Interplay of Science, Engineering and Technology in PV – Modelling and Monitoring

Becquerel Prize WINNER 2022 Keynote Speech

Marko Topič

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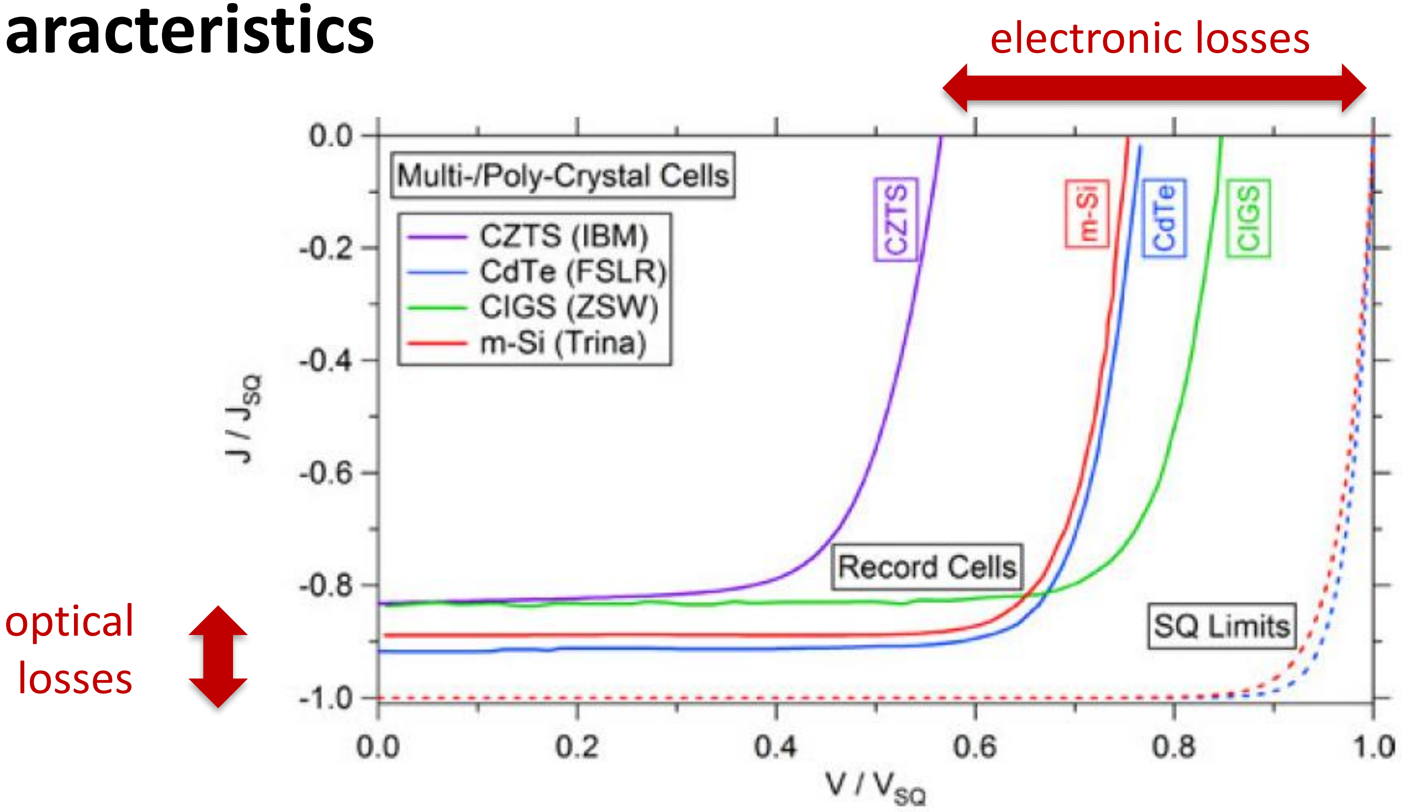
Faculty *of Electrical Engineering*
Laboratory *of Photovoltaics and Optoelectronics (LPVO)*

Metrics of solar cell performance limits – **normalized *J-V* characteristics (J/J_{SQ}-V/V_{oc_SQ})**



360 IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 5, NO. 1, JANUARY 2015

Performance Limits and Status of Single-Junction Solar Cells With Emphasis on CIGS

Marko Topič, *Senior Member, IEEE*, Russell M. Geisthardt, and James R. Sites

Abstract—**Limitations in performance and the status of single-junction solar cells are reviewed. Conversion efficiency in single-junction solar cells is systematically analyzed in terms of energy conversion efficiency, the Shockley–Queisser (SQ) efficiency limit, and two remaining efficiencies, i.e., optical efficiency and electri-**

As we will show for the case of single-juncti Cu(In,Ga)(Se,S)$_2$ (CIGS)-based solar cells that have achiev the highest energy conversion efficiency (>20%) among thi film PV technologies, there is further room for improvemen

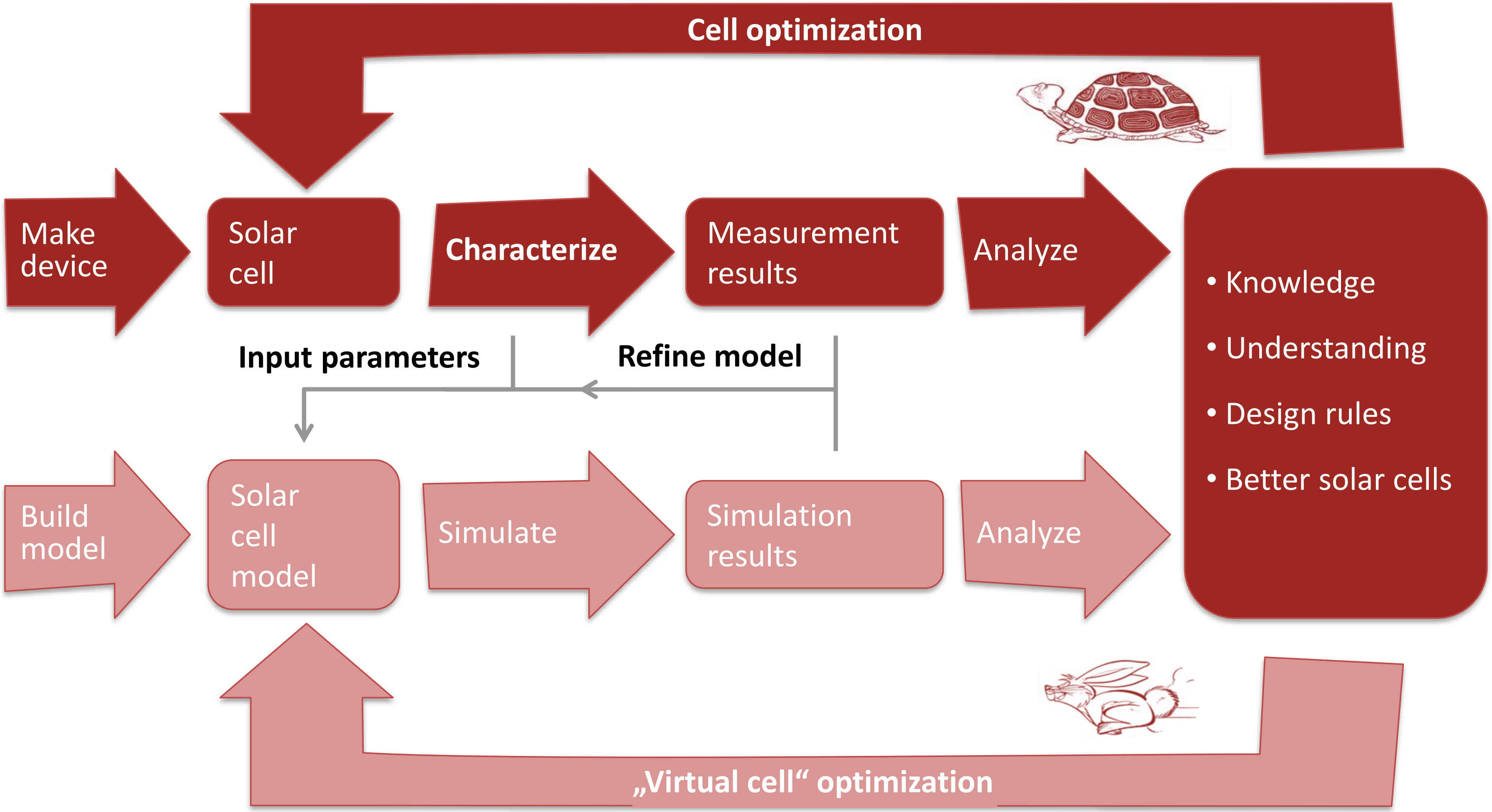
IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 5, NO. 4, JULY 2015 1217

Status and Potential of CdTe Solar-Cell Efficiency

Russell M. Geisthardt, Marko Topič, *Senior Member, IEEE*, and James R. Sites

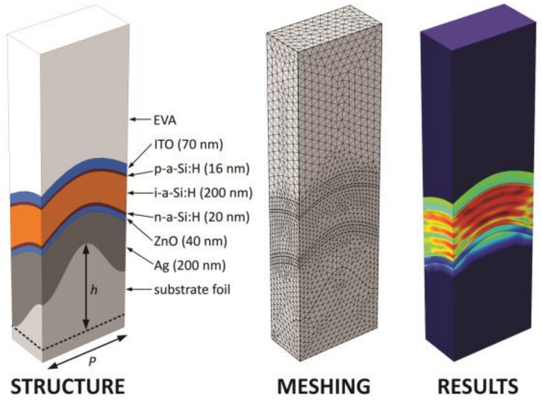
Abstract—**The status of the highest efficiency CdTe solar cells is presented in the context of comparative loss analysis among the**

Experimental and Simulation Cycles

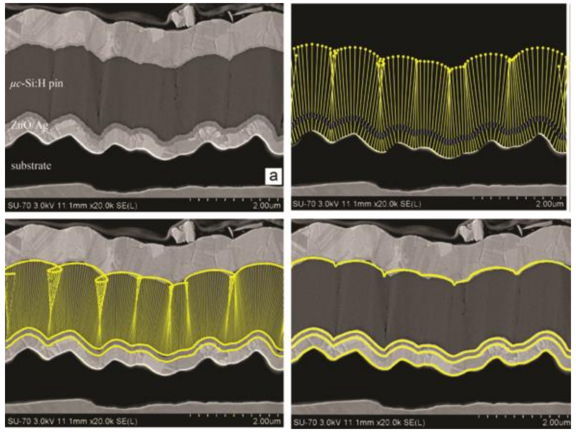


Numerical Modelling and Simulation

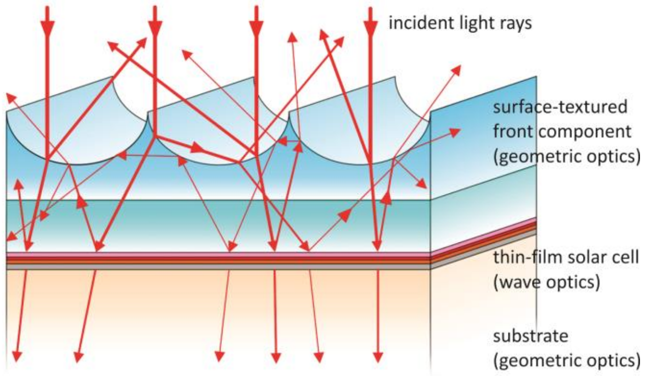
- Optical and electrical simulation of solar cells and other optoelectronic devices
- Combination of different modelling techniques (TMF, FEM, RCWA, RT)
- Development of specialized software for accurate design and optimization of inorganic and organic solar cells and photovoltaic modules (Sun*Shine*, FEMOS, CROWM, ASPIN2)



FEM simulation of a thin-film solar cell (results show A in each layer)



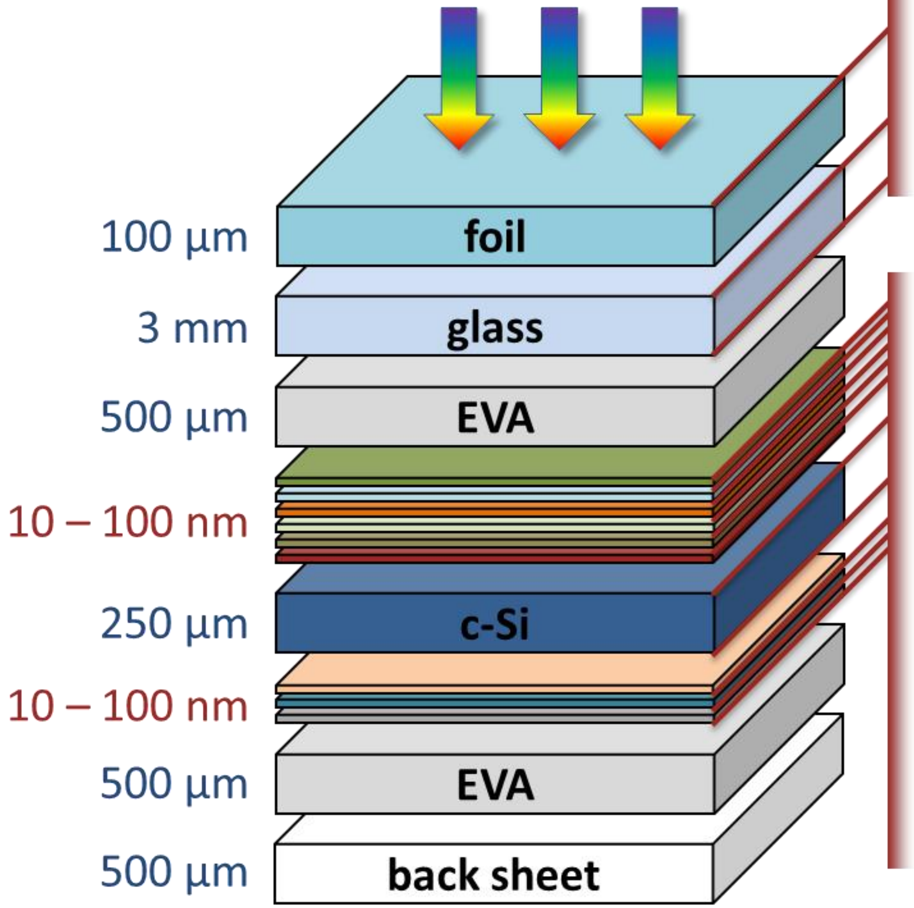
Non-conformal layer growth model for accurate simulation of nano-textured multi-layer solar cells

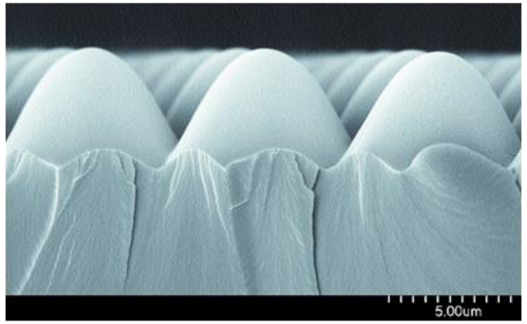


Combined geometric optics / wave optics model (CROWM) for simulation of micro-textured TFSC

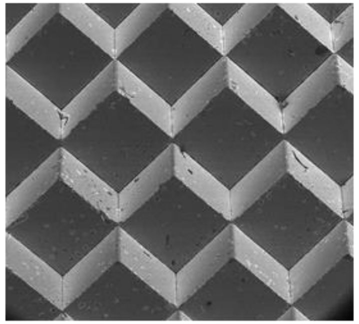
Optical modelling of modern PV devices

- Interface textures

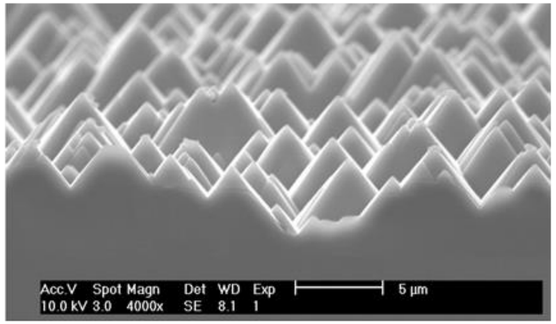


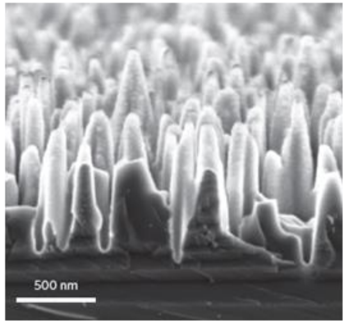


[HT-MLA-09, Holotools, Germany]

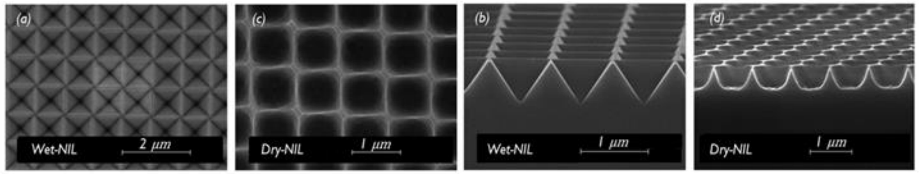


[C. Ulbrich et al., PIP, 2012]





[H. Savin et al., Nature Nanotechnology, 2015]

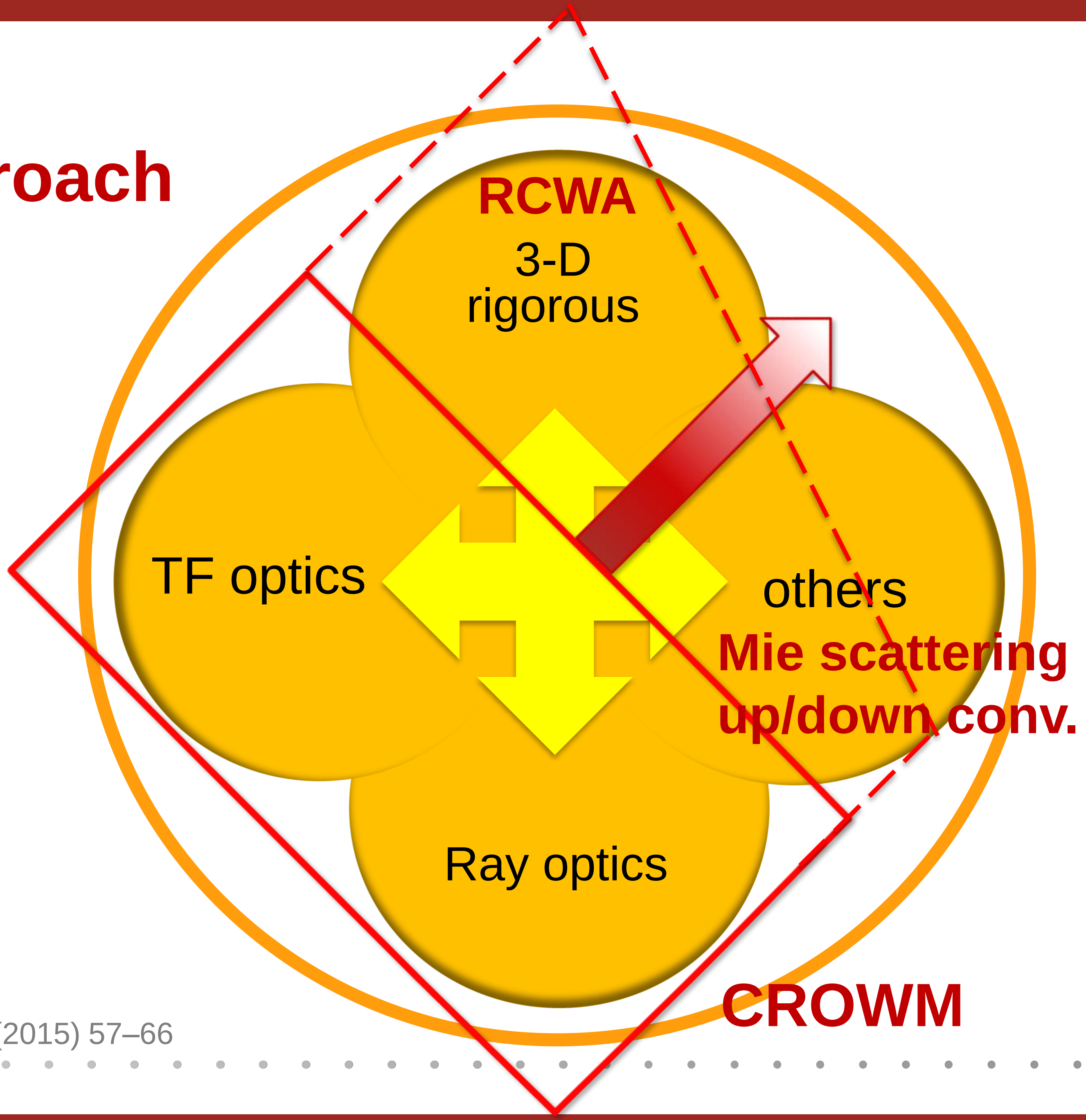


[C. Trompoukis et al., PIP, 2015]

Coupled modelling approach - CMA

Optical modelling for high efficiency solar cells

to take the advantage of accuracy and speed

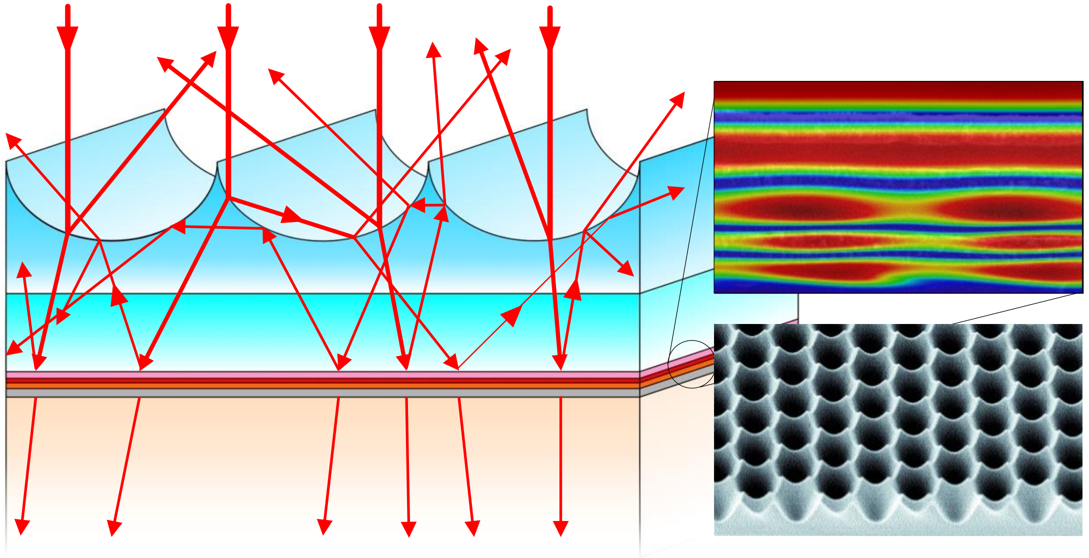


M. Topič et al., Solar Energy Materials and Solar Cells 135 (2015) 57–66

Simulator CROWM

(Combined Ray-Optics Wave-Optics Model)

http://lpvo.fe.uni-lj.si/en/software

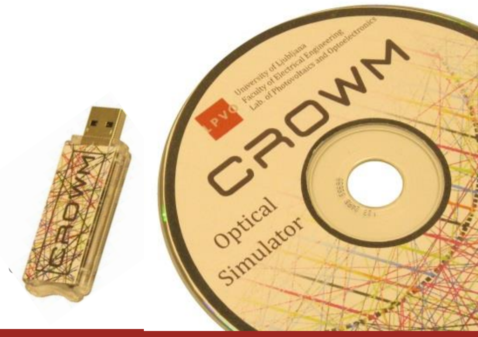


RAY TRACING
- textured superstrate
- 2D geometric optics
- incoherent propagation
- periodic boundary condition

~ 10 - 10000 μm (layer thickness, texture features)

TRANSFER MATRIX FORMALISM
- flat multi-layer optoelectronic device
- 1D wave optics
- coherent propagation

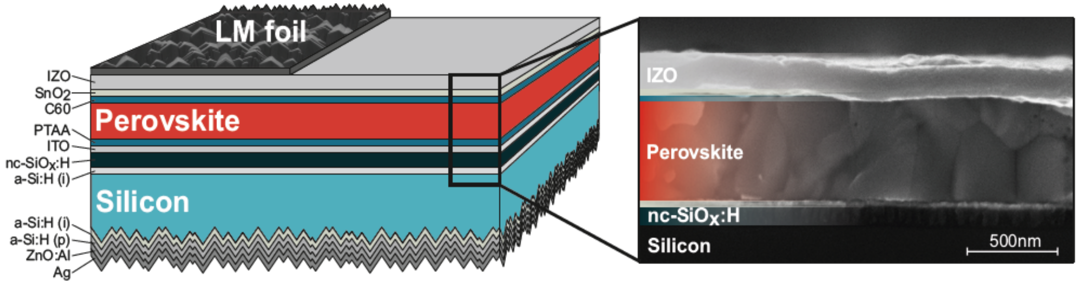
~ 0.01 - 10 μm (layer thicknesses)



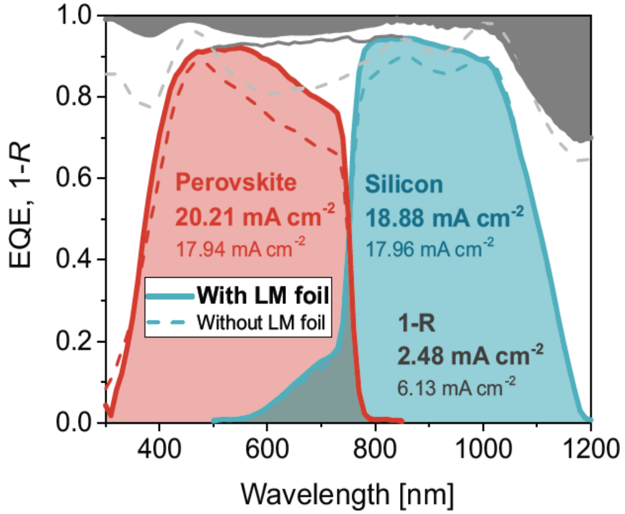
B. Lipovšek et al., Informacije MIDEM 41 (2011) 264-271.
B. Lipovšek et al., IEEE Journal of Photovoltaics 4 (2014) 639-646.

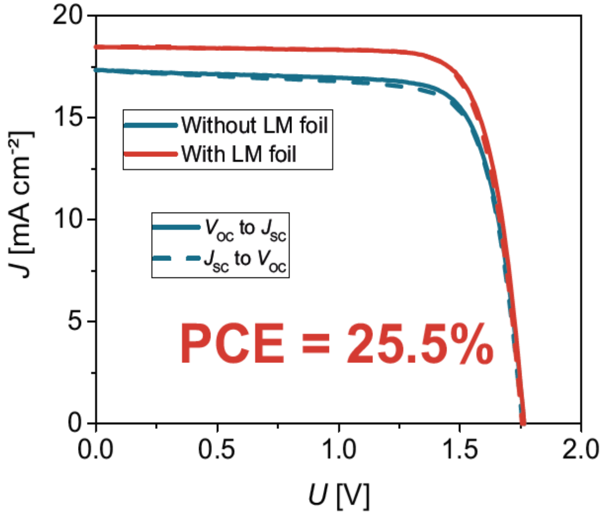
Tandem perovskite/Si solar cell

- Monolithic perovksite/silicon heterojunction (SHJ) tandem solar cell
- Bottom cell: back-side textured SHJ with nc-SiO_x:H front surface field
- Top cell: p-i-n type design with „triple cation“ absorber $Cs_{0.05}(MA_{0.17}FA_{0.83})Pb_{1.1}(I_{0.83}Br_{0.17})_3$
- Light Management (LM) from textured foil on a glass substrate[2] - resembling module integration



Illumination conditions		J_{SC} [mA cm^{-2}]	V_{OC} [V]	FF [%]	PCE [%]	PCE_{MPP} [%]
Mask area = active area	W/o LM foil	17.3	1.76	76.4	23.4	23.4
	With LM foil	18.5	1.76	78.5	25.5	
Mask area > active area	W/o LM foil	17.1	1.76	78.6	23.7	
	With LM foil	19.4	1.76	77	26.5	26.5

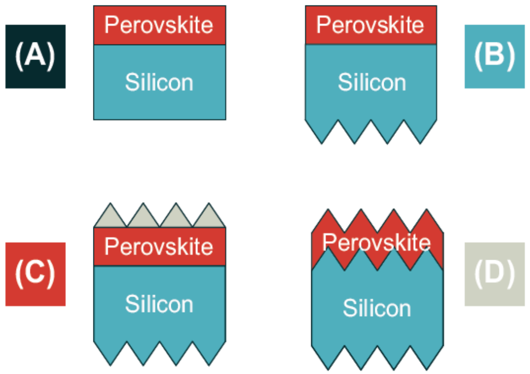




M. Jošt et al. Energy & Environmental Science **11** (2018) 3511–3523.

Tandem perovskite/Si solar cell

- Texture position comparison
  - Flat device **(A)** [4]
  - Back-side c-Si texture **(B)**
  - Back-side c-Si texture with LM foil **(C)**
  - Both-sided c-Si texture (D)
- Perovskite thickness fixed at 1000 nm, altering perovskite bandgap to reach the current-matching
- $V_{OC} = V_{OC,Si} + V_{OC,\,pero}$ = 710 mV + E_g/q - 400 mV [5]



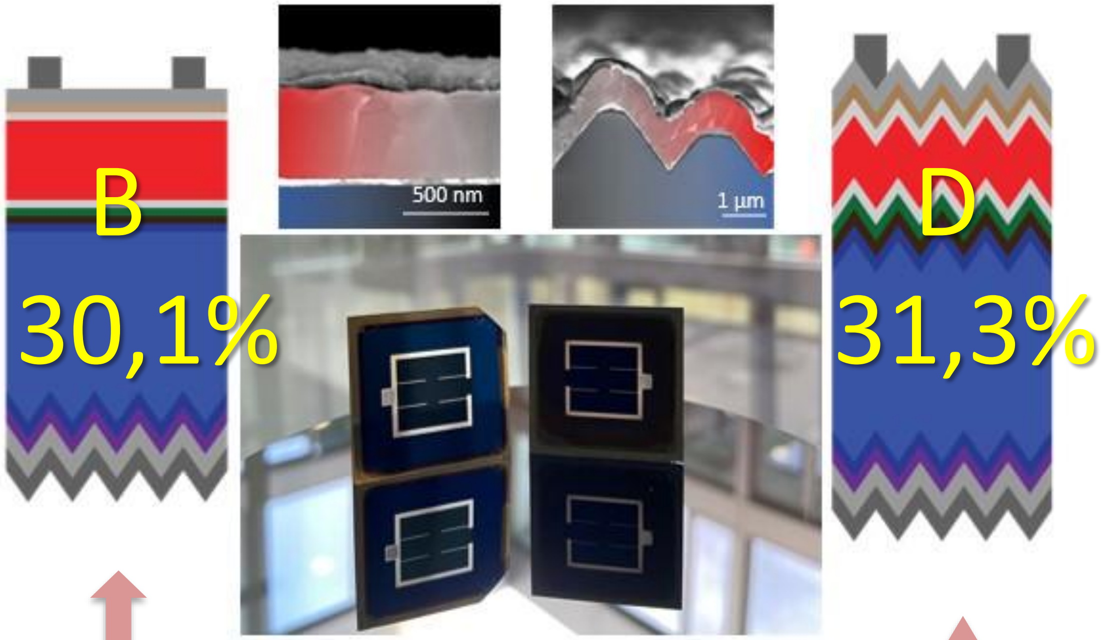
Device design	E_g opt. [eV]	J_{SC_SIM} [mA cm^{-2}]	V_{OC} [V]	FF [%]	PCE [%]
(A)	1.69	19.07	2.00	80	30.5
(B)	1.65	20.01	1.96	80	31.4
(C)	1.66	19.97	1.97	80	31.5
(D)	1.66	20.56	1.97	80	32.5

M. Jošt et al. Energy & Environmental Science **11** (2018) 3511–3523.

Tandem perovskite/Si solar cell

JULY 7, 2022

EPFL AND CSEM SMASH THROUGH THE 30% EFFICIENCY BARRIER FOR PEROVSKITE-ON-SILICON-TANDEM SOLAR CELLS—SETTING TWO CERTIFIED WORLD RECORDS.



https://www.csem.ch/page.aspx?pid=172296

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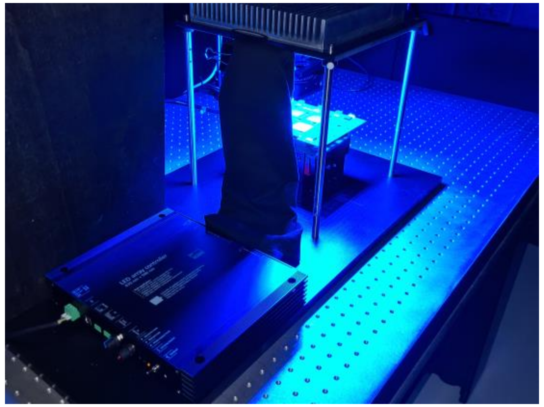
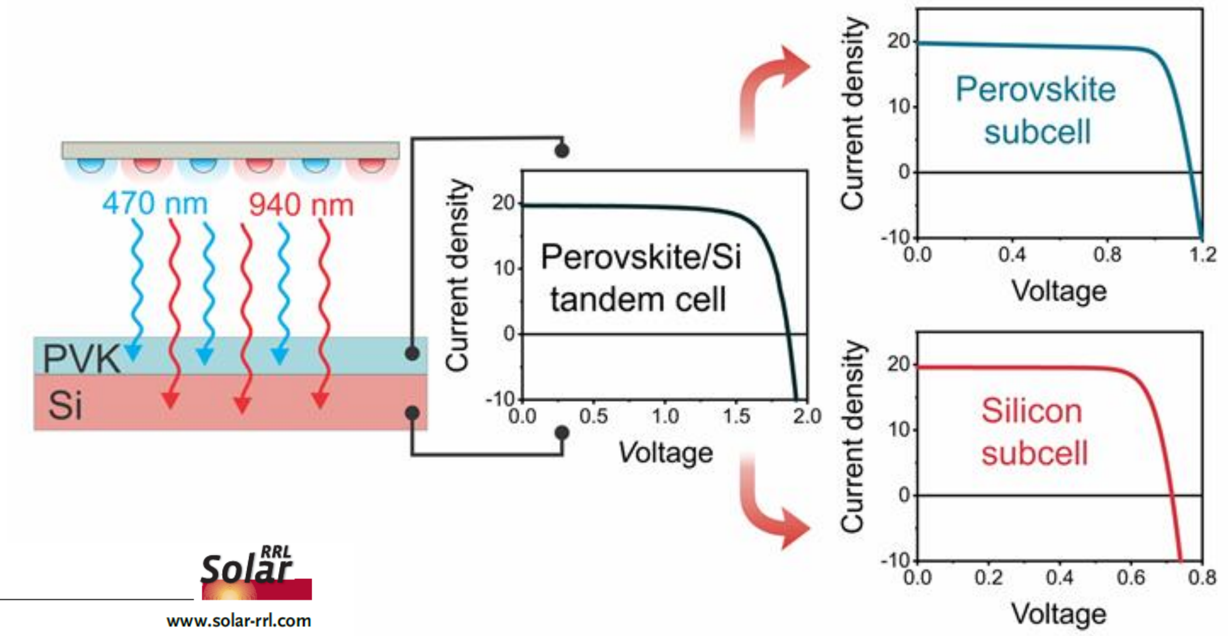
M. Jošt et al. Energy & Environmental Science **11** (2018) 3511–3523.

Method for subcell analysis in 2T tandem solar cells





RESEARCH ARTICLE

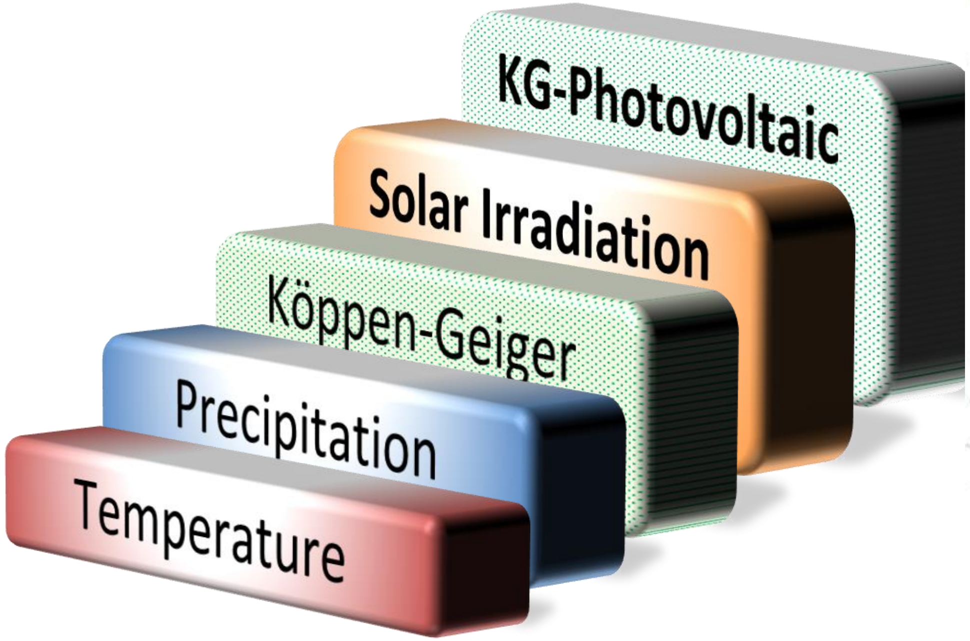
Solar RRL
www.solar-rrl.com

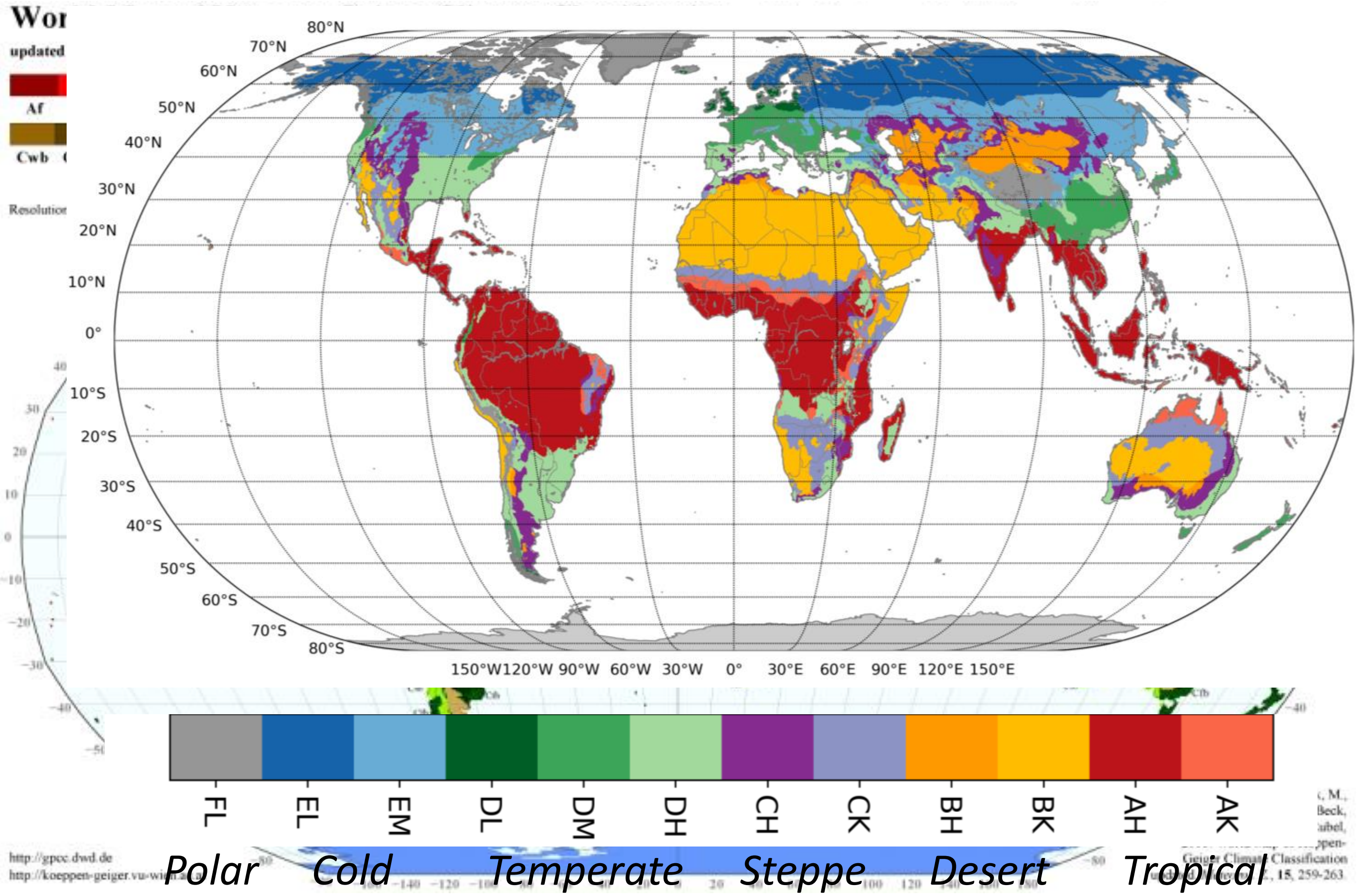
Subcell Operation and Long-Term Stability Analysis of Perovskite-Based Tandem Solar Cells Using a Bichromatic Light Emitting Diode Light Source

Marko Jošt, Gašper Matič, Eike Köhnen, Bor Li, Boštjan Glažar, Marko Jankovec, Steve Albrecht, and Marko Topič**

M. Jošt et al., Solar RRL, Aug. 2021, 2100311, str. 1-8. doi: 10.1002/solr.202100311.

Köppen-Geiger-Photovoltaic (KGPV) Climate Classification



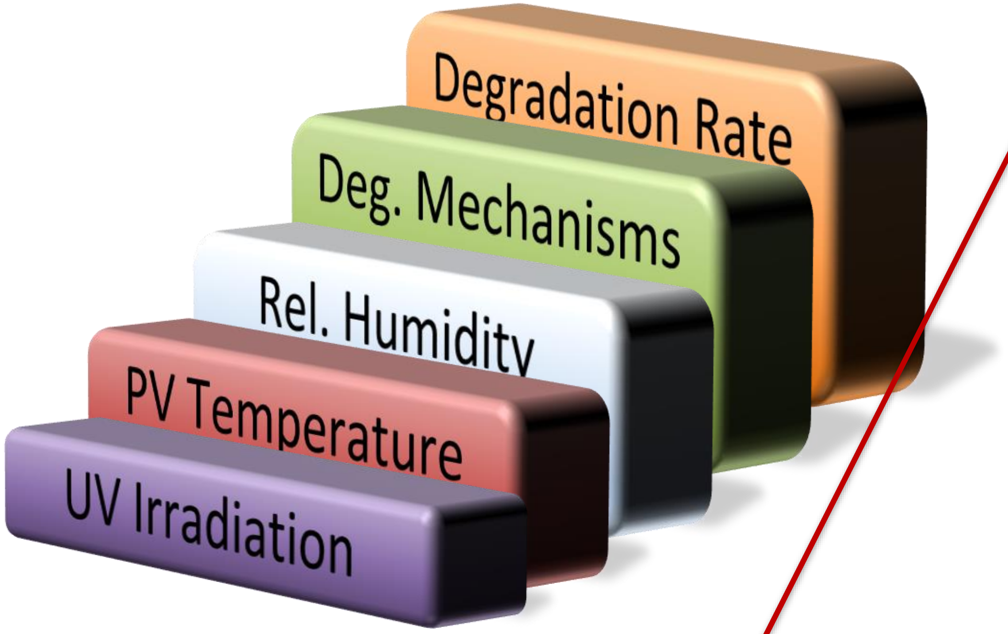


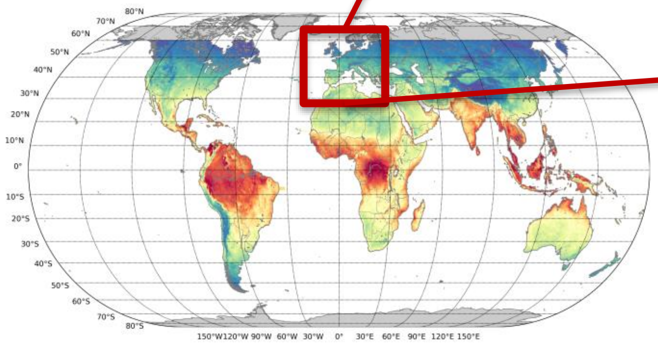
Irradiation Zones – L : Low, M: Medium, H: High, K: Very High

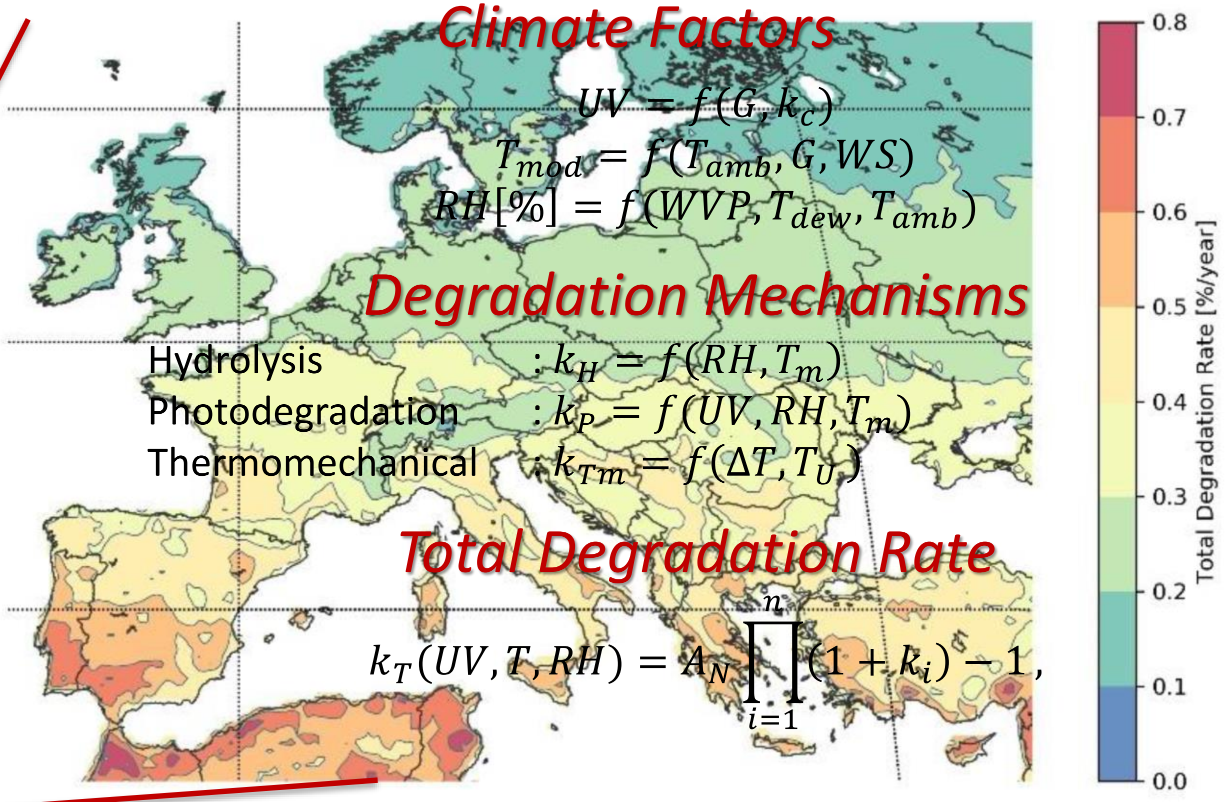
M. Kottek et al., Meteorol. Z., 2006

J. Ascencio-Vásquez, K. Brecl, M. Topič, Solar Energy, 2019

Global PV Module Degradation Rates

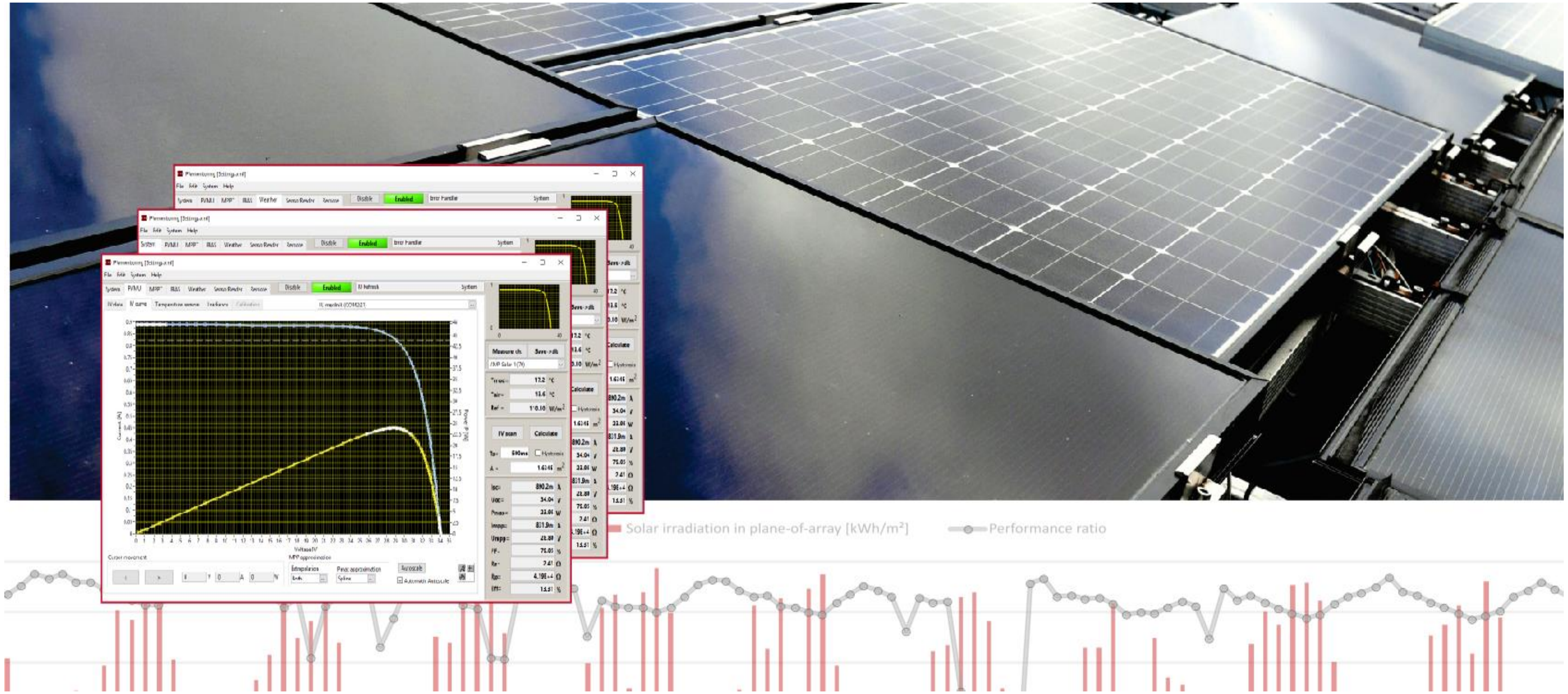






J. Ascencio-Vásquez, K. Brecl, M. Topič, Energies, 2019
I. Kaaya, J. Ascencio-Vásquez, K.-A. Weiss, M. Topič, IEEE JPV, 2019

Outdoor monitoring of PV modules



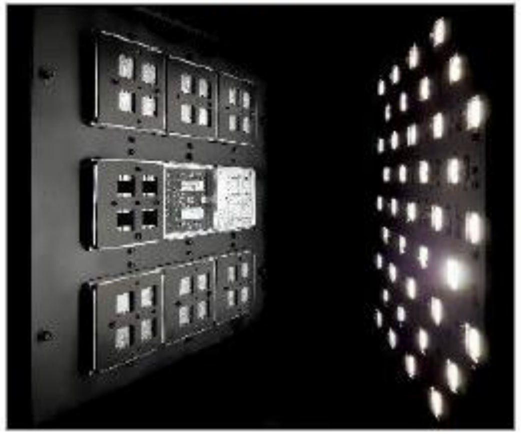
Made in LPVO

Booth E5: Laboratory of Photovoltaics and Optoelectronics

BCLED

24 channel system
for tandem cells

WLED

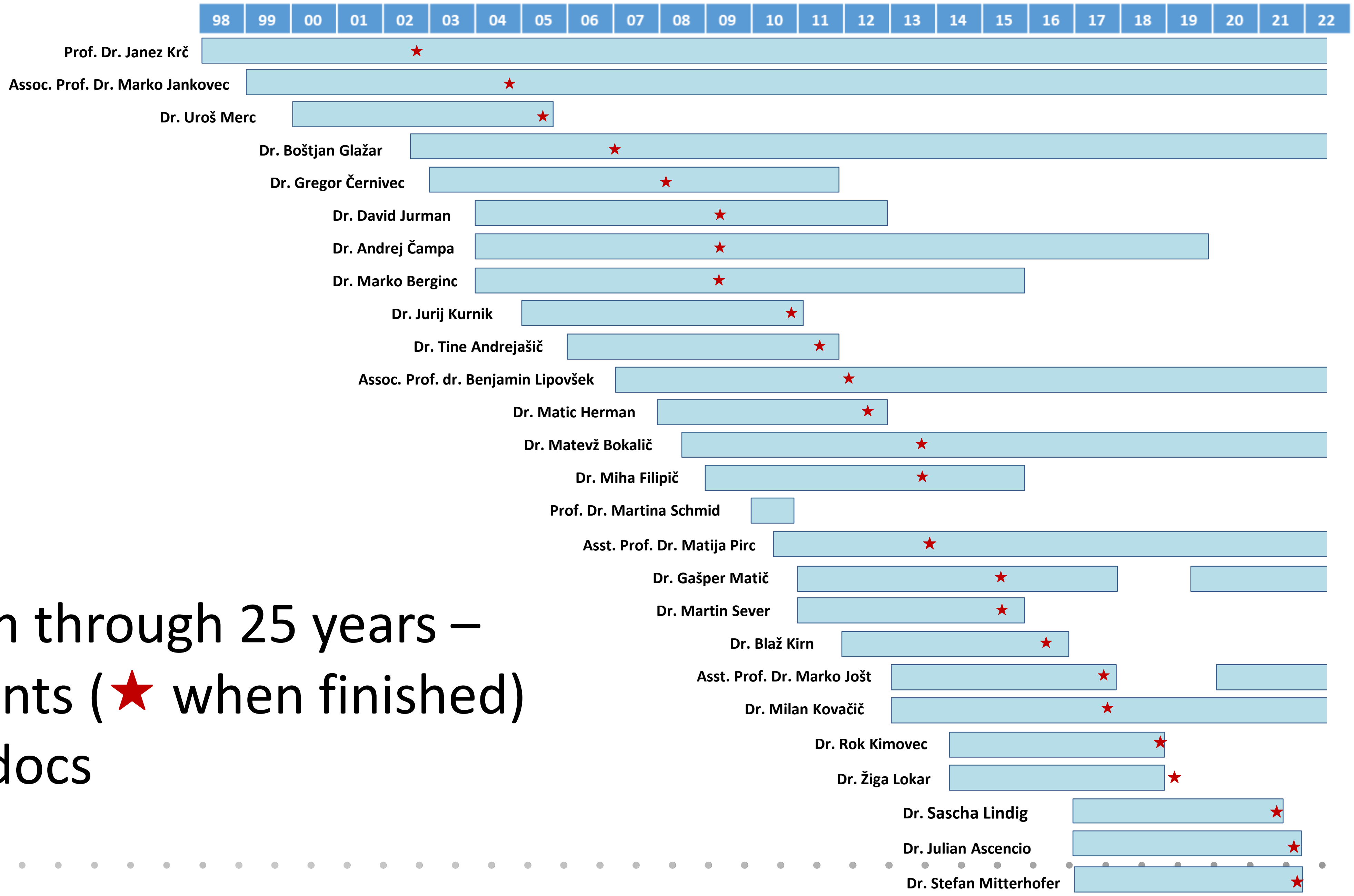


216 channel system
for single cells

550 W MPP TRACKER

16 channel system
for full-size PV modules

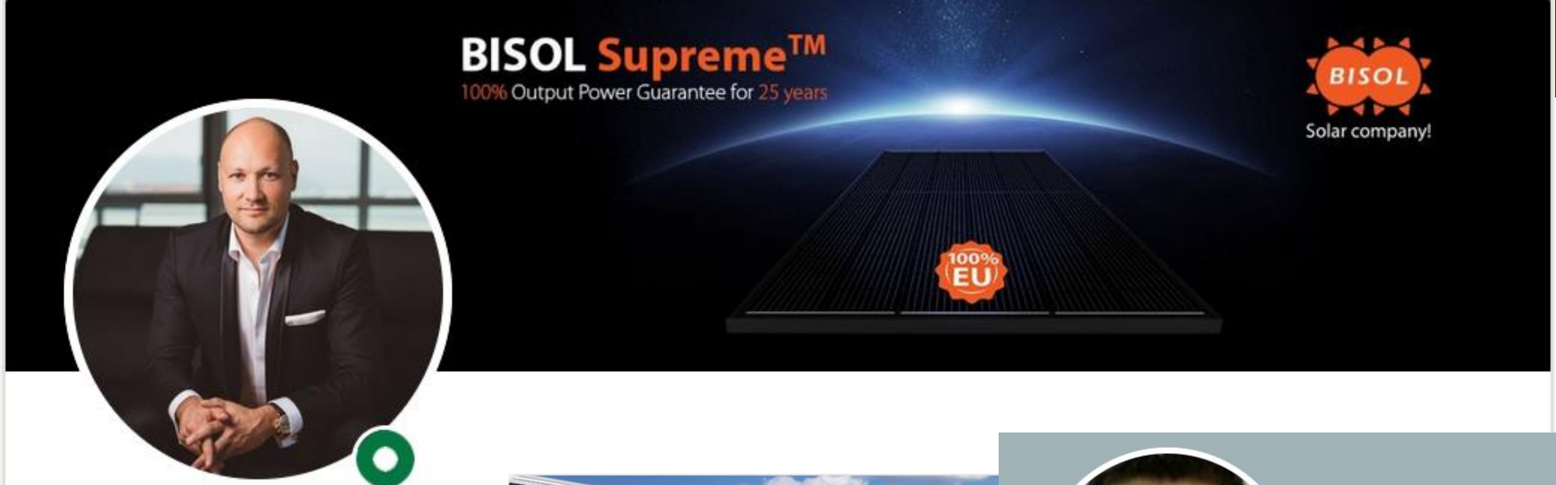
Berlaymont , 22 Jan 2020
Timmermans cabinet (12th floor)



LPVO team through 25 years – PhD students (★ when finished) and post-docs

Rok Kimovec · 1st
R&D Engineer

Julián Ascencio-Vásquez · 1st
Sr. R&D Consultant - PV Expert | Modelling | Big Data | Member IEA PVPS



Dr Uros Merc · 1st
President at BISOL Group

Tine Andrejasic · 1st
Head of Developement @ REC d.o.o.

Stefan Mitterhofer · 1st
Guest Researcher at National Inst Standards and Technology (NIST)

Miha Filipič · 1st
Programmer | Researcher | Electrical Engineer

Andrej Campa · 1st
R&I Manager at ComSensus, PhD in Electrical Engineering

Dr. Gregor Černivec · 1st
Head of R&D at Bosch Rexroth d.o.o., Skofja Loka

Martin Sever · 1st
Development Engineer at RLS Merilna tehnika d. o. o.

Matic Herman · 1st
Head of hardware development at Sentinel Marine Solutions

Berginc Marko · 2nd
Senior metrologist and head of research in metrology department at SIQ

David Jurman · 1st
R&D electronics engineer at Win Systems d.o.o.

What a Landatio!

Thank you, Rutger!

PhotoVoltaic
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climate neutrality ✓
reduced energy dependency ✓

We need to act NOW!
We need to act FAST!

www.etip-pv.eu/publications/sria-pv/


Photovoltaics

Acknowledgement:

ETIP PV
Steering Committee
and Secretariat

LPVO team

many friends and
colleagues in PV

Thank you for your attention!

arrs
SLOVENIAN RESEARCH AGENCY