konstanz, 2017
L. Kreinin et al. 26th EUPVSEC, 2014.

Metric:
Equivalent efficiency by energy

HOW ENERGY YIELD COMPARES IN OUTDOOR OPERATIONS?

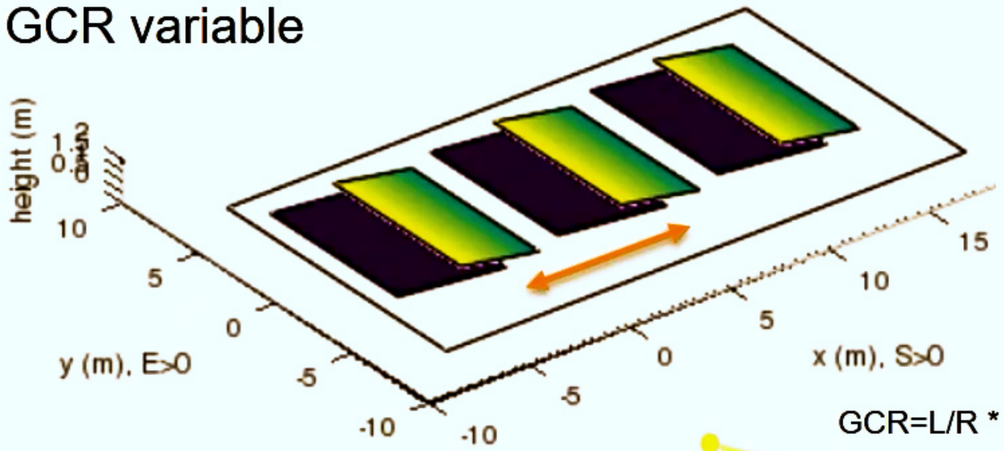
Configuration: Shed, Amsterdam, South facing

3 rows landscape, 2 module height

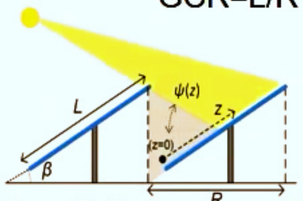
Ground clearance 1m, Tilt fixed 37°

Constant total module area, Albedo 30%

GCR variable

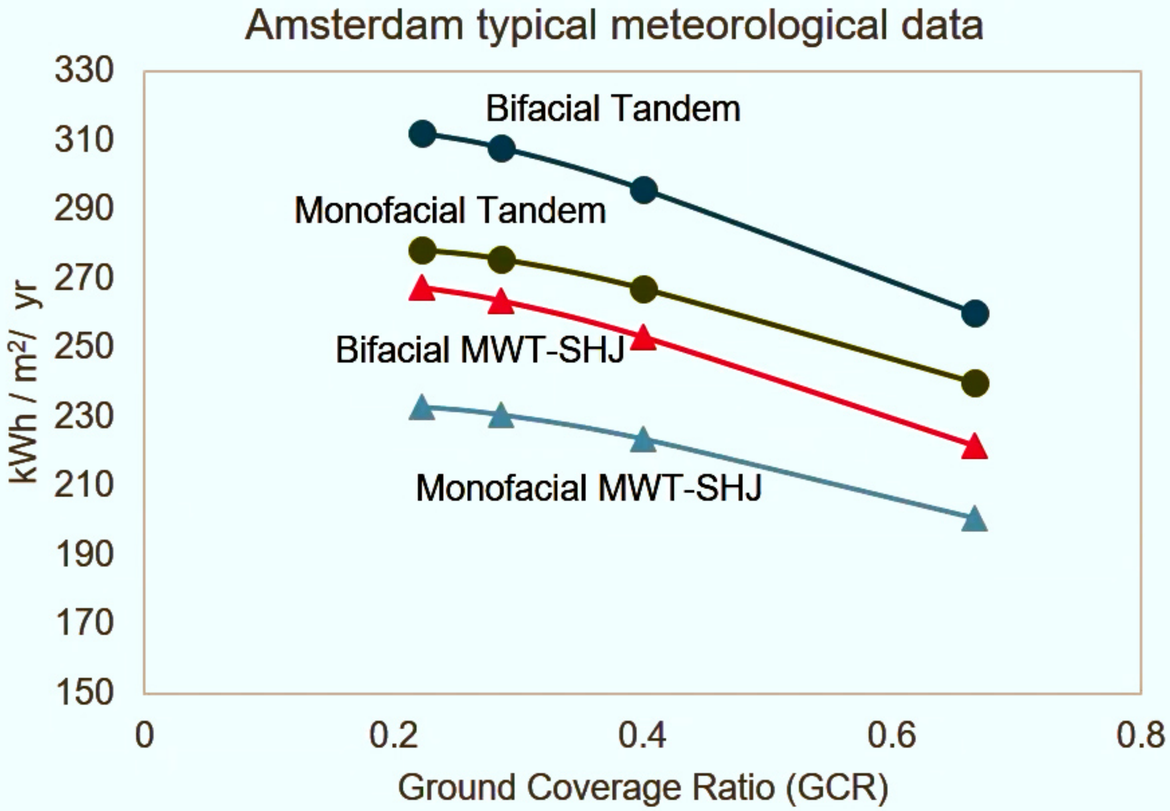


GCR=L/R *



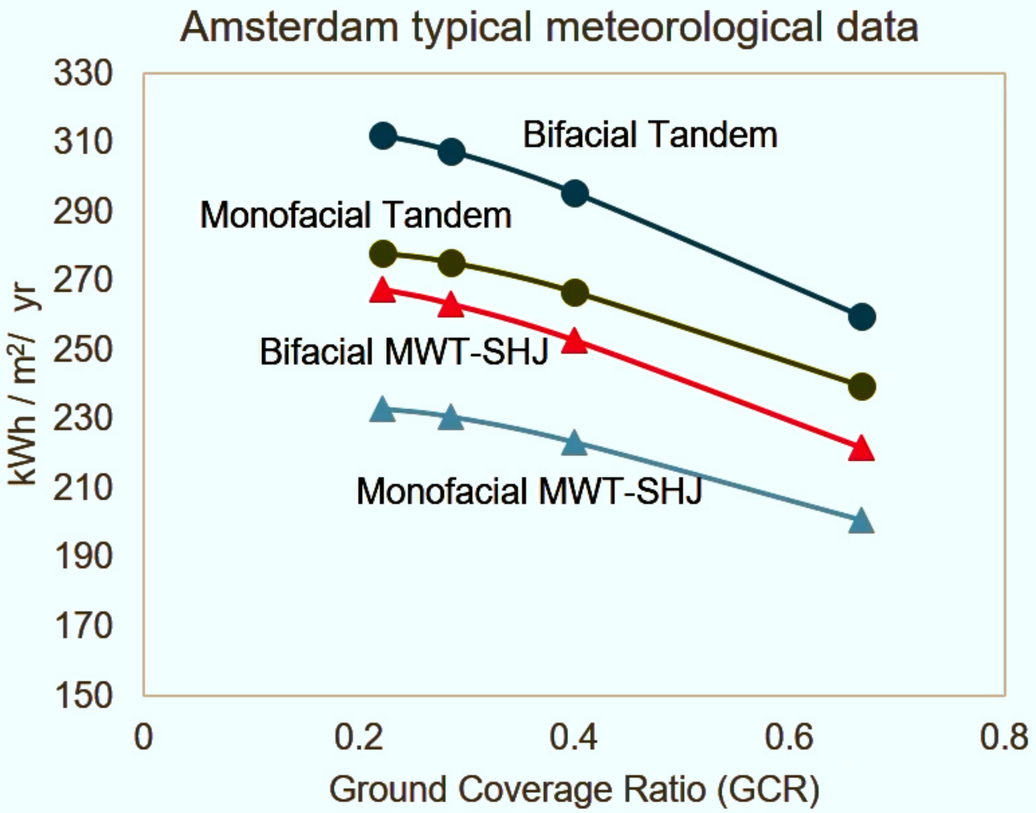
Energy yield simulation BIGEYE

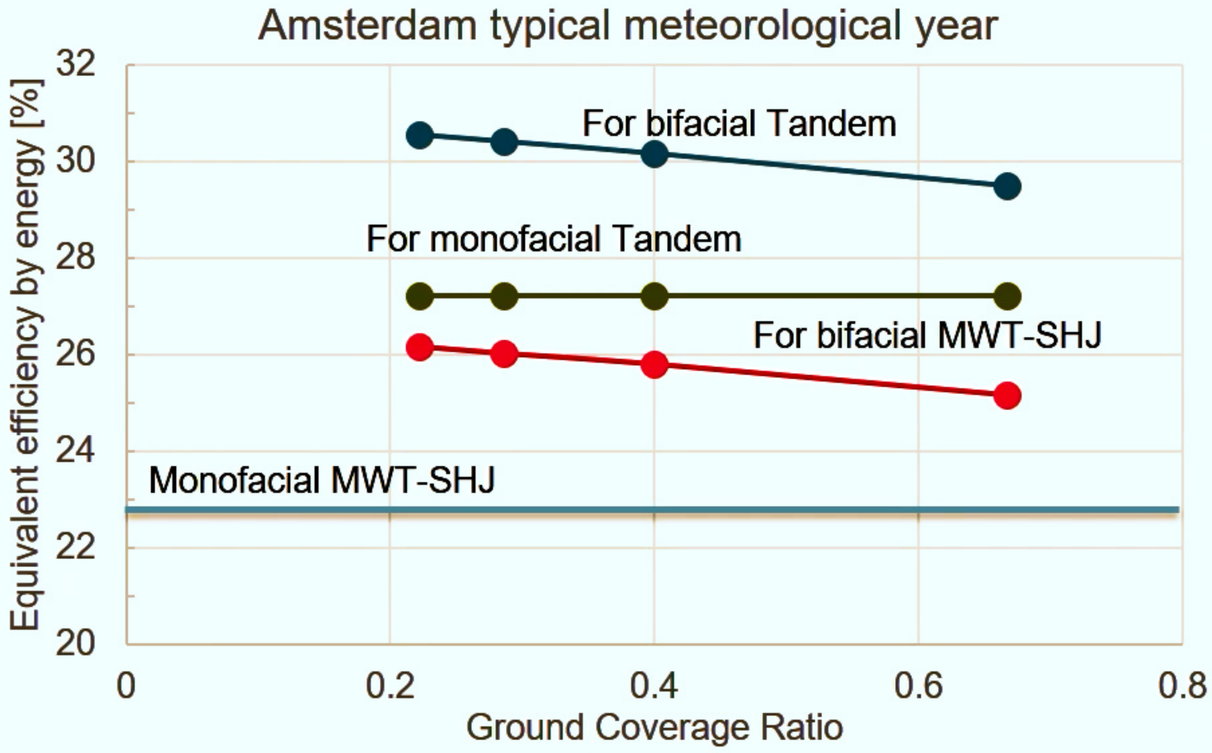
*K. Doubleday, Solar energy 135:512



Bifacial single junction similar energy yield as tandem monofacial

WHAT MONOFACIAL SINGLE-JUNCTION EFFICIENCY IS NEEDED TO MATCH THE SAME kWh?



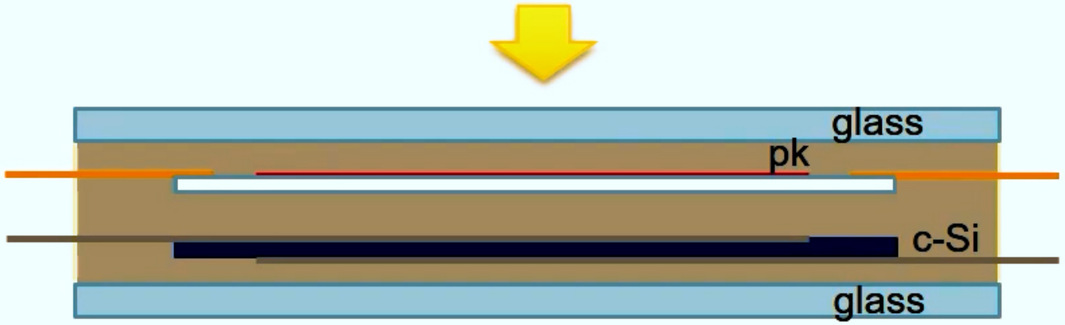


Simulation software BIGEYE

MINI-MODULES AND ACCELERATED TESTING

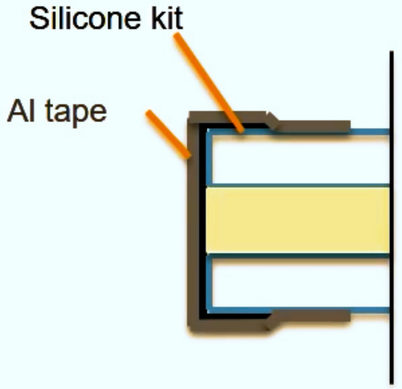
- Glass-glass minimodule
- pk minimodules on 2x2cm^2 glass 6 cells interconnected
- Commercial PERC+ c-Si cells cut down to 2x2cm2
- Thermoplastic encapsulant
- Assembled including pk under normal lab conditions

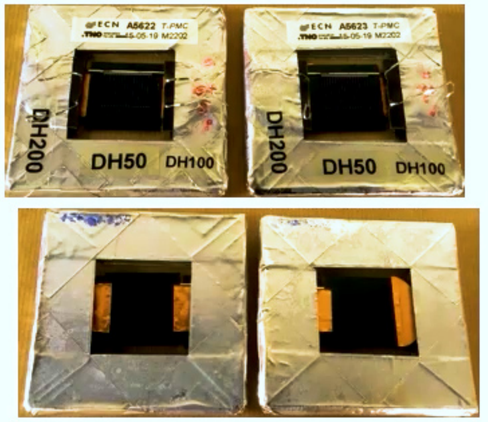
Lay-out + edge seal solution



Preliminary accelerated stress testing for sealing

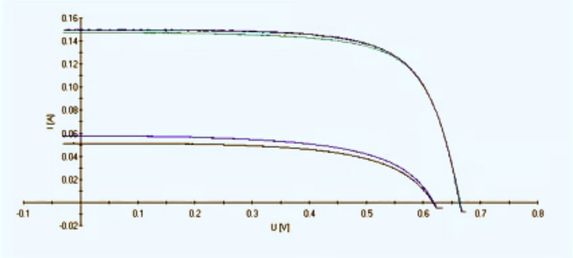
- DH100 (85/85) = 96% of initial performance
- Thermal Shock (TS50) 0°C -65°C = 106%
- Combined test TS50-DH100 = 102%

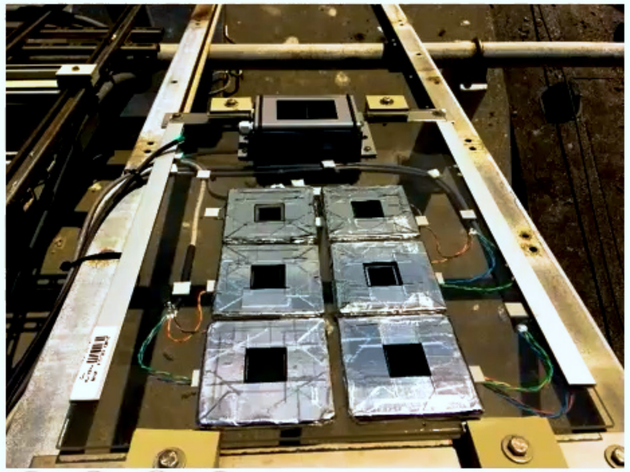


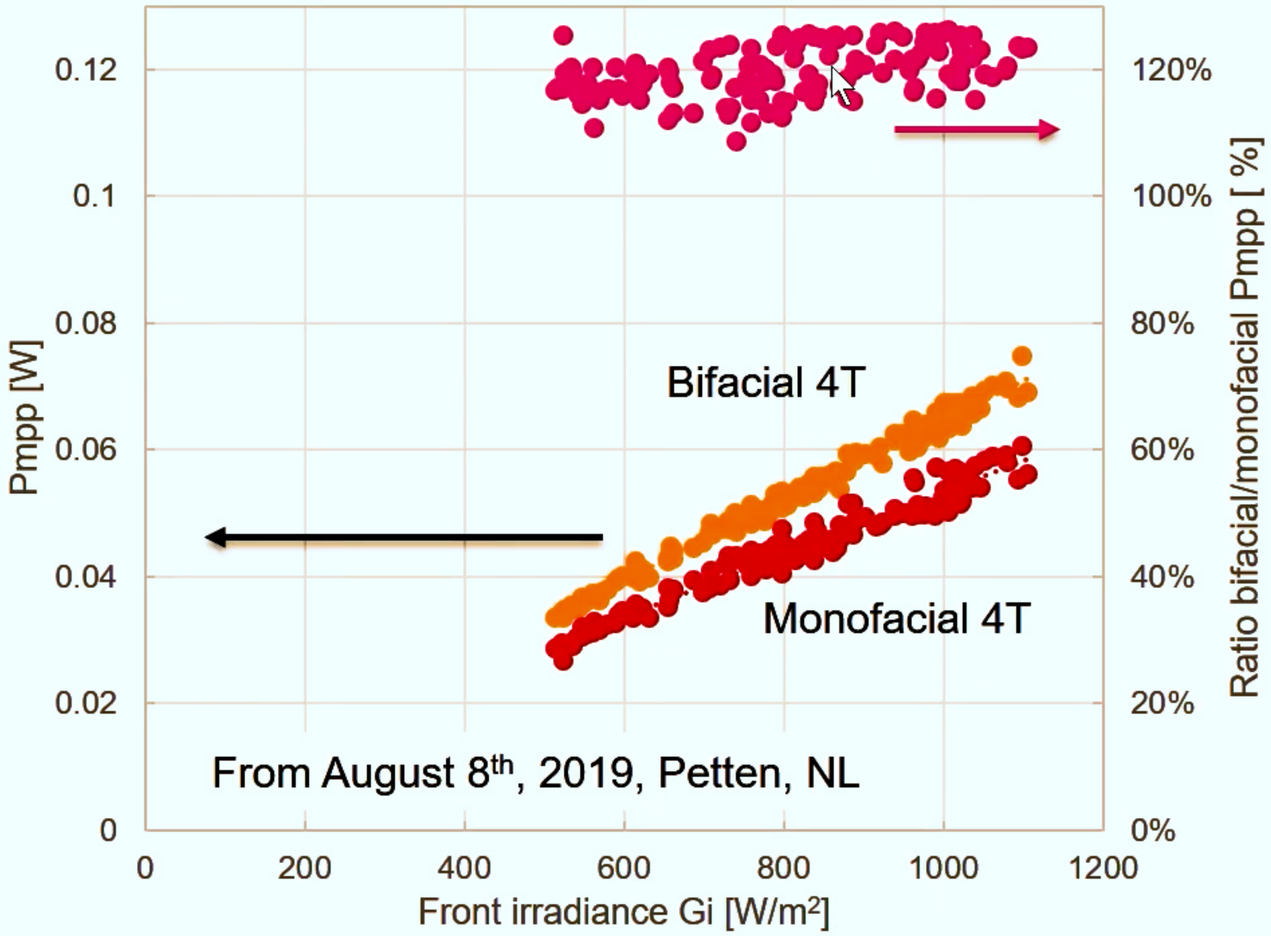


OUTDOOR TESTING

- Simultaneous IV tracing, every 10 min
- Vmpp in between scans
- Results first 100 hrs



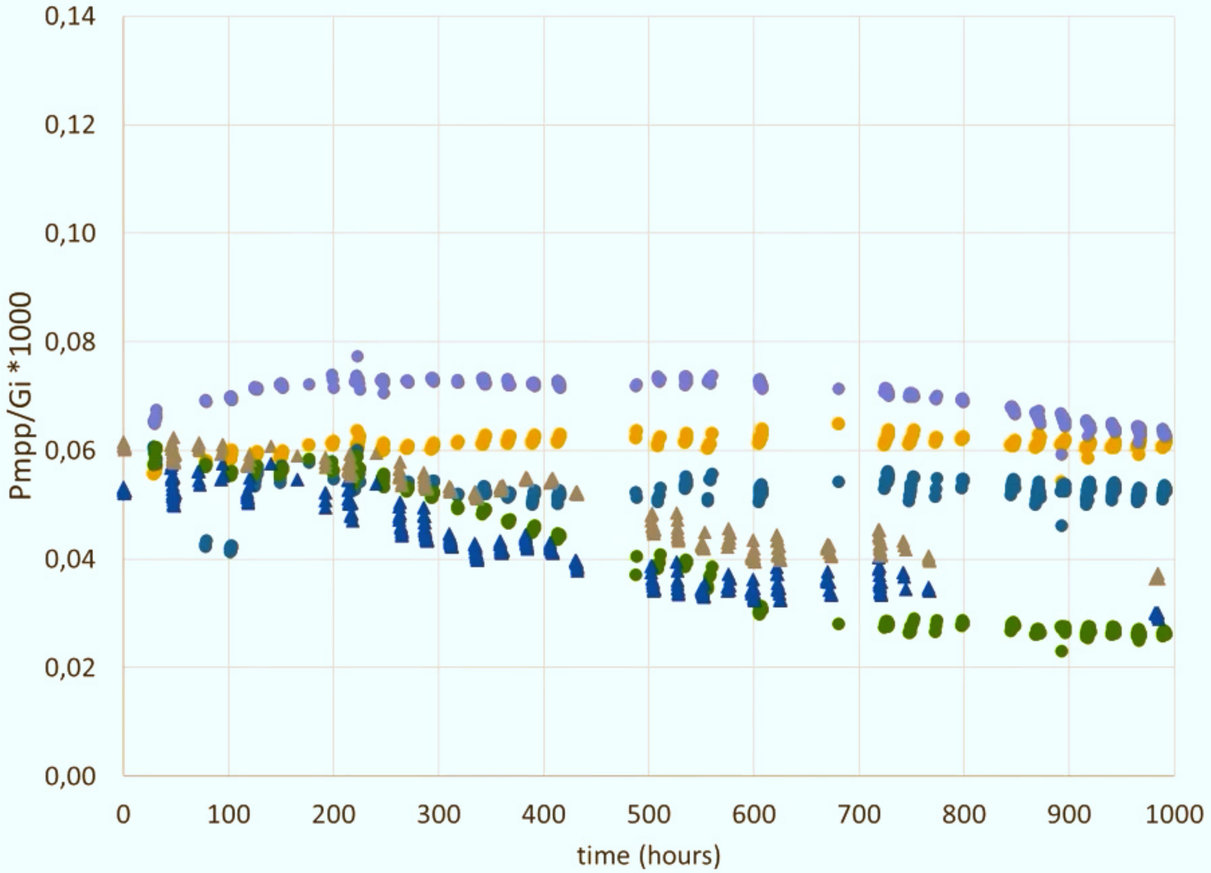




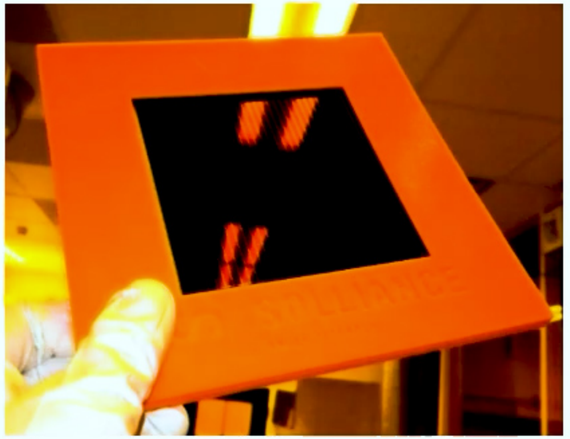
Tandem bifacial power gain ~20%

PRELIMINARY OUTDOOR DATA

- Up to 1000 hrs data collection
- Pmpp/Gi
  - Plot for 900 < Gi < 1100 W/m^2
- Two module generations and 3x PSM tested
- 1000hrs stability at least 2 configurations
- Early to late degradation onset in others



100 CM² BIFACIAL 4T PEROVSKITE/c-Si TANDEM



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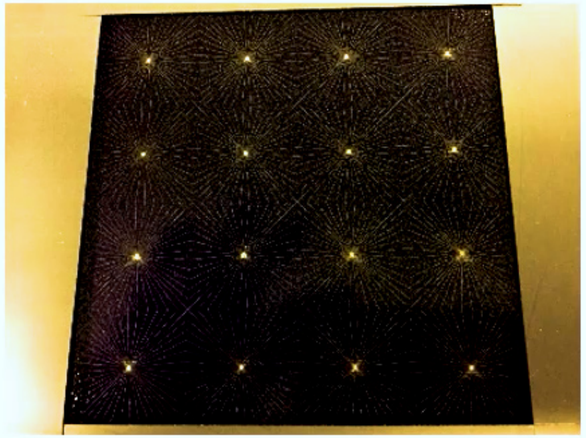

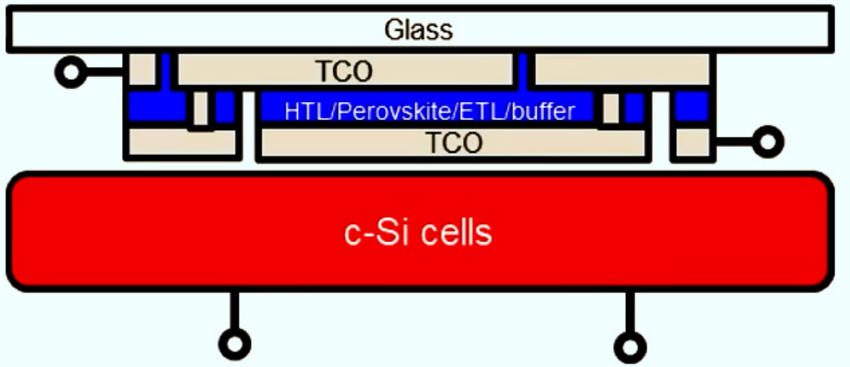

		V_{oc} (V)	J_{sc} (mA/cm²)	FF (%)	Eff (%)	4T Tandem	Bifacial gain
Semi Transparent Perovskite module 10x10cm²	Backward scan	33.1 (1.10 per cell)	15.9	76.6	13.5		
	Forward scan	33.2 (1.11 per cell)	15.9	76.2	13.4		
	5 min MPPT	-	-	-	**13.5**		
MWT-SHJ cell 6 inch	Front single junction	0.730	39.4	79.4	22.8		84%
	Filtered bottom cell	0.705	14.3	79.8	**8.1**	**21.6%**	88%

CONCLUSIONS

- 26.5% 4-terminal bifacial tandem cell on cell efficiency with bifaciality of 72%
- Bifacial power density over 30 mW_p/cm^2 (BiFi200)
- Energy yield simulation with BIGEYE (location Amsterdam):
  - An MWT-SHJ of over 30% efficiency is needed to achieve same energy yield of the bifacial 4T tandem
  - Bifacial single-junction and monofacial tandem devices yield similar annual energy yield
- Outdoor data show a bifacial power gain of 20% in the first 100 hrs of operation
- 4T tandem efficiency of 21.6% is demonstrated on 100 cm^2 with perovskite module and MWT-SHJ cell


THANK YOU FOR YOUR ATTENTION
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