HIGH EFFICIENCY PHOTOVOLTAICS, PRINCIPLES AND TECHNOLOGIES

40 YEARS
FRAUNHOFER ISE
#CreatingTheEnergyFuture

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Fraunhofer Institute for Solar Energy Systems ISE

Workshop on HIPERION hybrid CPV/PV modules pilot installations at UPM and Fraunhofer ISE
Online Event – July 22, 2021

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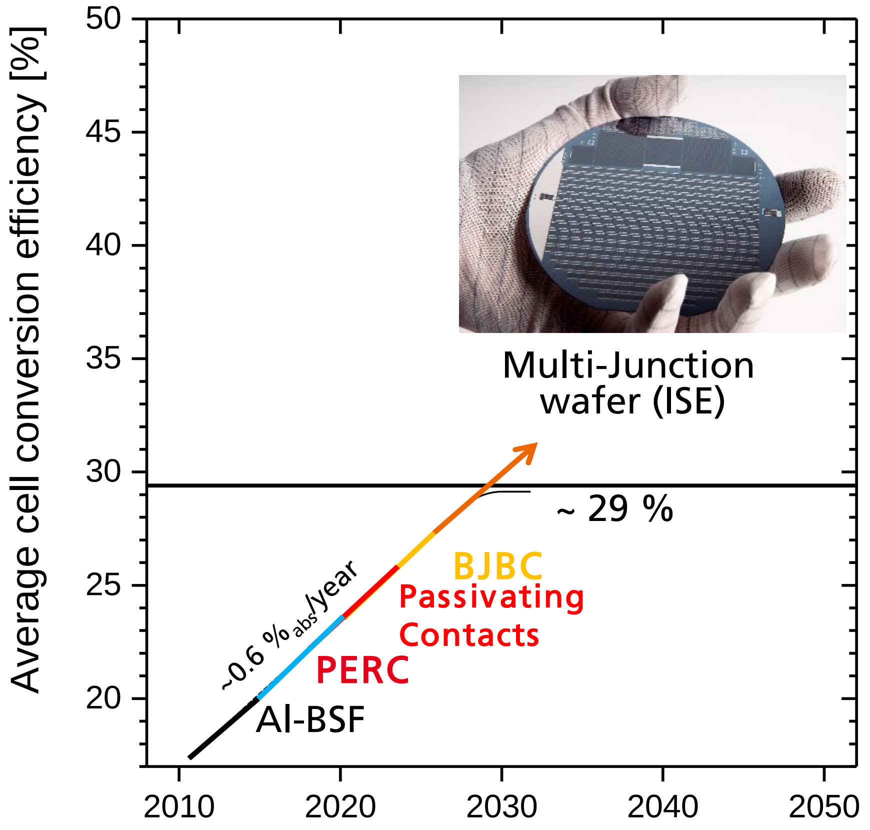
Most of the costs of a PV system are area related…

Reducing area while remaining the same power?

→ efficiency is the key

Why Multi-Junction Cells and why CPV?
The Limit of Silicon Solar Cells – Efficiency is main Driver!

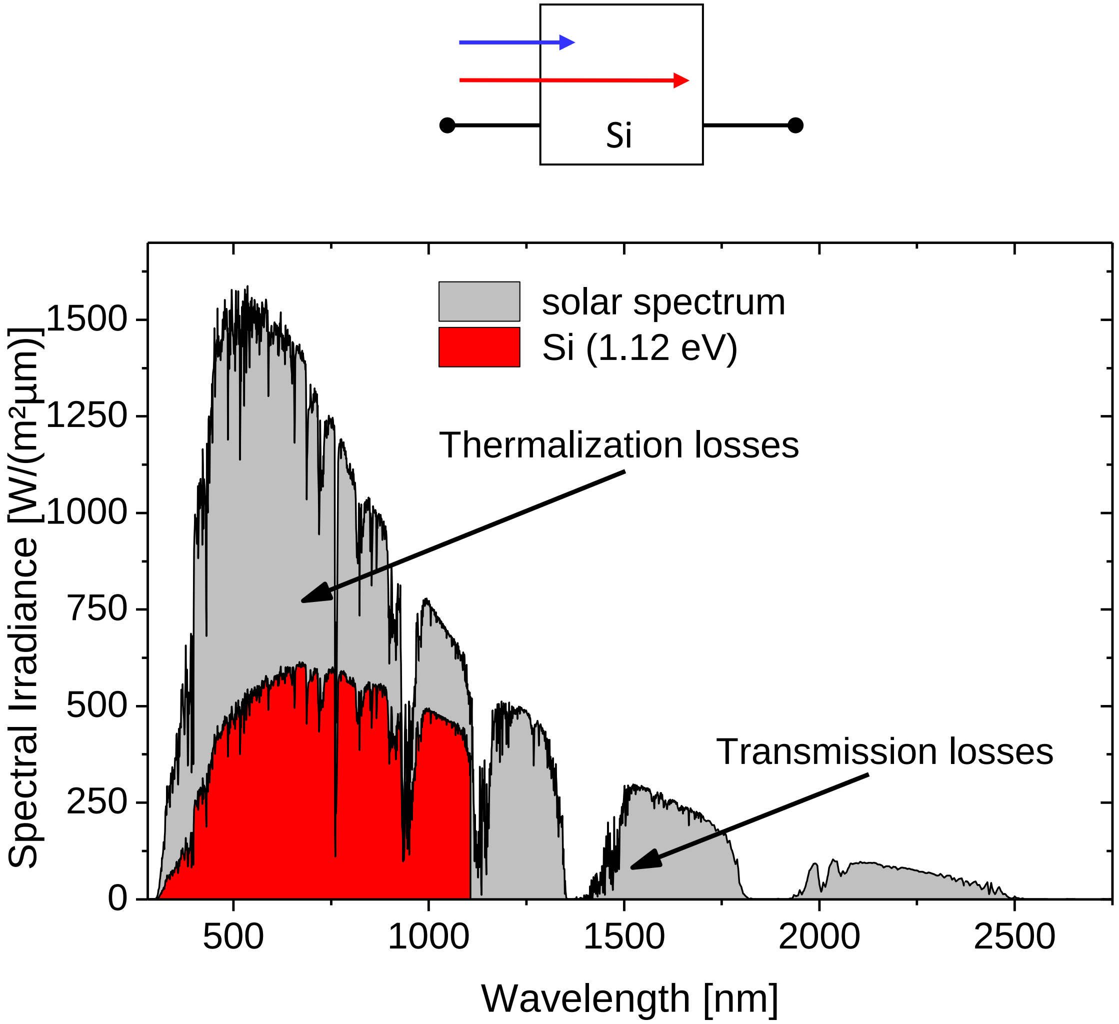
- Shockley, Queisser (1961)
  Limit for Si 33% (AM1.5)
- Limitations by thermalization and transmission
- **Auger Limit 29.4 %**[1]
- Can only be surpassed introducing tandem/multi-junction structures

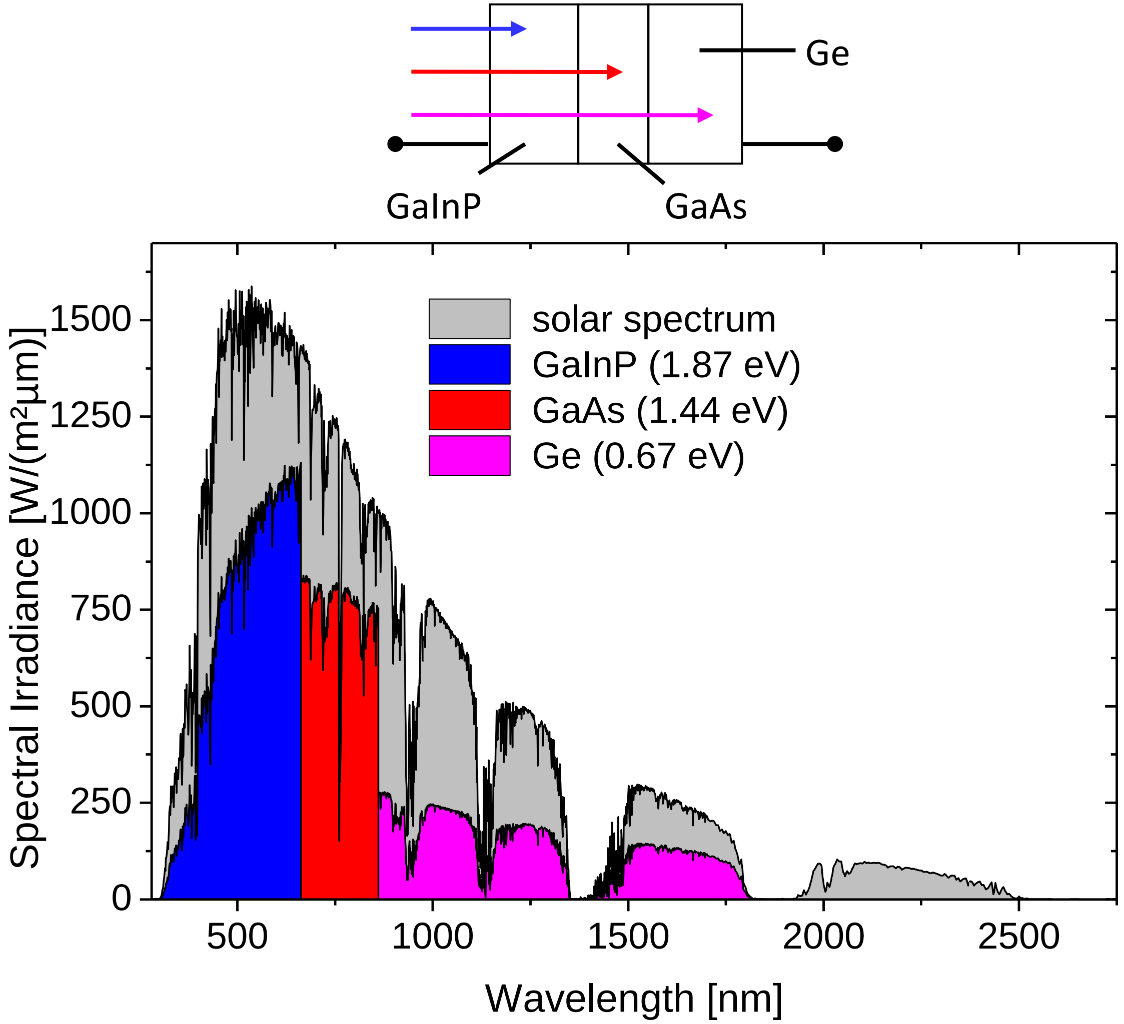


[1]Richter et al. IEEE JPV, **3** (4), 2013,
DOI: 10.1109/JPHOTOV.2013.2270351

Minimizing Transmission and Thermalization Losses

Multi-Junction Solar Cells





Map of III-V Semiconductors

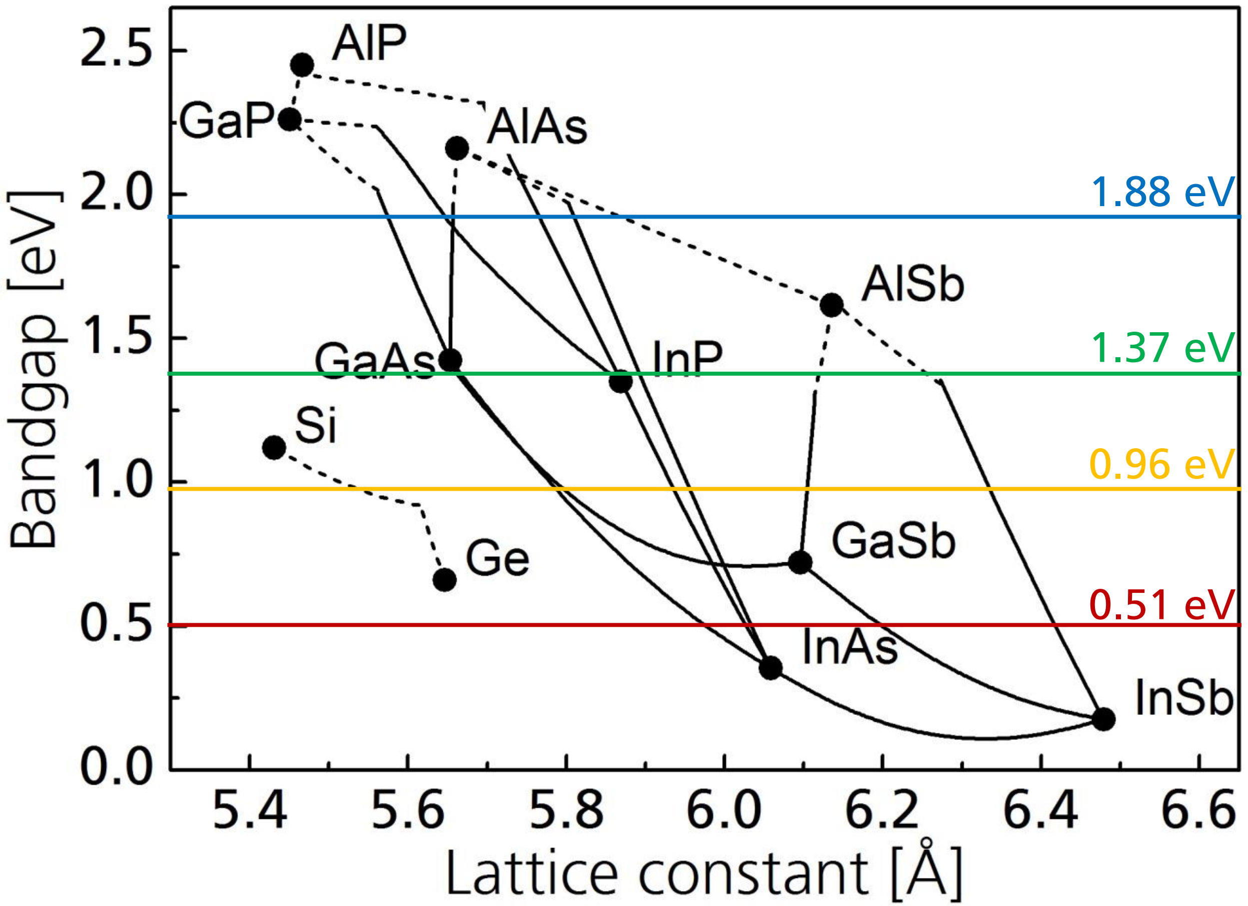
Example: Most promising Bandgap Combination Four Junction Cell for CPV

From the material growth perspective:

Lattice matching is preferred.

However – most promising bandgap combinations are not available at the same lattice constant!

Transition in lattice constant required!



*Predan et al. IEEE JPV **10** (2), 2020*
DOI: 10.1109/JPHOTOV.2019.2957663

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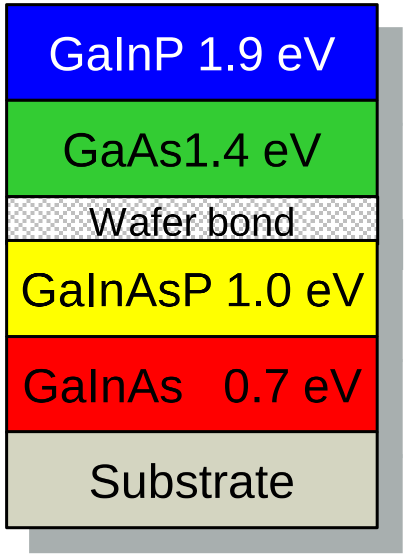
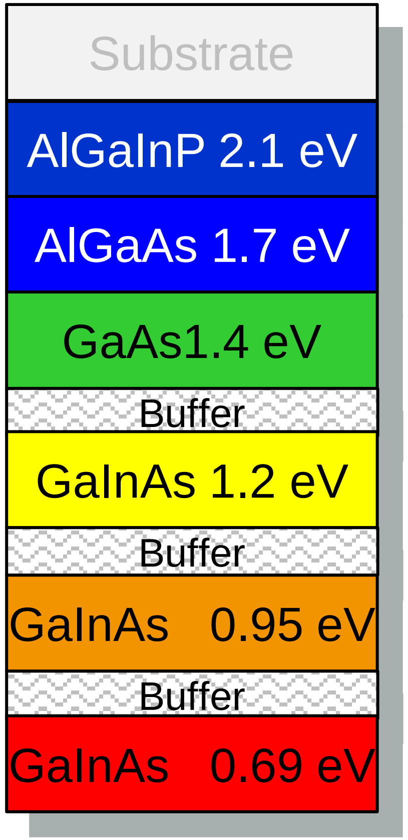
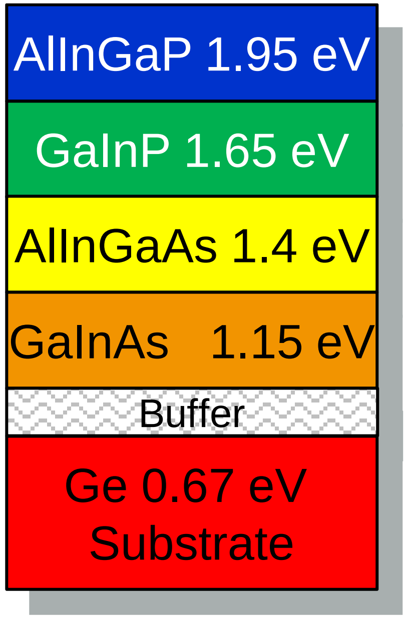
Highest Efficient III-V Multi-Junction Cells
Wafer Bonding and Metamorphic Growth are Key Technologies



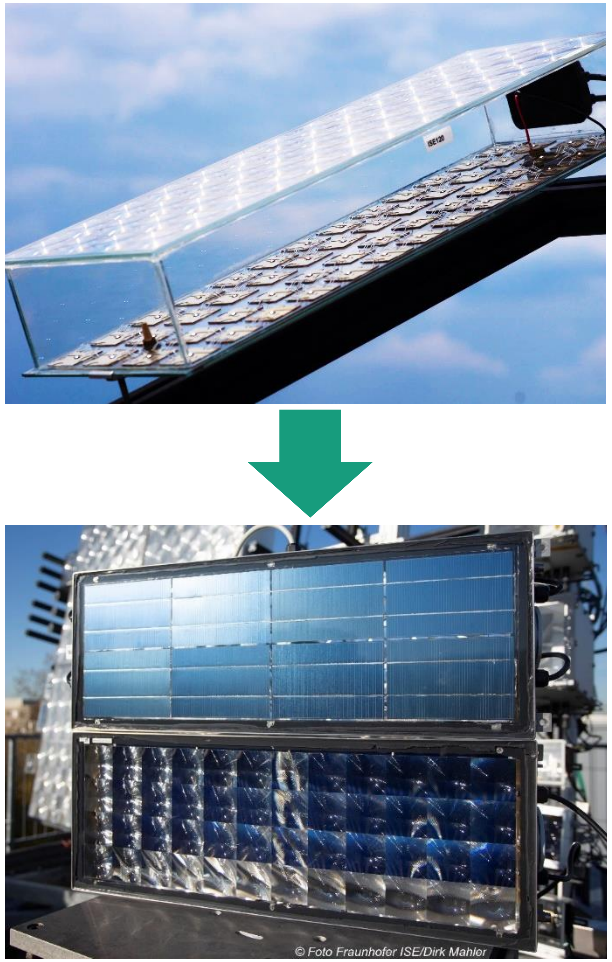
ISE/Soitec 4J
Wafer bond[1]



NREL 6J IMM
inverted metamorphic[2]



AZUR SPACE 5J UMM
upright metamorphic[3]



[1]*Dimroth et al. IEEE JPV **6** (1), 2016*
DOI: 10.1109/JPHOTOV.2015.2501729

[2]*Geisz et al. Nat Energy **5**, 2020*
DOI: 10.1038/s41560-020-0598-5

[3]*Schroth et al. CPV-17 proceedings, available soon in open access*

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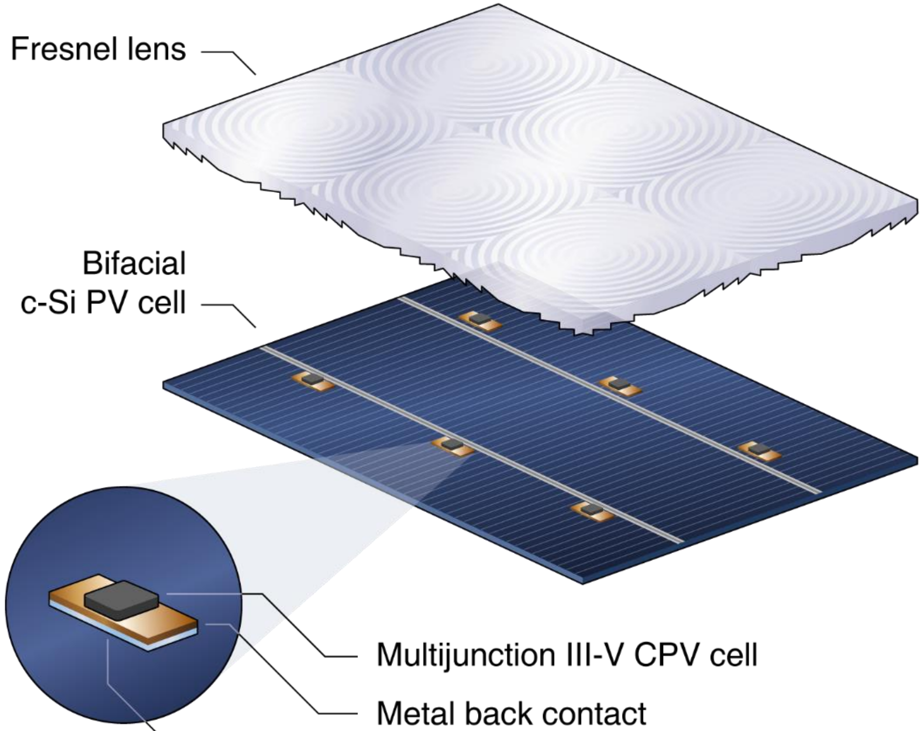
EyeCon Hybrid CPV/PV Technology[1)]

Concentrator + Flat-plate Photovoltaics

- Module architecture and operation
  - SoG Fresnel lens **+ III-V 4J CPV cells** + Si bifacial cell
  - 4-terminal electrical output
  - Requires dual-axis tracking



[1)] *Martínez et al, Prog Photovolt Res Appl. 2020;**28**:349–357.*

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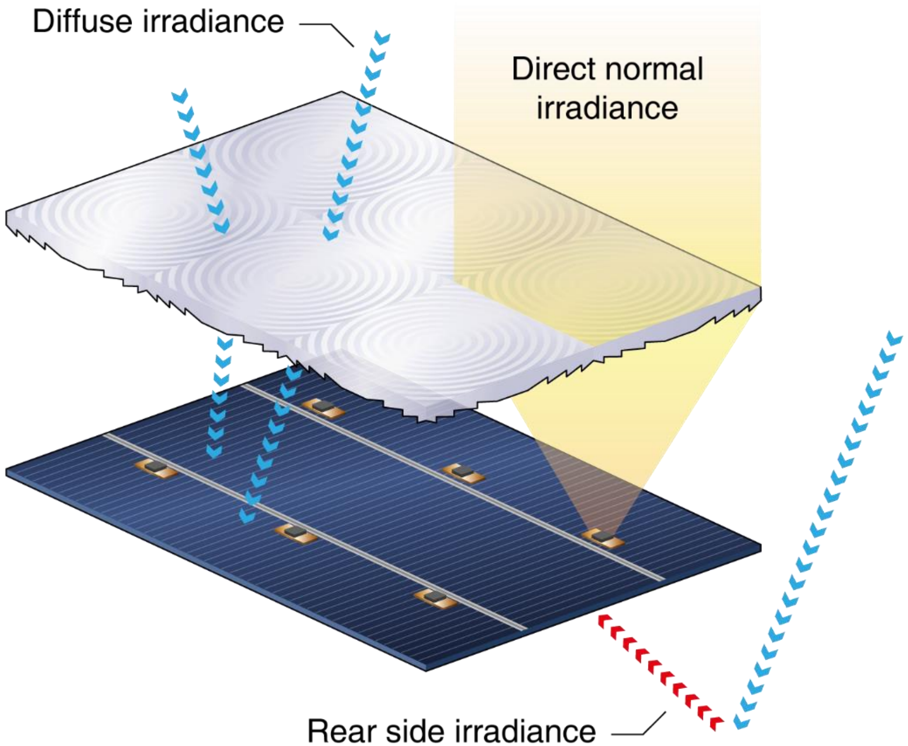
- Optical functionality
  - DNI concentrated 321x onto CPV cells
  - Front and rear diffuse light absorbed by Si bifacial cell



[1)]*Martínez et al, Prog Photovolt Res Appl. 2020;**28**:349–357.*

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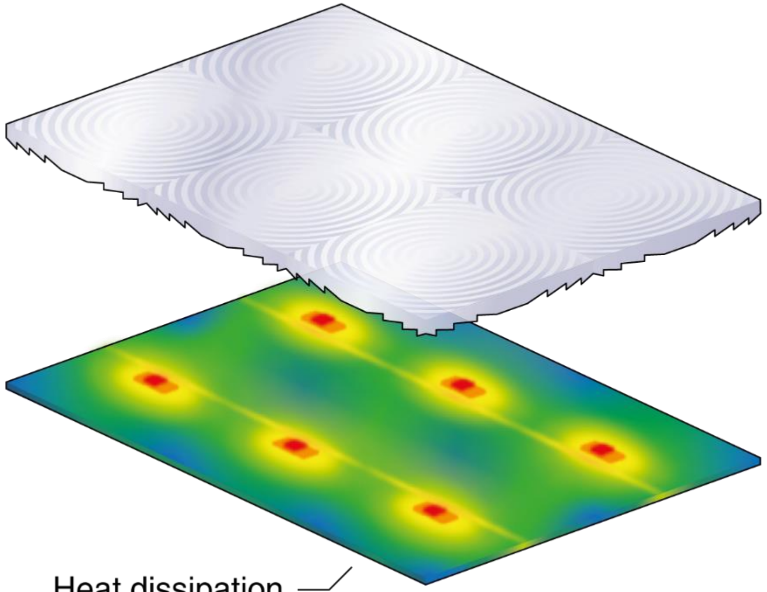
- Thermal functionality[2)]
  - Si cell enables heat dissipation for the CPV cells



[1)]*Martínez et al, Prog Photovolt Res Appl. 2020;**28**:349–357.*

[2)]*Martínez et al, 10.1109/JPHOTOV.2018.2877004*

Hybrid CPV/PV Power Rating[1)]

Based on CPV, Flat-plate PV and Bifacial PV IEC Standards

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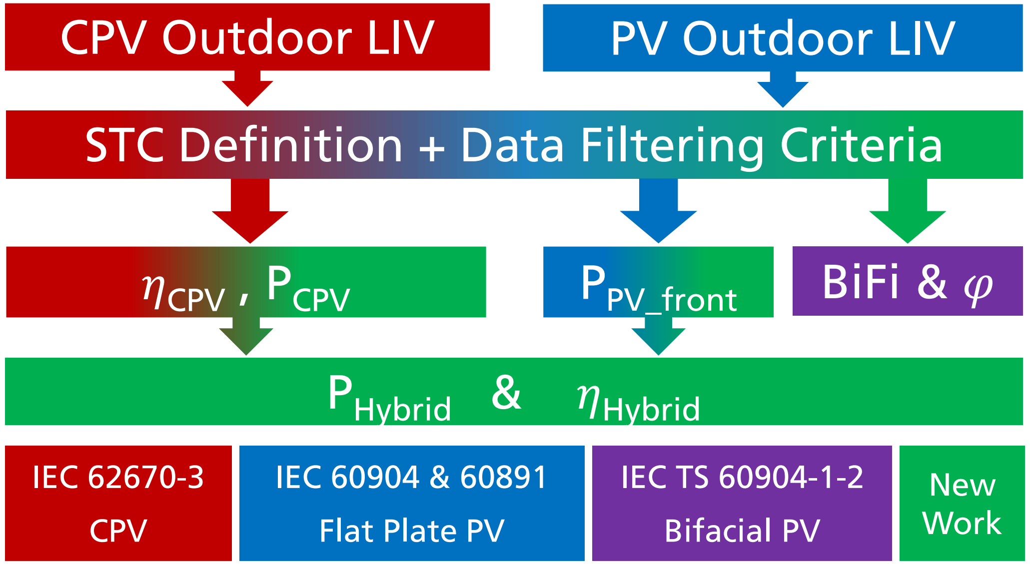
DOI: 10.1002/pip.3410

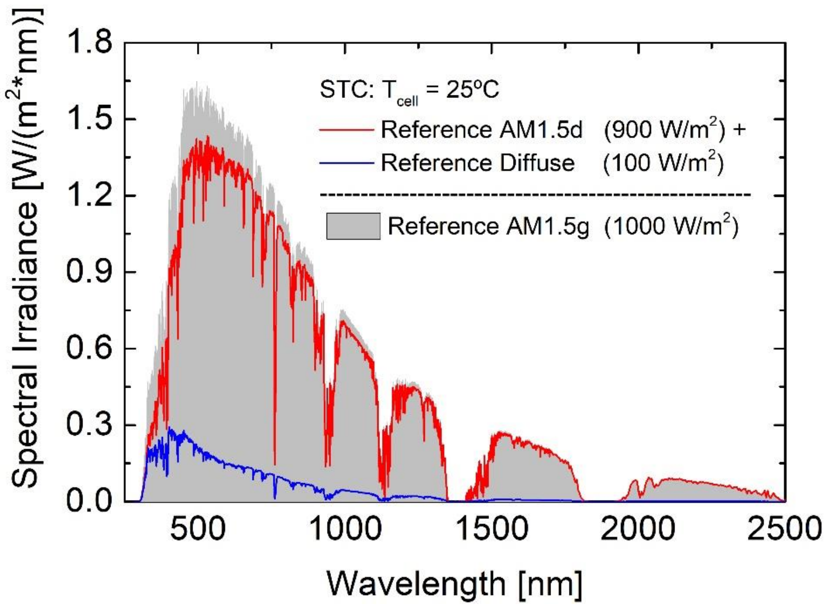
RESEARCH ARTICLE

PROGRESS IN PHOTOVOLTAICS WILEY

Power rating procedure of hybrid concentrator/flat-plate photovoltaic bifacial modules

Juan F. Martínez | Marc Steiner | Maike Wiesenfarth | Gerald Siefer | Stefan W. Glunz | Frank Dimroth



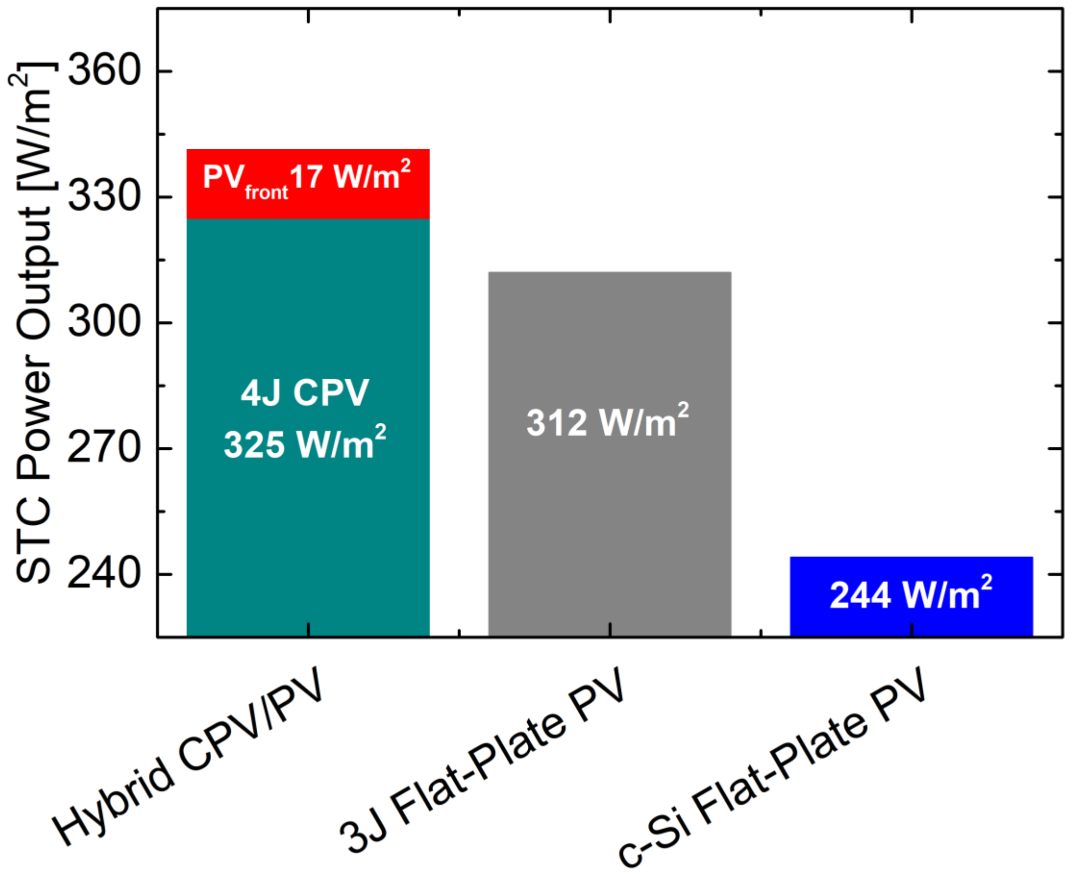


- CPV filtering criteria (IEC 62670-3):
  - Stable and close to AM1.5d conditions
- $0.97 <$ global $SMR_{1\text{-}2} < 1.03$:
  - Compliance with reference diffuse spectrum

[1)]*Martínez et al, Prog Photovolt Res Appl. 2021;**29**:614–629.*

Hybrid CPV/PV Power Rating[1)]
CPV + Flat-plate PV Power Rating

- $P_{Hybrid} = P_{CPV} + P_{PV\_front}$
- $\eta_{STC} = 34.2\%$
- P_{PV_rear} = 11 W/m² for every 100 W/m² of rear irradiance
- $P_{Hybrid\_bifacial}$ > 350 W/m²
- EyeCon surpasses record flat-plate PV modules[2)]



[1)]*Martínez et al, Prog Photovolt Res Appl. 2021;**29**:614–629.*

[2)]*Green et al, Prog Photovolt Res Appl. 2021;**29**:3–15.*

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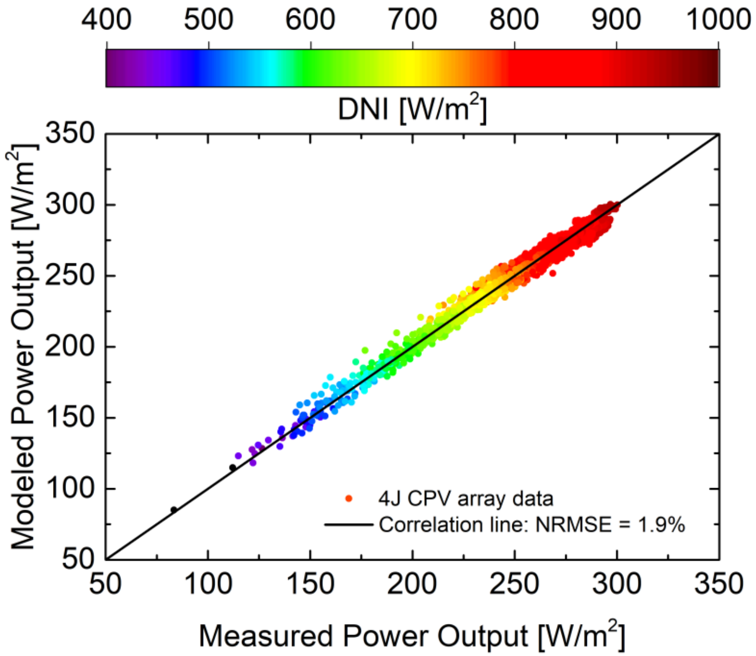
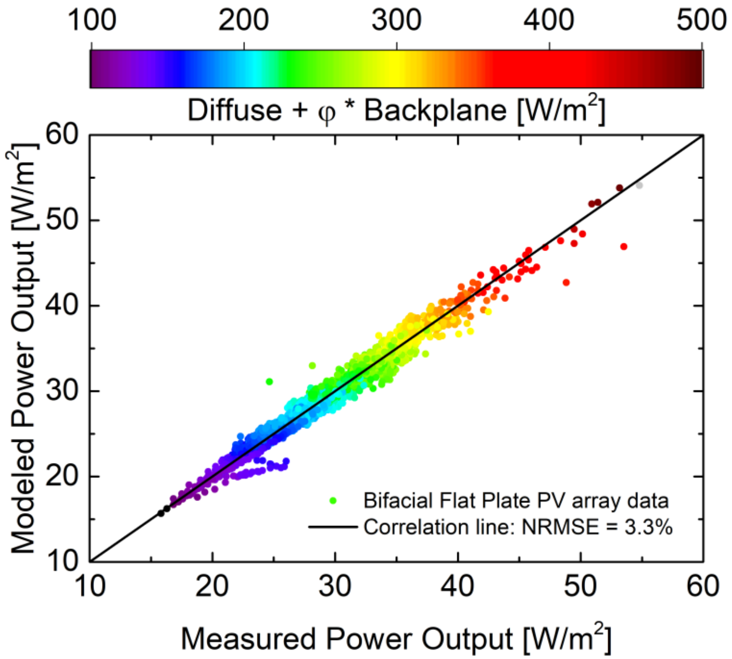
Hybrid CPV/PV Energy Yield

CPV and Flat-plate PV Power Output Models

- Empirical CPV power output model[1)]
  - DNI, T_{amb} and spectral variation



- Empirical flat-plate PV power output model[2)]
  - Effective irradiance (G_{eff}) and T_{cell}



- Input parameters taken or derived from PV energy yield standard (IEC 61853-4)[3)] climatic profiles

[1)] *Peharz, Ph.D. dissertation, (2011) adapted*
[2)] *Huld et al, Solar Energy Materials & Solar Cells 95 (2011) 3359-3369*
[3)] *PV module performance testing and energy rating – Part 4: Standard reference climatic profiles, (2018)*

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Annual Energy Yield Results[1)]

Hybrid, CPV and Flat-Plate PV Technologies

Bifacial EyeCon (η_{STC} = 34.2% | φ = 65%)

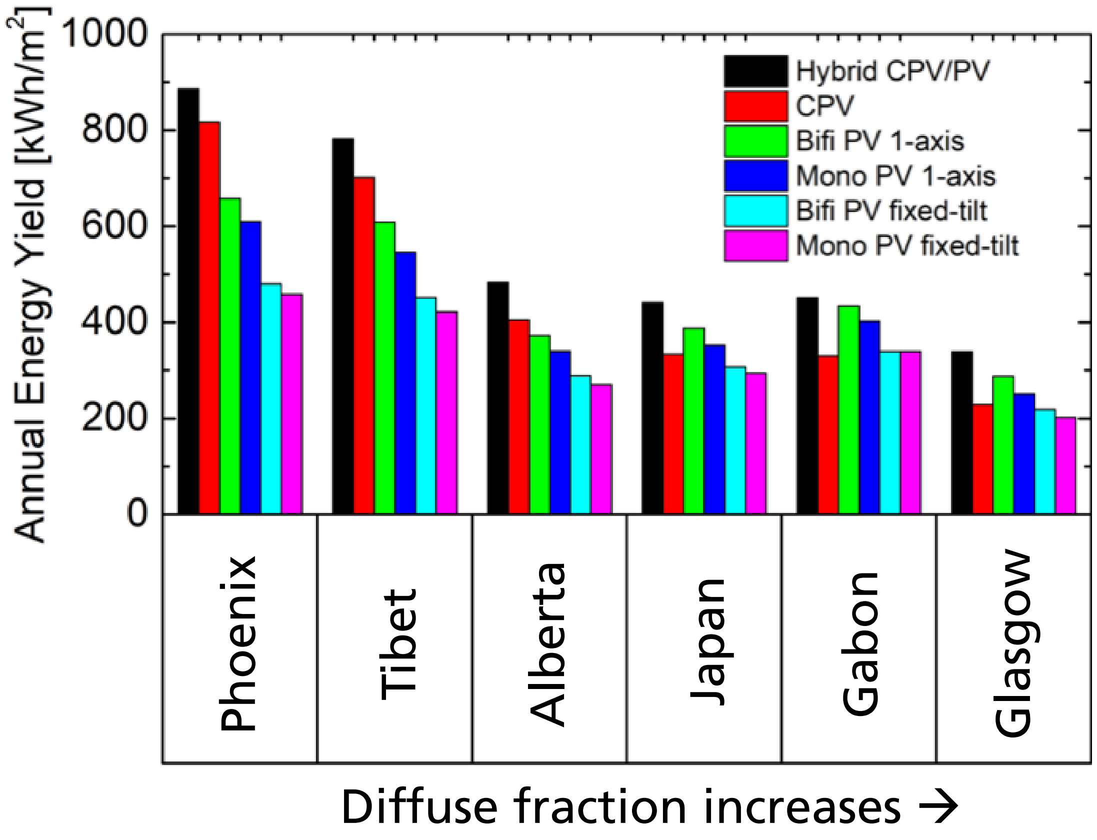
4J FLATCON (η_{CSTC} = 36.7%)

Bifacial c-Si 1-axis tracked (η_{STC} = 20% | φ = 90%)

Monofacial c-Si 1-axis tracked (η_{STC} = 20%)

Bifacial c-Si fixed-tilt (η_{STC} = 20% | φ = 90%)

Monofacial c-Si fixed-tilt (η_{STC} = 20%)



[1)] *Martínez et al, submitted to **CPV-17** Conference Proceedings, (2021)*

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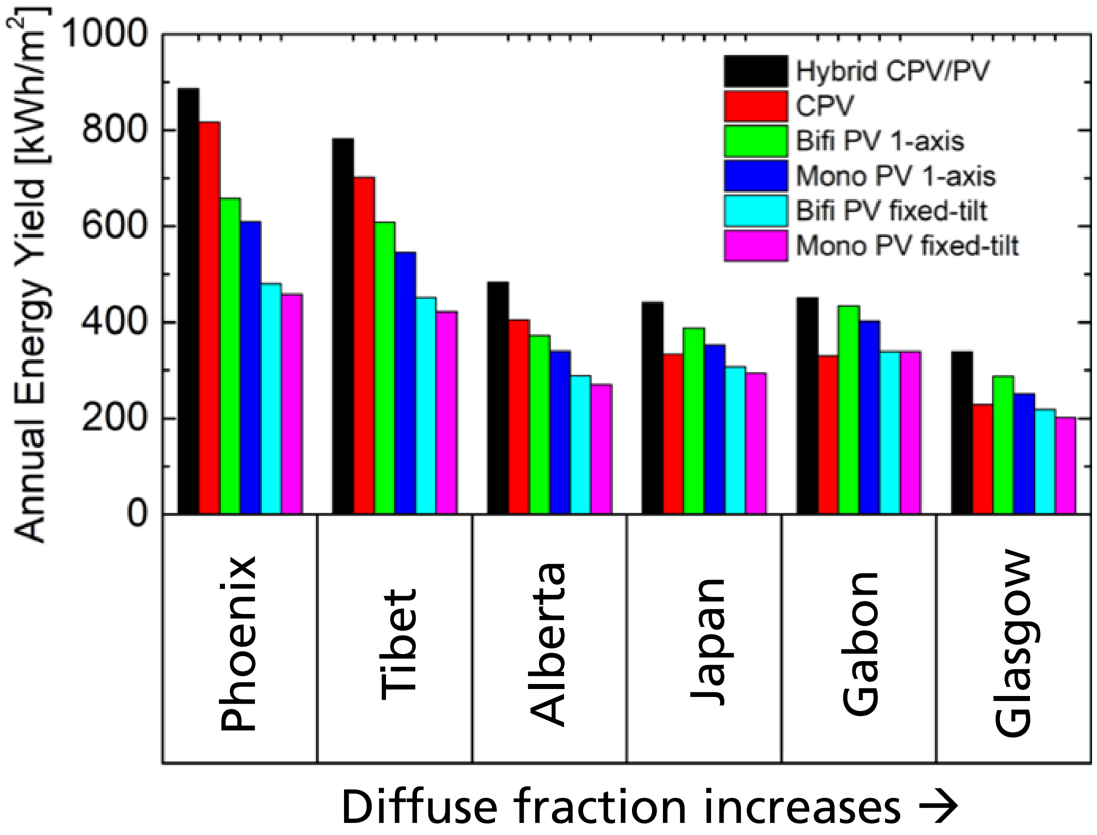
Annual Energy Yield Results[1)]
Hybrid, CPV and Flat-Plate PV Technologies

Hybrid CPV/PV yield larger in every climatic profile

Minimum advantage (10%) relative to CPV in arid and high elevation climate due to high DNI

Minimum advantage (15%) relative to bifacial tracked PV in humid and coastal climate due to high diffuse irradiance

Maximum advantage of 20% in temperate continental climate



1) *Martínez et al, submitted to **CPV-17** Conference Proceedings, (2021)*

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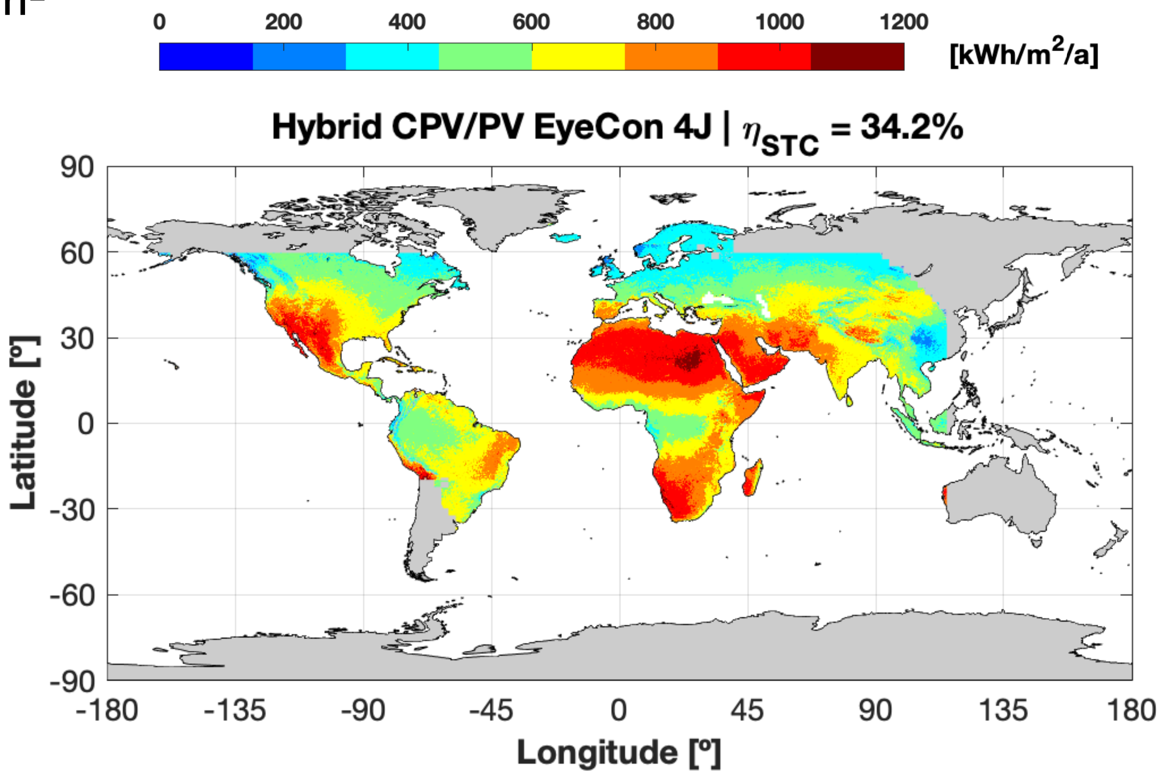
Hybrid CPV/PV Worldwide Annual Energy Yield Results[1)]

Based on Typical Meteorological Year Data

- Yield > 900 kWh/m^2 where yearly DNI > 2.5 MWh/m^2
  - Up to 1150 kWh/m^2 in Northeastern Africa
  - Bifacial Si cells contribute 15.6% in average
  - High yield expected for Chile and Australia (data missing)

- Worldwide average conversion efficiencies:
  - $\eta_{DNI} = 30.2 \pm 1.3\%$
  - $\eta_{Front\ Diffuse} = 14.1 \pm 1.2\%$
  - $\eta_{Rear\ Diffuse} = 7.1 \pm 1.1\%$



[1)]*Martínez et al, in revision at* ***Joule****, (2021)* http://dx.doi.org/10.2139/ssrn.3815001

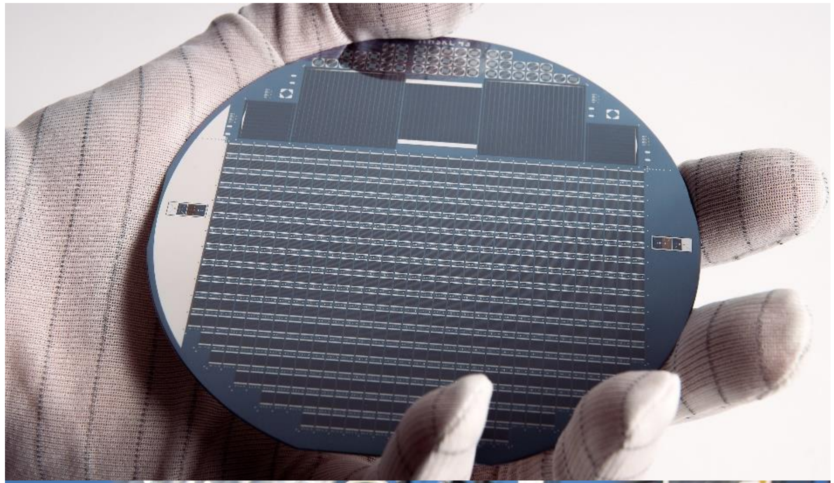
Summary

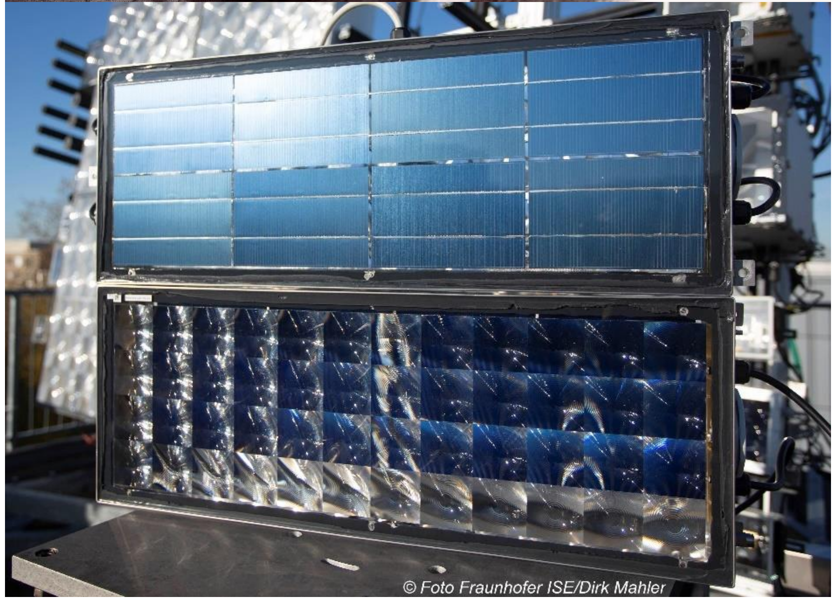
Multi-junction cells

- Only way to achieve efficiencies >> **30%**
- III-V MJ's: **Proven** and **stable** performance (space & CPV)

Hybrid CPV/PV module

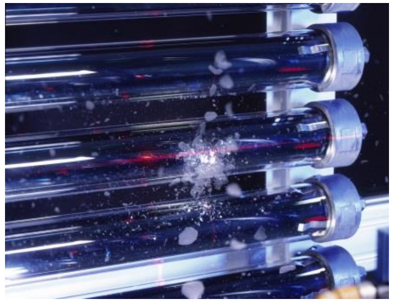
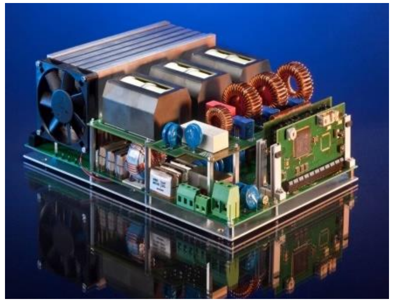
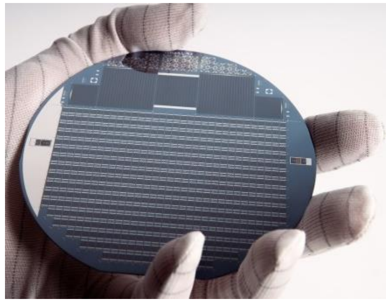
- η_{STC} = **34.2%** for conversion of the AM1.5g spectrum
- Power output > **350 W/m²** under bifacial illumination
- Up to **1150 kWh/m²** energy yield in high DNI regions
- Up to **20%** higher energy yield relative to closest contender in temperate continental climate





Thank you for your Attention!

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