Dvořák Lecture at Czech Academy of Sciences FZU
13 June 2023

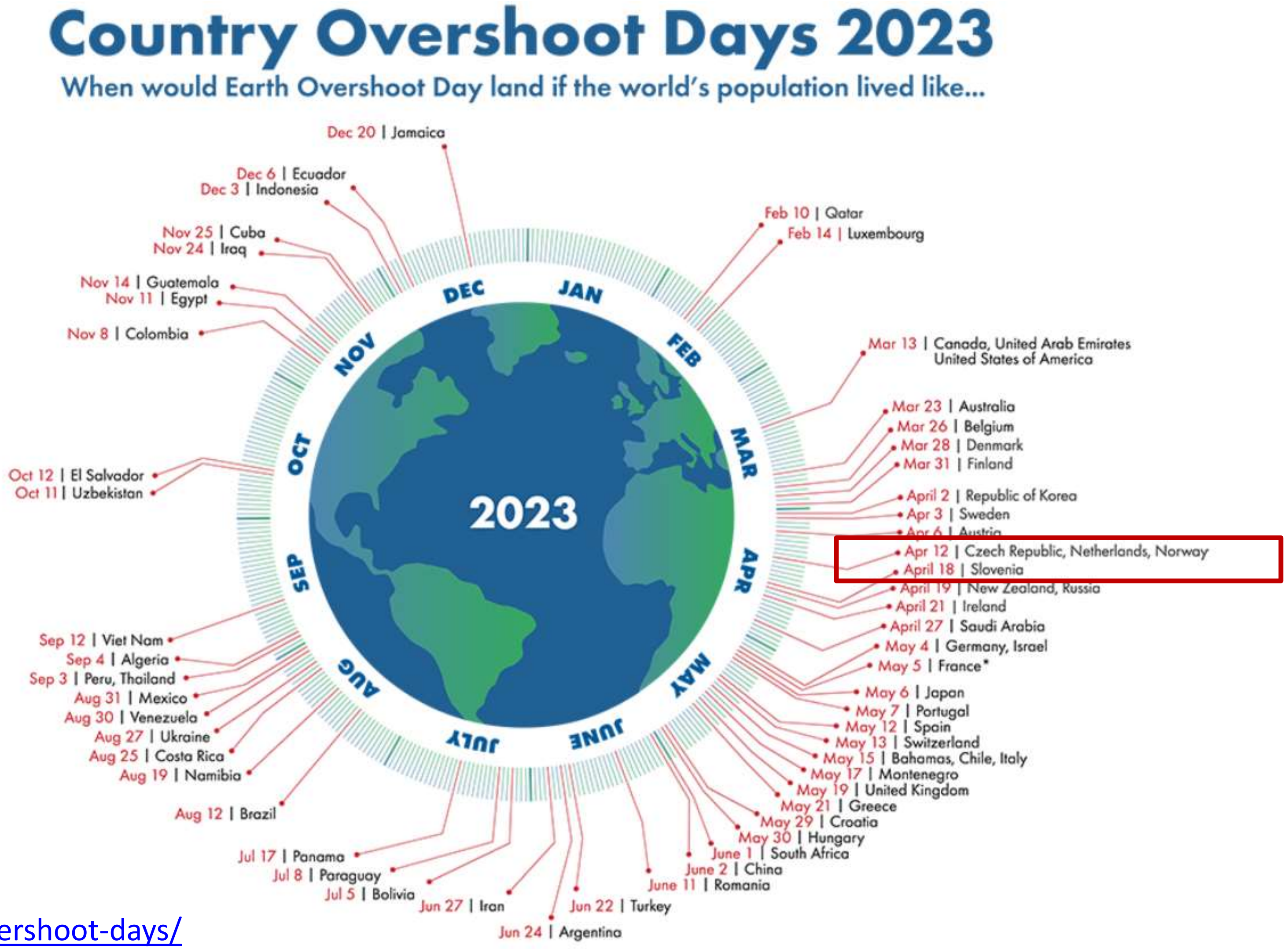
Photovoltaics at Terawatt scale –

Science, Engineering and Technology in Energy Transition

Marko Topič

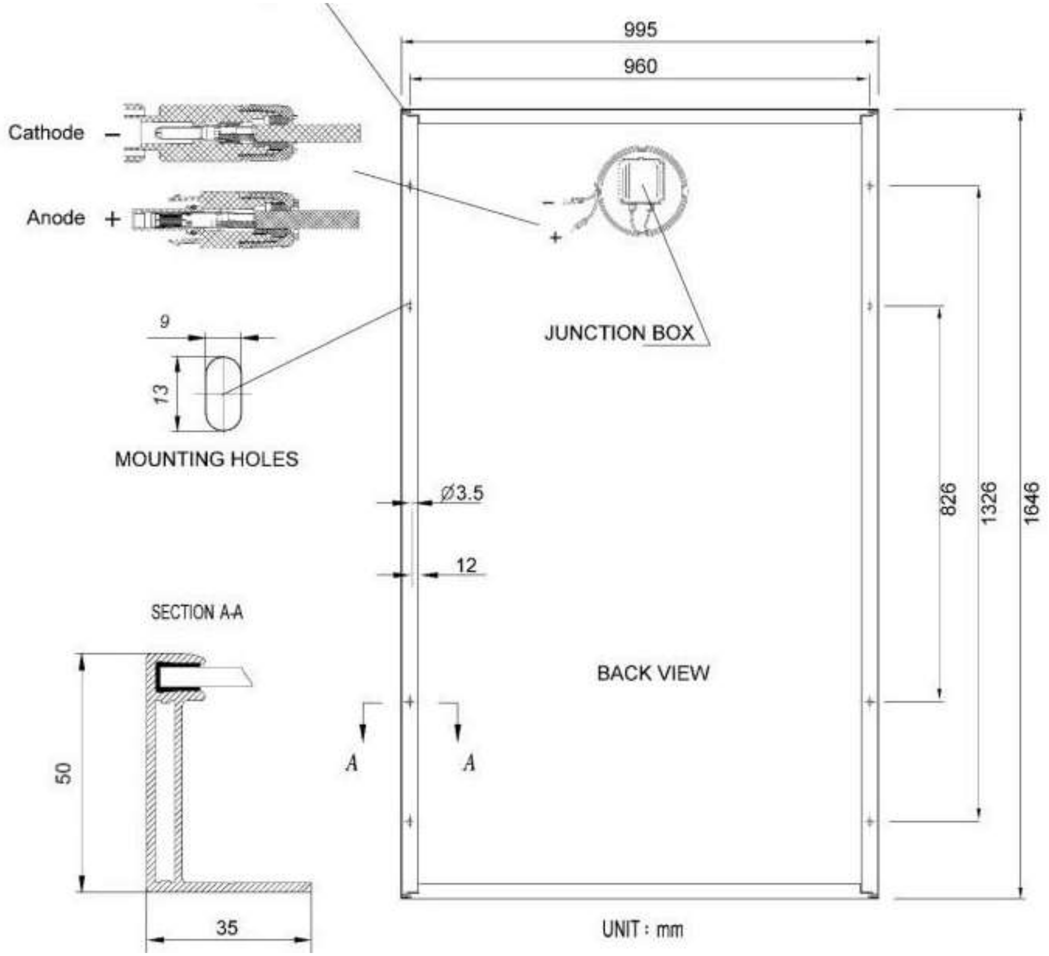
University *of Ljubljana*
Faculty *of Electrical Engineering*
Laboratory *of Photovoltaics and Optoelectronics (LPVO)*

SLOVENSKA AKADEMIJA
ZNANOSTI IN UMETNOSTI



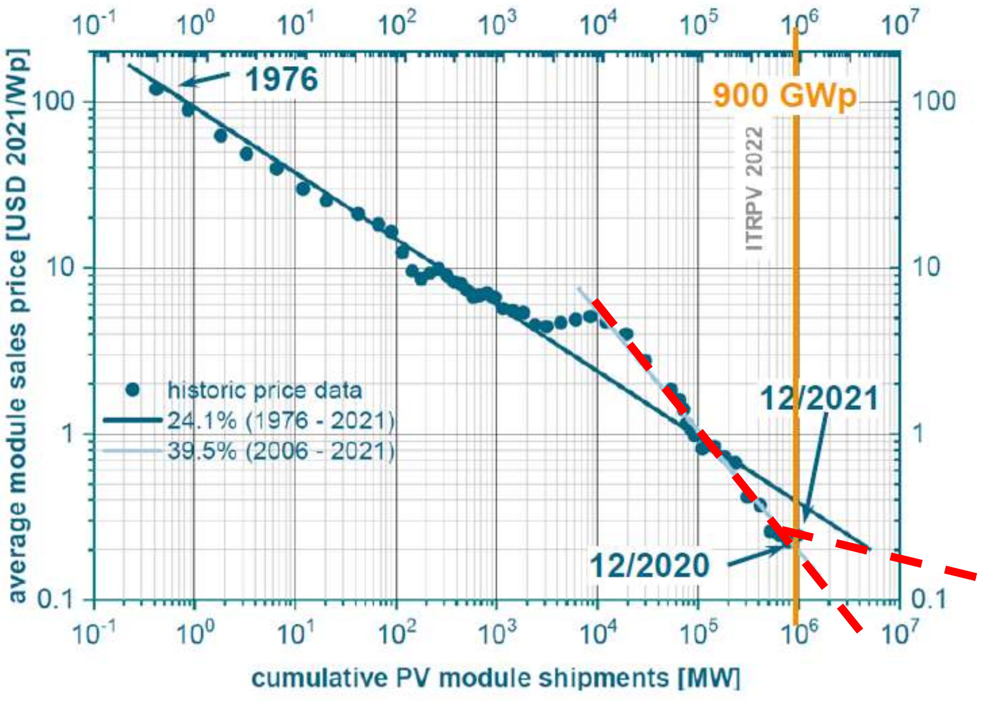
Source: https://www.overshootday.org/newsroom/country-overshoot-days/

0,01 € / kWh


995
960
Cathode –
Anode +
9
13
MOUNTING HOLES
JUNCTION BOX
Ø3.5
12
SECTION A-A
50
35
A
A
BACK VIEW
826
1326
1646
UNIT : mm

PV learning curve

VDMA



Shipments/avg. module spot market price at year end:

ITRPV

2020: 135 GWp / 0.21 US$/Wp
2021: 183 GWp / 0.24 US$/Wp

o/a shipment: ≈ 972 GWp
o/a installation: ≈ 940 GWp

Production capacity end of 2021: ≈ 470 GWp
≈ 95% is c-Si based

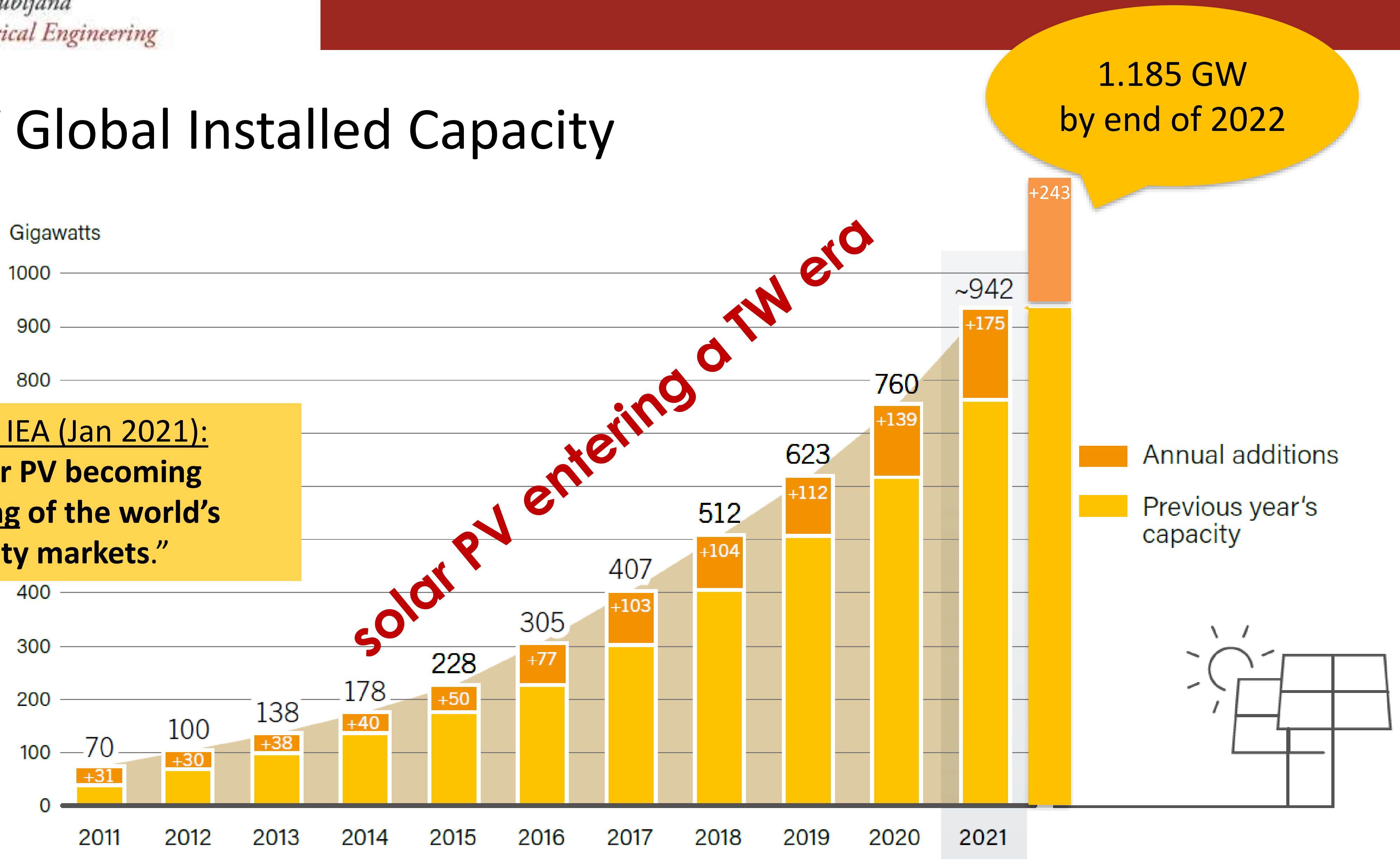
LR ≈ 24.1 % (1976 .... 2021)
LR ≈ 39.5 % (2006 .... 2021)

→ Significant shipment increase in 2021 despite Covid19
→ change in module size continued
→ PERC stays PV workhorse

→ **Price increased significantly**
→ **Further burden due to increased logistic cost**

Source: ITRPV Roadmap Webinar, 14 Apr 2022

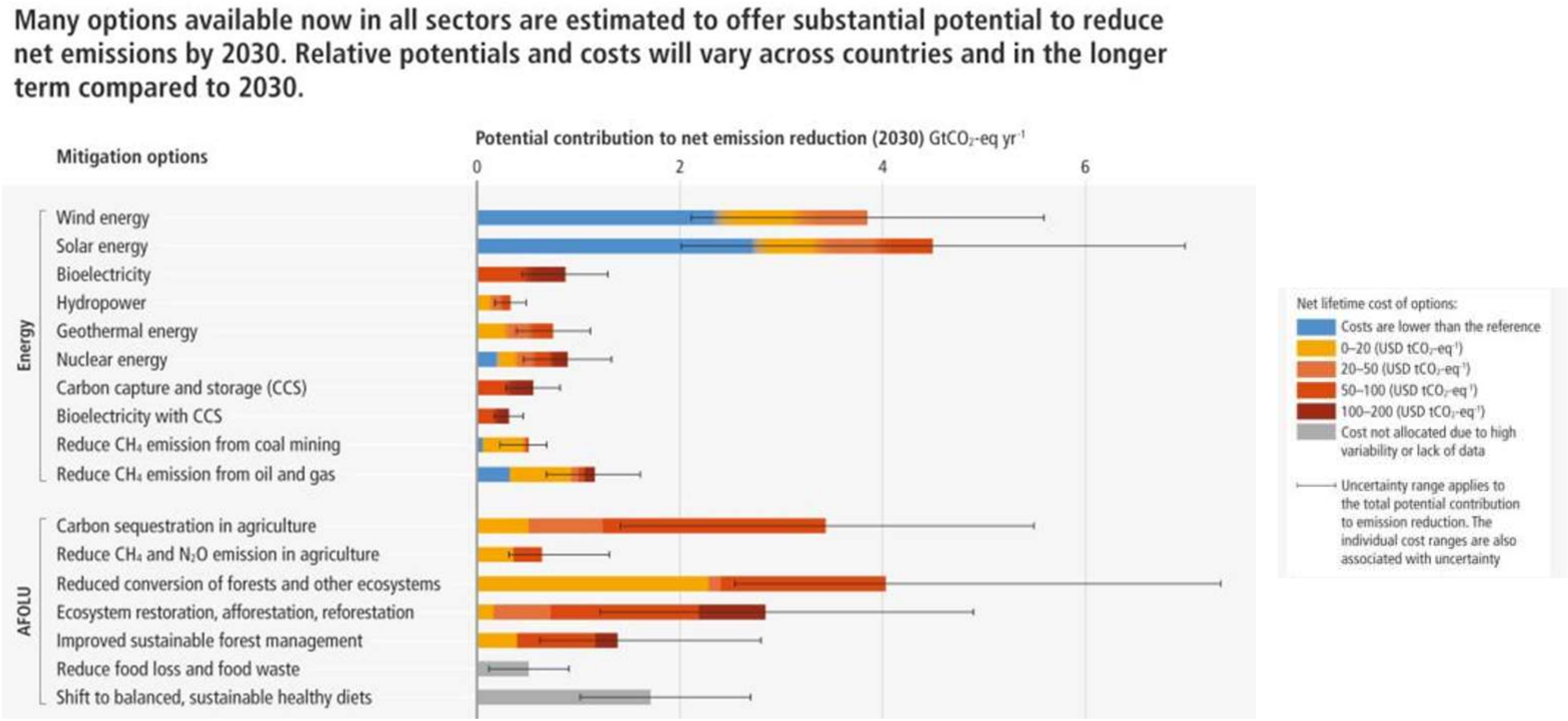
Solar PV Global Installed Capacity



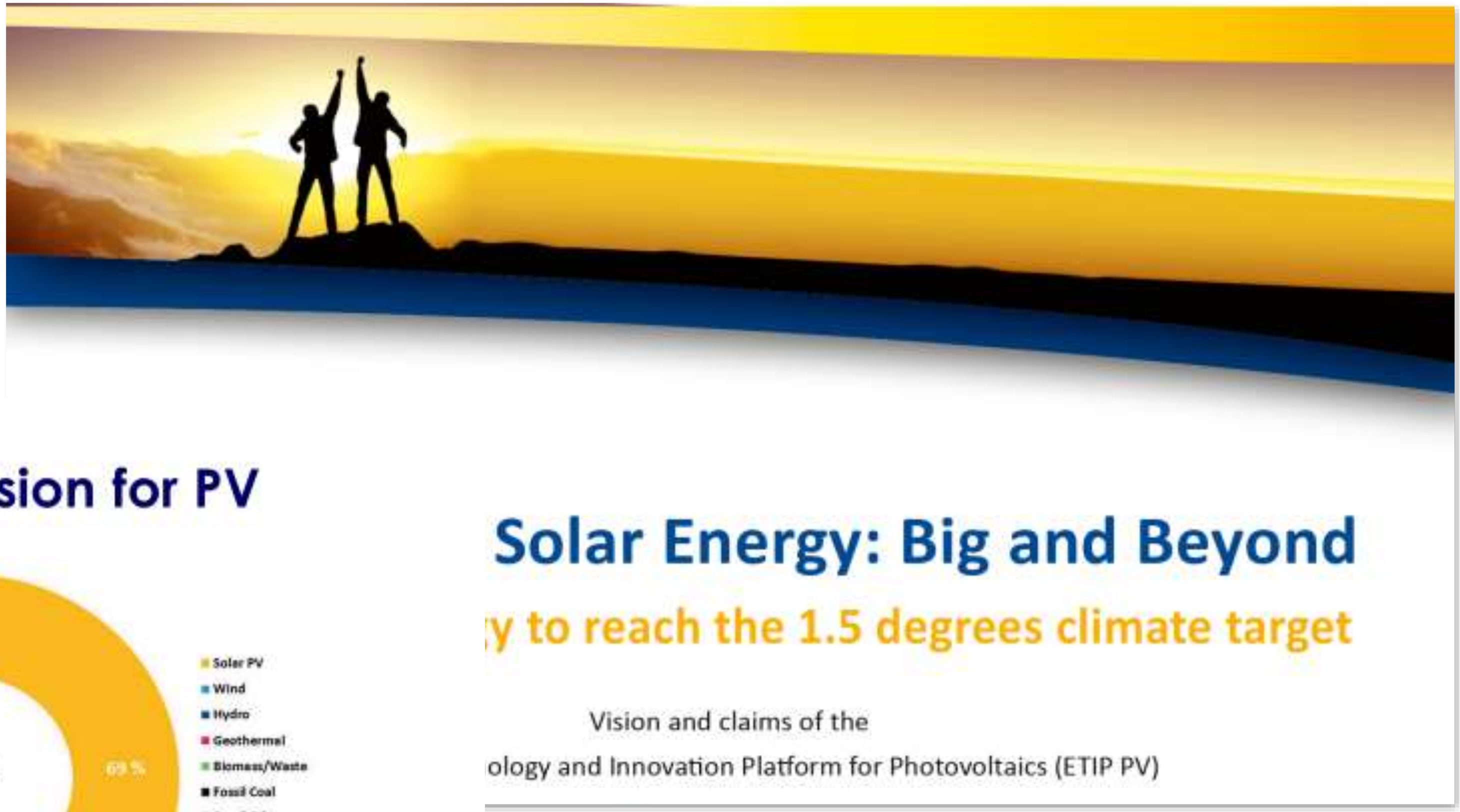
REN21 Renewables 2022 Global Status Report

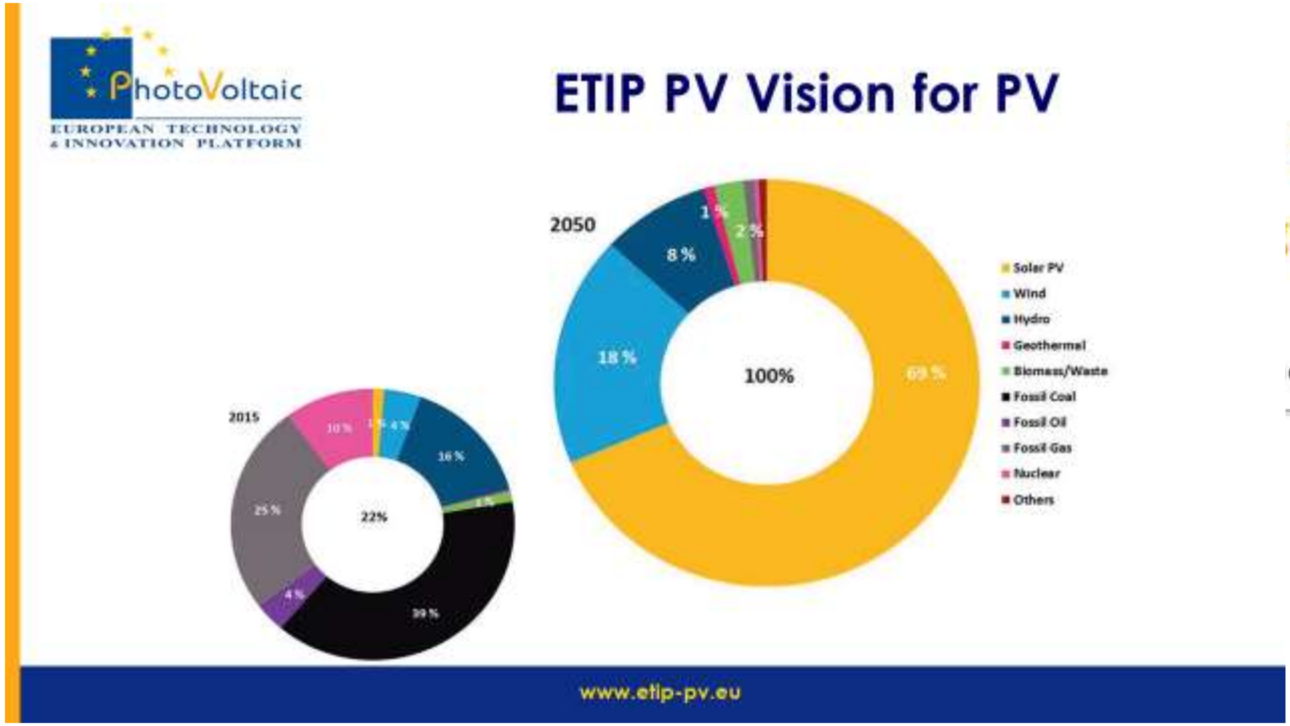
<u>Fatih Birol, IEA (Jan 2021):</u>
"I see **solar PV becoming the new king of the world's electricity markets.**"

Latest IPCC report (4 Apr 2022)



Source: IPCC Report: “Mitigation of Climate Change”, 4 Apr 2022





Published 2019

Science Policy

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POLICY FORUM | RENEWABLE ENERGY

Terawatt-scale photovoltaics: Transform global energy

Nancy M. Haegel, Harry Atwater Jr., Teresa Barnes, Christian Breyer, Anthony Burrell, Yet-Ming Chiang, Stefaan De Wolf, Bernhard Dimmler, David Feldman, Stefan Glunz, Jan Christoph Goldschmidt, David Hochschild, Ruben Inzunza, Izumi Kaizuka, Ben Kroposki, Sarah Kurtz, Sylvere Leu, Robert Margolis, Koji Matsubara, Axel Metz, Wyatt K. Metzger, Mahesh Morjaria, Shigeru Niki, Stefan Nowak, Ian Marius Peters, Simon Philipps, Thomas Reindl, Andre Richter, Doug Rose, Keiichiro Sakurai, Rutger Schlatmann, Masahiro Shikano, Wim Sinke, Ron Sinton, B.J. Stanbery, Marko Topic, William Tumas, Yuzuru Ueda, Jao van de Lagemaat, Pierre Verlinden, Matthias Vetter, Emily Warren, Mary Werner, Masafumi Yamaguchi, Andreas W. Bett

Author affiliations are listed in the supplementary materials.

Email: nancy.haegel@nrel.gov

- Hide authors and affiliations

Science 31 May 2019:
Vol. 364, Issue 6443, pp. 836-838
DOI: 10.1126/science.aaw1845

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HOME > SCIENCE > VOL. 380, NO. 6640 > PHOTOVOLTAICS AT MULTI-TERAWATT SCALE: WAITING IS NOT AN OPTION

POLICY FORUM | RENEWABLE ENERGY

Photovoltaics at multi-terawatt scale: Waiting is not an option

25% annual PV growth is possible over the next decade

NANCY M. HAEGEL , PIERRE VERLINDEN, MARTA VICTORIA, PIETRO ALTERMATT, HARRY ATWATER, TERESA BARNES, CHRISTIAN BREYER, CHRIS CASE, STEFAAN DE WOLF, CHRIS DELINE, MARWAN DHARMRIN, BERNHARD DIMMLER, MARKUS GLOECKLER, JAN CHRISTOPH GOLDSCHMIDT, BRETT HALLAM, SOPHIA HAUSSENER, BURKHARD HOLDER, ULRICH JAEGER, ARNULF JAEGER-WALDAU, IZUMI KAIZUKA, HIROSHI KIKUSATO, BENJAMIN KROPOSKI, SARAH KURTZ, KOJI MATSUBARA, STEFAN NOWAK, KAZUHIKO OGIMOTO, CHRISTIAN PETER, IAN MARIUS PETERS, SIMON PHILIPPS, MICHAEL POWALLA, UWE RAU, THOMAS REINDL, MARIA ROUMPANI, KEIICHIRO SAKURAI, CHRISTIAN SCHORN, PETER SCHOSSIG, RUTGER SCHLATMANN, RON SINTON, ABDELILAH SLAOUI, BRITTANY L. SMITH, PETER SCHNEIDEWIND, BJ STANBERY, MARKO TOPIC, WILLIAM TUMAS, JUZER VASI, MATTHIAS VETTER, EICKE WEBER, A. W. WEEBER, ANKE WEIDLICH, DIRK WEISS, AND ANDREAS W. BETT fewer Authors Info & Affiliations

SCIENCE • 6 Apr 2023 • Vol 380, Issue 6640 • pp. 39-42 • DOI: 10.1126/science.adf6957

A major renewable-energy milestone occurred in 2022: Photovoltaics (PV) exceeded a global installed capacity of 1 TW_{dc}. But despite considerable growth and cost reduction over time, PV is still a small part of global electricity generation (4 to 5% for 2022), and

CURRENT ISSUE

Transforming the understanding of brain immunity

BY GIULIA CASTELLANI, TOMMASO CROESE, ET AL.

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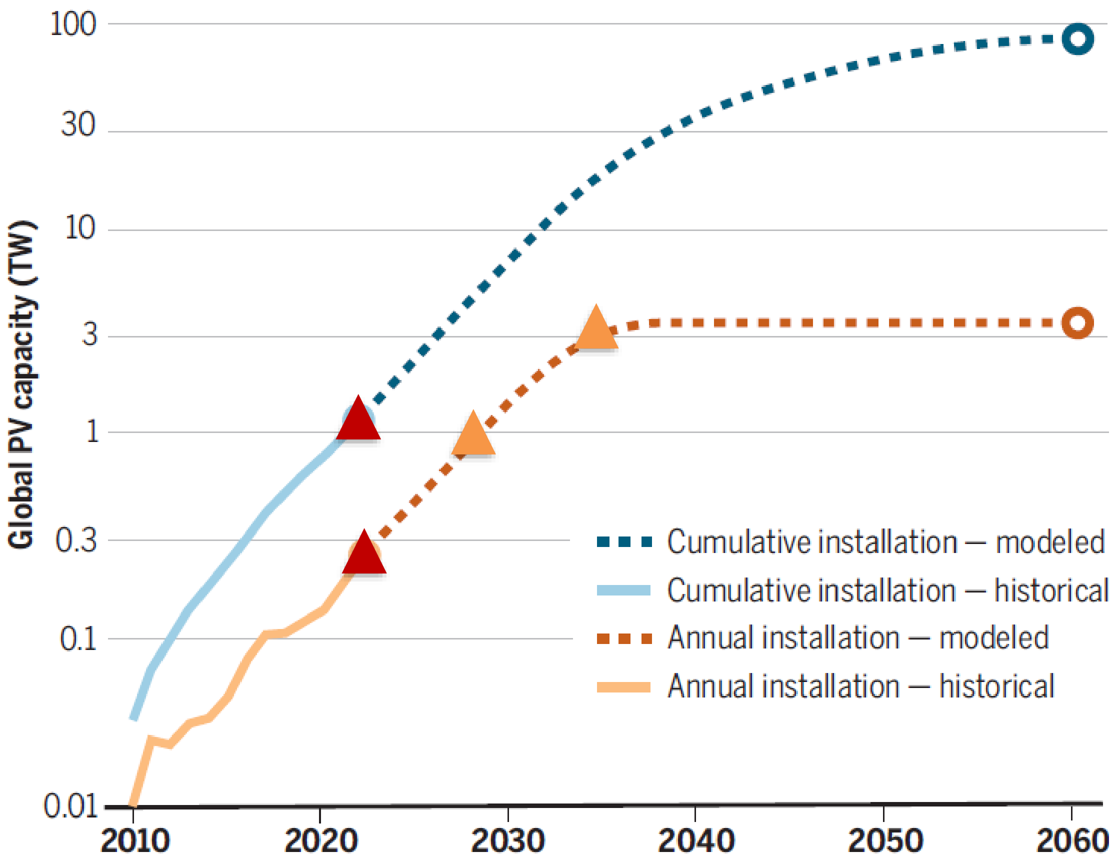
POLICY FORUM RENEWABLE ENERGY

Photovoltaics at multi-terawatt scale: Waiting is not an option

25% annual PV growth is possible over the next decade

PV installations and growth toward 75 TW by 2050

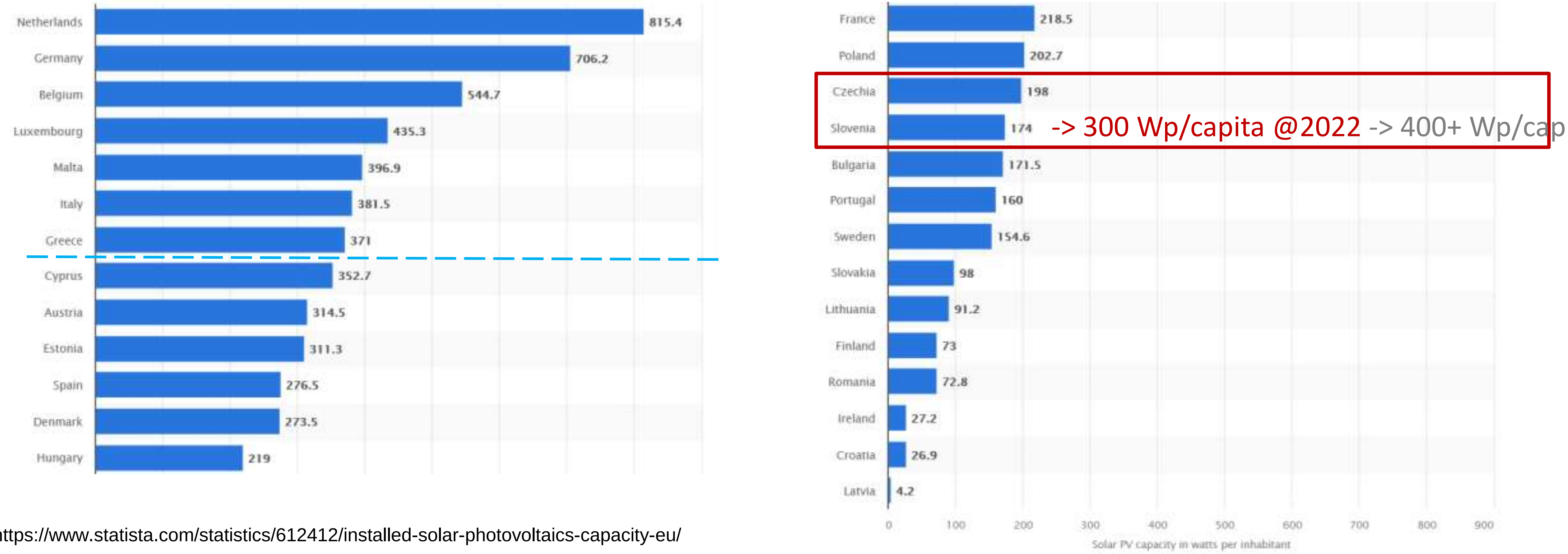
Modeled cumulative capacity going forward is based on sustaining 25% production rate growth over the next 7 years and then reducing slowly to steady state. Replacement needs are included by simple subtraction of installations 25 years before the modeled date.



Source: https://www.science.org/doi/10.1126/science.adf6957

Installed PV power in Wp/capita in EU (2021)

EU-27: *355 Watts per capita*

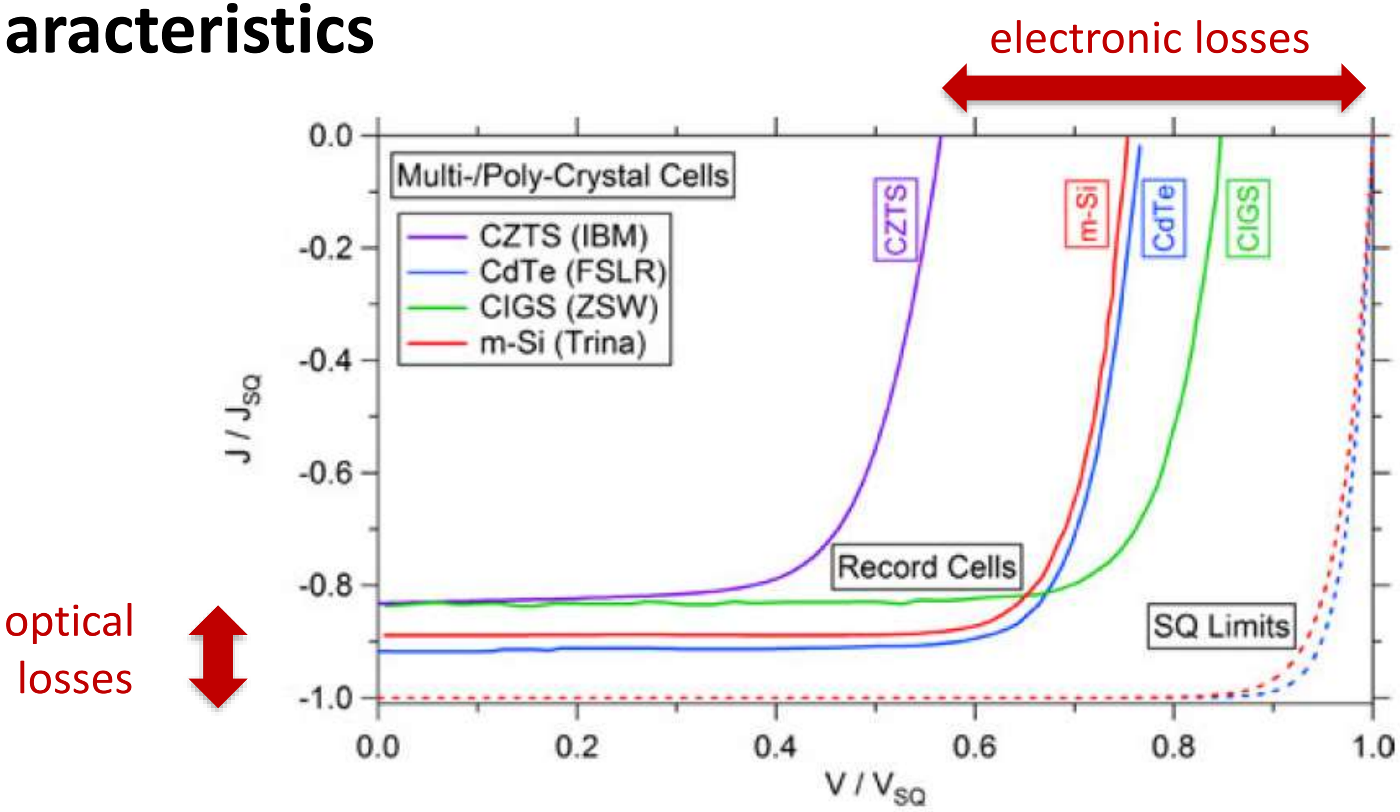


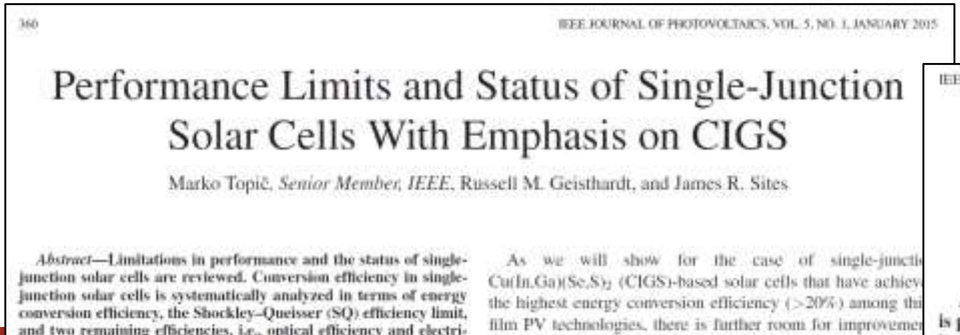
https://www.statista.com/statistics/612412/installed-solar-photovoltaics-capacity-eu/

AURORA

ŠEK
ŠTUDENTSKI ENERGETSKI KLUB
www.s3k.si

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





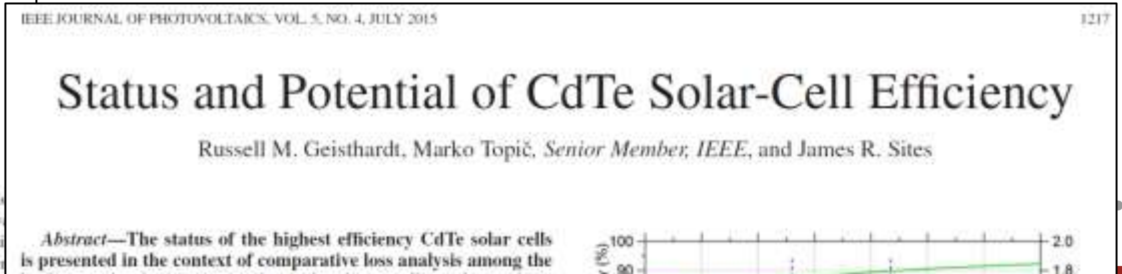
360 IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 5, NO. 1, JANUARY 2015

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...



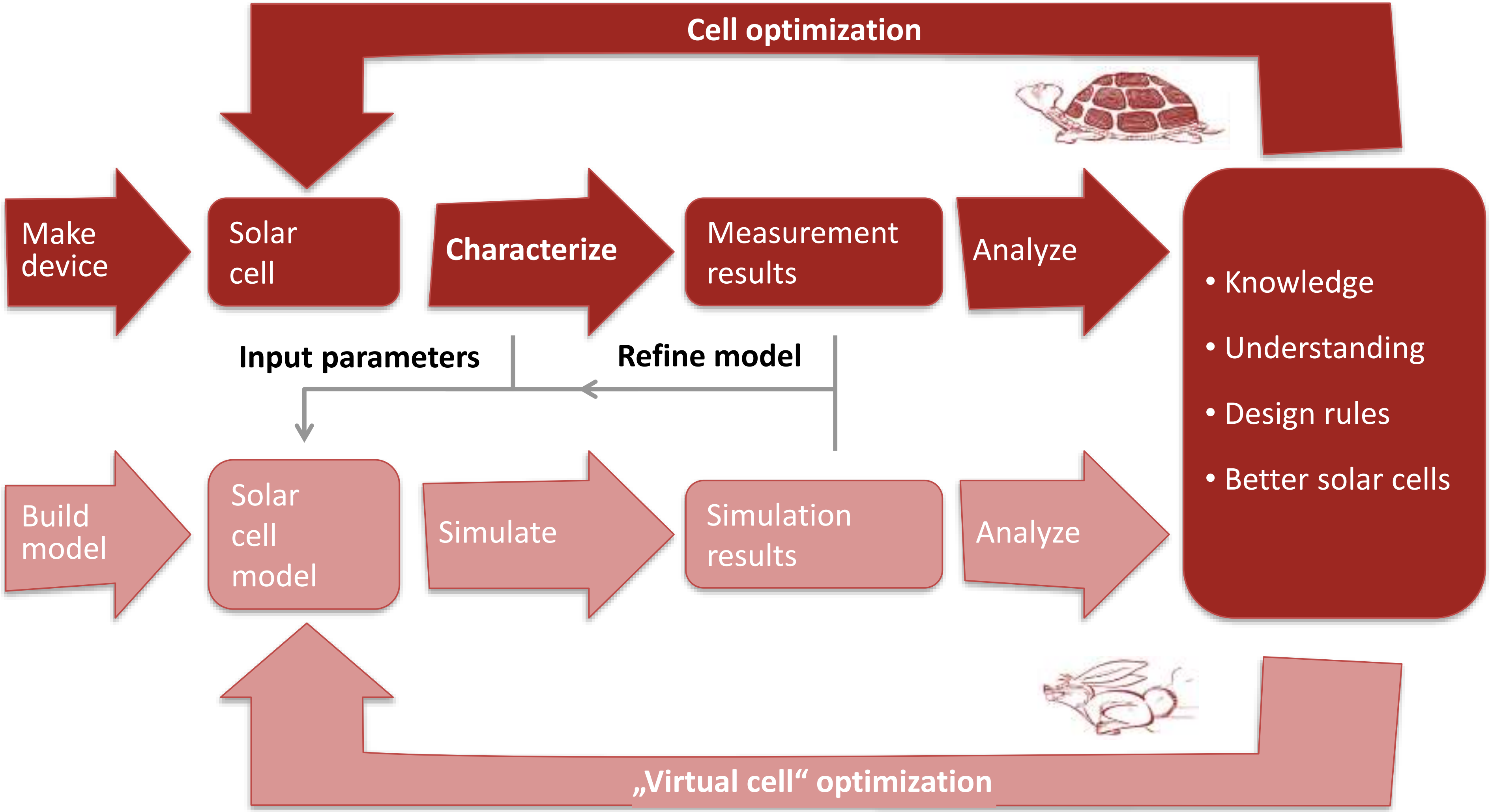
IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 5, NO. 4, JULY 2015 1217

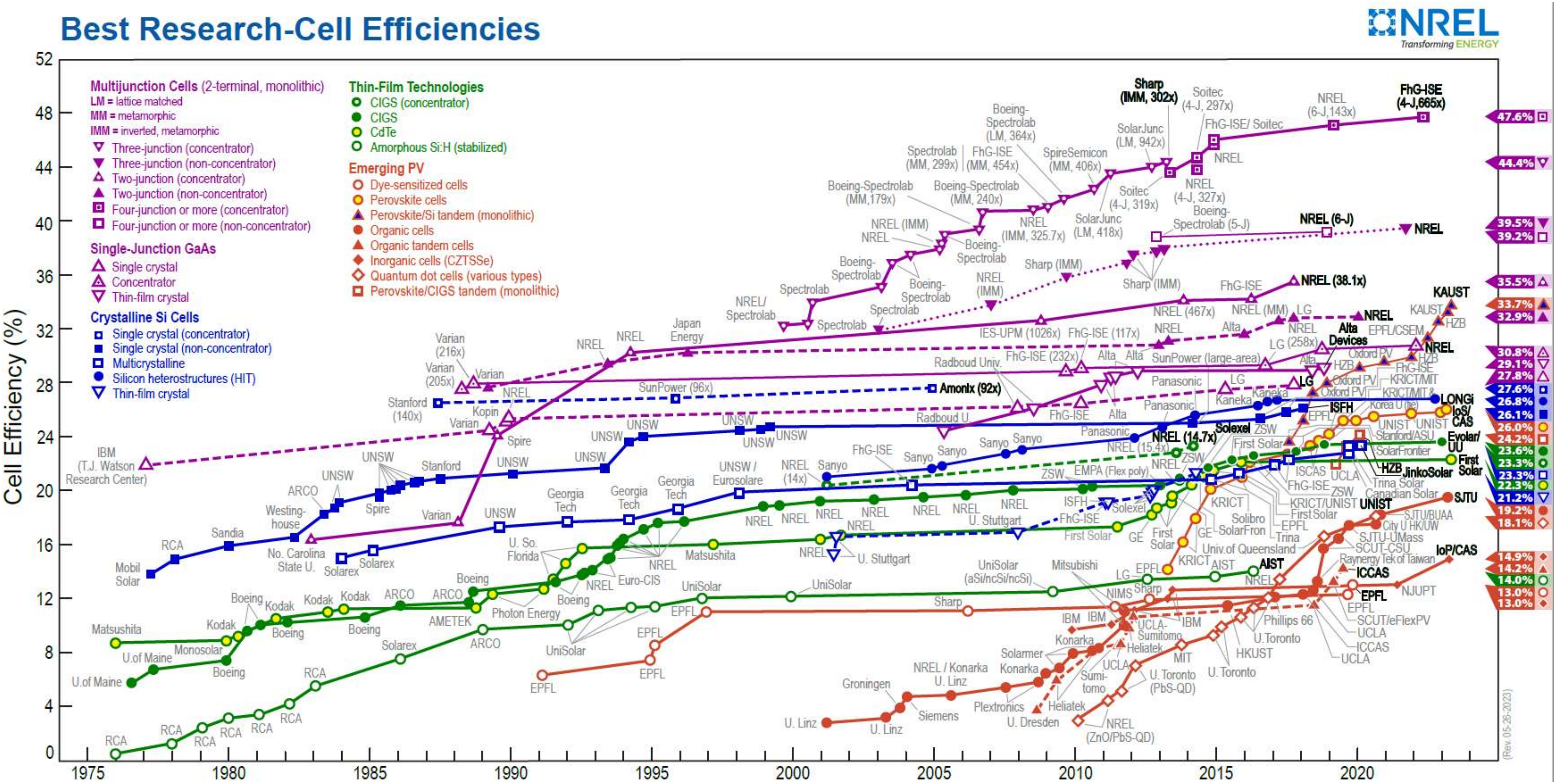
Status and Potential of CdTe Solar-Cell Efficiency

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




Best Research-Cell Efficiencies
NREL
Transforming ENERGY
Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Three-junction (concentrator)
Three-junction (non-concentrator)
Two-junction (concentrator)
Two-junction (non-concentrator)
Four-junction or more (concentrator)
Four-junction or more (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Emerging PV
Dye-sensitized cells
Perovskite cells
Perovskite/Si tandem (monolithic)
Organic cells
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells (various types)
Perovskite/CIGS tandem (monolithic)
Cell Efficiency (%)
47.6%
44.4%
39.5%
39.2%
35.5%
33.7%
32.9%
30.8%
29.1%
27.8%
27.6%
26.8%
26.1%
26.0%
24.2%
23.6%
23.3%
23.3%
22.3%
21.2%
19.2%
18.1%
14.9%
14.2%
14.0%
13.0%
13.0%
(Rev. 05-26-2023)

Annual relative efficiency, c-Si

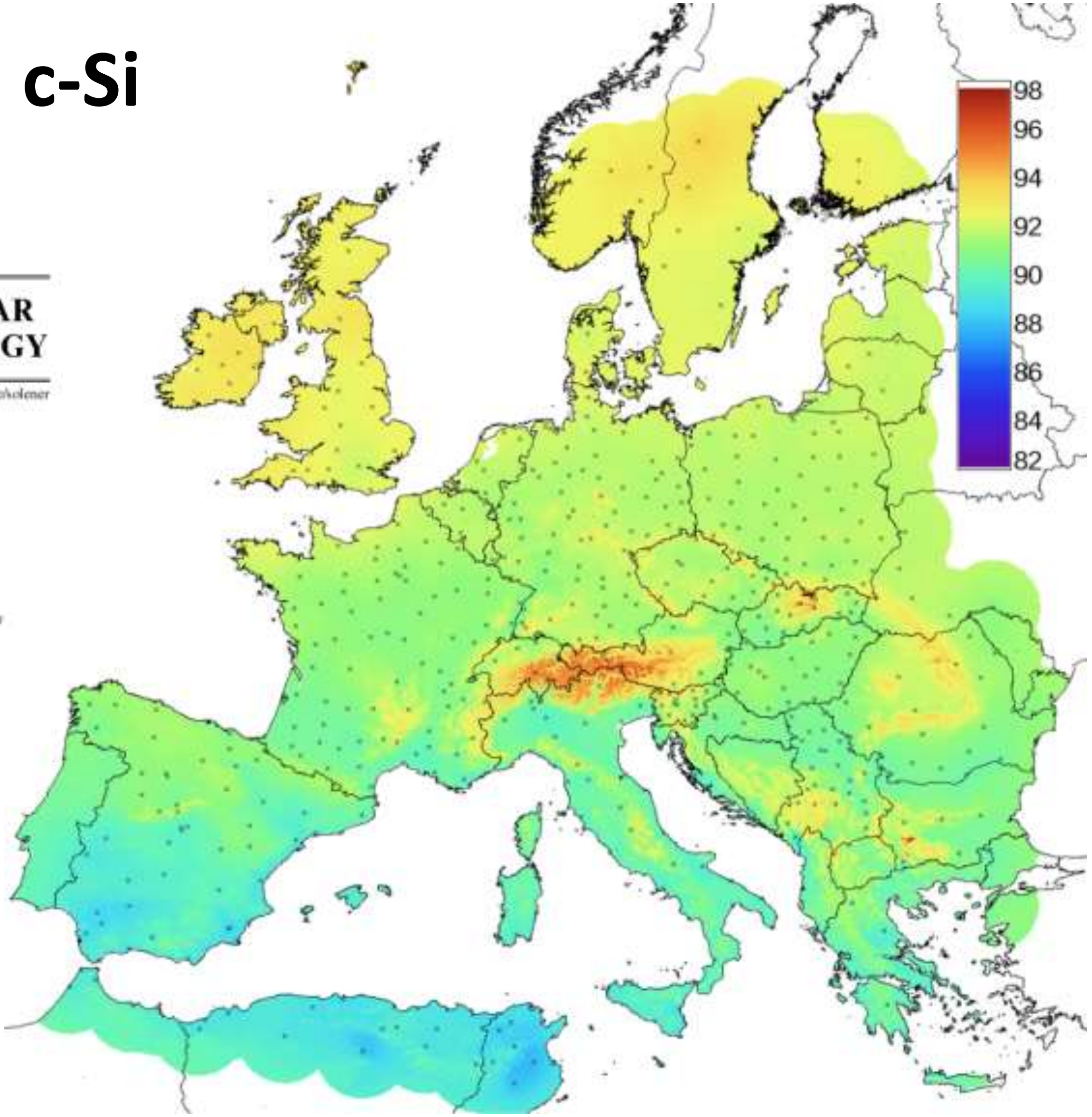
Available online at www.sciencedirect.com
ScienceDirect
Solar Energy 84 (2010) 324–338
ELSEVIER
SOLAR ENERGY
www.elsevier.com/locate/solener

Mapping the performance of PV modules, effects of module type and data averaging

Thomas Huld [a,*], Ralph Gottschalg [b,1], Hans Georg Beyer [c,2], Marko Topič [d,3]

[a] European Commission, Joint Research Centre, T.P. 450, I-21027 Ispra, Italy
[b] Centre for Renewable Energy Systems Technology, Loughborough University, Loughborough, Leicestershire LE11 3TU, United Kingdom
[c] Institut für Elektrotechnik, Hochschule Magdeburg-Stendal, Breitscheidstrasse 2, D-39114 Magdeburg, Germany
[d] Faculty of Electrical Engineering, University of Ljubljana, Trzaska 25, SI-1000 Ljubljana, Slovenia

Received 12 July 2009; received in revised form 26 November 2009; accepted 3 December 2009

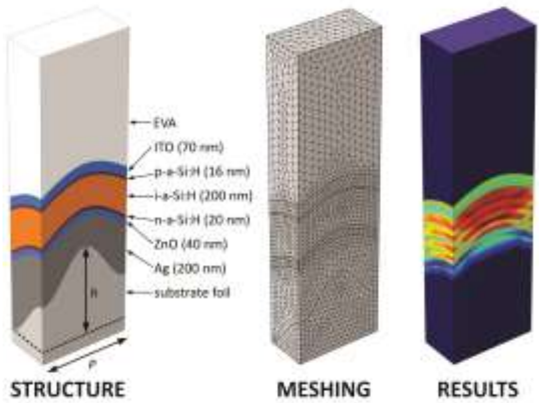


Relative Efficiency as percentage of the STC Eff. value for free-standing PV modules

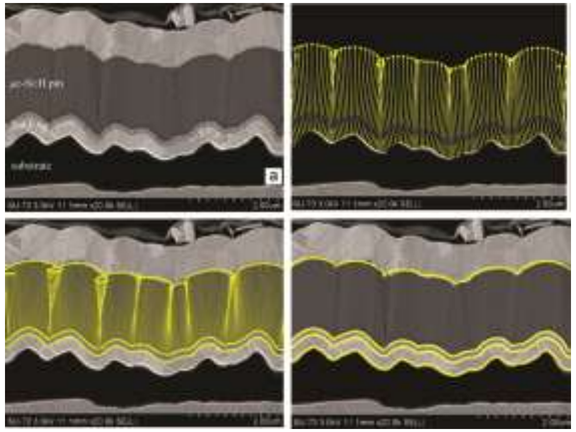
T. HULD, R. GOTTSCHALG, H.G. BEYER, M. TOPIČ, Solar Energy 84 (2010) 324-338.

Numerical Modelling and Simulation

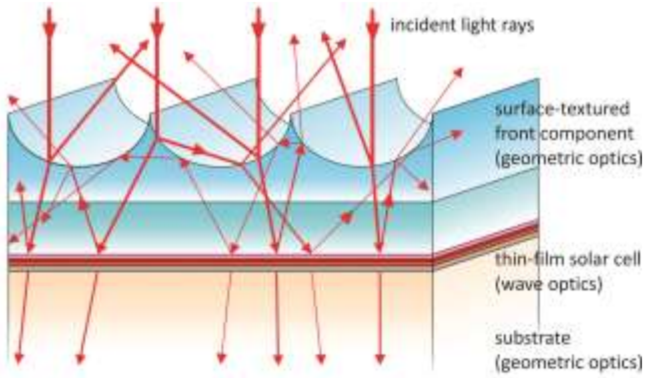
- Optical and electrical simulation of solar cells and other optoelectronic devices
- Combination of different modelling techniques (TMF, FEM, RCWA, RT)
- Development of specialized software for accurate design and optimization of inorganic and organic solar cells and photovoltaic modules (Sun*Shine*,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



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



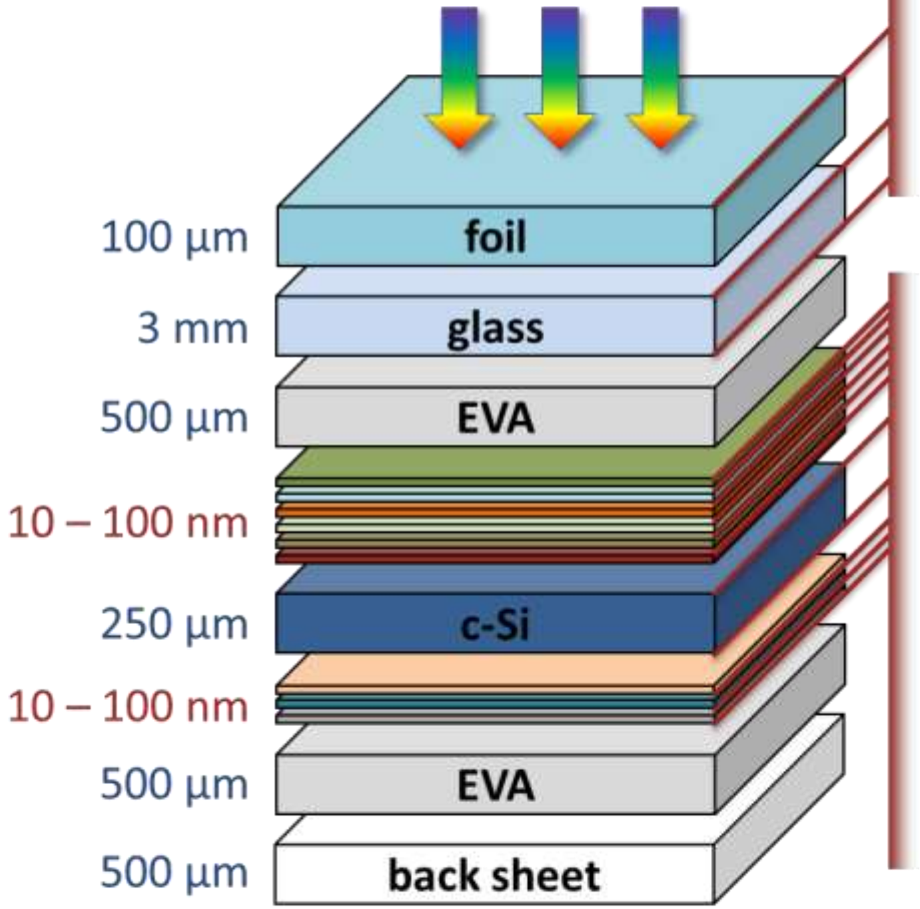
Non-conformal layer growth model for accurate simulation of nano-textured multi-layer solar cells



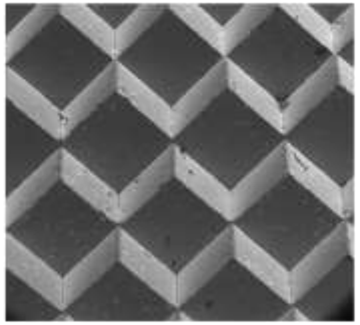
Combined geometric optics / wave optics model (CROWM) for simulation of micro-textured TFSC

Optical modelling of modern PV devices

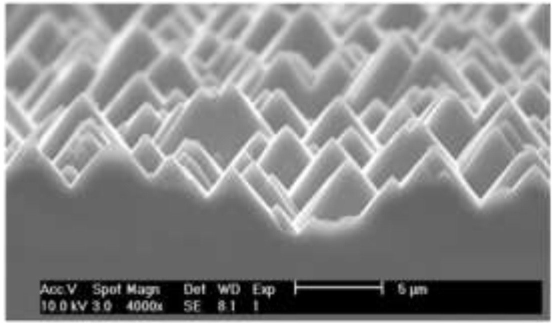
- Interface textures

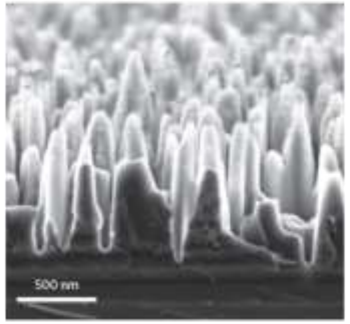


[HT-MLA-09, Holotools, Germany]

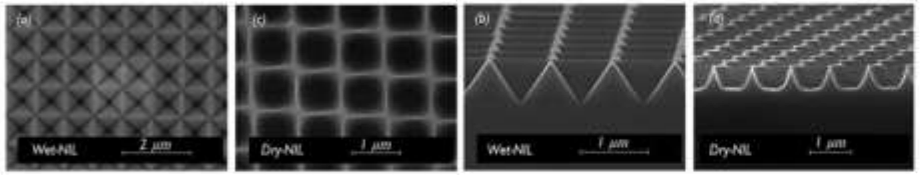


[C. Ulbrich et al., PIP, 2012]





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

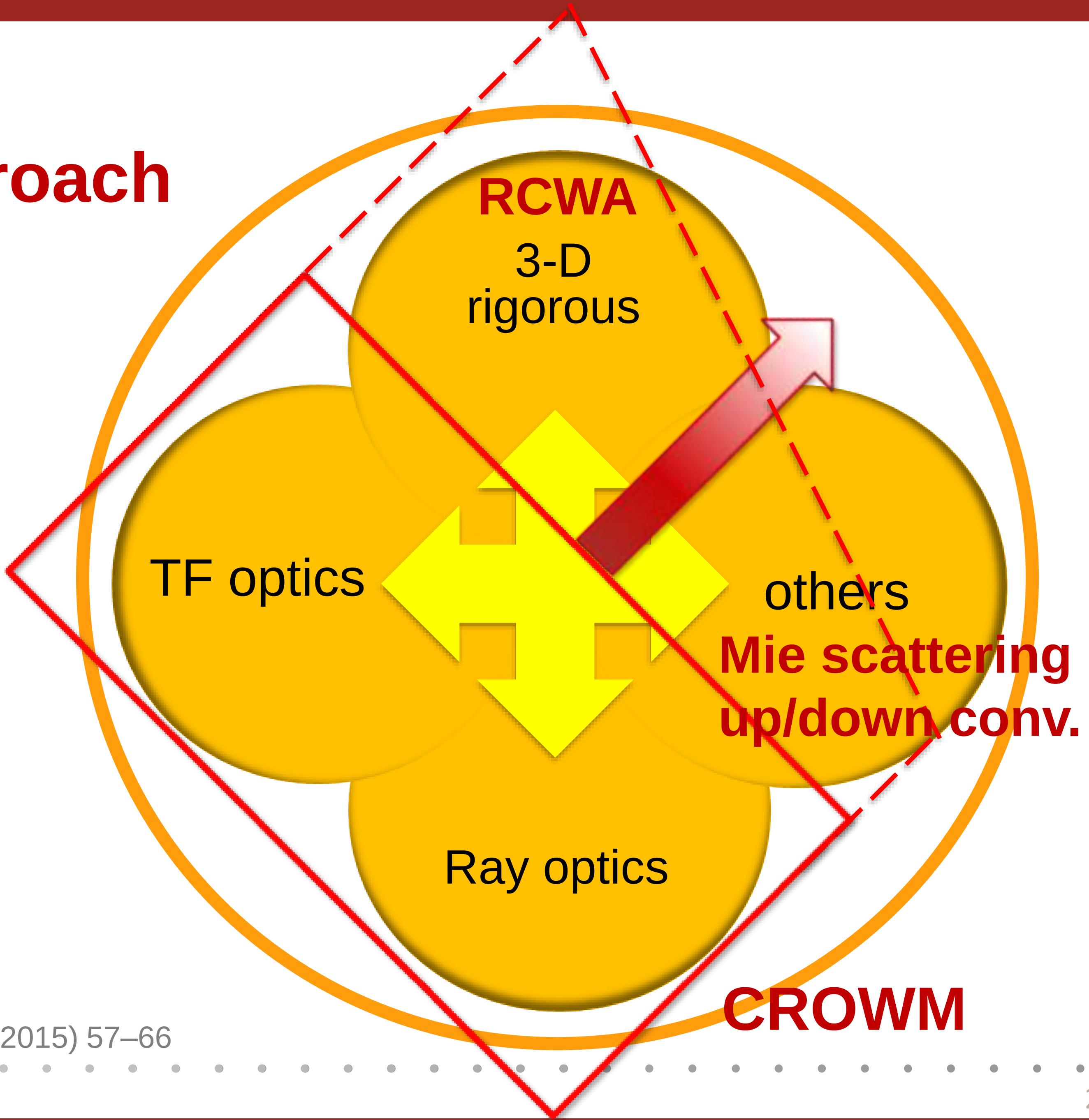


[C. Trompoukis et al., PIP, 2015]

Coupled modelling approach - CMA

Optical modelling for high efficiency solar cells

to take the advantage of accuracy and speed

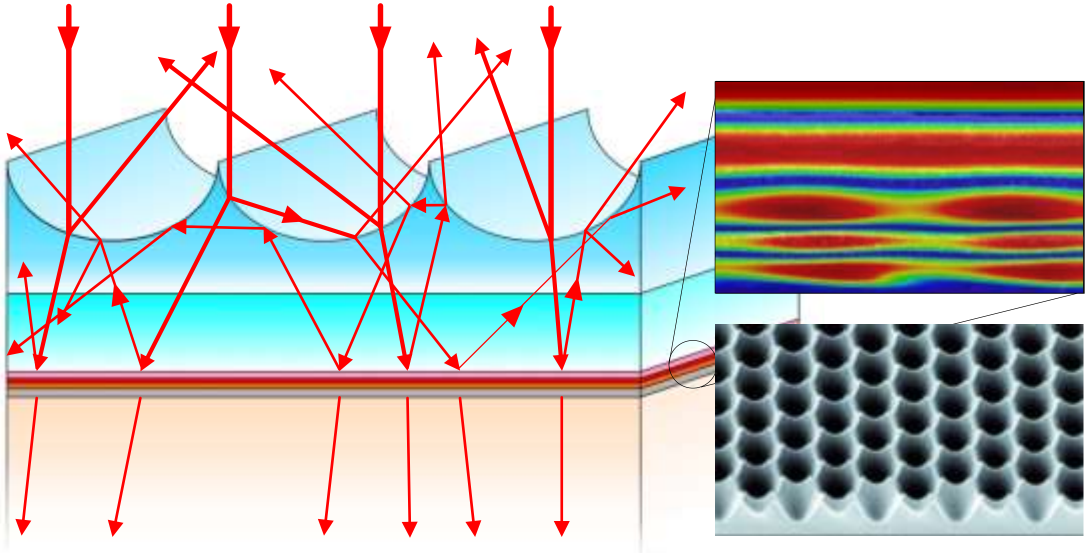


M. Topič et al., Solar Energy Materials and Solar Cells 135 (2015) 57–66

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)

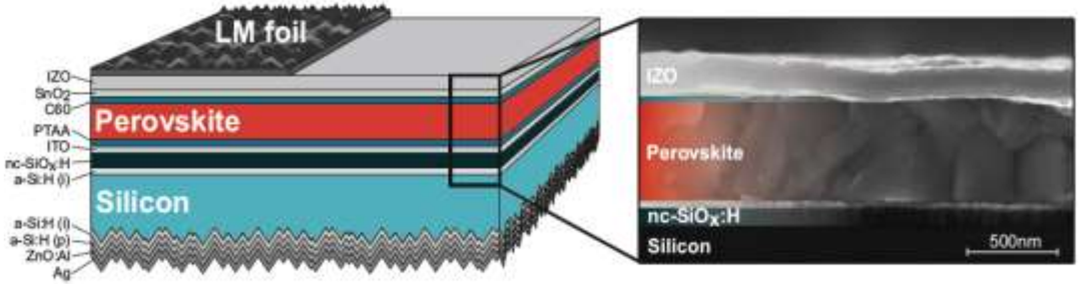
TRANSFER MATRIX FORMALISM
- flat multi-layer optoelectronic device
- 1D wave optics
- coherent propagation

~ 0.01 - 10 µm (layer thicknesses)

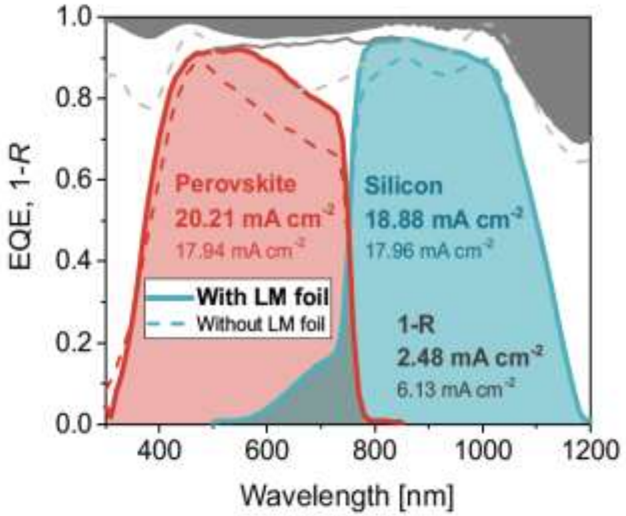
B. Lipovšek et al., Informacije MIDEM 41 (2011) 264-271.
B. Lipovšek et al., IEEE Journal of Photovoltaics 4 (2014) 639-646.

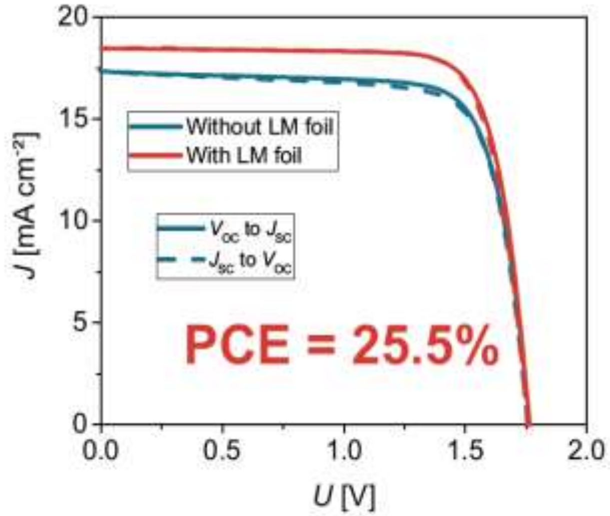
Tandem perovskite/Si solar cell

- 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

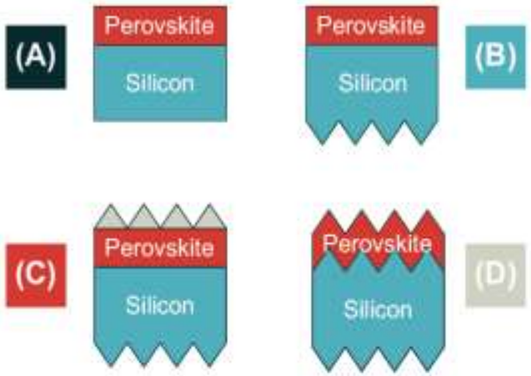




M. Jošt et al. Energy & Environmental Science **11** (2018) 3511–3523.

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
- $V_{OC} = V_{OC,Si} + V_{OC,\ pero} = 710\ \text{mV} + E_g/q - 400\ \text{mV}$ [5]



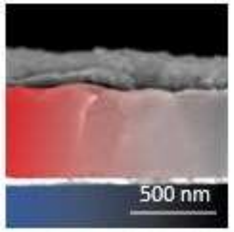
Device design	E_g opt. [eV]	J_{SC_SIM} [mA cm^{-2}]	V_{OC} [V]	FF [%]	PCE [%]
(A)	1.69	19.07	2.00	80	30.5
(B)	1.65	20.01	1.96	80	31.4
(C)	1.66	19.97	1.97	80	31.5
(D)	1.66	20.56	1.97	80	32.5

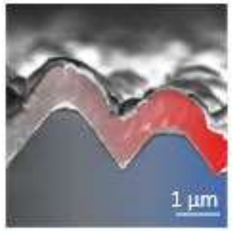
M. Jošt et al. Energy & Environmental Science **11** (2018) 3511–3523.

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.





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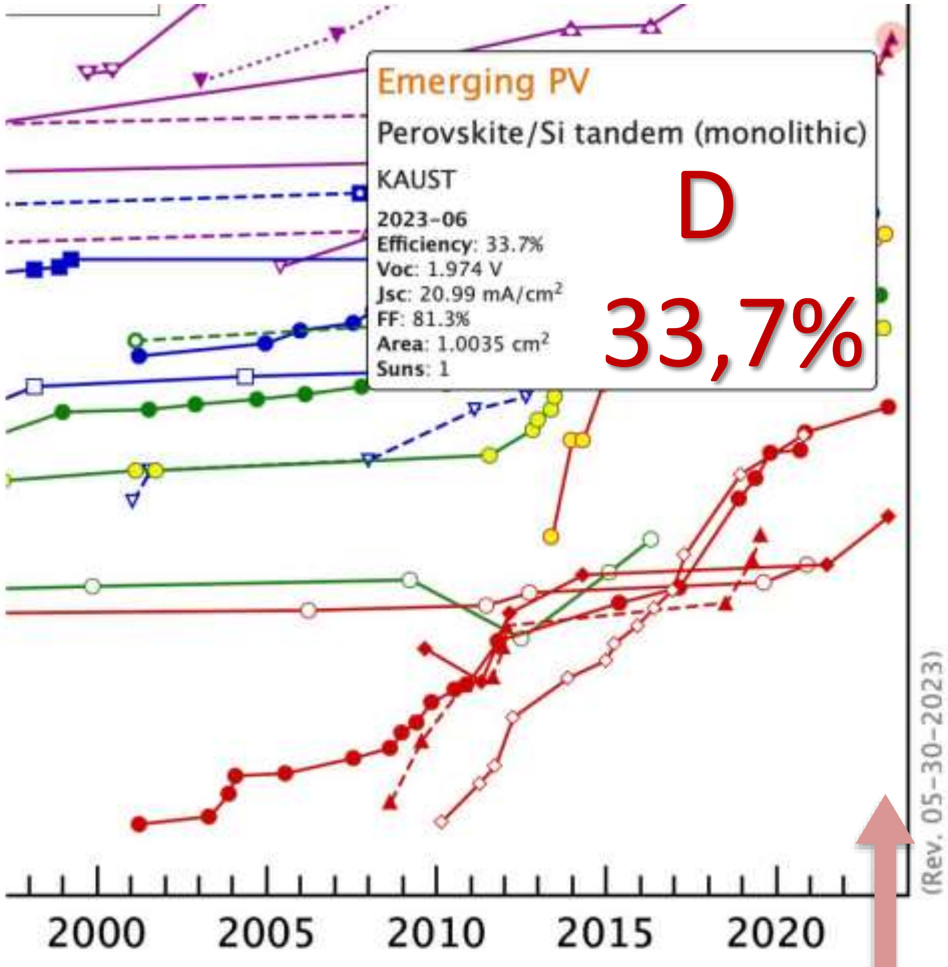
https://www.csem.ch/page.aspx?pid=172296

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

Tandem perovskite/Si solar cell

Researchers in the KAUST Photovoltaics Laboratory (KPV-Lab) of the KAUST Solar Center have produced a perovskite/silicon tandem solar cell with a power conversion efficiency (PCE) of 33.2% — the highest tandem device efficiency in the world to date, surpassing that of Helmholtz Zentrum Berlin's (HZB) record at 32.5% ... 16. apr. 2023



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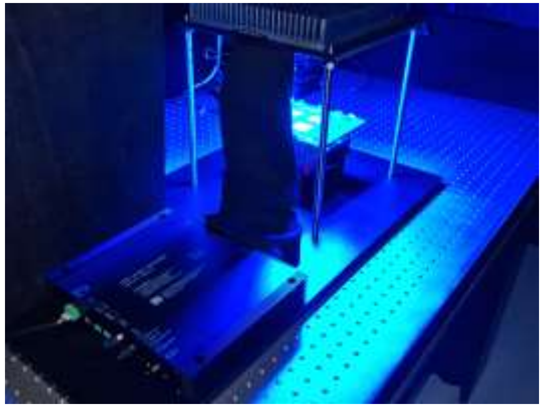
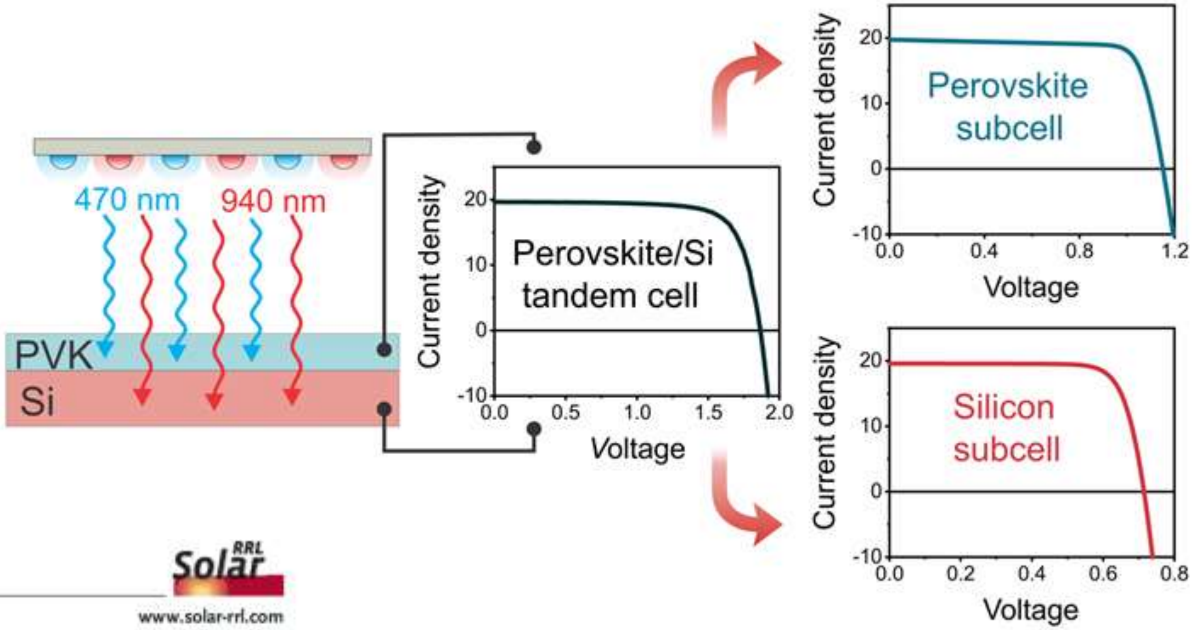
M. Jošt et al. Energy & Environmental Science **11** (2018) 3511–3523.

Method for subcell analysis in 2T tandem solar cells





RESEARCH ARTICLE

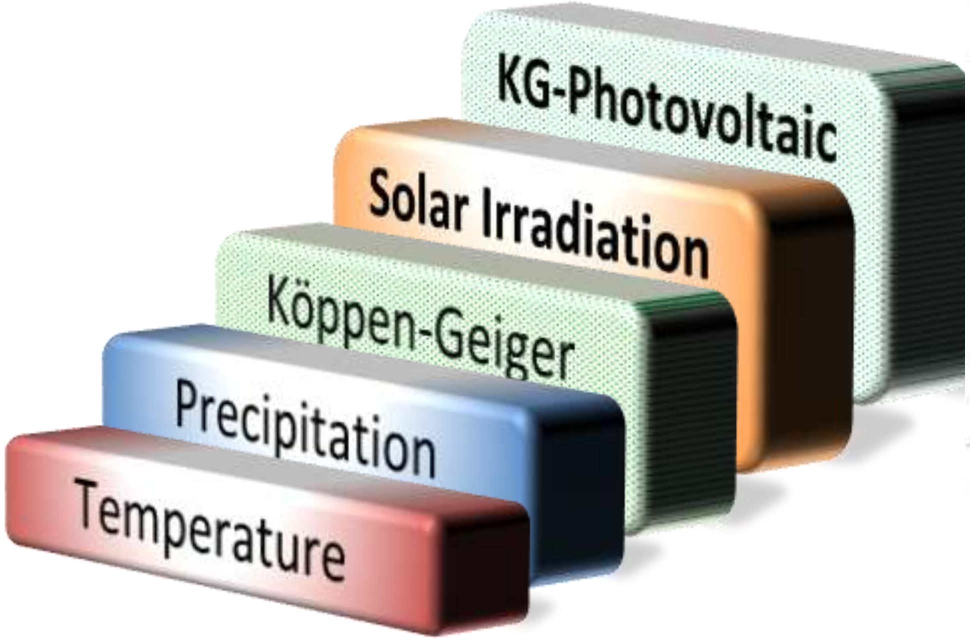
Solar RRL
www.solar-rrl.com

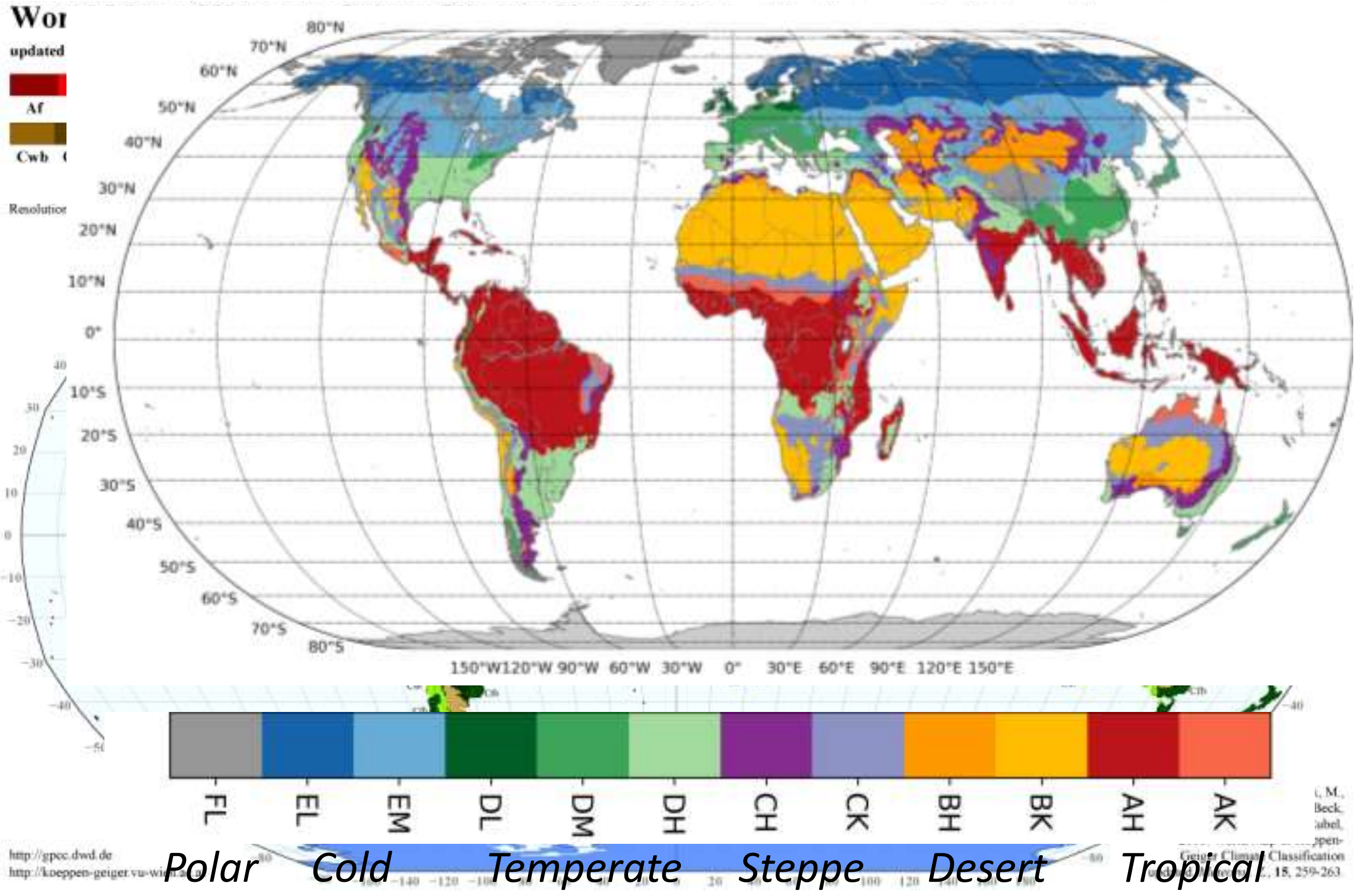
Subcell Operation and Long-Term Stability Analysis of Perovskite-Based Tandem Solar Cells Using a Bichromatic Light Emitting Diode Light Source

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



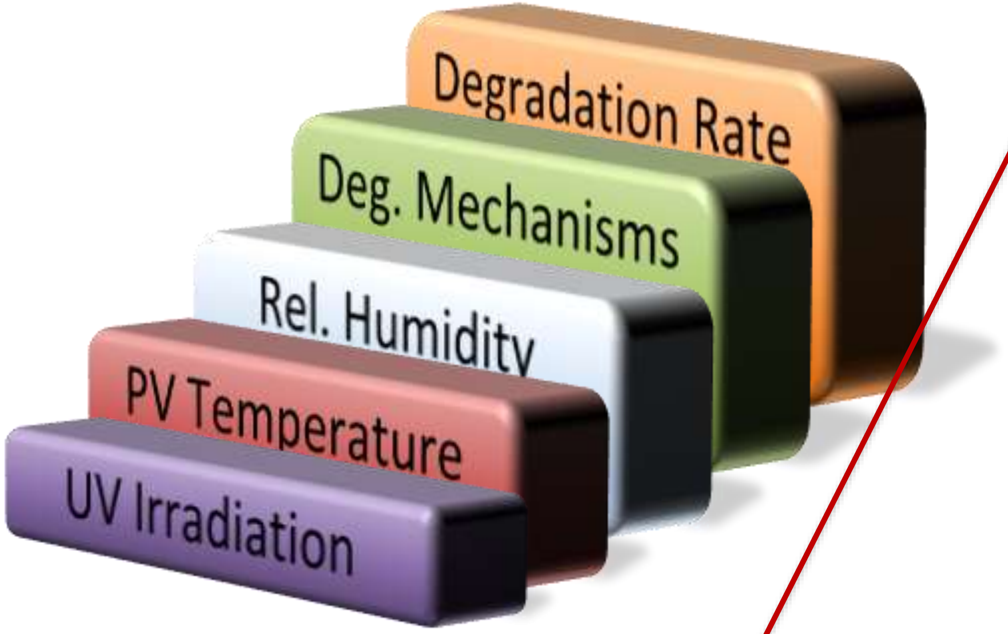


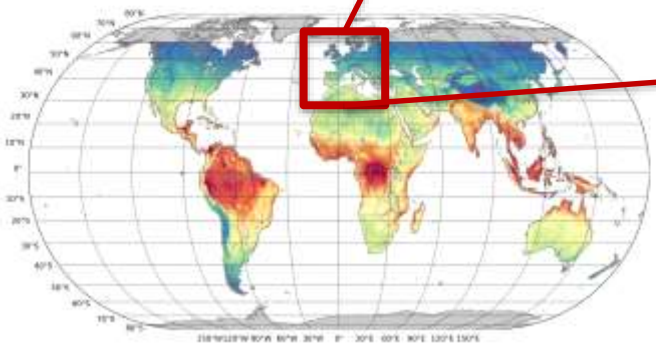
Irradiation Zones – L : Low, M: Medium, H: High, K: Very High

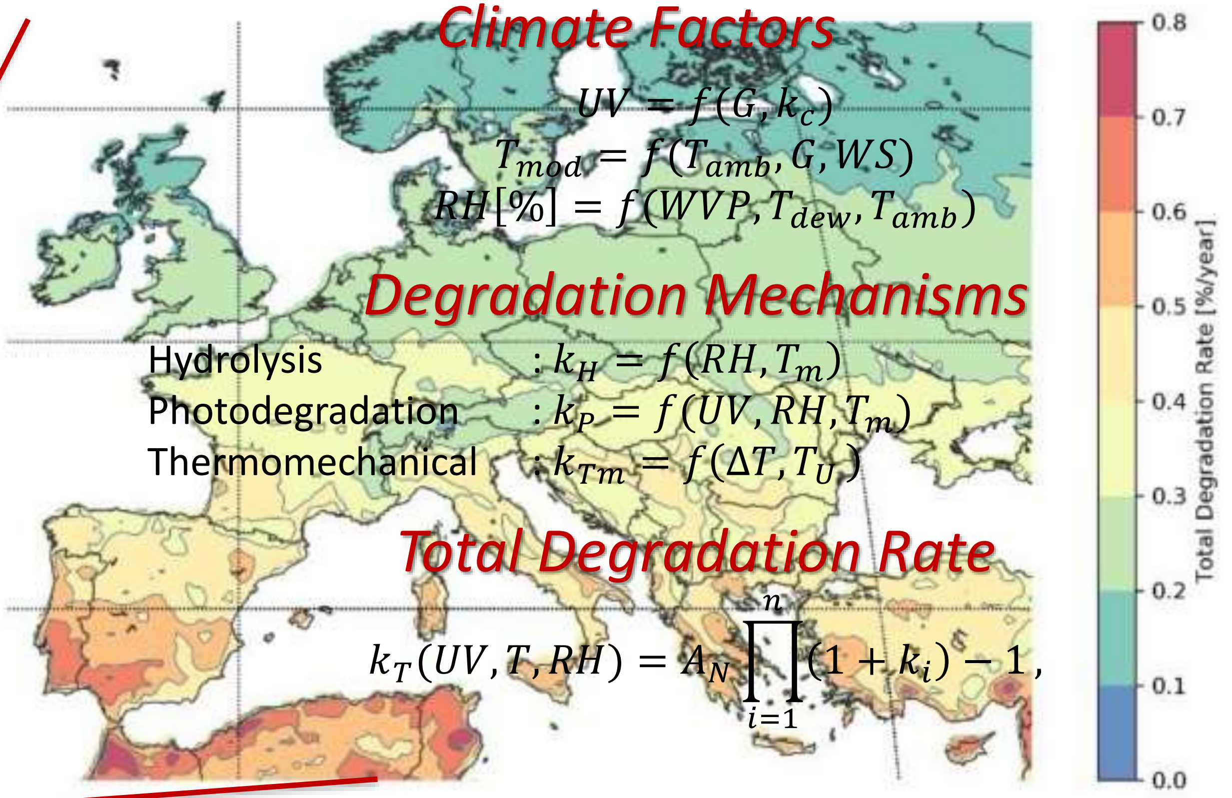
M. Kottek et al., Meteorol. Z., 2006

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

Global PV Module Degradation Rates, c-Si PVM







Climate Factors

$$UV = f(G, k_c)$$
$$T_{mod} = f(T_{amb}, G, WS)$$
$$RH[\%] = f(WVP, T_{dew}, T_{amb})$$

Degradation Mechanisms

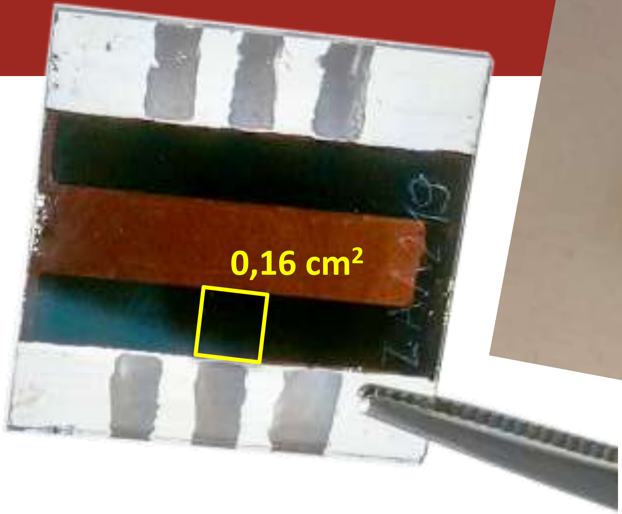
Hydrolysis : $k_H = f(RH, T_m)$
Photodegradation : $k_P = f(UV, RH, T_m)$
Thermomechanical : $k_{Tm} = f(\Delta T, T_U)$

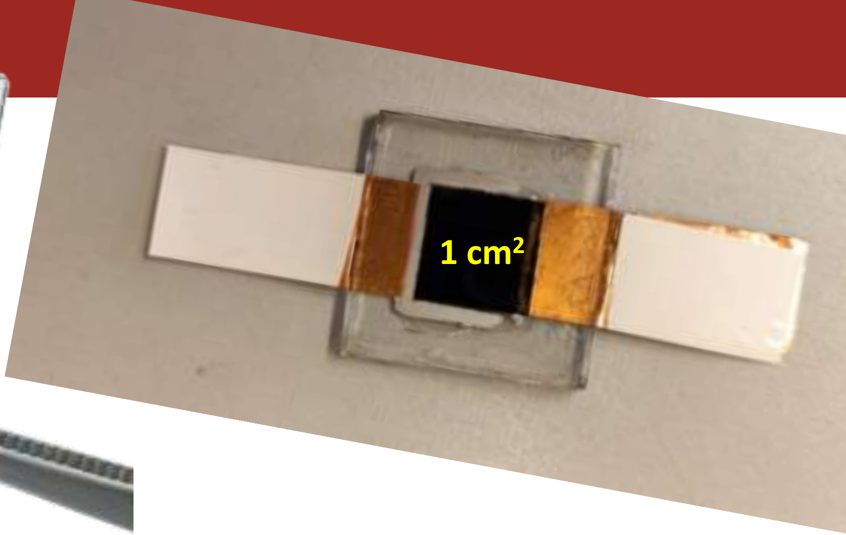
Total Degradation Rate

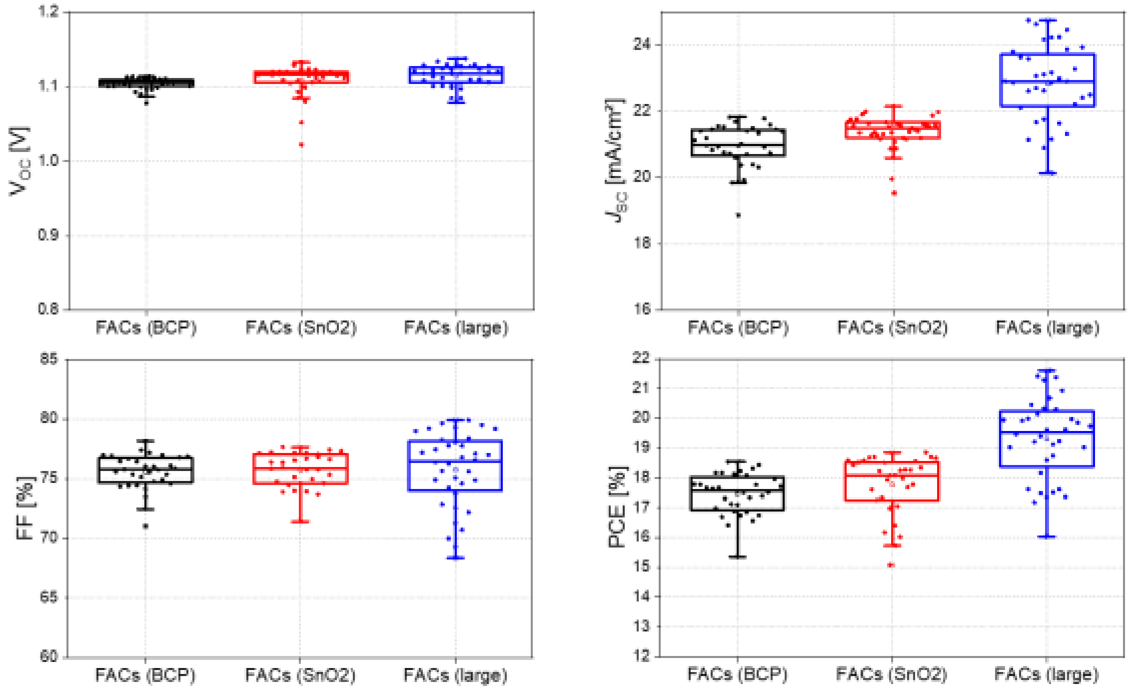
$$k_T(UV, T, RH) = A_N \prod_{i=1}^{n} (1 + k_i) - 1,$$

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

LPVO perovskite technology

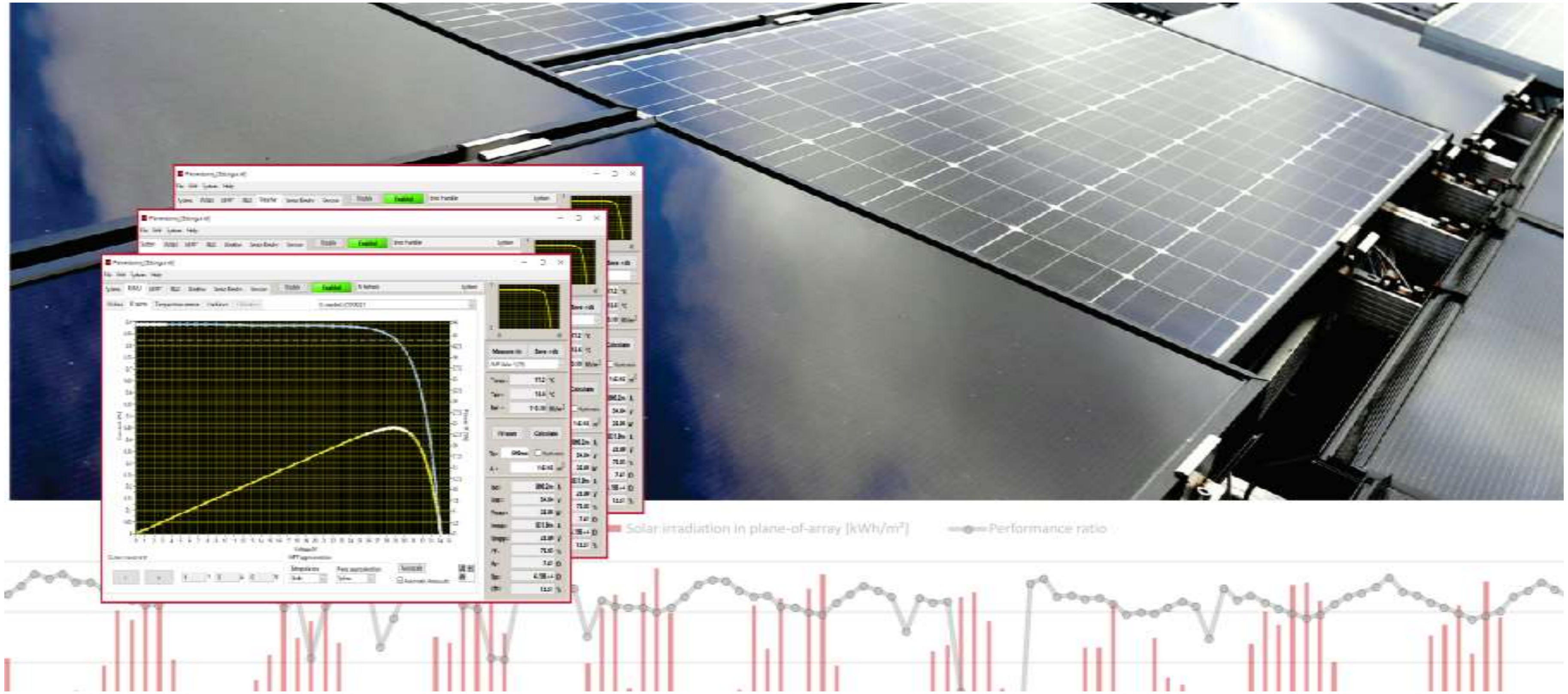






M. Jošt, Žan Ajdič et al. submitted for publication.

Outdoor monitoring of PV cells and modules



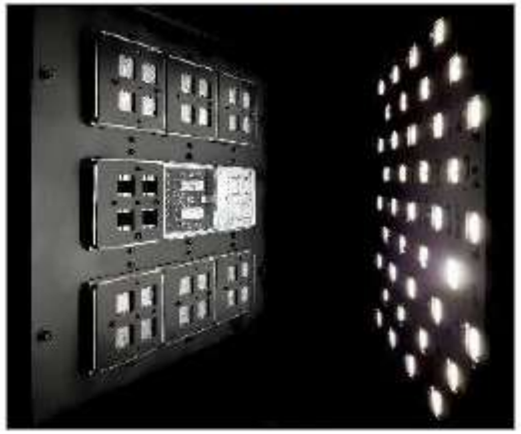
Made in LPVO

Booth E5: Laboratory of Photovoltaics and Optoelectronics

BCLED

24 channel system
for tandem cells

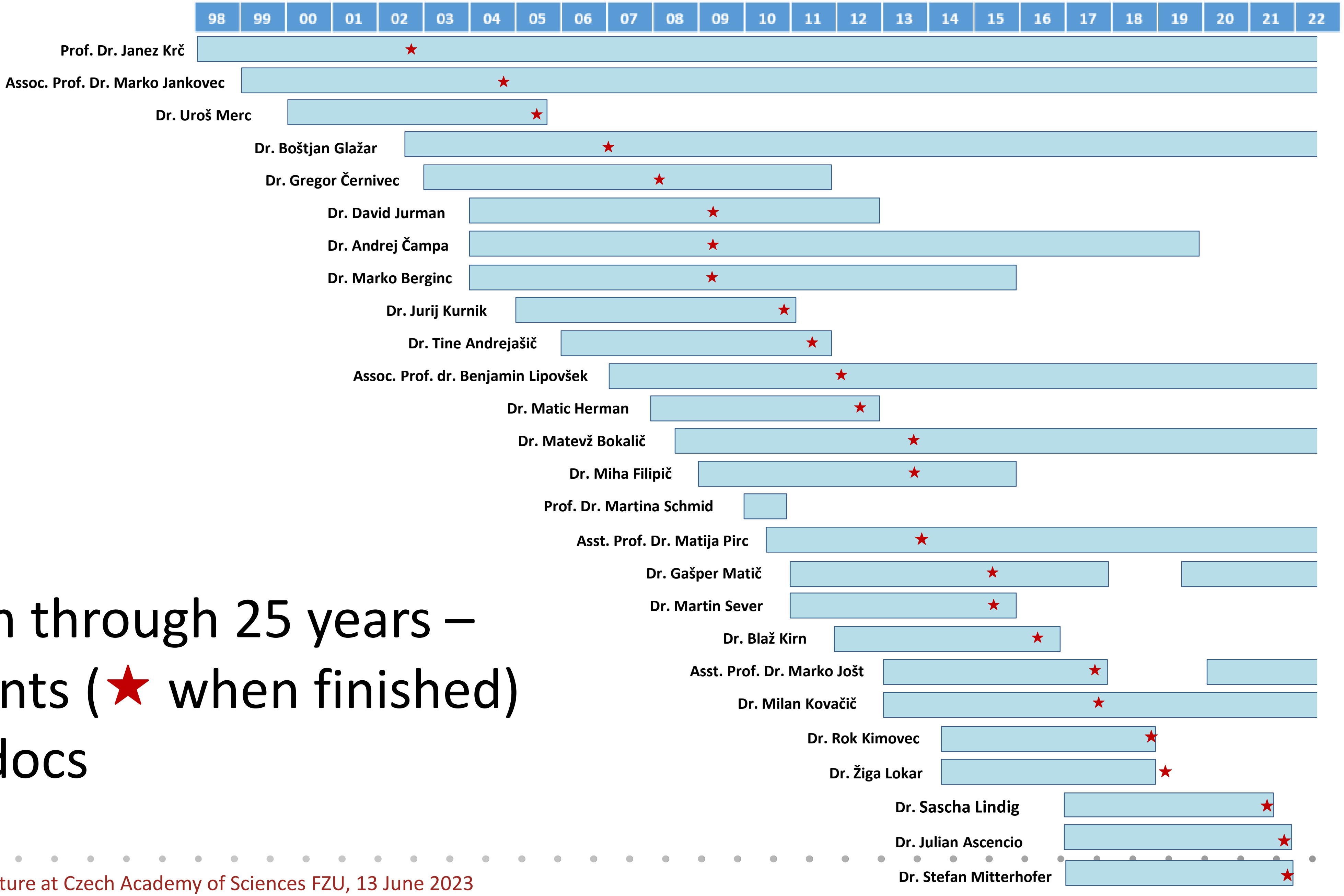
WLED



216 channel system
for single cells

550 W MPP TRACKER

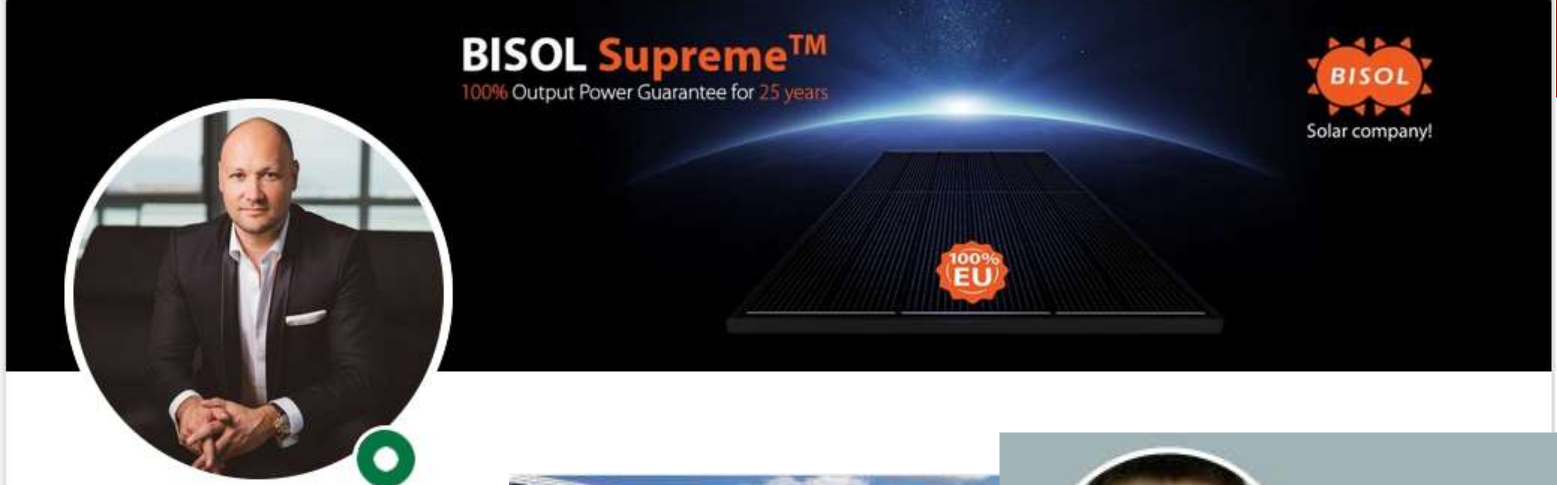
16 channel system
for full-size PV modules



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.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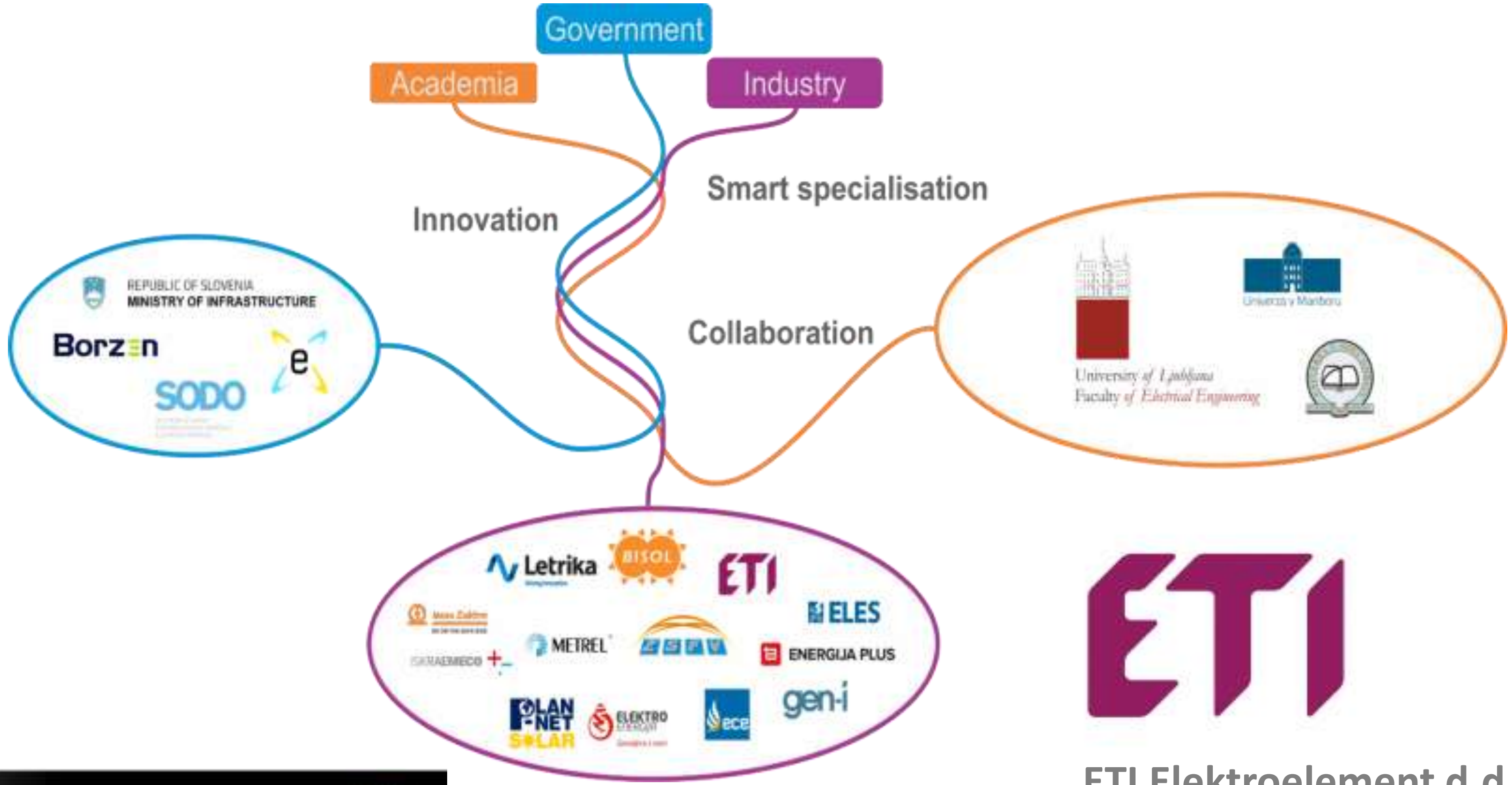
Fakulteta za elektrotehniko
Laboratorij za fotovoltaiko in optoelektroniko

Slovenian triple helix photovoltaic cluster



ETI Elektroelement d.d.

(Protective devices)

NH gPV 1500V DC

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

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reduced energy dependency ✓

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We need to act FAST!

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Acknowledgement:

ETIP PV
Steering Committee and Secretariat

LPVO team

many friends and colleagues in PV

Thank you for your attention!

arrs
SLOVENIAN RESEARCH AGENCY

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