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

Becquerel Prize WINNER 2022 Keynote Speech

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Metrics of solar cell performance limits – normalized $J$-$V$ characteristics ($J/J_{SQ}$-$V/V_{oc\_SQ}$)

optical losses

electronic losses
Experimental and Simulation Cycles

Make device → Solar cell → Characterize → Measurement results → Analyze

- Input parameters
- Refine model

Build model → Solar cell model → Simulate → Simulation results → Analyze

Cell optimization

Input parameters → Refine model → "Virtual cell" optimization

Output parameters

- Knowledge
- Understanding
- Design rules
- Better solar cells

M. Topič
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 (SunShine, 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

100 µm
foil
3 mm
glass
500 µm
EVA
10 – 100 nm
c-Si
250 µm
500 µm
EVA
500 µm
back sheet

[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

RCWA
3-D rigorous

TF optics

Ray optics

Mie scattering up/down conv.

CROWM

Simulator **CROWN**

*(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)

Tandem perovskite/Si solar cell

- Monolithic perovskite/silicon heterojunction (SHJ) tandem solar cell
- Bottom cell: back-side textured SHJ with nc-SiO$_2$:H front surface field
- Top cell: p-i-n type design with "triple cation" absorber Cs$_{0.05}$(MA$_{0.37}$FA$_{0.63}$)Pb$_{1.1}$(I$_{0.83}$Br$_{0.17}$)$_3$
- Light Management (LM) from textured foil on a glass substrate$^{[ii]}$ resembling module integration

<table>
<thead>
<tr>
<th>Mask area</th>
<th>Active area</th>
<th>W/o LM foil</th>
<th>17.3</th>
<th>1.76</th>
<th>76.4</th>
<th>23.4</th>
<th>23.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mask area &gt;</td>
<td>With LM foil</td>
<td>18.5</td>
<td>1.76</td>
<td>78.5</td>
<td>25.5</td>
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<td>77.0</td>
<td>26.5</td>
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PCE = 25.5%
Tandem perovskite/Si solar cell

- Texture position comparison
  - Flat device (A) \cite{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

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

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<th>Device design</th>
<th>( E_g \text{ opt.} ) [eV]</th>
<th>( J_{SC,\text{SIM}} ) [mA cm(^{-2})]</th>
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<td>(A)</td>
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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

Method for subcell analysis in 2T tandem solar cells

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 Glazar, Marko Jankovec, Steve Albrecht, and Marko Topič*

Köppen-Geiger-Photovoltaic (KGPV) Climate Classification

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

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

Polar  Cold  Temperate  Steppe  Desert  Tropical
Global PV Module Degradation Rates

Climate Factors
- $\text{UV} = f(G, k_c)$
- $T_{\text{mod}} = f(T_{\text{amb}}, G, W/S)$
- $\text{RH} = f(WVP, T_{\text{dew}}, T_{\text{amb}})$

Degradation Mechanisms
- Hydrolysis: $k_H = f(RH, T_m)$
- Photodegradation: $k_P = f(\text{UV}, RH, T_m)$
- Thermomechanical: $k_{TM} = f(\Delta T, T_m)$

Total Degradation Rate
- $k_T(\text{UV}, T, RH) = \prod_{i=1}^n (1 + k_i) - 1.$

References:
J. Ascencio-Vásquez, K. Brecl, M. Topič, Energies, 2019
Outdoor monitoring of PV modules
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
What a Laudatio!

Thank you, Rutger!
-55% emissions by 2030
climate neutrality
reduced energy dependency

We need to act NOW!
We need to act FAST!
Acknowledgement:

ETIP PV  
Steering Committee  
and Secretariat

LPVO team

many friends and  
colleagues in PV

Thank you for your attention!