PERCISTAND SCIENTIFIC WORKSHOP

JUNE 9TH, 2021

Economical & ecological assessment

Perovskite-on-chalcogenide tandem PV

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Program of today

PERovskite-on-CIS TANDem PV

12:30 – Welcome & introduction

12:45 – Energy yield modelling

13:00 – Life cycle assessment

13:15 – Techno-economic assessment

13:30 – Industrial perspective

13:45 – Closure

Program of today

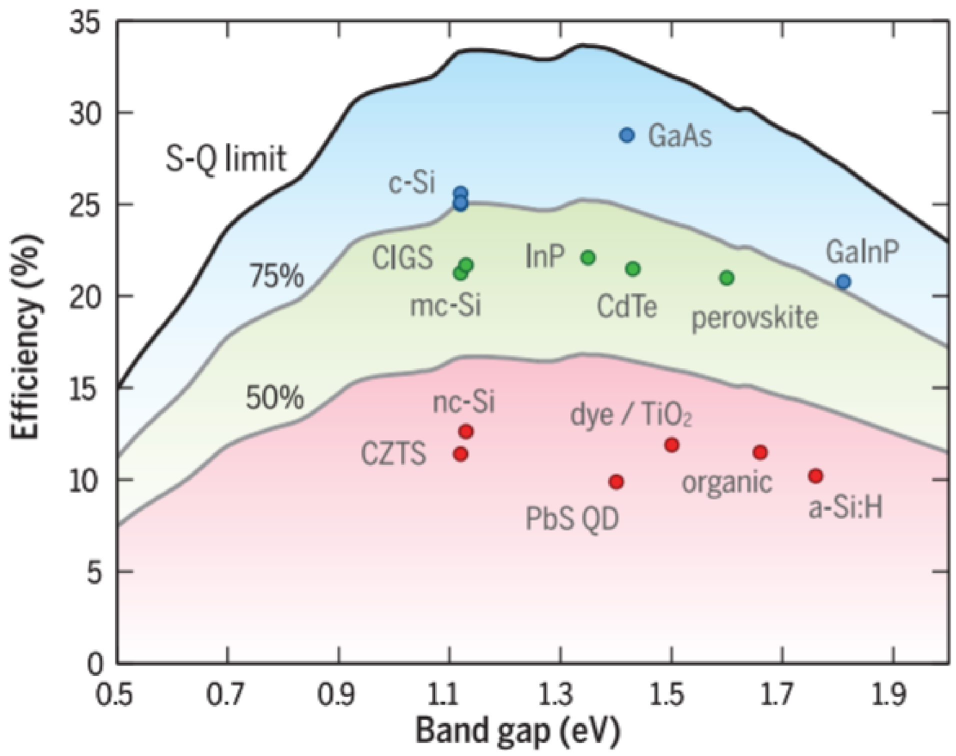
PERovskite-on-CIS TANDem PV

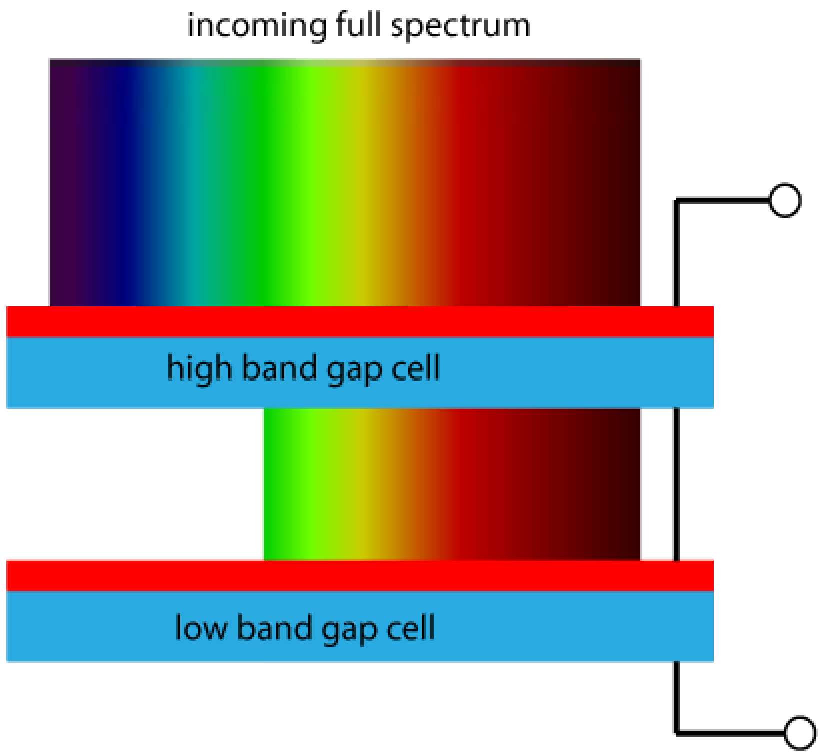
Q&A – Use chat

Moderator Sarallah Hamtaei

- Doctoral researcher
- Topic: $CuInSe_2$ development

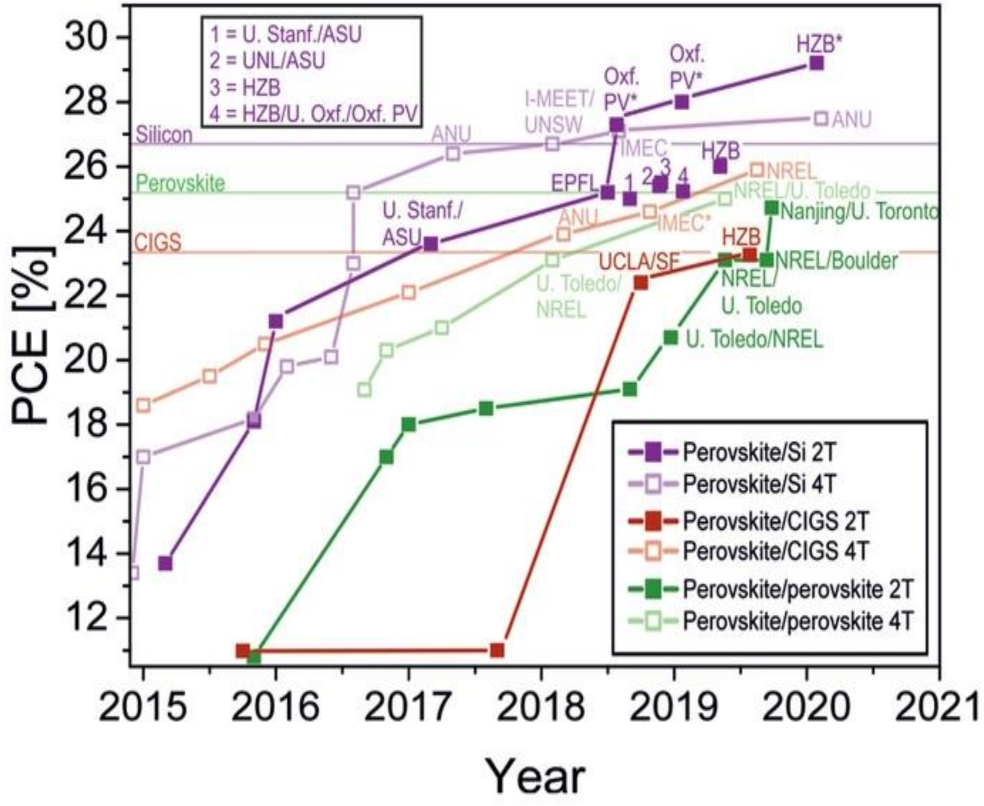
Why tandem PV?
High efficiency

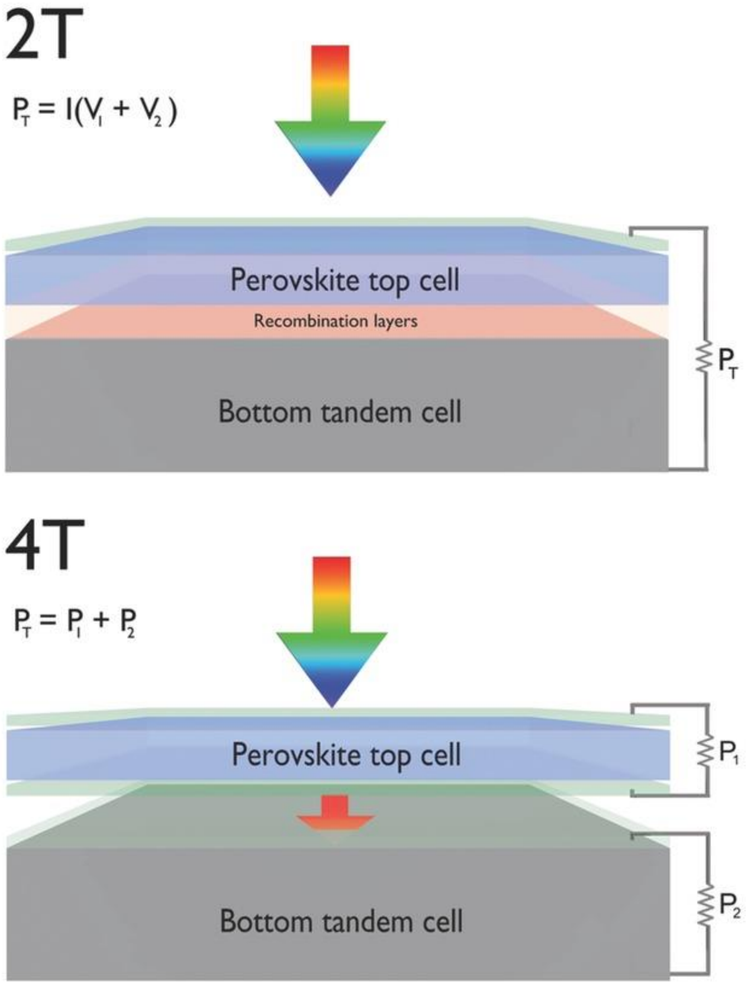




DOI: 10.1126/SCIENCE.AAD4424 / HTTPS://WWW.PVEDUCATION.ORG/

Status of tandem PV





DOI: 10.1002/AENM.201904102

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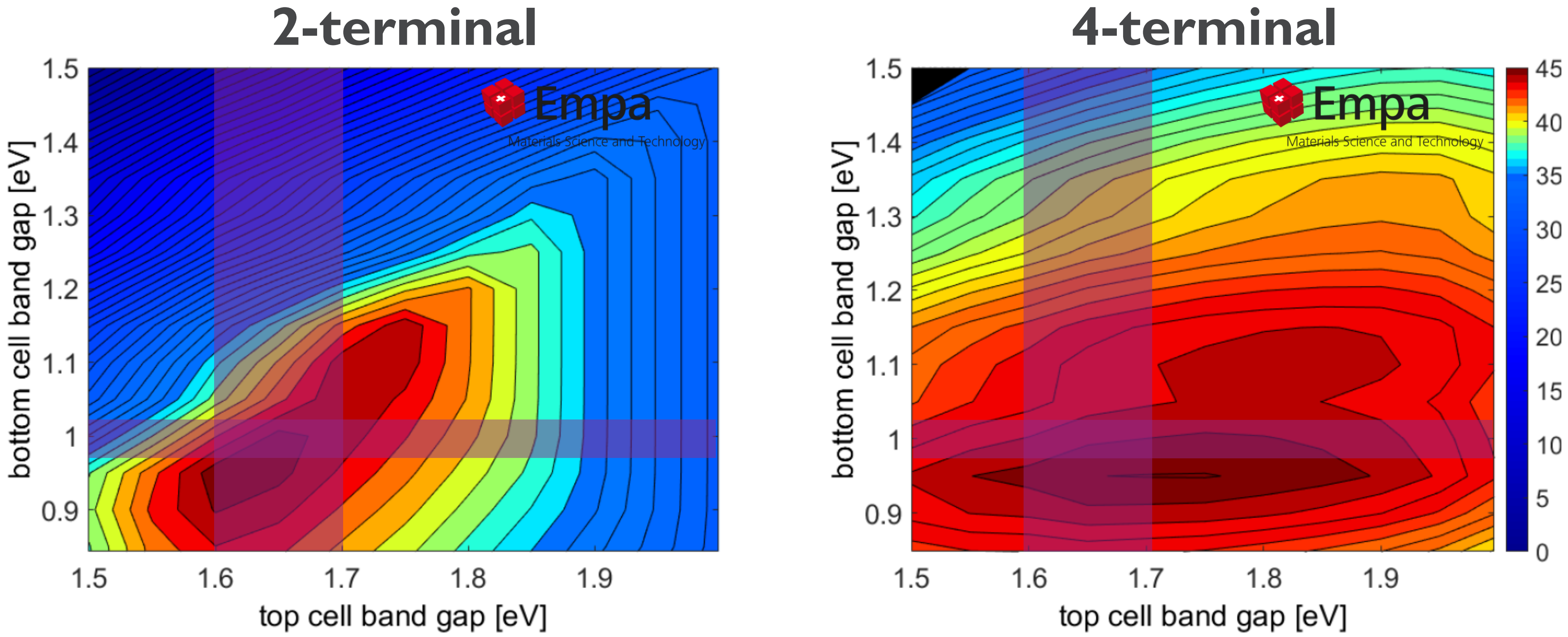
Why perovskite-on-CIS?

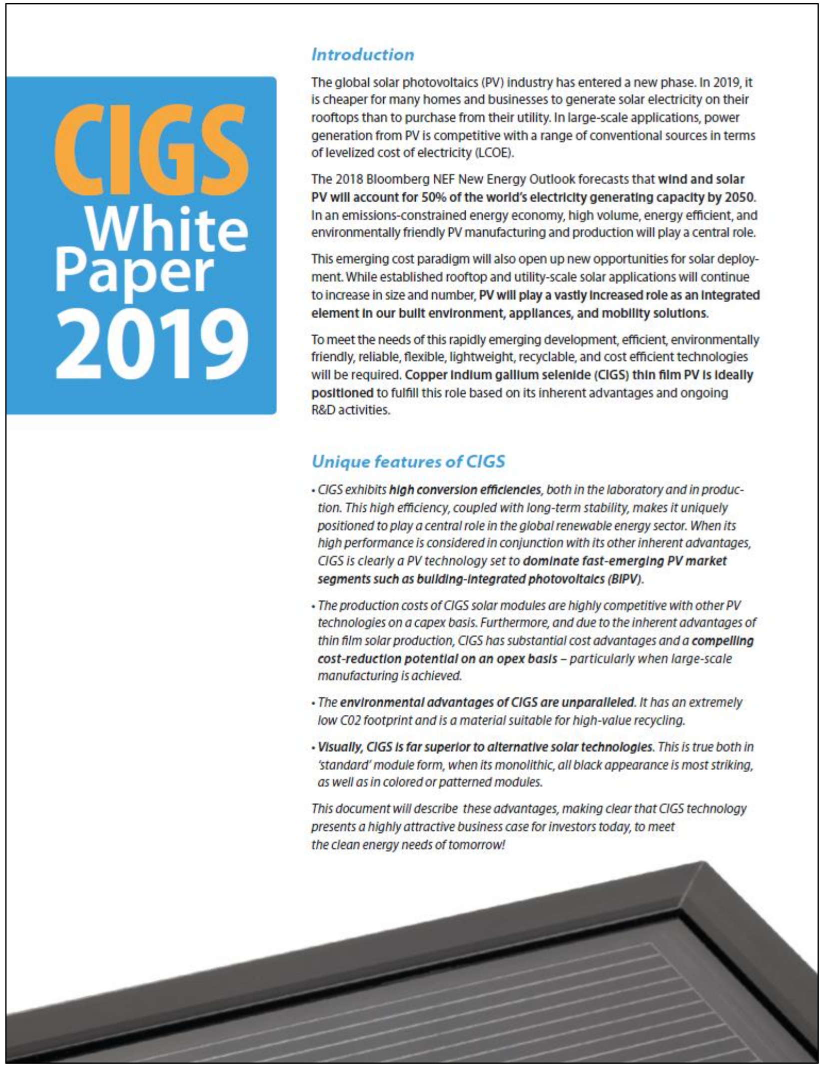
$CuInSe_2$ (CIS) has 1 eV as bandgap



Why perovskite-on-CIS?

Thin film + thin film = thin film

- High efficiency, energy yield and reliability
- Fully vertically integrated, low-cost production on a GW scale
- **Utility scale, rooftop and BIPV applications, colored, patterned and/or flexible products**
- Low material consumption, short energy payback times, low carbon footprint


CIGS White Paper 2019

Introduction

The global solar photovoltaics (PV) industry has entered a new phase. In 2019, it is cheaper for many homes and businesses to generate solar electricity on their rooftops than to purchase from their utility. In large-scale applications, power generation from PV is competitive with a range of conventional sources in terms of levelized cost of electricity (LCOE).

The 2018 Bloomberg NEF New Energy Outlook forecasts that **wind and solar PV will account for 50% of the world's electricity generating capacity by 2050.** In an emissions-constrained energy economy, high volume, energy efficient, and environmentally friendly PV manufacturing and production will play a central role.

This emerging cost paradigm will also open up new opportunities for solar deployment. While established rooftop and utility-scale solar applications will continue to increase in size and number, **PV will play a vastly increased role as an integrated element in our built environment, appliances, and mobility solutions.**

To meet the needs of this rapidly emerging development, efficient, environmentally friendly, reliable, flexible, lightweight, recyclable, and cost efficient technologies will be required. **Copper indium gallium selenide (CIGS) thin film PV is ideally positioned** to fulfill this role based on its inherent advantages and ongoing R&D activities.

Unique features of CIGS

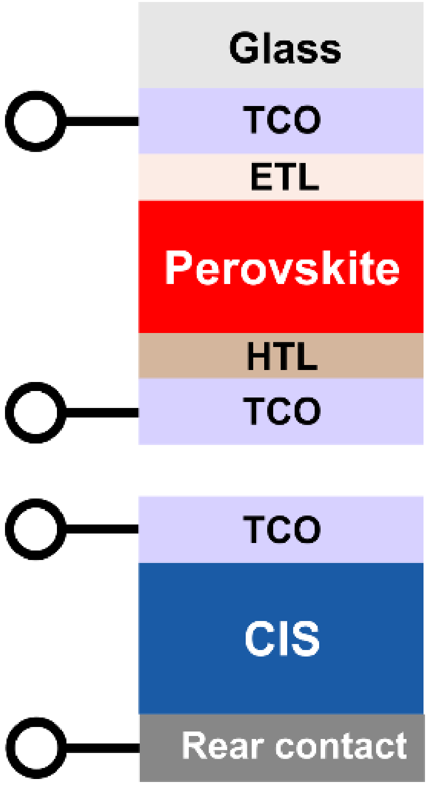
- *CIGS exhibits* ***high conversion efficiencies****, both in the laboratory and in production. This high efficiency, coupled with long-term stability, makes it uniquely positioned to play a central role in the global renewable energy sector. When its high performance is considered in conjunction with its other inherent advantages, CIGS is clearly a PV technology set to* ***dominate fast-emerging PV market segments such as building-integrated photovoltaics (BIPV).***
- *The production costs of CIGS solar modules are highly competitive with other PV technologies on a capex basis. Furthermore, and due to the inherent advantages of thin film solar production, CIGS has substantial cost advantages and a* ***compelling cost-reduction potential on an opex basis*** *– particularly when large-scale manufacturing is achieved.*
- *The* ***environmental advantages of CIGS are unparalleled.*** *It has an extremely low C02 footprint and is a material suitable for high-value recycling.*
- ***Visually, CIGS is far superior to alternative solar technologies.*** *This is true both in 'standard' module form, when its monolithic, all black appearance is most striking, as well as in colored or patterned modules.*

This document will describe these advantages, making clear that CIGS technology presents a highly attractive business case for investors today, to meet the clean energy needs of tomorrow!

HTTPS://CIGS-PV.NET/

Consortium

10 EU and 2 intercontinental partners



KIT
Karlsruhe Institute of Technology

ZSW

imec

Empa
Materials Science and Technology

TNO

cnrs
IPVF
INSTITUT PHOTOVOLTAÏQUE D'ILE-DE-FRANCE

vito

SOLARONIX

NICE
SOLAR ENERGY

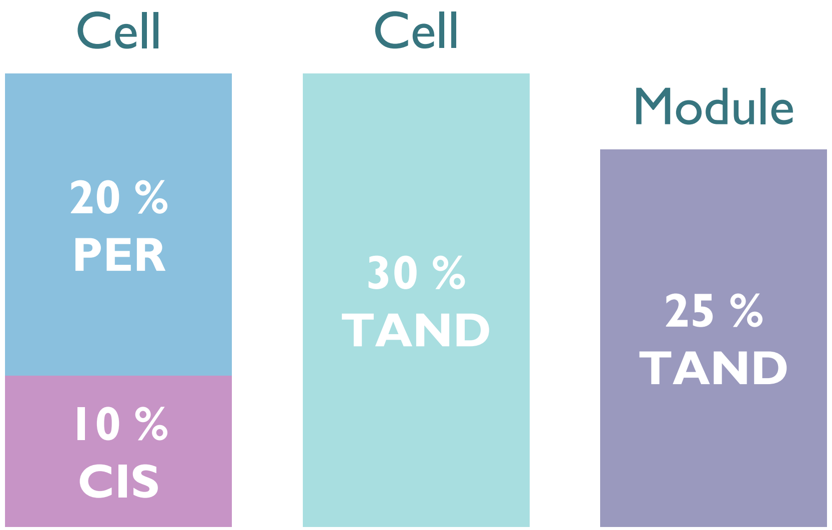
UHASSELT

Australian National University

NREL
Transforming ENERGY

Targets

By end of project



- Stability
  - IEC standards
- Manufacturability
  - Scalable to 20×20 cm^2
- Cost and environmental footprint
  - ISO standards

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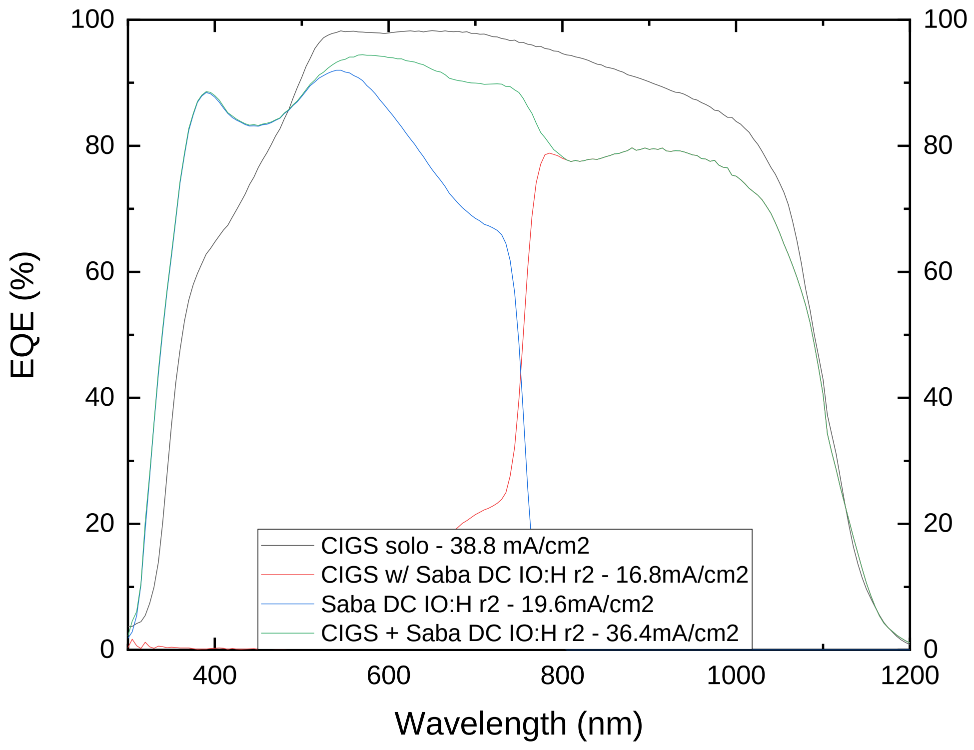
Current status

Joint result with the German CAPITANO project

- Perovskite top cell
  - 18.5 %
- CI(G)S bottom cell
  - 8.8 %
- **4T tandem cell**
  - **27.3 %**



Acknowledgements & Social Media

European Union's Horizon 2020 research and innovation programme, grant agreement Nº 850937.

Progress in PV tandem technology

HTTPS://WWW.LINKEDIN.COM/GROUPS/8931403/

Energy yield modelling

Fabrizio Gota

Karlsruhe Institute of Technology

Karlsruher Institut für Technologie

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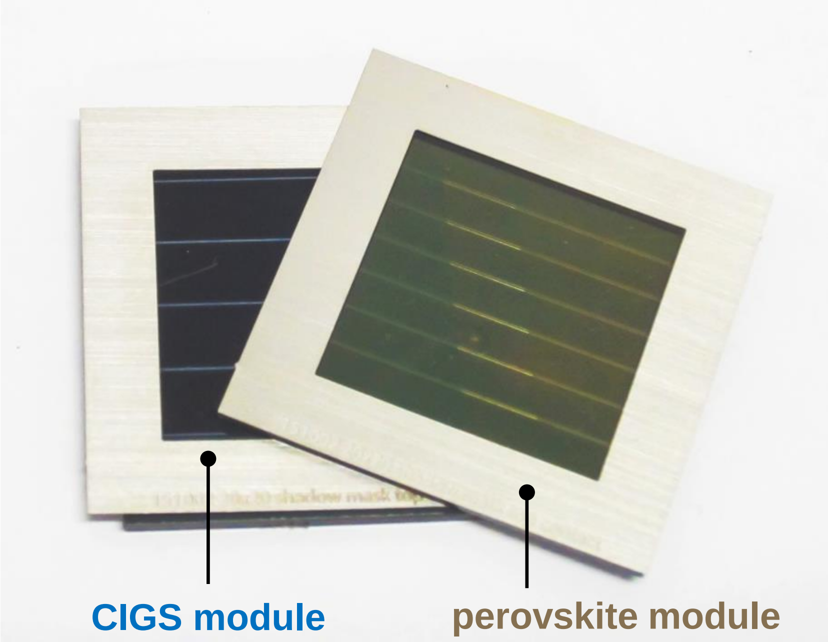
Advanced Optics and Materials for Next Generation Photovoltaics group



Led by Ulrich W. Paetzold

The Research University in the Helmholtz Association

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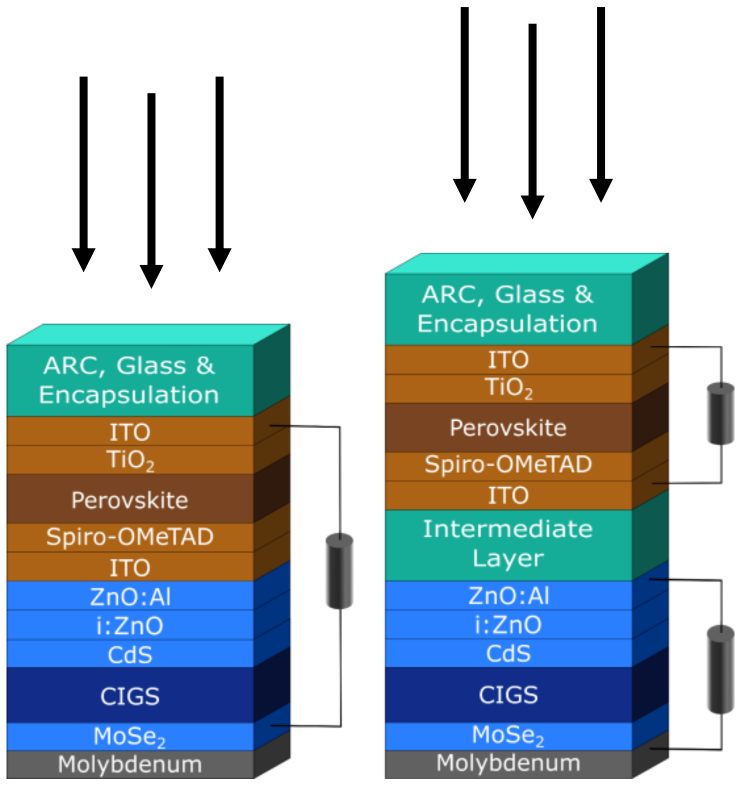
Why energy yield modelling?

Why energy yield modelling?

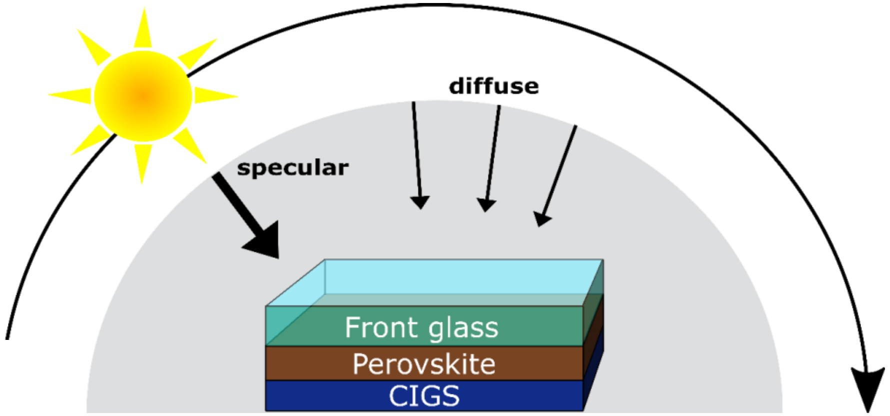


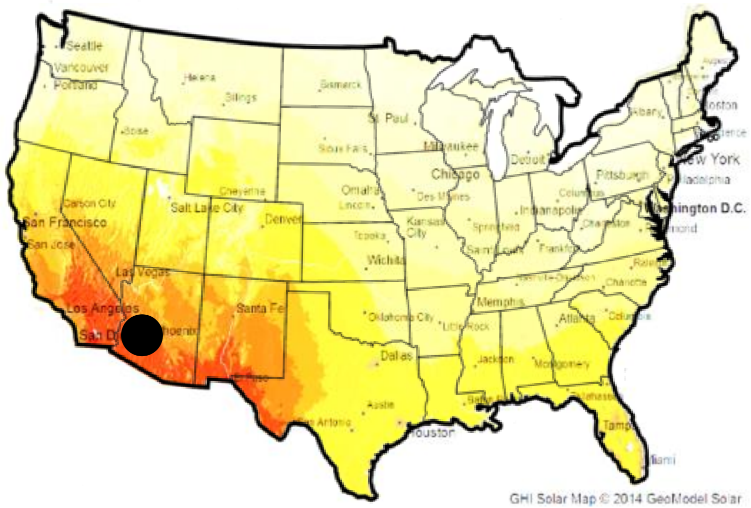
2T vs. 4T

Example: What is the superior architecture for perovskite/CIGS tandem PV?

	2T	4T
PCE under STC (%)	**25.7**	25.3

Why energy yield modelling?





Example: What is the superior architecture for perovskite/CIGS tandem PV?

	2T	4T
PCE under STC (%)	**25.7**	25.3
EY in Phoenix, AZ ($kWh \cdot m^{-2} \cdot a^{-1}$)	553	**572**

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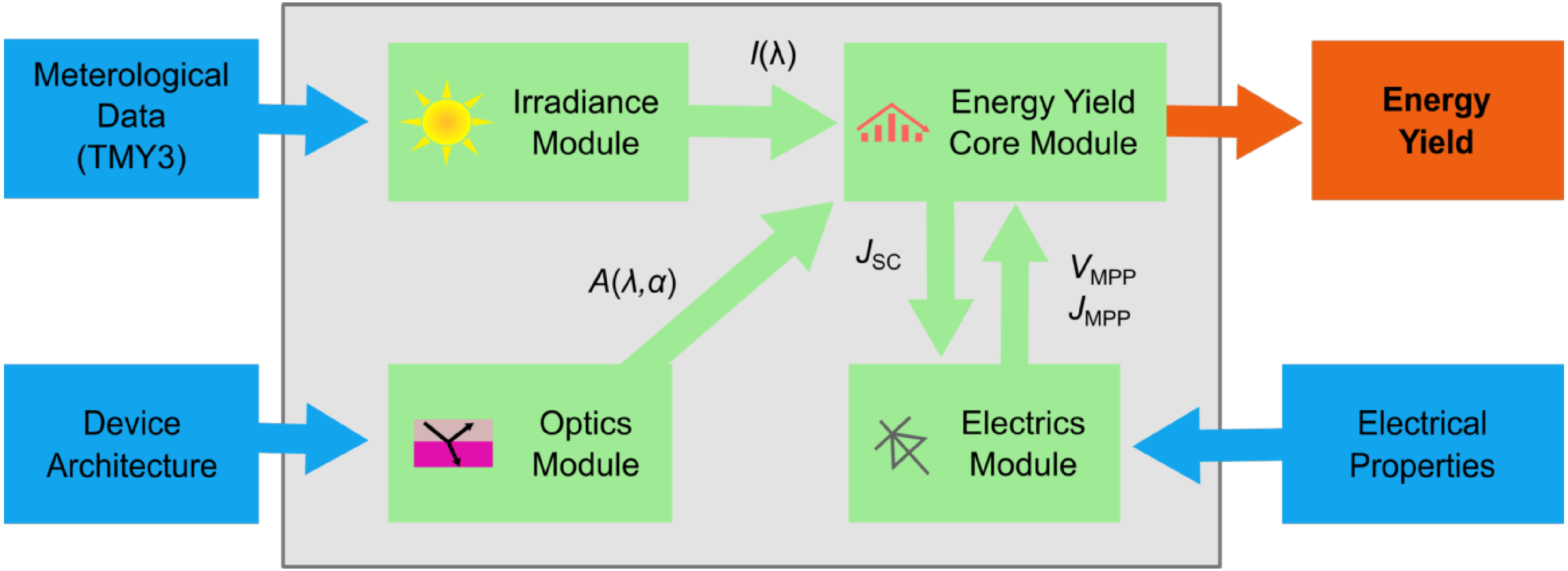
Why energy yield modelling?

- Compare different architectures under realistic irradiation conditions
- Optimize layer thickness
- Optimize energy gap of bottom and top absorber layers

- **Standard test conditions fail to provide correct advice for the design of architectures for perovskite-based tandem PV**
- **Identify trends in the power output of PV devices under realistic conditions depending on variations of the device architecture**

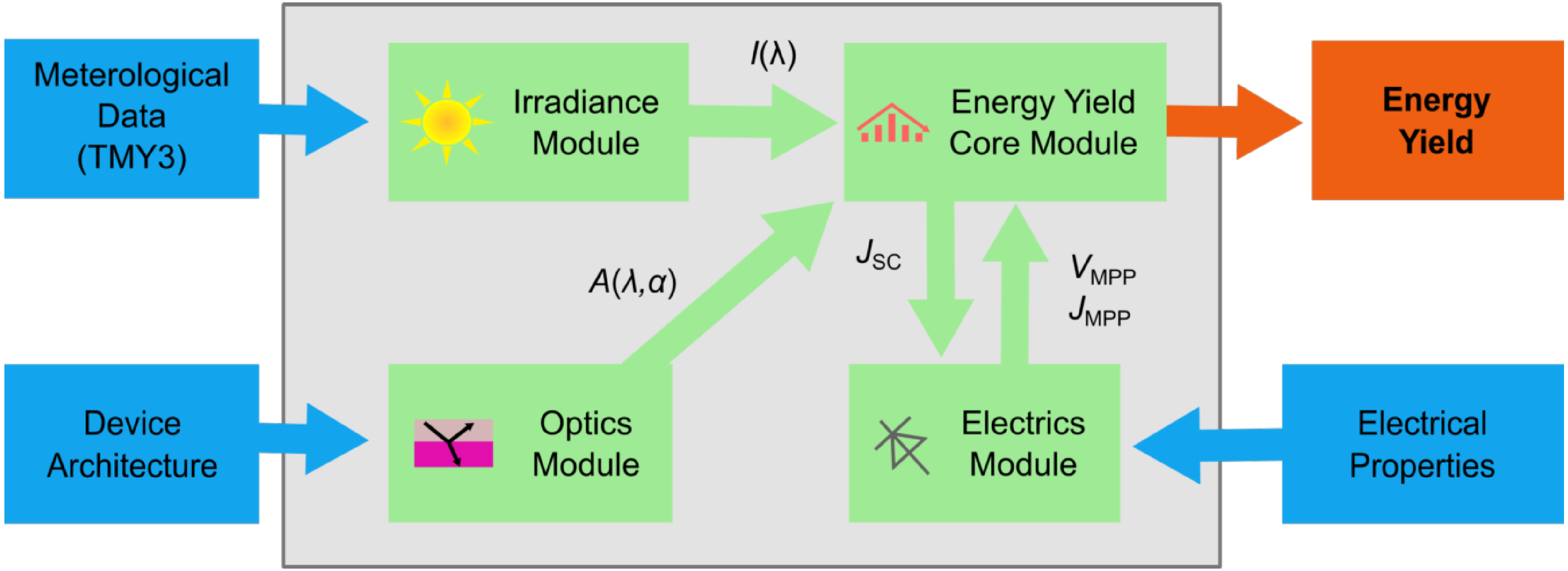
Energy yield modelling platform



Irradiance Module

- Hundreds of location in the USA using TMY3 data set (NREL)
- Accounting for cloud coverage

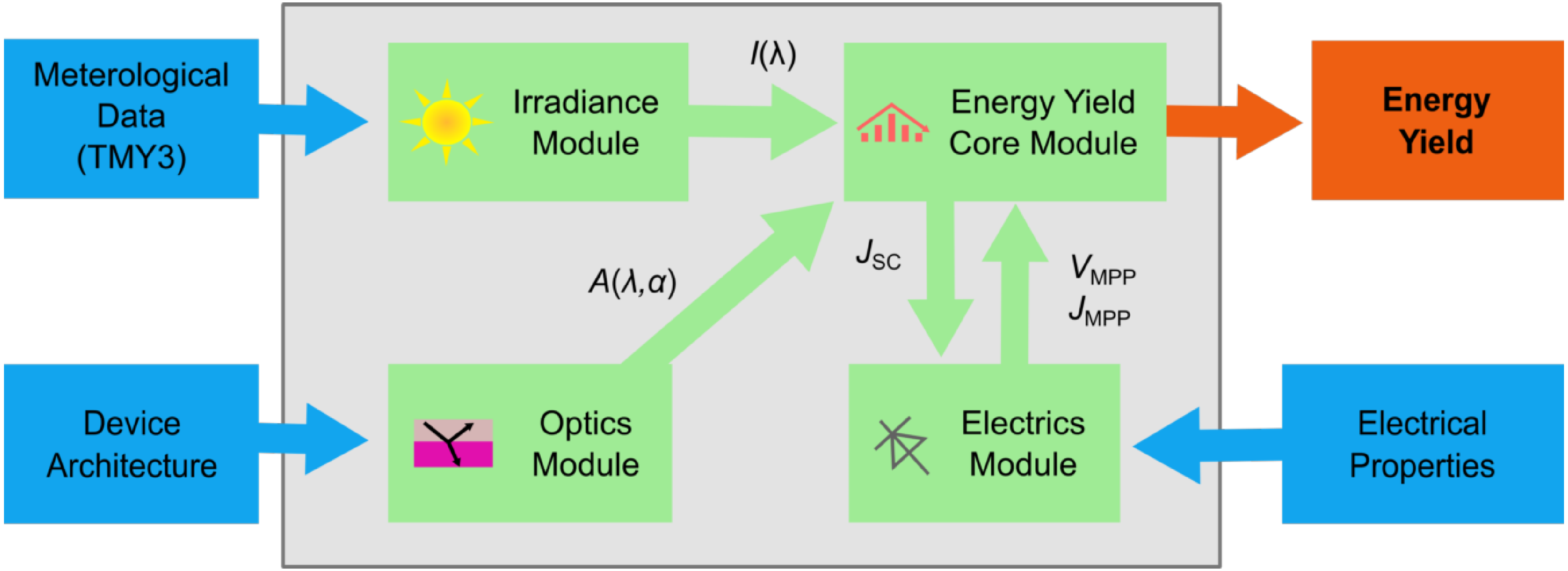
Energy yield modelling platform



Optics Module

- Transfer-matrix method (TMM) for thin film layers
- Series expansion of Beer-Lambert for incoherent layers

Energy yield modelling platform



Energy Yield Core Module

- Monofacial and bifacial solar modules
- Possibility to set tilt, rotation and sun tracking

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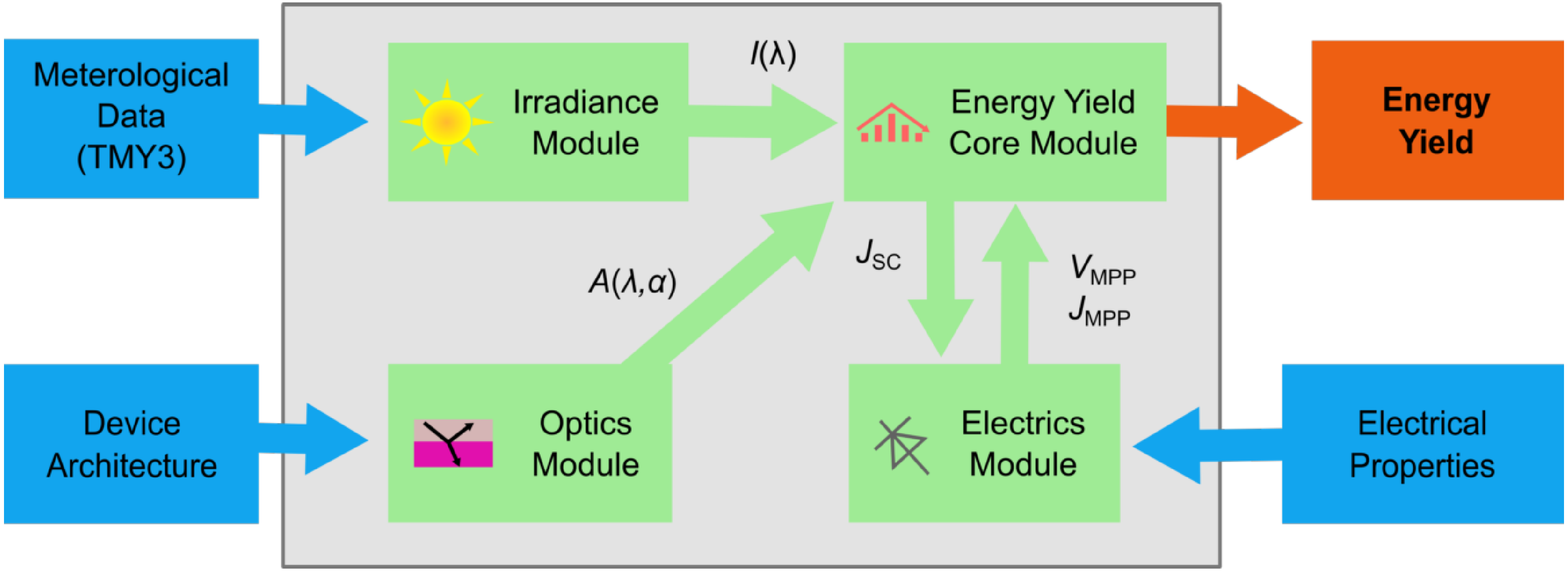
Energy yield modelling platform

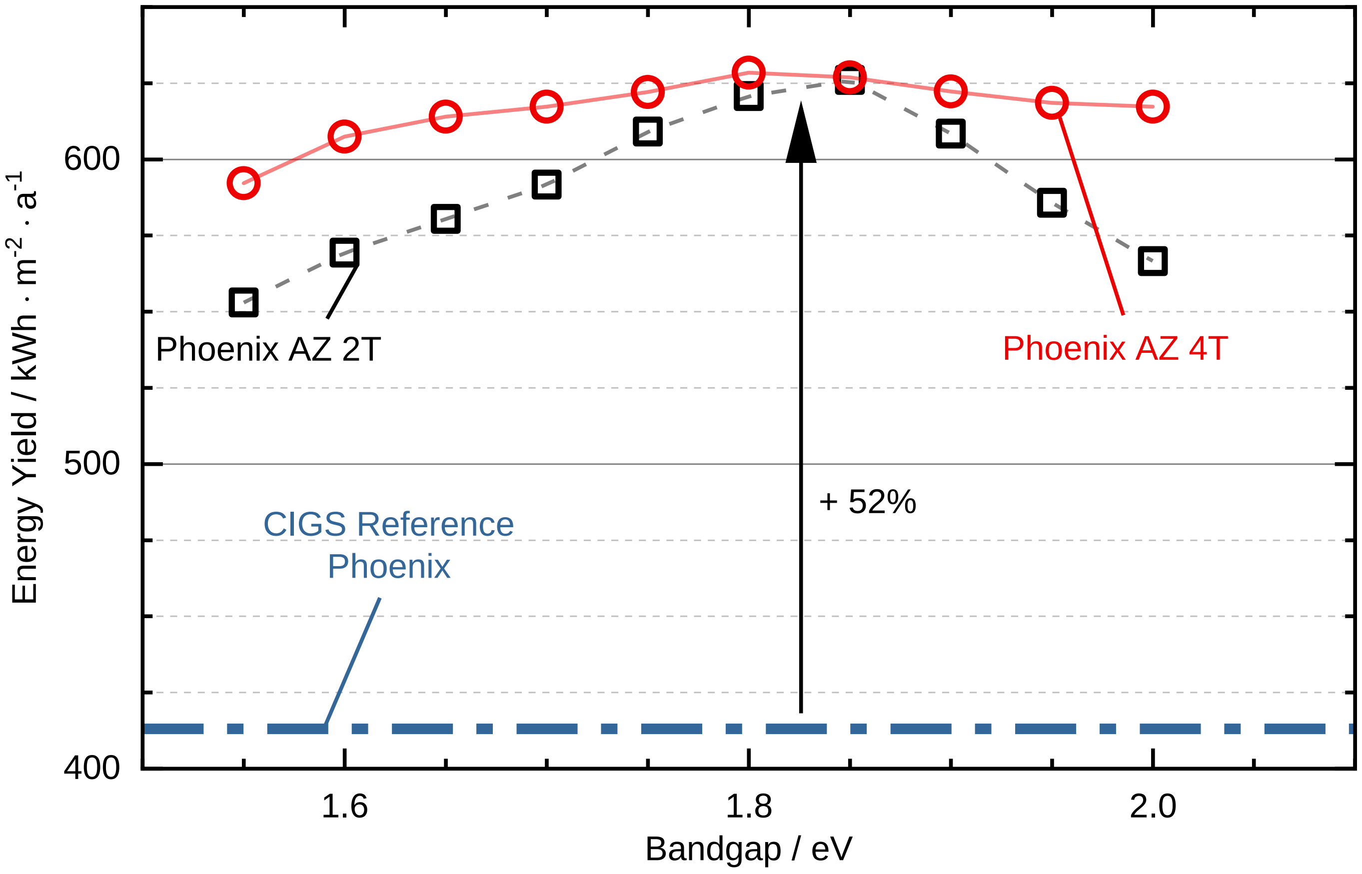


Electrics Module

- Calculates maximum power point (MPP)
- 2T, 4T and 3T architectures possible

Result highlights

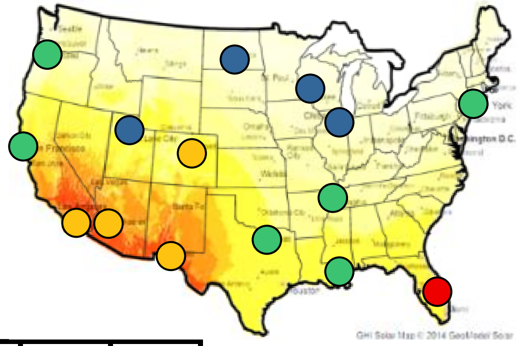
Perovskite/CIGS: perovskite bandgap

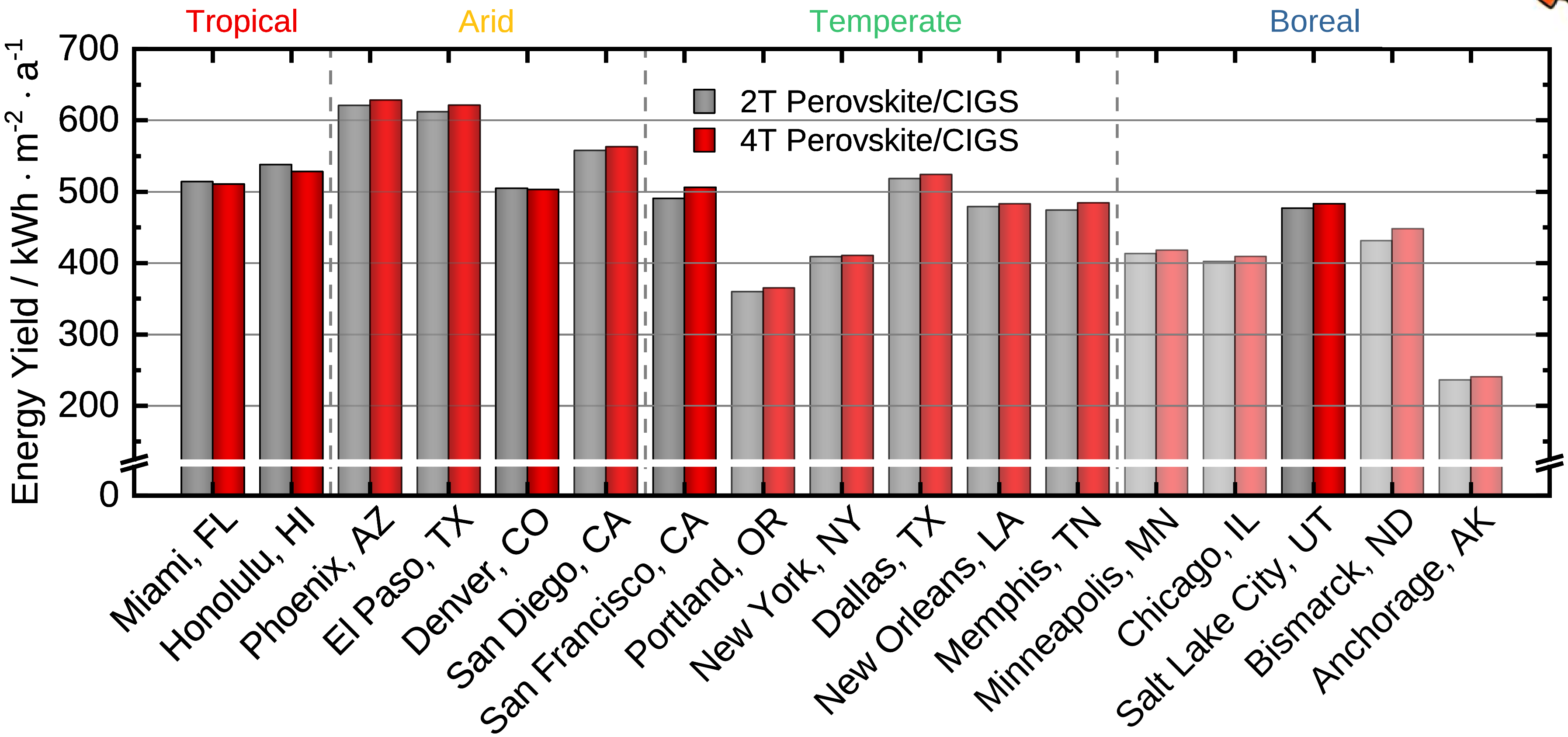


*adapted from Langenhorst *et al.*, *Progress in Photovoltaics* 2018

- CIGS bandgap = 1.2 eV
- Optimum perovskite bandgap ~ 1.80 - 1.85 eV
- With 4T architecture lower losses for not optimal perovskite bandgap

Perovskite/CIGS





2T vs. 4T: comparable energy yield for optimal perovskite bandgap!

*adapted from Langenhorst *et al.*, *Progress in Photovoltaics* 2018

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Reference layer stack for Percistand

2T tandem

Material	Thickness
MgF_2 Glass EVA	100 nm 3 mm 0.5 mm
IZO	120 nm
SnO_2/C_{60}	20 nm/12 nm
Perovskite	530 nm
SAM/NiO_x	1 nm/10 nm
ITO	20 nm
Al-doped Zinc Oxide Zinc Oxide	50 nm 75 nm
Cadmium Sulfide	60 nm
CIGS (1.13 eV)	2.5 µm
Molybdenum	800 nm
Glass	3 mm

4T tandem

Material	Thickness
MgF_2 Glass	100 nm 3 mm
ITO	120 nm
NiO_x/SAM	10 nm/1 nm
Perovskite	530 nm
C_{60}/SnO_2	12 nm/20 nm
IZO	120 nm
EVA	0.5 mm
Al-doped Zinc Oxide Zinc Oxide	500 nm 75 nm
Cadmium Sulfide	60 nm
CIGS (1.13 eV)	2.5 µm
Molybdenum	800 nm
Glass	3 mm

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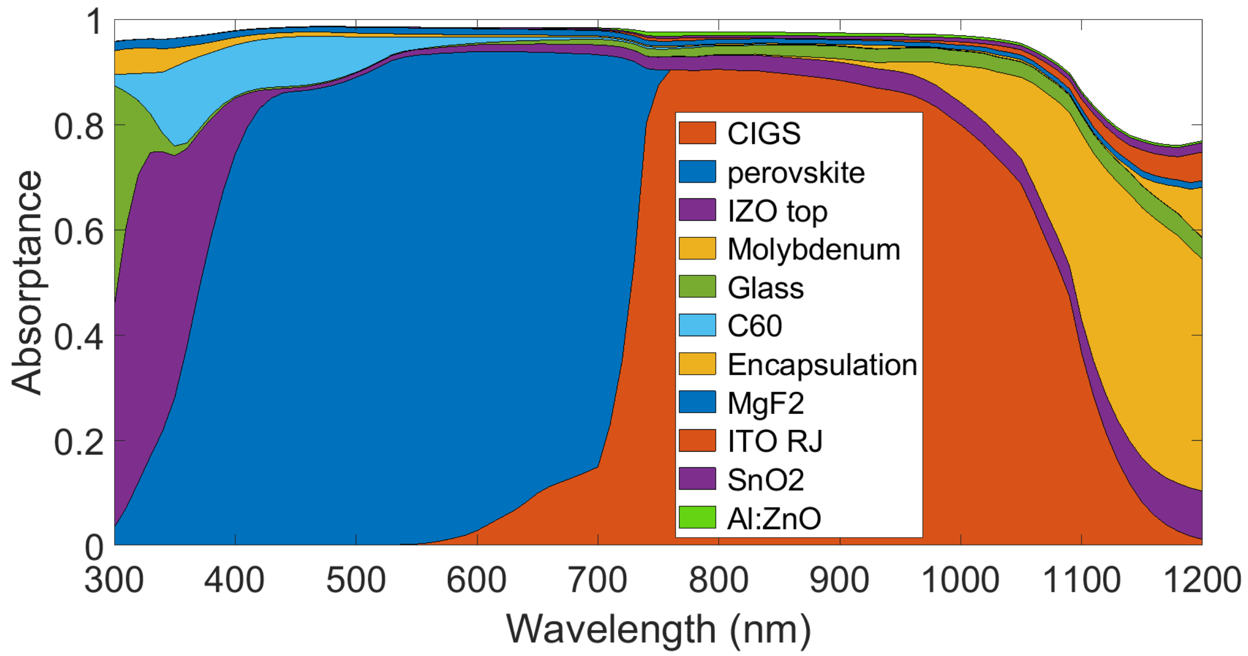
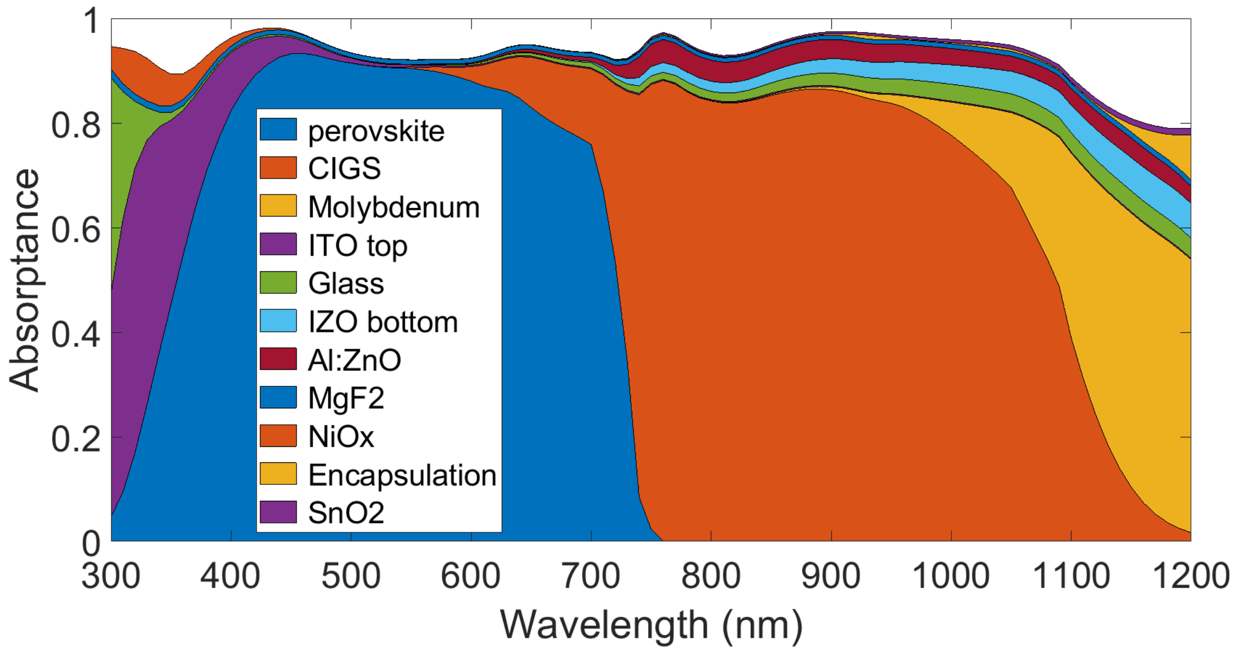
Layer resolved absorptance

2T tandem



4T tandem



$J_{sc,total}$	$J_{sc,parasitic}$	$J_{sc,reflection}$
37.6 mA/cm^2	7.2 mA/cm^2	1.7 mA/cm^2

$J_{sc,total}$	$J_{sc,parasitic}$	$J_{sc,reflection}$
37.1 mA/cm^2	6.5 mA/cm^2	2.9 mA/cm^2

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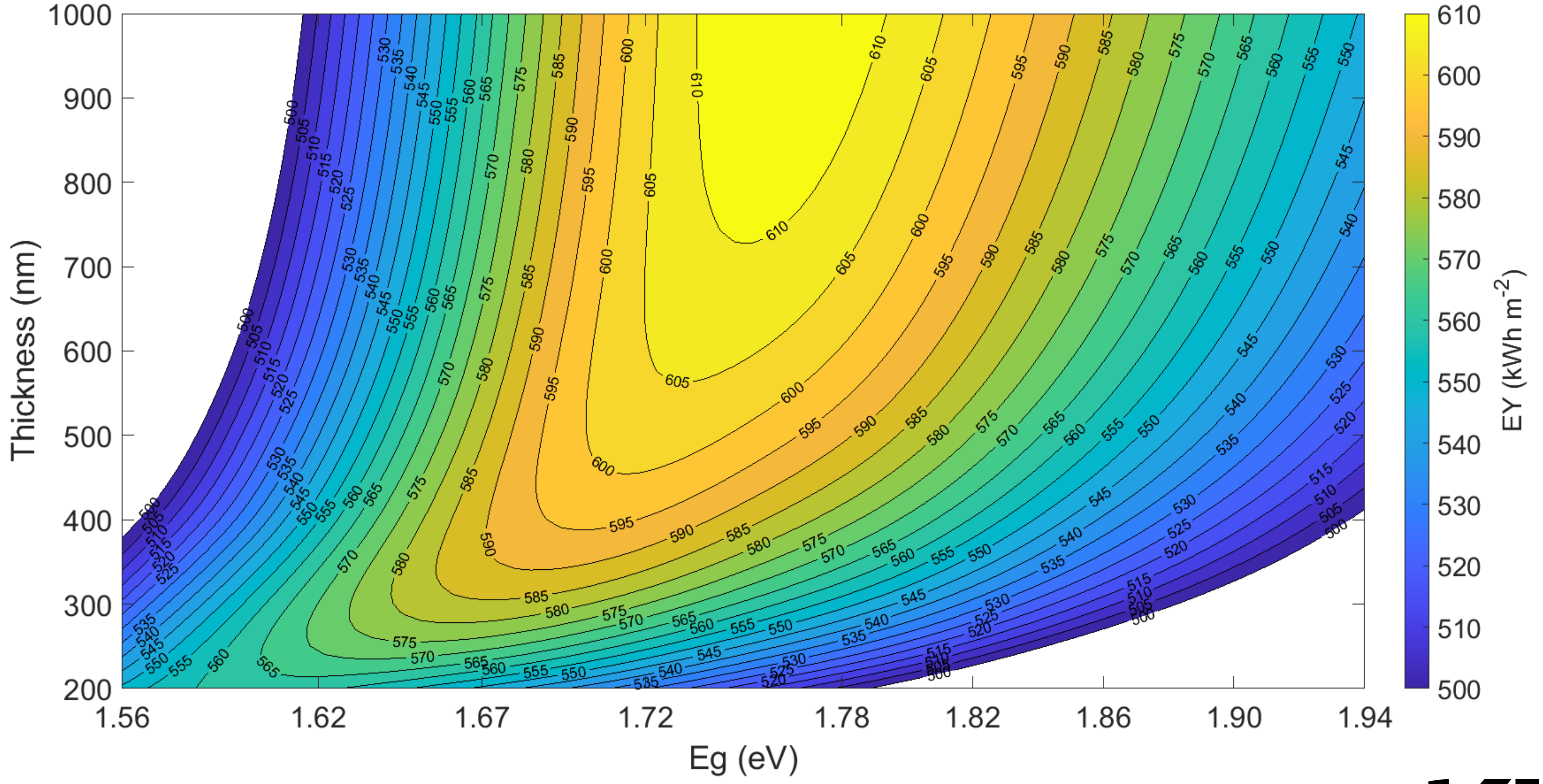
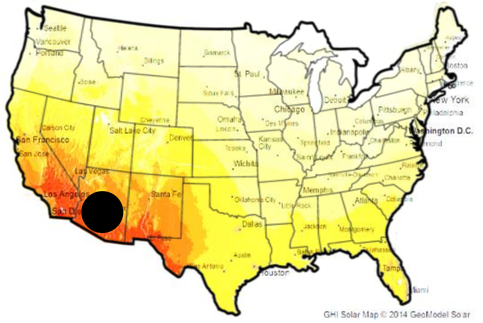
Perovskite thickness and energy gap optimization



2T tandem

Phoenix, AZ



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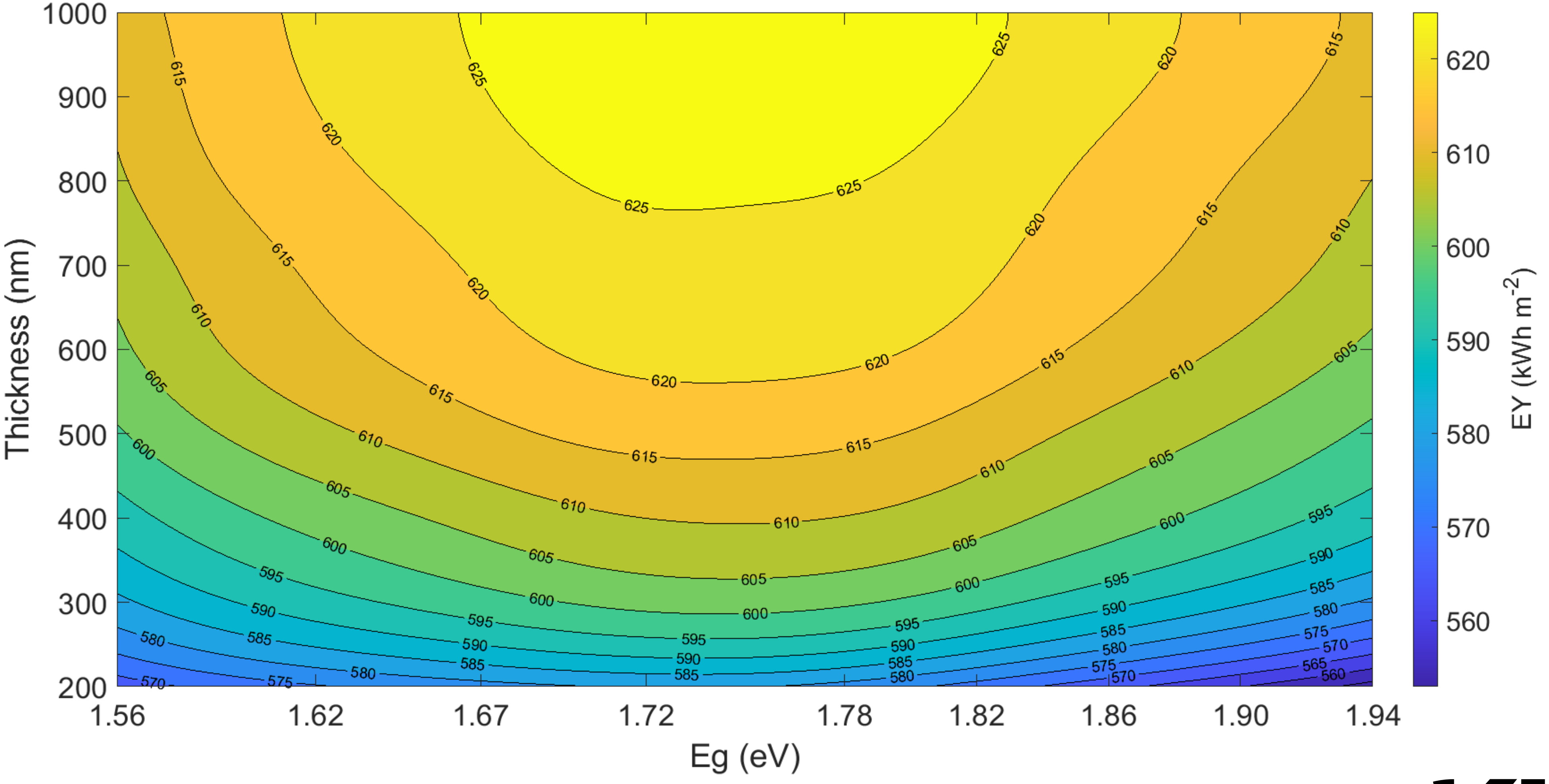
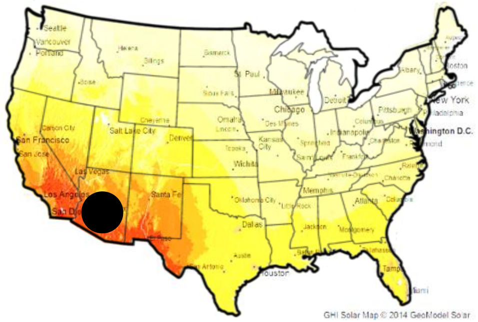
Thickness and energy gap optimization



4T tandem

Phoenix, AZ



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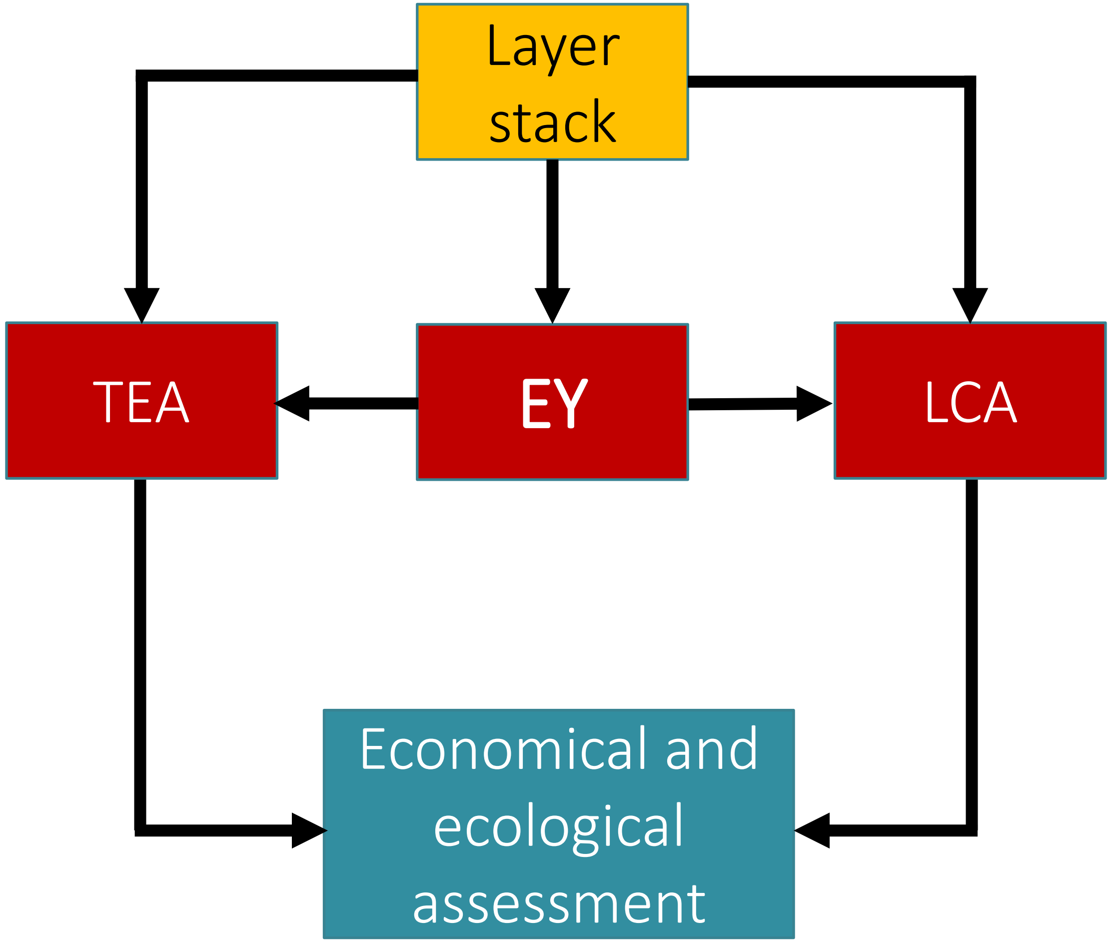
Energy Yield simulations are essential



- Energy yield module results are input to Techno-Economic Assessment (TEA) and Life-Cycle Assessment (LCA) modules
- The 3 modules allow us to deliver a final economical and ecological assessment

Many thanks to...

... Ulrich Paetzold.

... the Perovskite Taskforce at KIT.

... the fantastic technical support.

... all collaboration partners.

... the funding organizations.

partners:

OXFORD PV™ The Perovskite Company

ISFH

HZB Helmholtz Zentrum Berlin

SOLLIANCE

JÜLICH Forschungszentrum

SUNOVATION

Australian National University

Universität Heidelberg

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imec

Fraunhofer

ZSW

NICE

KAUST

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funding:

KSOP

Federal Ministry for Economic Affairs and Energy

HELMHOLTZ ASSOCIATION

Federal Ministry of Education and Research

Gefördert durch DFG Deutsche Forschungsgemeinschaft

HEiKA Heidelberg Karlsruhe Research Partnership

Baden-Württemberg Stiftung

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Thank You for your attention

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Prospective Life Cycle Assessment of Tandem PV- A Preliminary Analysis

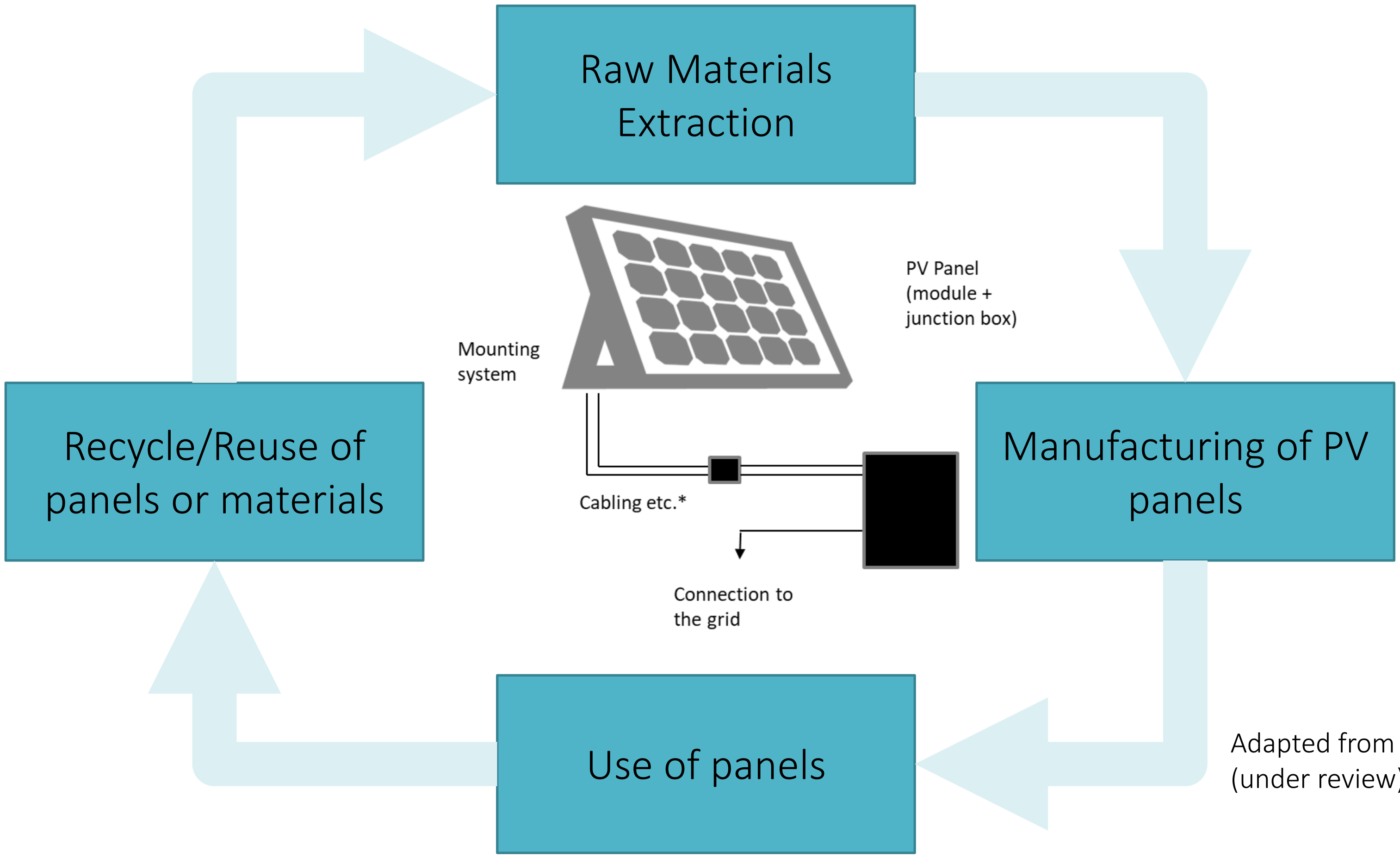
Neethi Rajagopalan

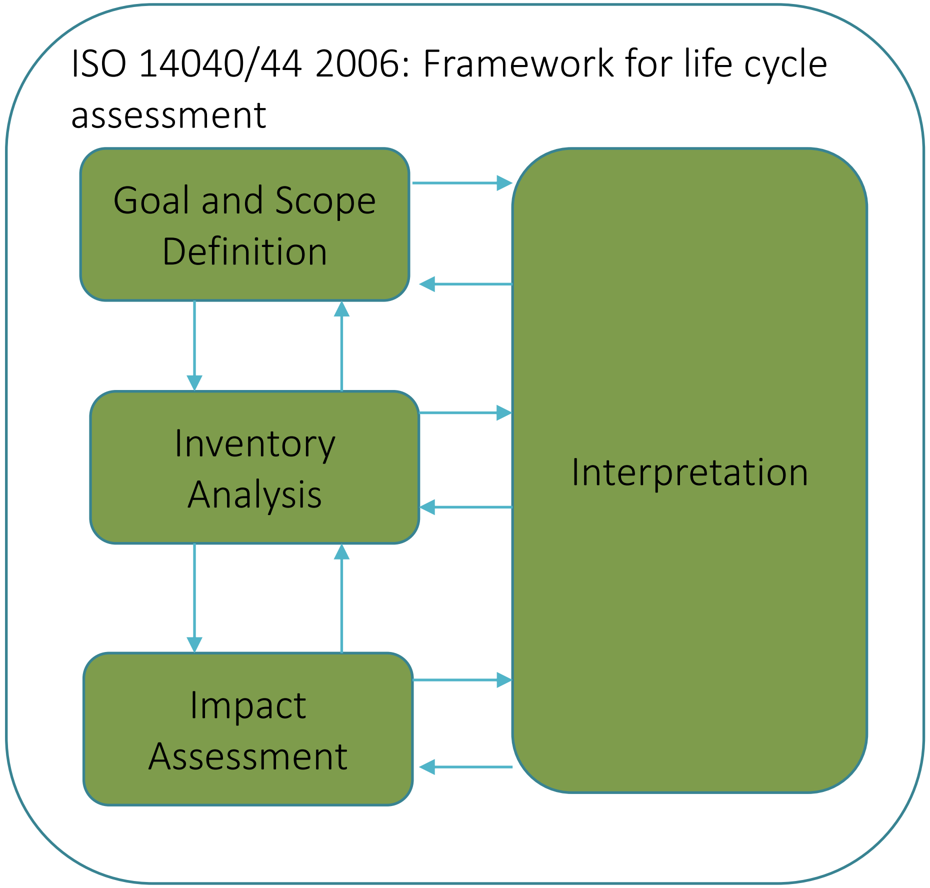
VITO/Energyville

VITO/Energyville- Research Theme Sustainable Energy

EnergyVille

Life Cycle Assessment





Adapted from Rajagopalan et al. (under review)

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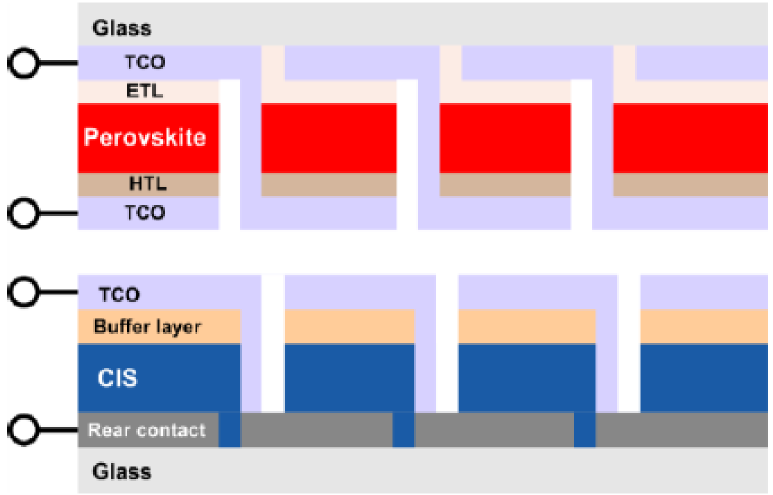
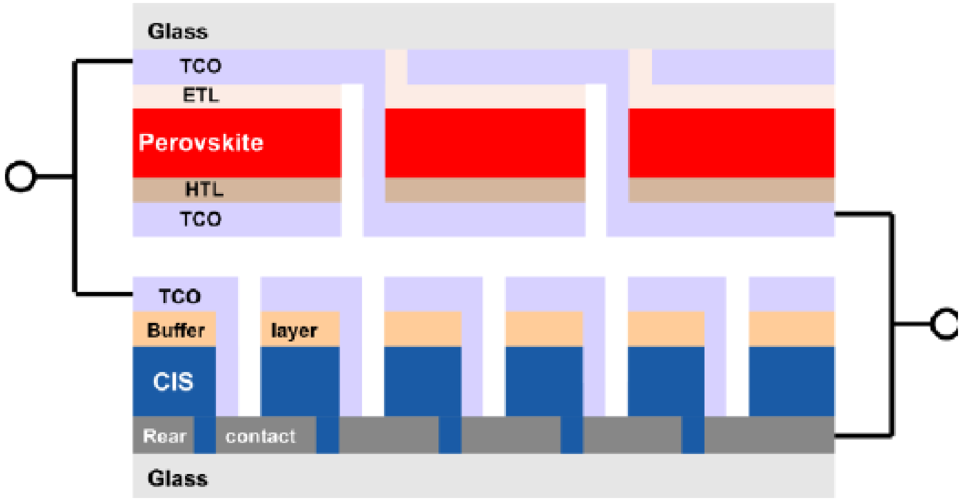
Goal & Scope of LCA

TRL 3 in 2020 → TRL 4 in 2024



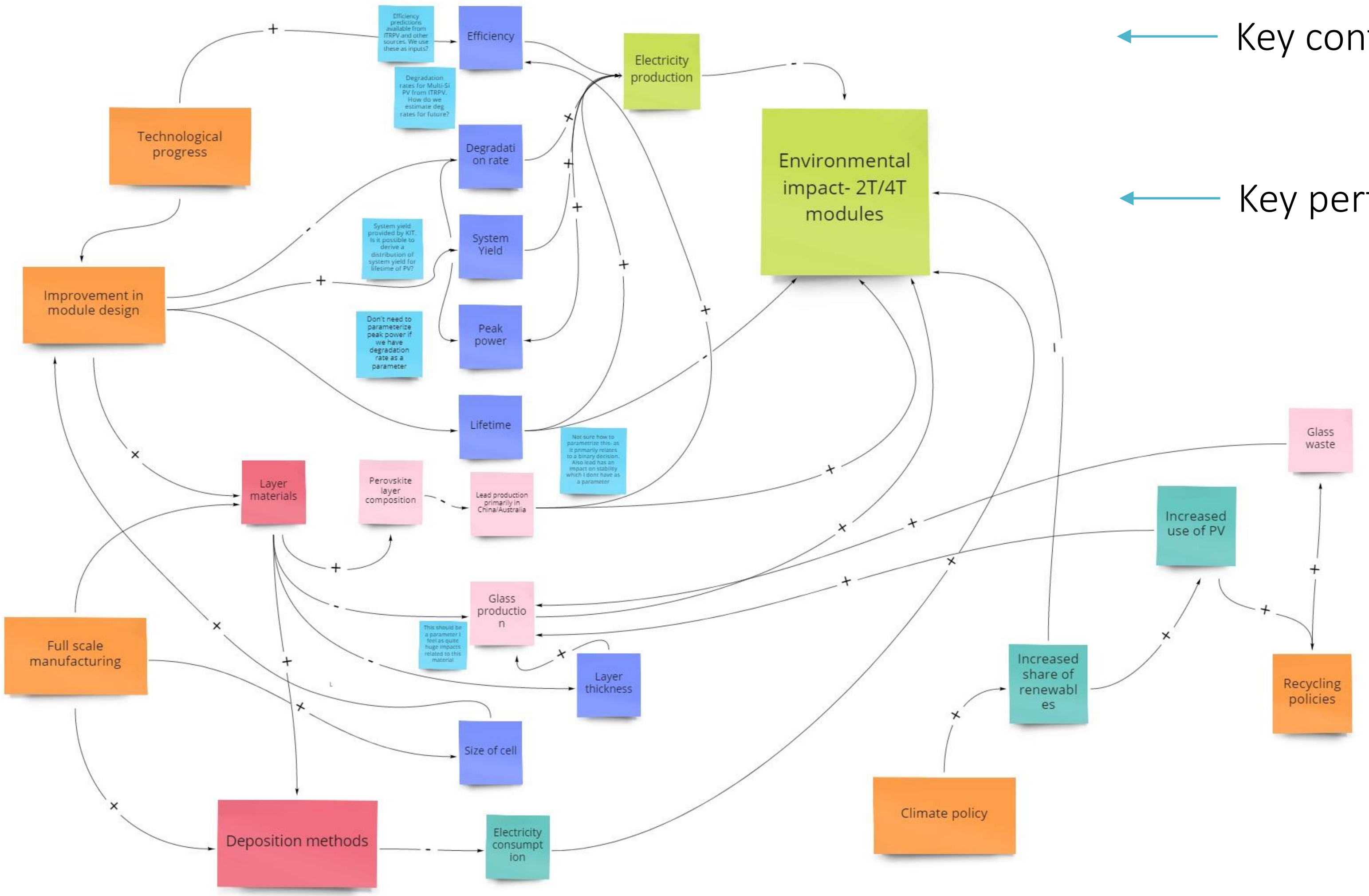
TRL 2 in 2020 → TRL 3 in 2024



Full scale manufacturing of perovskite panels in 2050

Functional unit = 1 kWh of electricity production

Identifying Causal Loops



Key contributor to performance

Key performance indicator for LCA

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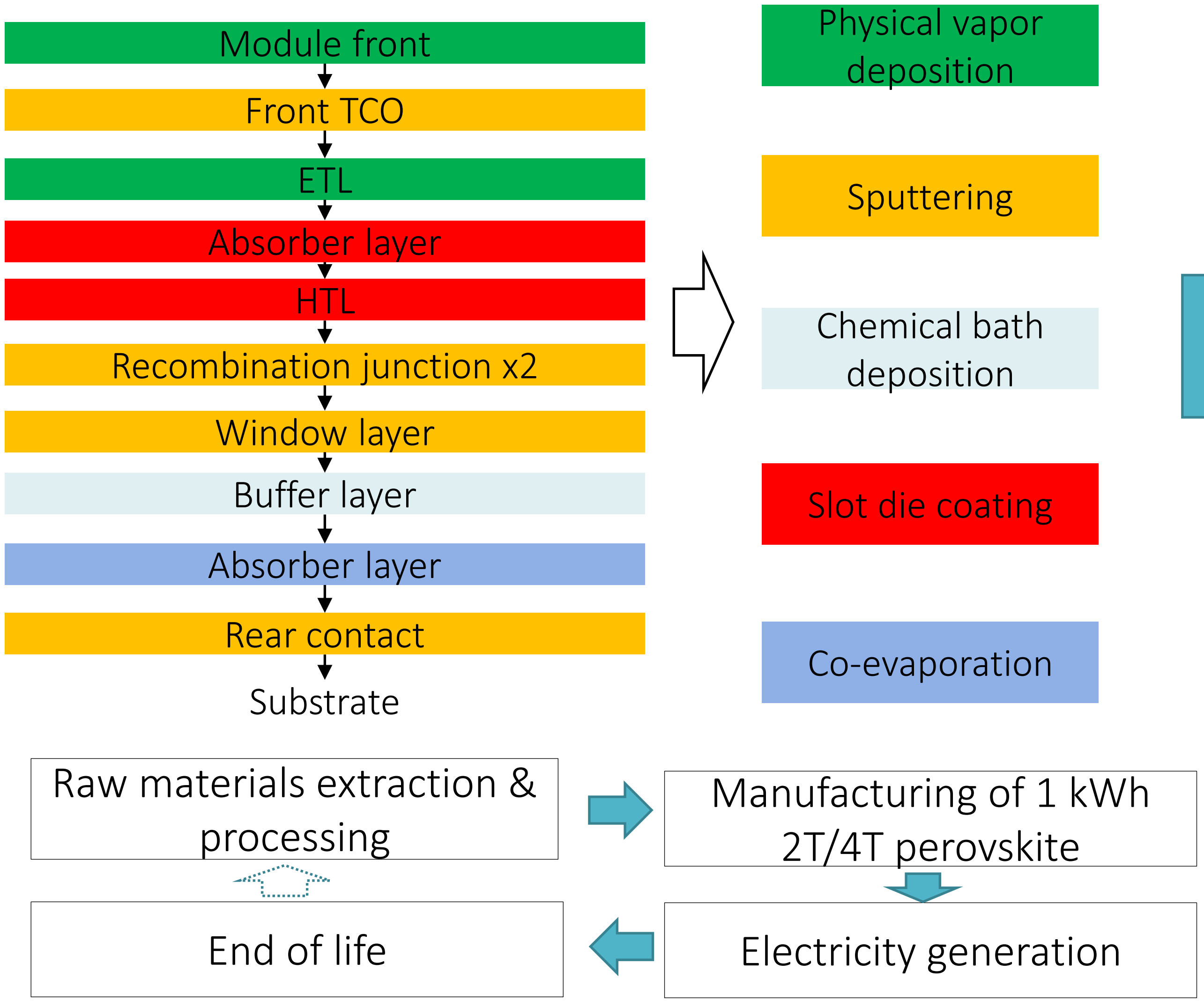
Product System Boundary



Full Scale manufacturing in 2050

Material parametrization

- Changes in deposition methods
- Layer thickness
- Material properties

Factory & Equipment sizing

- Size scaling

External factors

- Increased recycling of glass
- Increased use of renewables in electricity mix of future
- Energy yield modelling in various locations

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LCA Process

SOLARONIX

Activity data provided by manufacturer Solaronix for carbon-based perovskite solar cells

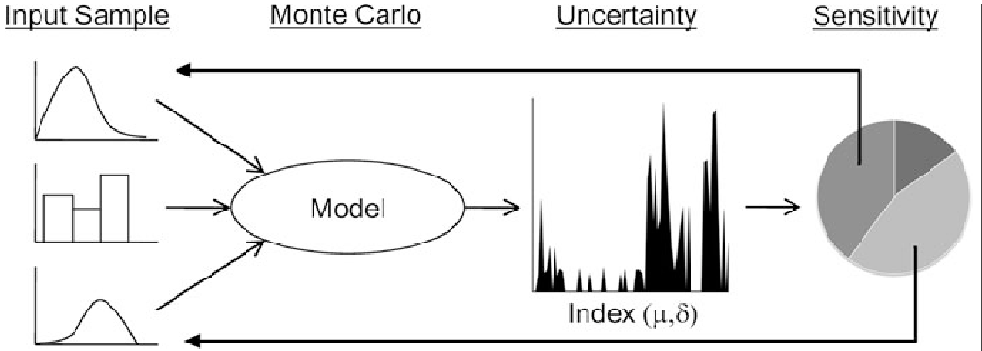
ecoinvent

LCA-ActivityBrowser/
activity-browser
GUI for brightway2

Background data from Ecoinvent database uploaded to LCA tool Brightway-Activity Browser

Life Cycle Impact Assessment

- Impacts to environment
- Impacts to human health
- Resource use



Source: Tate 2012

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Future Research Focus

- Combining LCA and TEA
- Parametrizing panel properties till 2050
  - Eg: efficiency, lifetime, degradation rate
- Complete environmental profile of emerging 2T/4T technology
- Identify potential improvements for emerging technology

Thanks for your attention!

Questions & Comments?

Contact

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Techno-economic assessment of tandem perovskite/CIGS solar cells

Alessandro Martulli – PhD Student

Environmental Economics - Centre for Environmental Sciences

Faculty of Business Economics, Hasselt University

confidential

Who we are

- Environmental Economics Research group
- Within the Centre for Environmental Sciences at Hasselt University (Belgium)
- Research group focuses:
  - Techno-economic, environmental and social assessments of clean technologies
  - Monetary valuation of ecosystem services and nature's contribution to people

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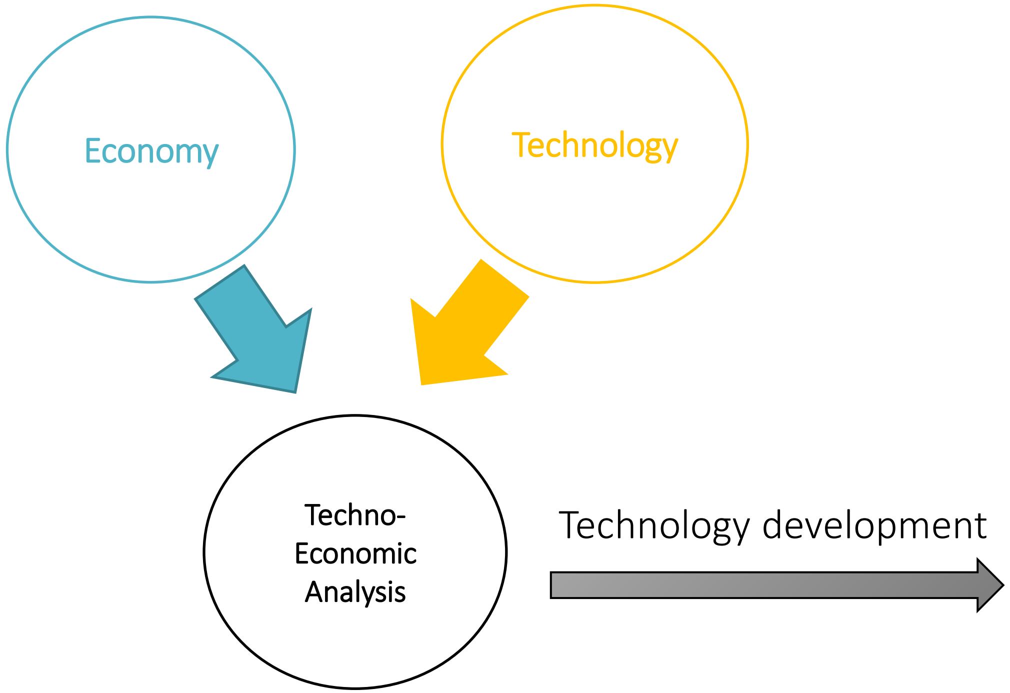
Techno-economic assessment (TEA)

- Generally, TEA combines process modeling and economic evaluation

GOAL
Analyzing the **impact** of *changes* in **technical and economic** parameters on the **financial viability**



- Answer two questions:

1. How does the technology work?
2. Is the technology profitable?

Van Dael, M., et al. (2015). *Techno-economic Assessment Methodology for Ultrasonic Production of Biofuels.*

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Techno-economic assessment (TEA) - Steps

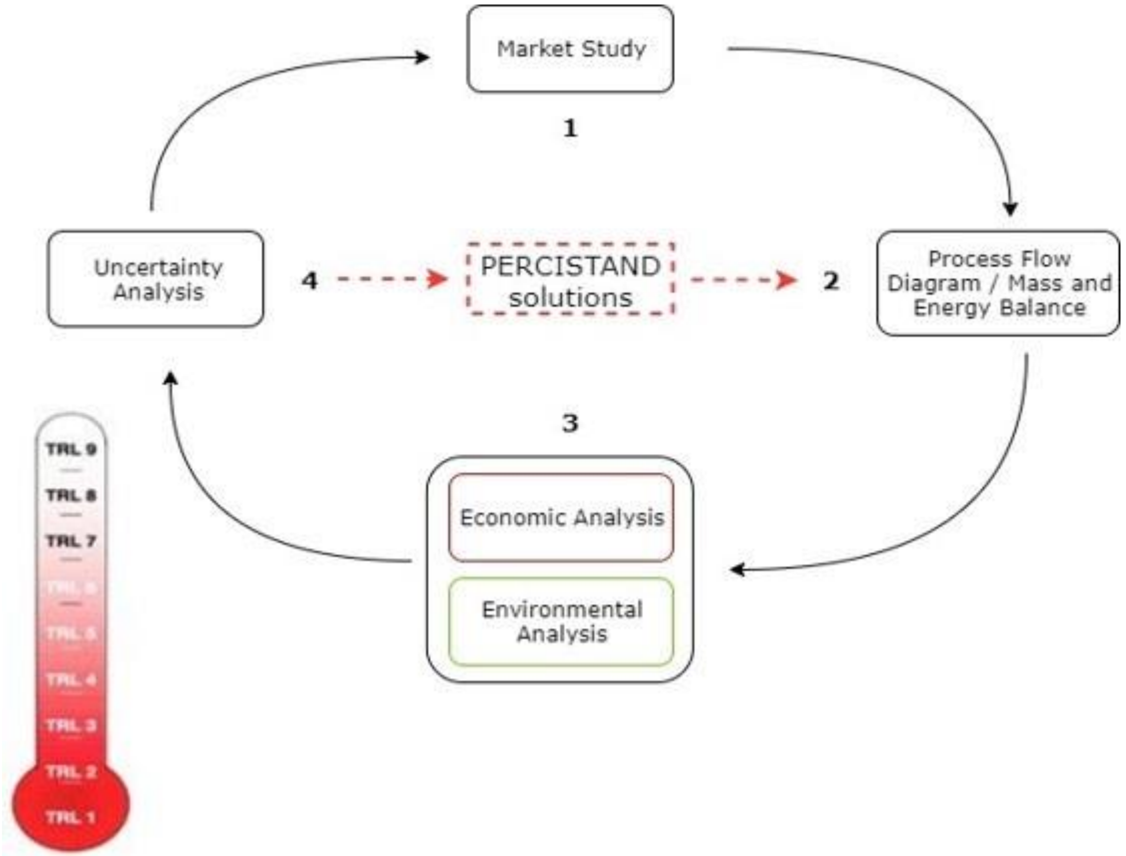
- Methodology consists in four steps

1. Market study
2. Process flow diagram/ Mass and Energy Balance definition
3. Economic analysis (can be expanded to economic-environmental analysis)
4. Uncertainty analysis

Link mass-energy balance with:

- Environmental analysis
- Economic analysis

→ **Key parameters identification**



Iterative approach

- As more data become available, accuracy improves

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TEA Steps - detail

1. Market study

- Identify market size, trends, competitors, customers, legislation
- Gather input data

2. Process flow diagram (PFD) / Mass and Energy Balance (M&E) definition

- PFD gives overview of main process steps with inputs/outputs
- M&E balance contains mass and energy data of the process

3. Economic Analysis

- Capital (CAPEX) and operational costs (OPEX) calculations
- Feasibility assessment through relevant indicators (e.g., LCOE for PV applications)

4. Uncertainty Analysis

- Determine parameters with highest impact

TEA – Economic feasibility indicators - PV

1. **Manufacturing cost (MC – EUR/m2) :**

$$MC = \sum_i M_i + E_i + O_i + R_i$$

Cost per unit area of:

- M_i= Material
- E_i = Equipment
- O_i = Utilities, Insurance and Labor
- R_i = Repair and maintenance

2. **Minimum Sustainable Price (MSP – EUR/Wp):**

$$MSP = \frac{MC + OH + WACC}{PCE\ x\ P_0}$$

- OH = overheads (14% of MC)
- $WACC$ = weighted average cost of capital (15% of MC)
- PCE = Module power conversion efficiency
- P_0 = Irradiance power density at standard test conditions (1000 W/m²)

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TEA – Economic feasibility indicators - PV

3. Levelized cost of electricity (LCOE – EUR/kWh) :

$$LCOE = \frac{\sum_{i=0}^{N} \frac{C_i}{(1+\ D)^i}}{\sum_{i=0}^{N} E_i}$$

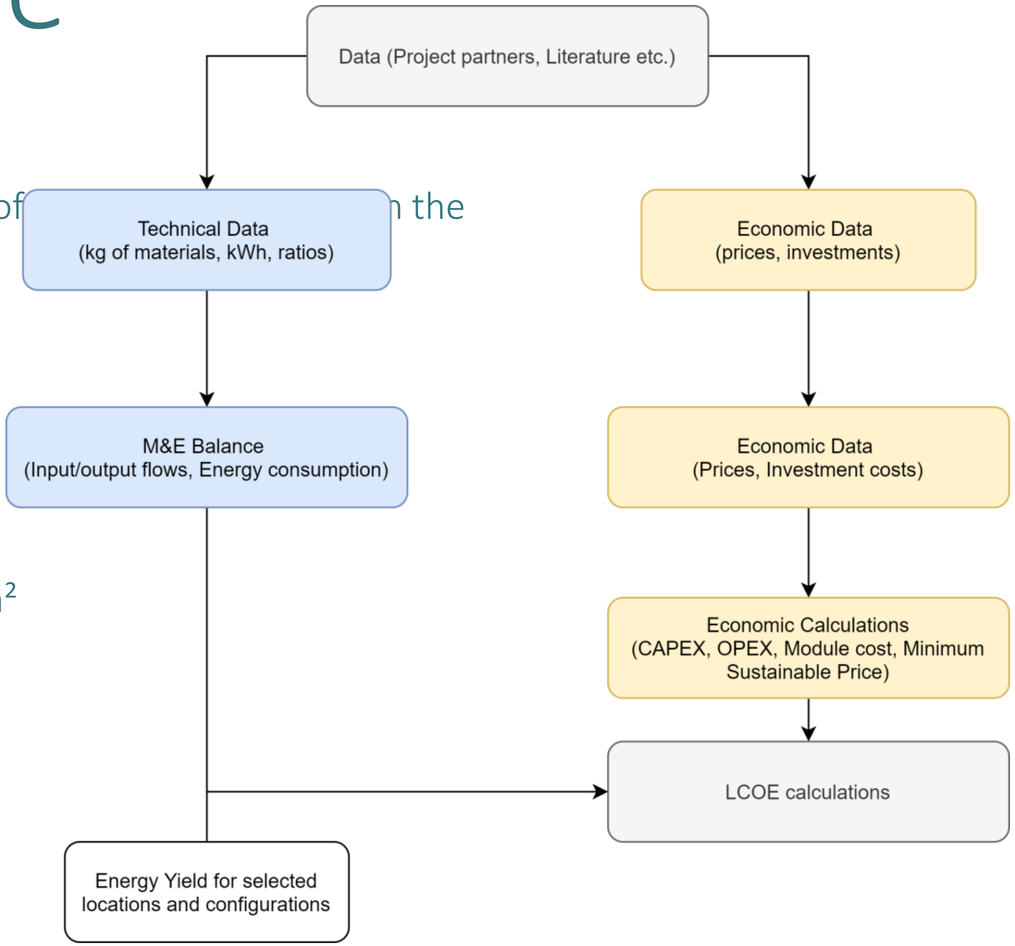
- C_i = system cost
- E_i = energy generated in the i-th year
- D = discount rate
- N = total lifetime of PV system

Energy yield data input:

- Realistic irradiation conditions
- Meteorological data from NREL

PERCISTAND – TEA structure

- **Bottom-up model construction**
  - Manufacturing process divided in smallest parts and product cost is sum of … the production cycle of the product
  - Accurate, intuitive, aligns with LCA (environmental impact assessment)
- **PFD and M&E balance linked to:**
  - Operating scale: throughput → industrial scale production (0.9 m^2/min)
  - Inputs (e.g., kg of material, kWh) → PERCISTAND module size = 20x20 cm^2
  - Manufacturing techniques (e.g., sputtering, coating)
- **Capex and Opex calculations for different scenarios**
  - Manufacturing cost and Minimum Sustainable Price (MSP)
- **LCOE calculation**
  - Energy yield input



PERCISTAND – TEA scenarios

Several scenarios have been constructed, corresponding to PERCISTAND technologies:

- Carbon-based perovskite single-junction (Solaronix) – used as benchmark for LCA/TEA model construction
- CIGS single- junction (preliminary data)
- 2T tandem (preliminary data)
- 4T tandem (preliminary data)

Every scenario contains:

- Process flow diagram
- Mass and energy balance
  - *Process step*
  - *Inputs for each step*
- Economic calculations
  - *CAPEX*
  - *OPEX*
- LCOE calculation (so far, only Solaronix case)
  - Energy yield calculation for carbon-based perovskite single junction

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Next steps – Indicator estimates

- Accurately estimate 2T/4T configuration manufacturing cost (€/ m^2)
- Calculate 2T/4T configuration Minimum Sustainable Price (MSP) (€/ W)
- Estimate 2T/4T configuration LCOE with energy yield input data (€/kWh):
  - PERCISTAND target: 5 EUR cents/kWh
  - Southern Europe conditions
- Compare indicators with alternative PV technologies
  - Perovskite/perovskite or Perovskite/Silicon tandems
  - Silicon, perovskite and CIGS single junction (SJ)

PV technology	MSP (US$/W)	LCOE (US$/kWh)	Source
Perovskite SJ	0.21 – 0.25	3.5 – 4.9	Cai et al. (2017)
Perovskite SJ	0.41	4.9 – 7.9	Song et al. (2017)
Perovskite SJ	0.17	4.34	Li et al. (2018)
Perovskite/Silicon tandem	0.48	5.22	Li et al. (2018)
Perovskite/Perovskite tandem	0.21	4.22	Li et al. (2018)
Silicon SJ	0.20-0.30		Solar price index, pVexchange (2021)
CIGS SJ	0.33		Wang et al. (2021)

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Next steps – Research gaps

- Focus on main techno-economic challenges:
  - Upscaling
  - Performance (efficiency, lifetime, cost)
  - Toxicity

- Address the on-going research questions within the community of PV technology developers

- Define a roadmap towards commercially viable Perovskite/CI(G)S tandem

Thank you for your attention

Questions?

Contact

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Environmental Economics - Centre for Environmental Sciences

Hasselt University

alessandro.martulli@uhasselt.be

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Full thin-film tandems solar cells

Industry Perspective

Cesar Omar Ramirez Quiroz

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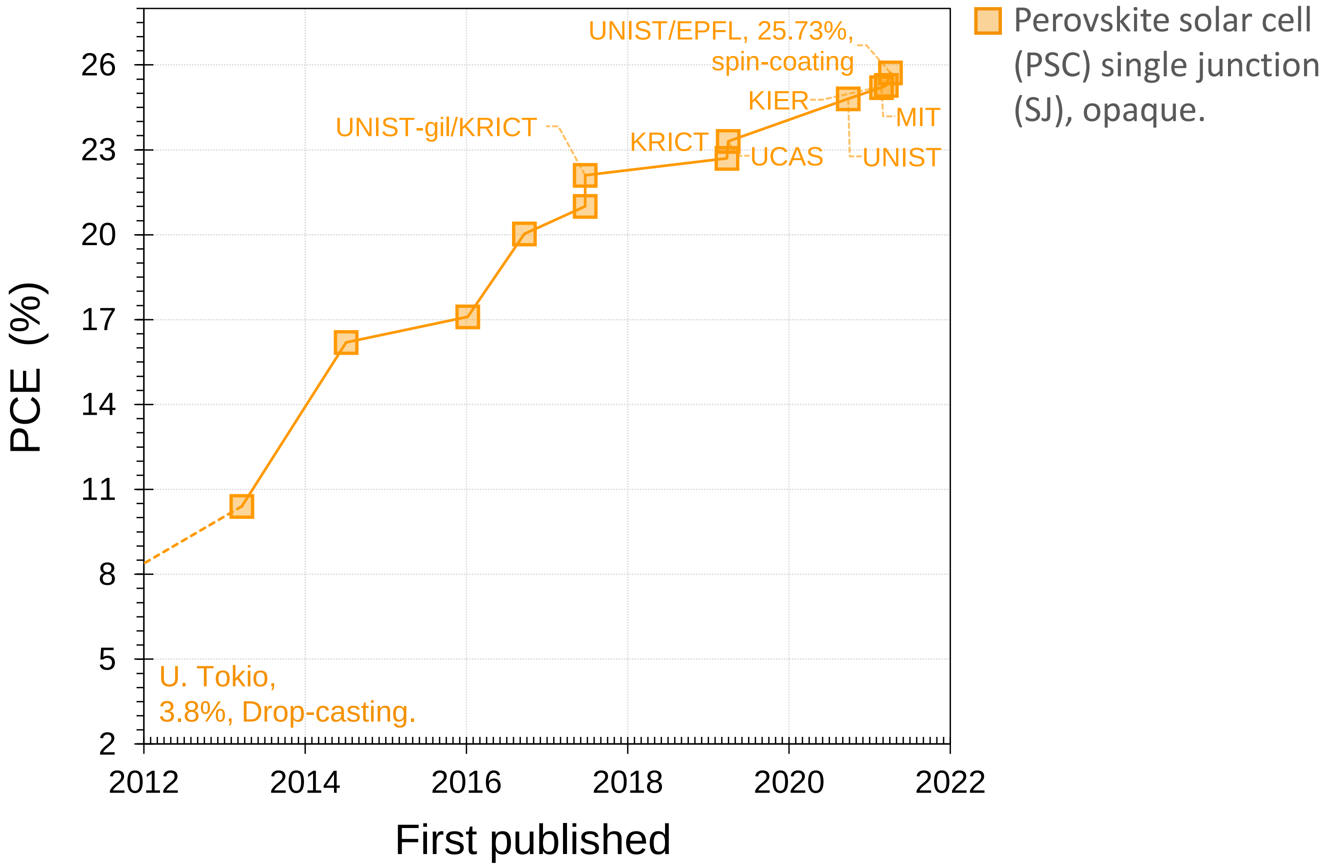
Perovskite single-junction time evolution.

Since the technology of perovskite solar cell was introduced in 2009, the efficiency has evolved fast from 3.8% to 25.73% in 2021.



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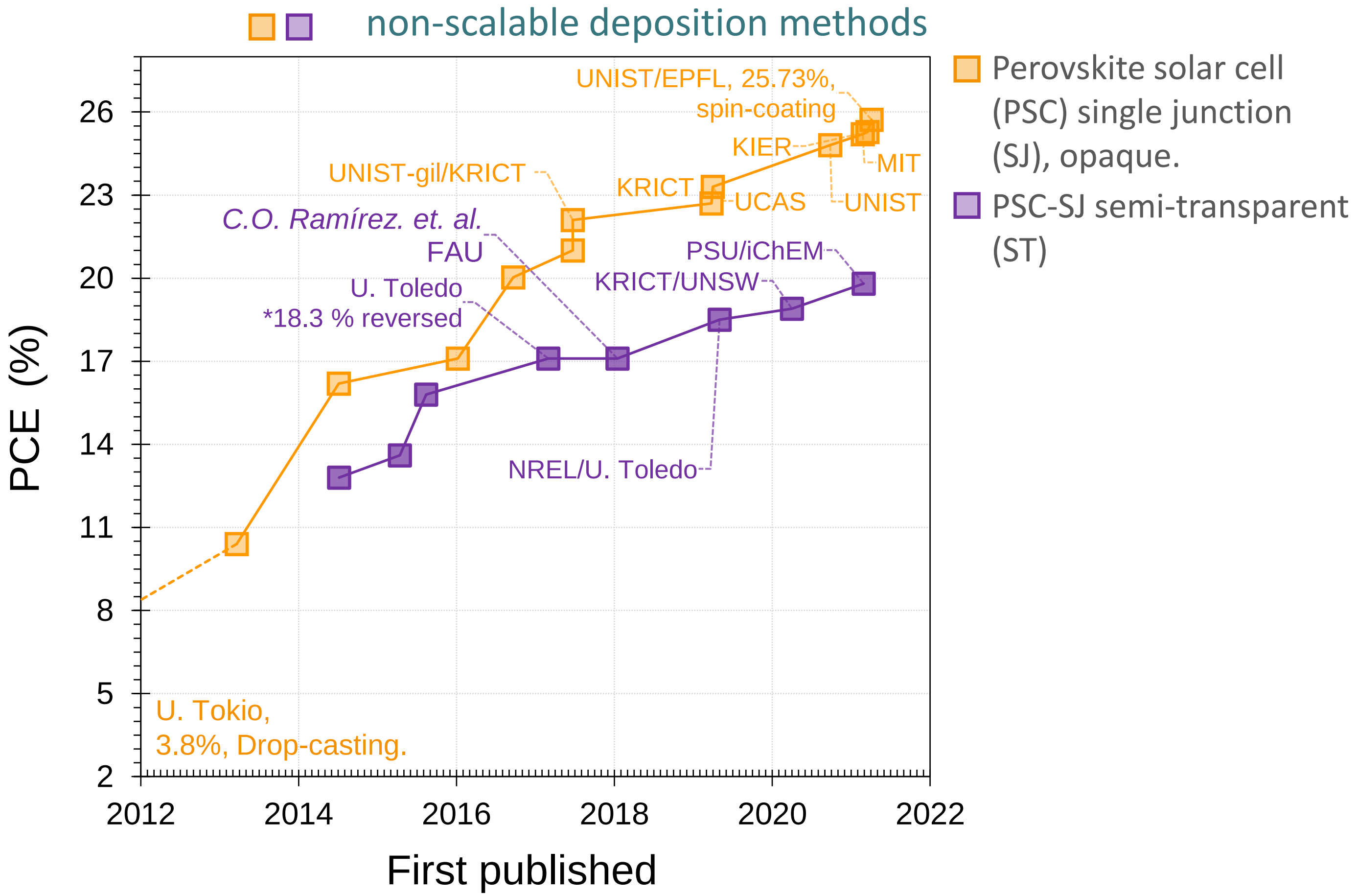

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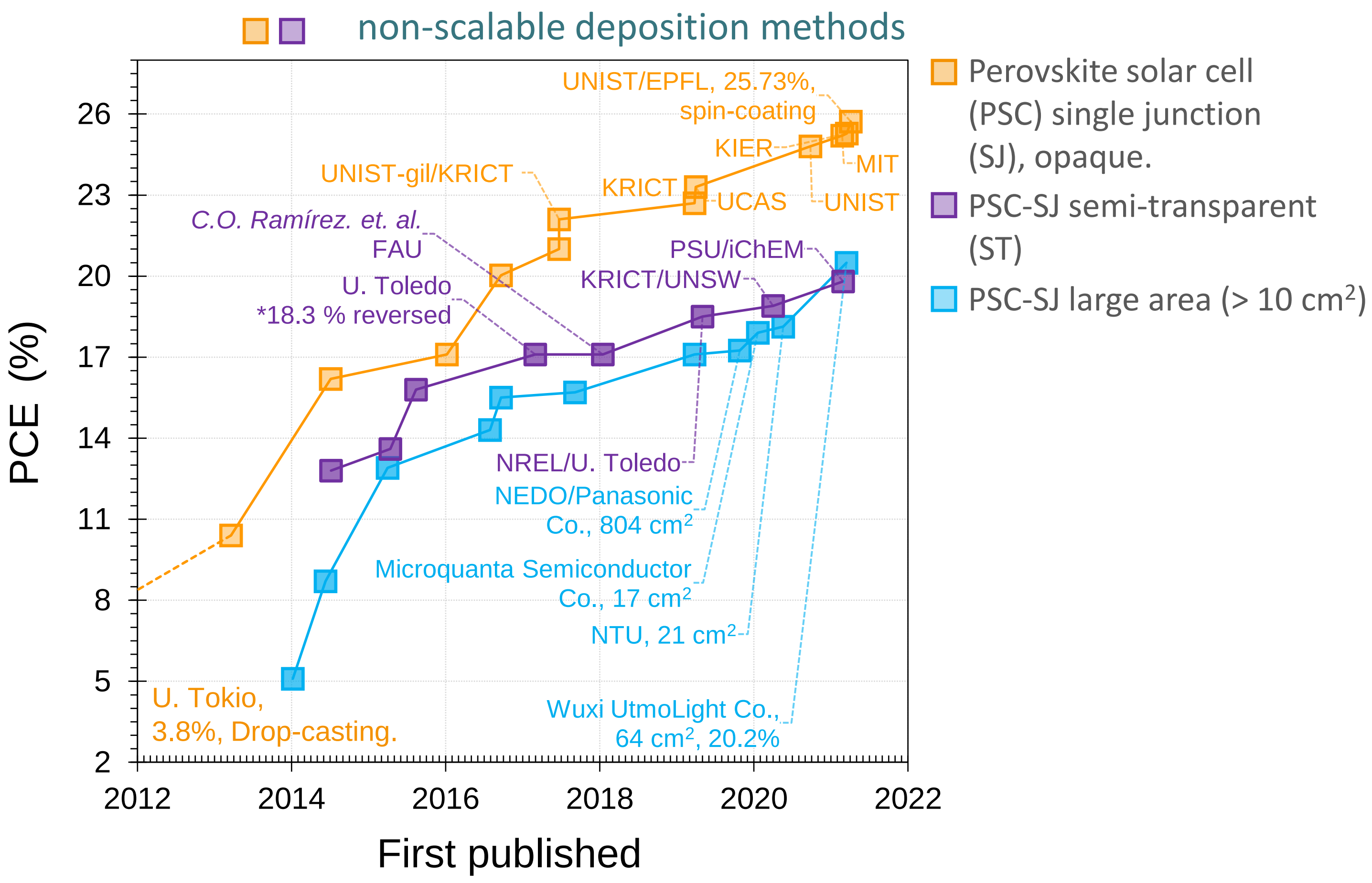

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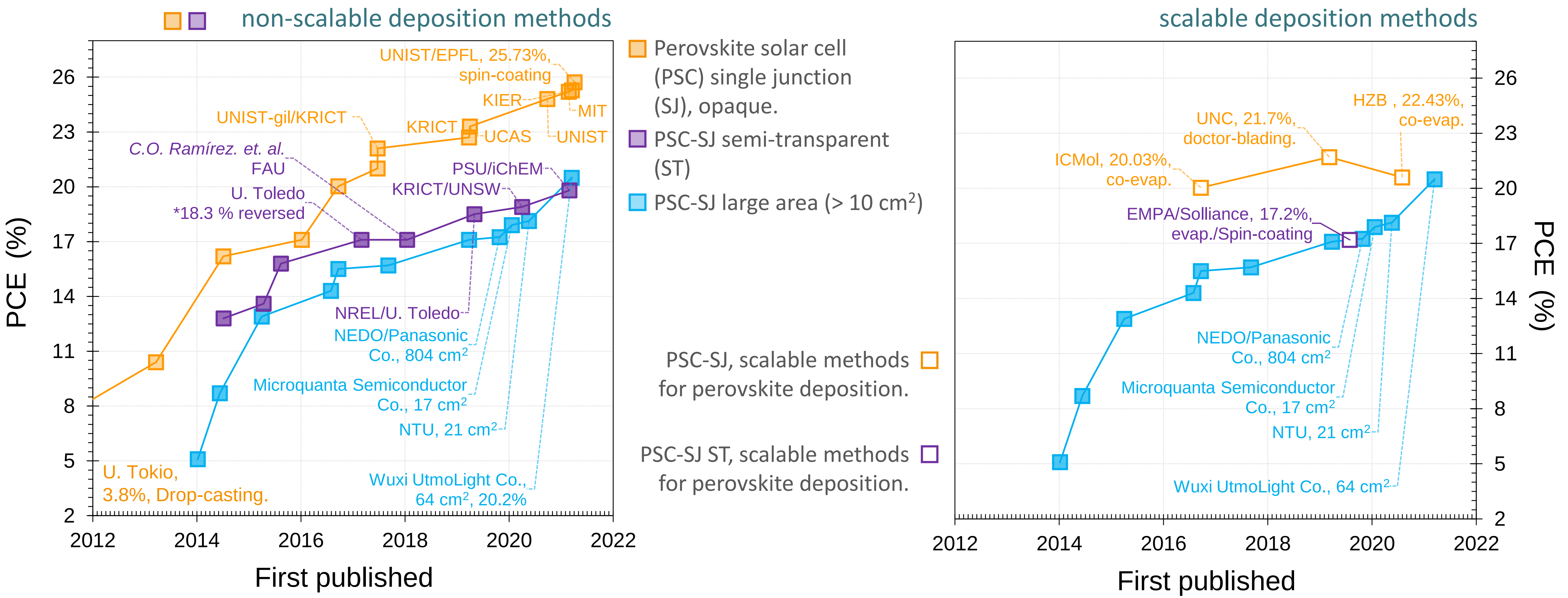

Roß, M. et al. ACS Appl. Mater. Interfaces 12, 39261–39272 (2020).
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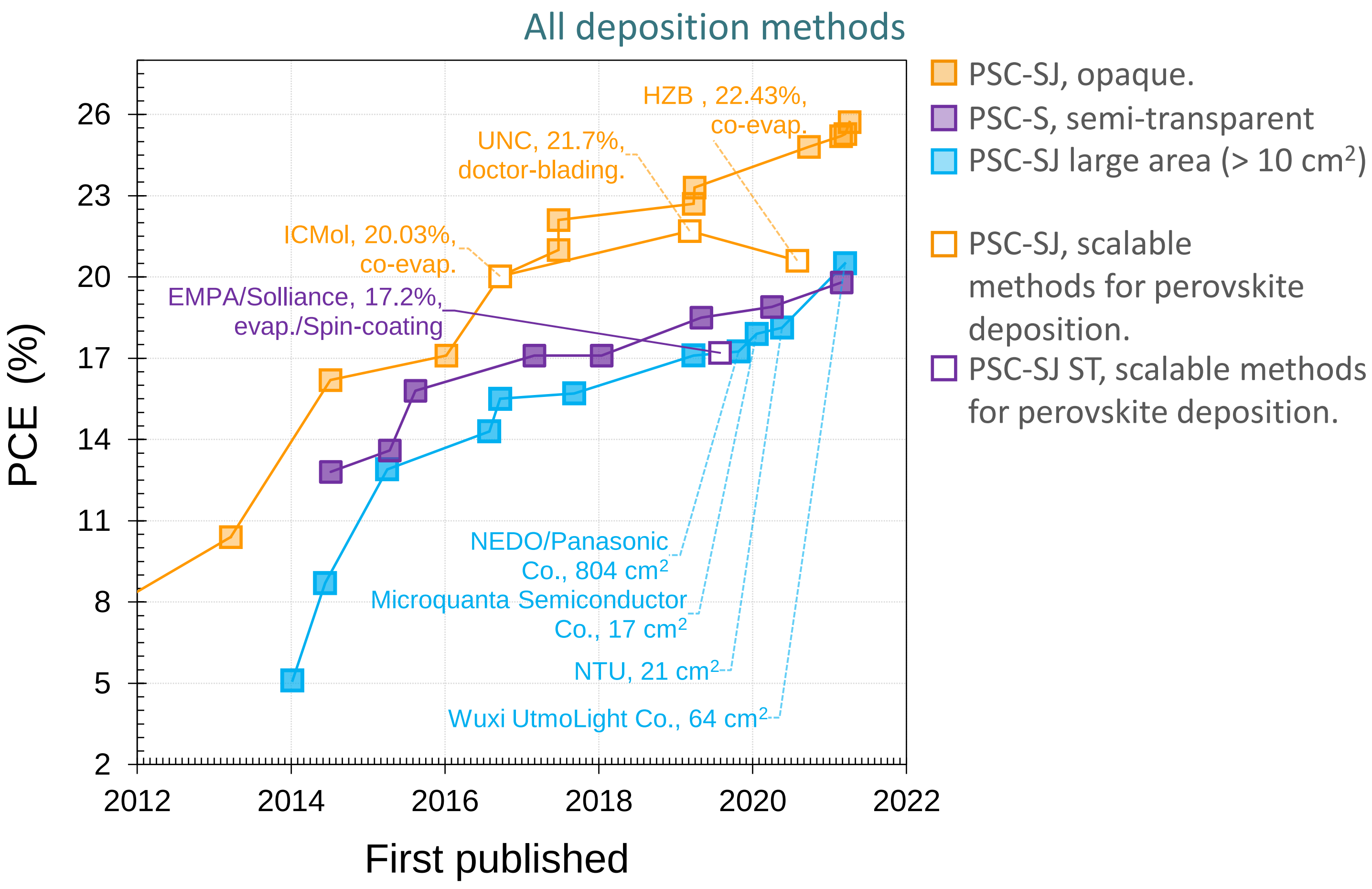

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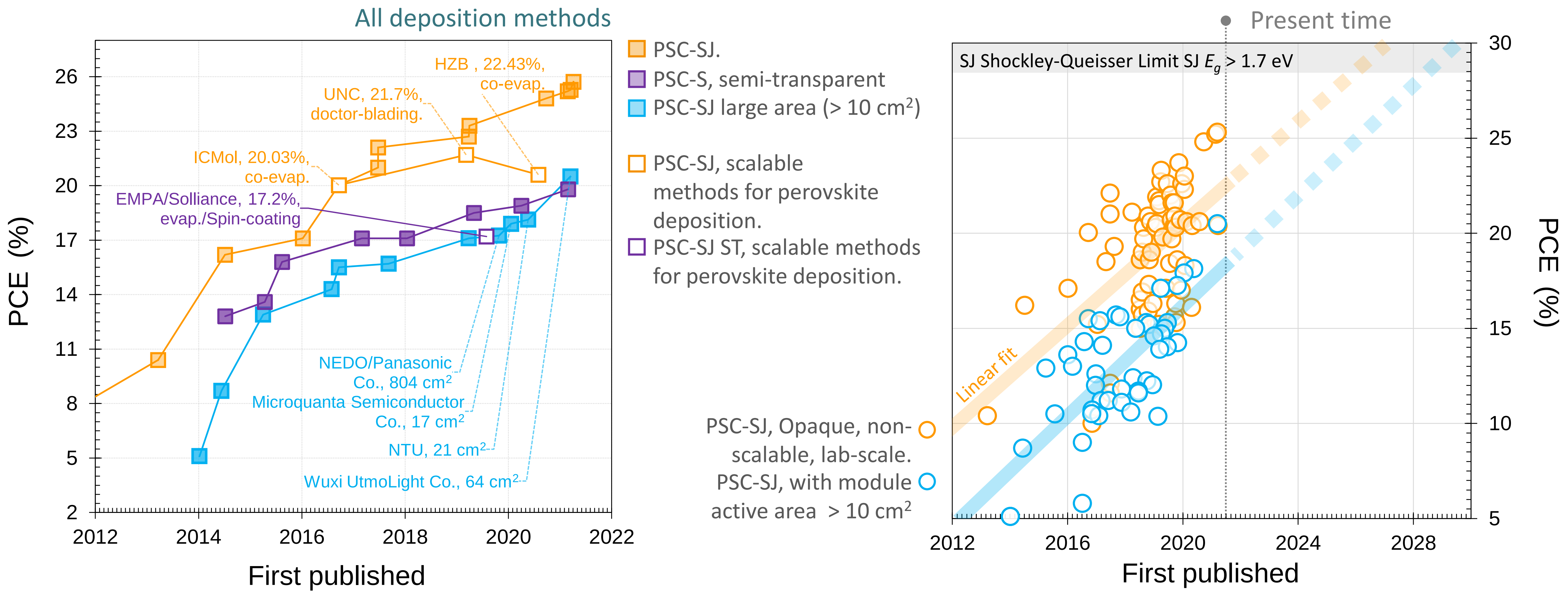

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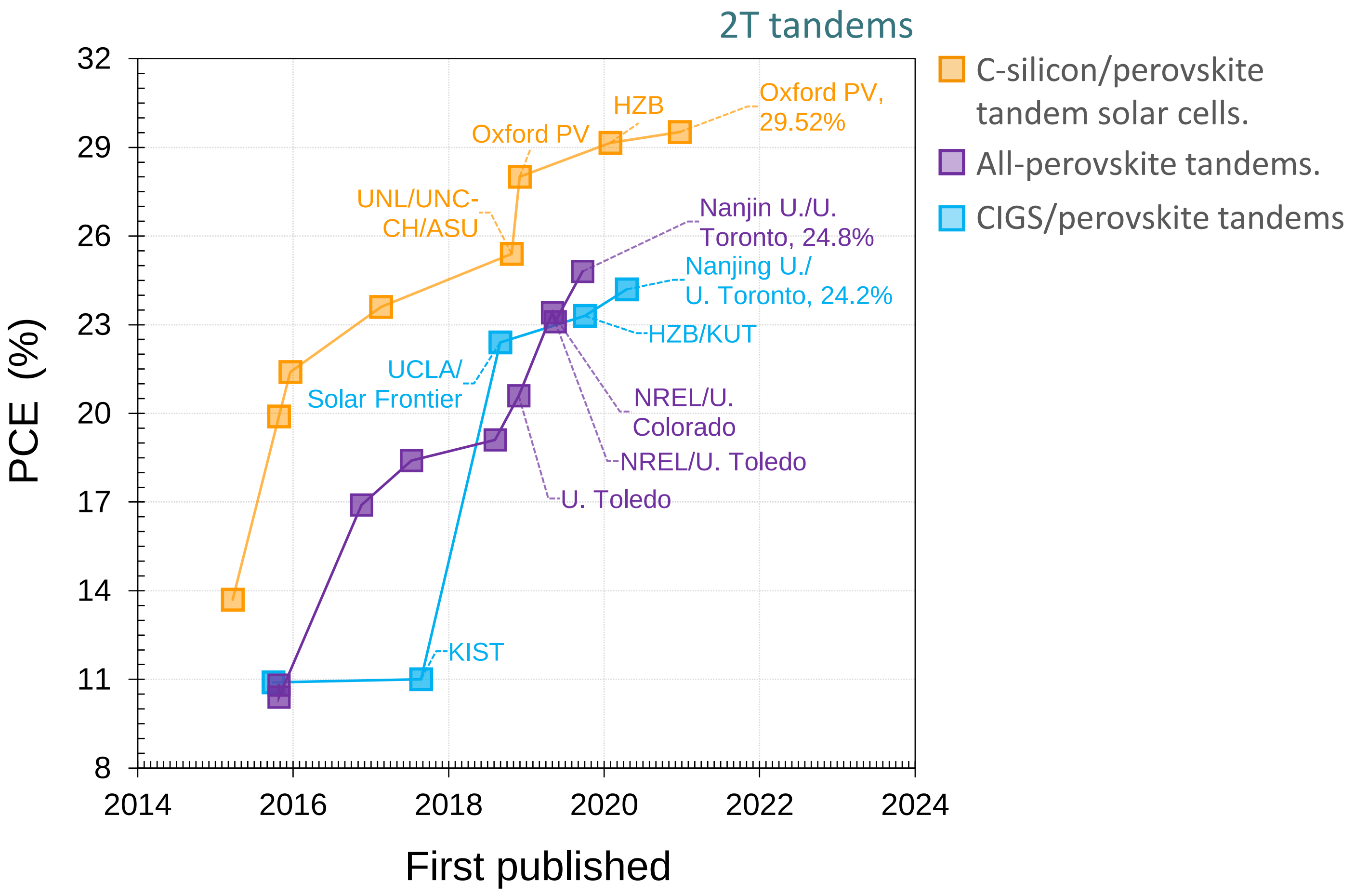

Chen, B. et al. Joule 4, 850–864 (2020).
Al-Ashouri, A. et al. Energy Environ. Sci. 12, 3356–3369 (2019).

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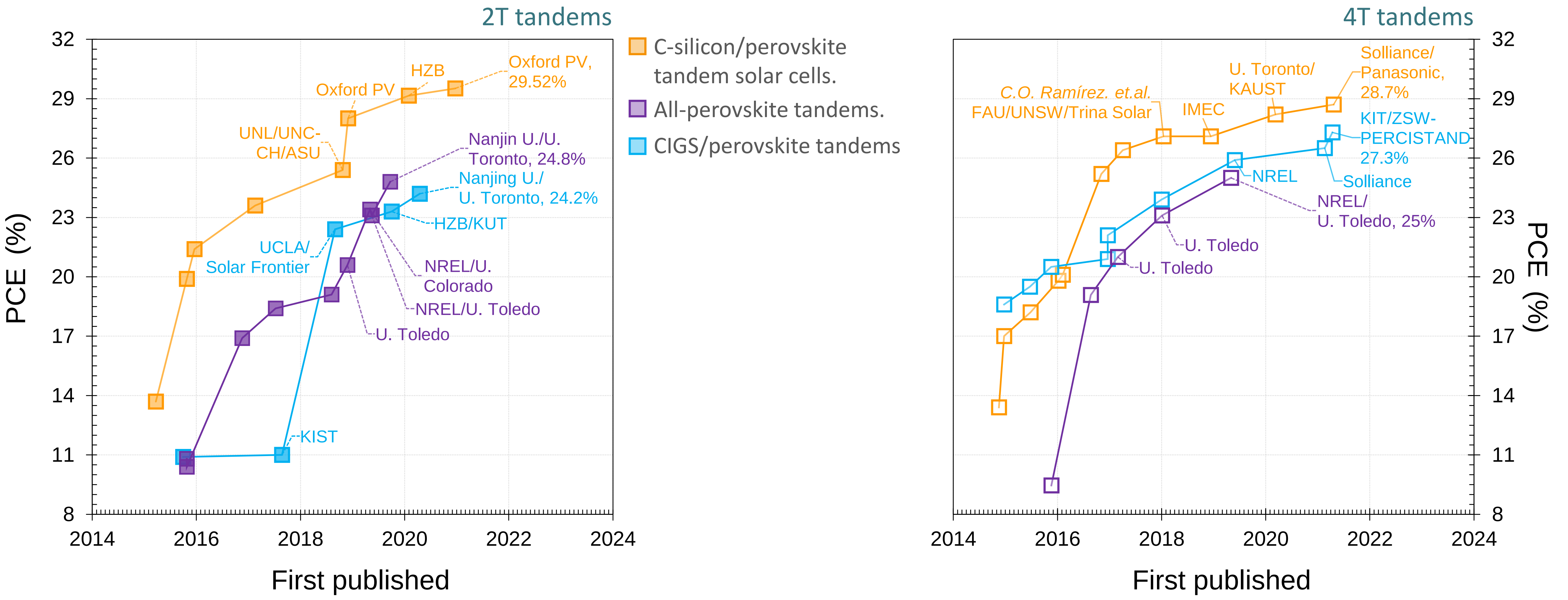

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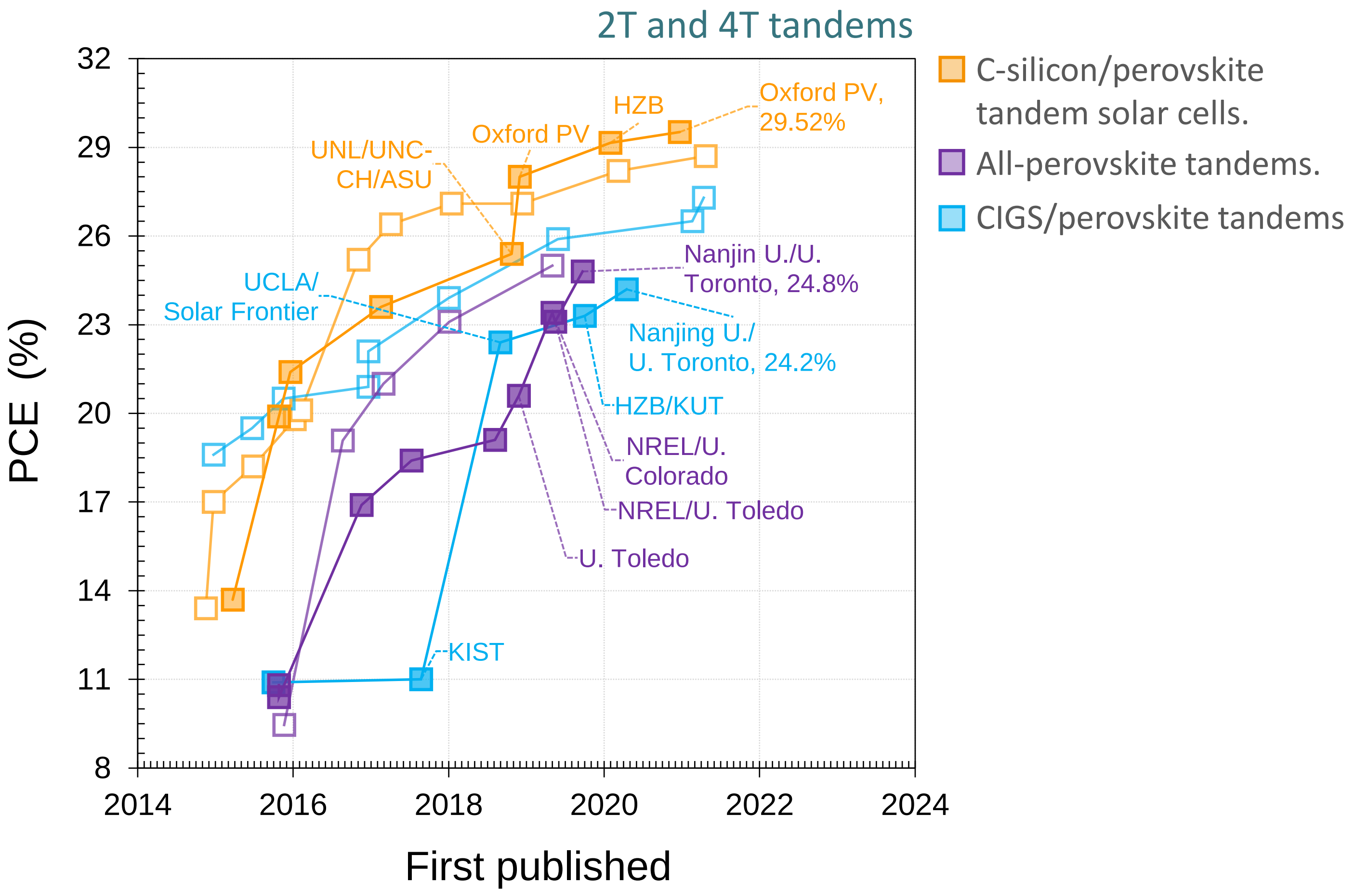

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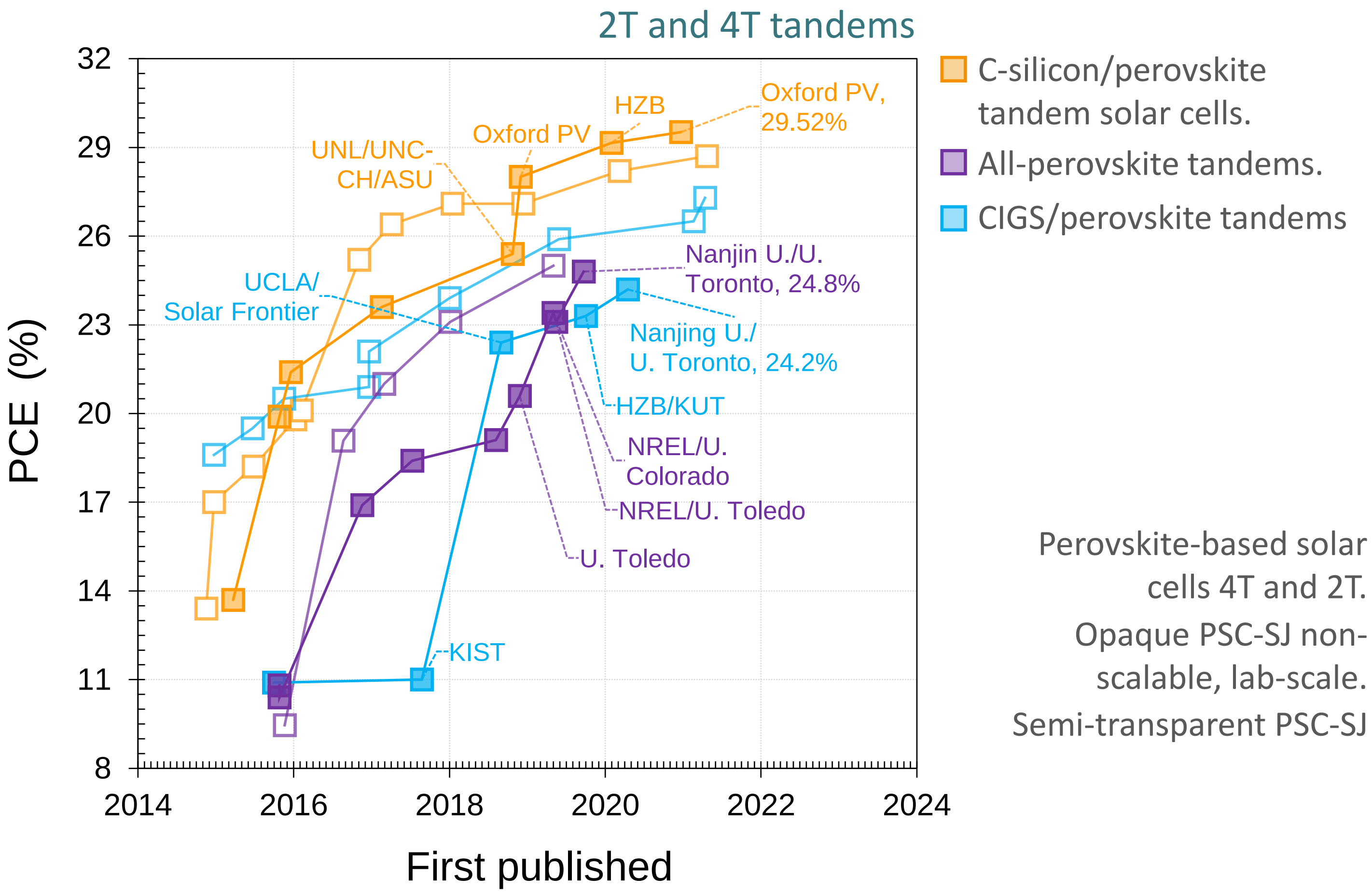
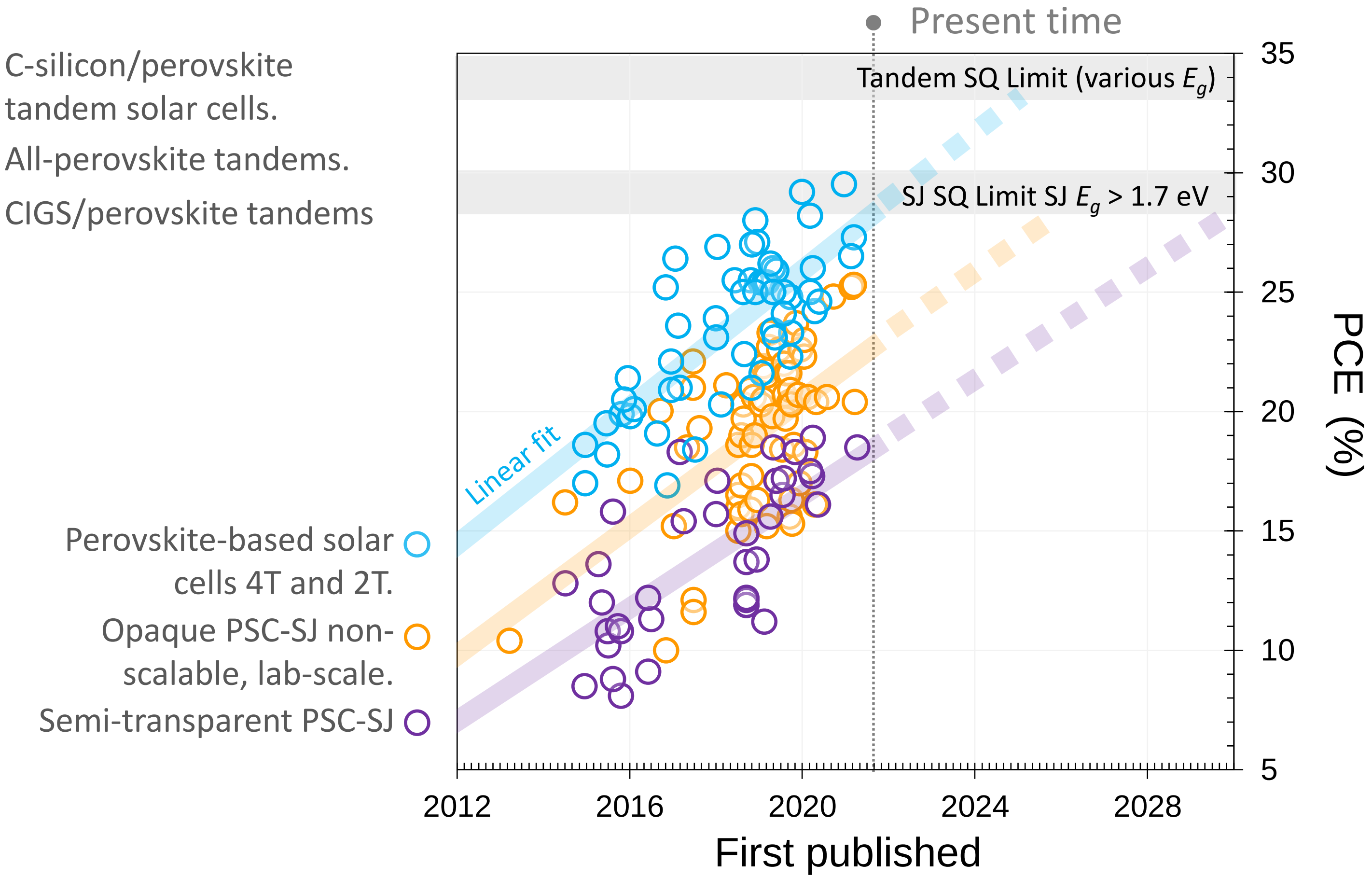
Academia and industry interest on perovskite-based tandem devices is reflected on time evolution





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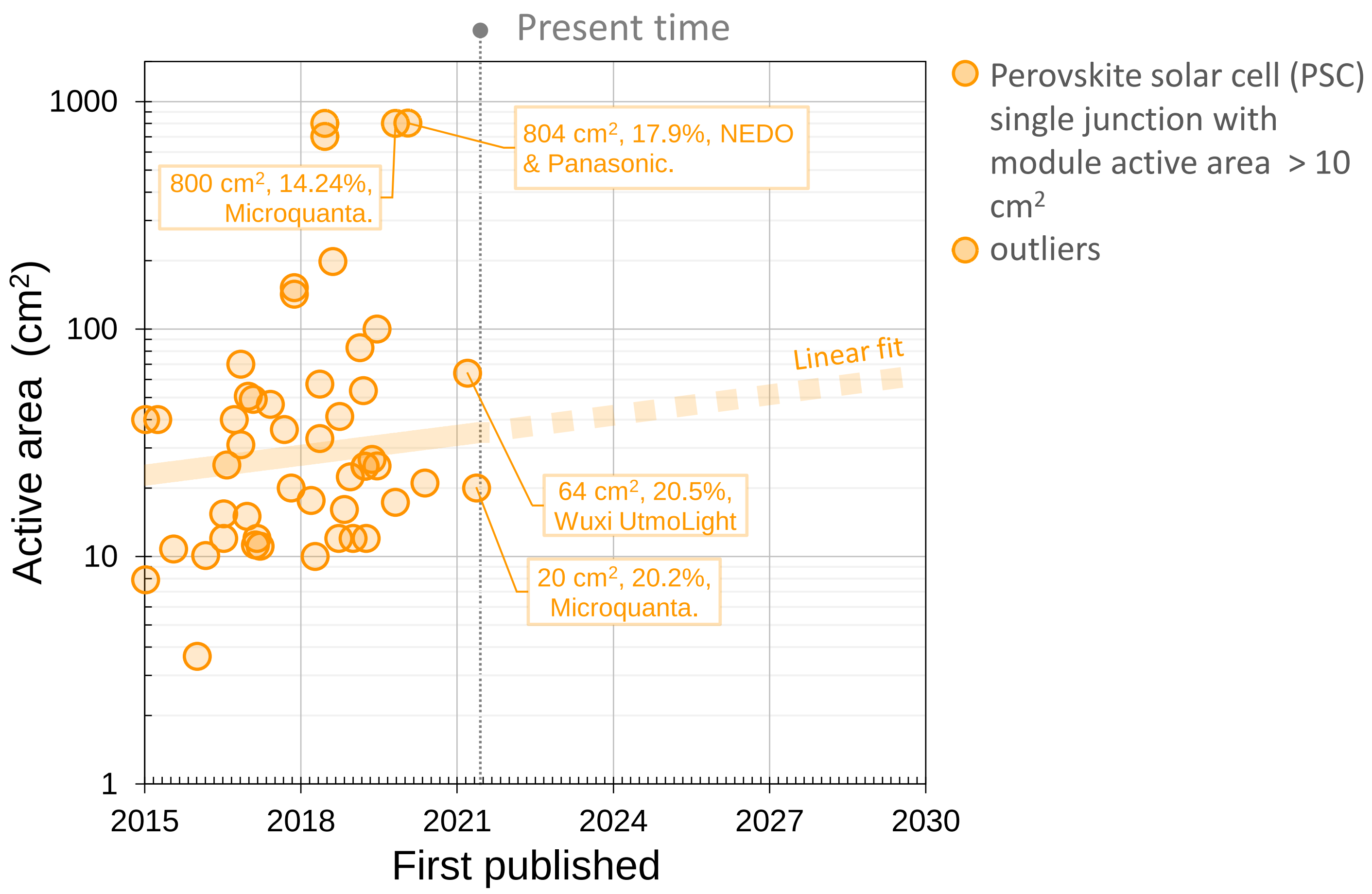
Perovskite-based PV scale evolution.

Active area and efficiency time evolution illustrate the challenge of scaling up. Perspective including the International Technology Roadmap for PV (ITRPV)



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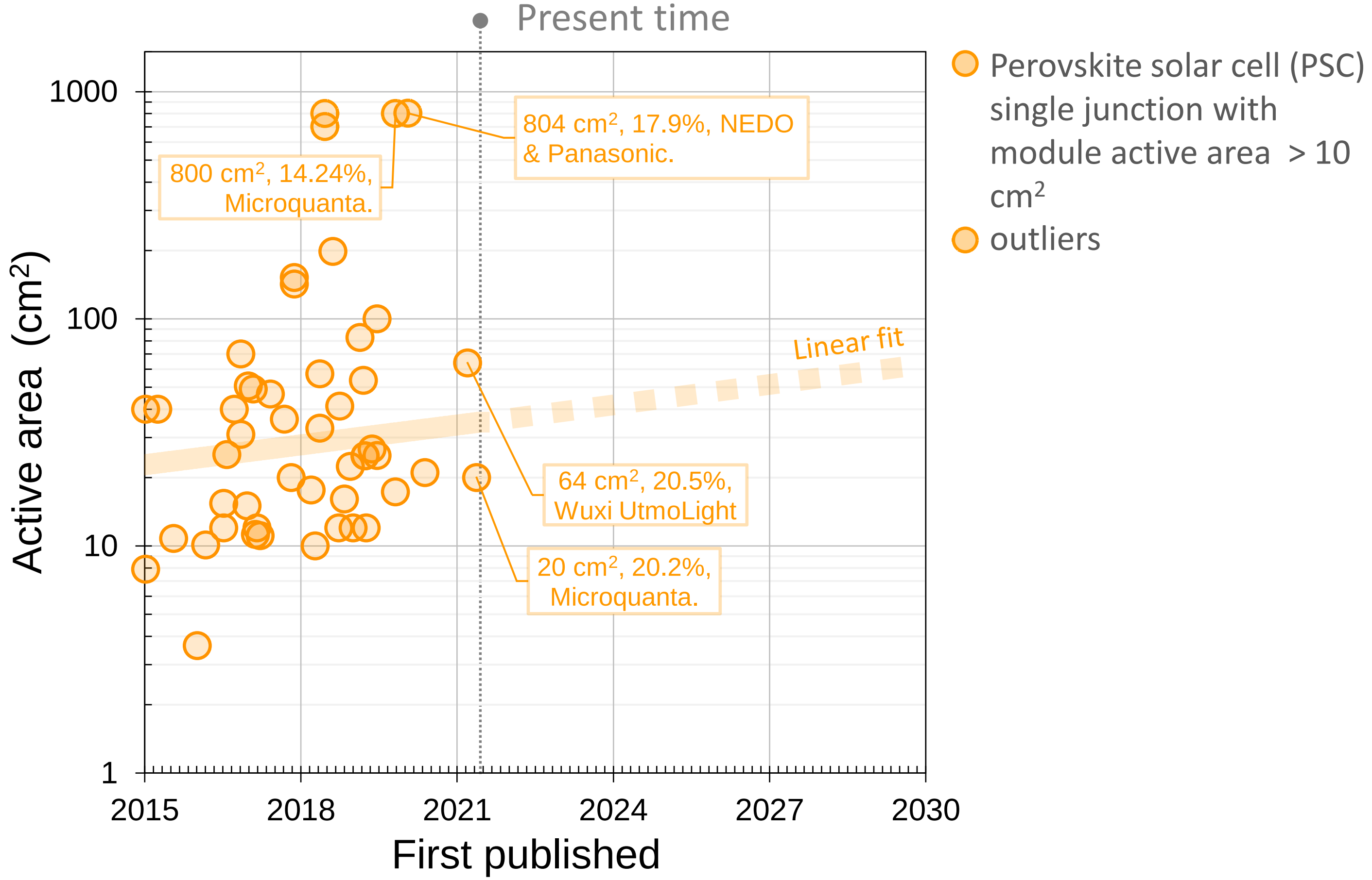

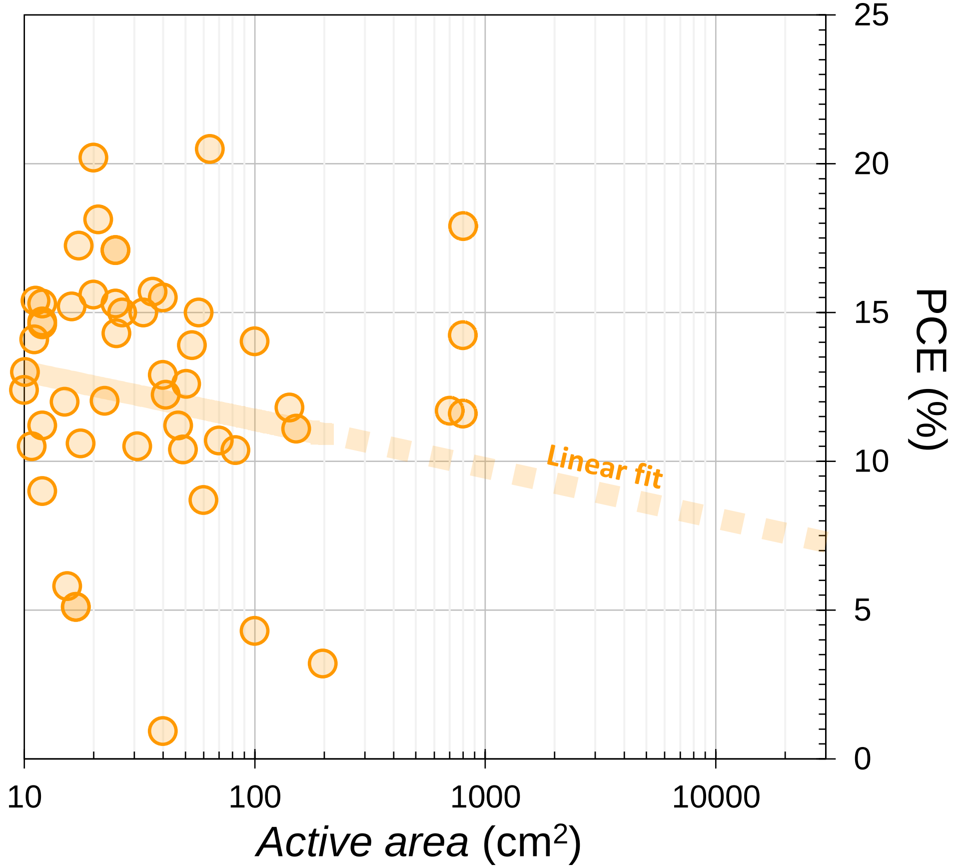

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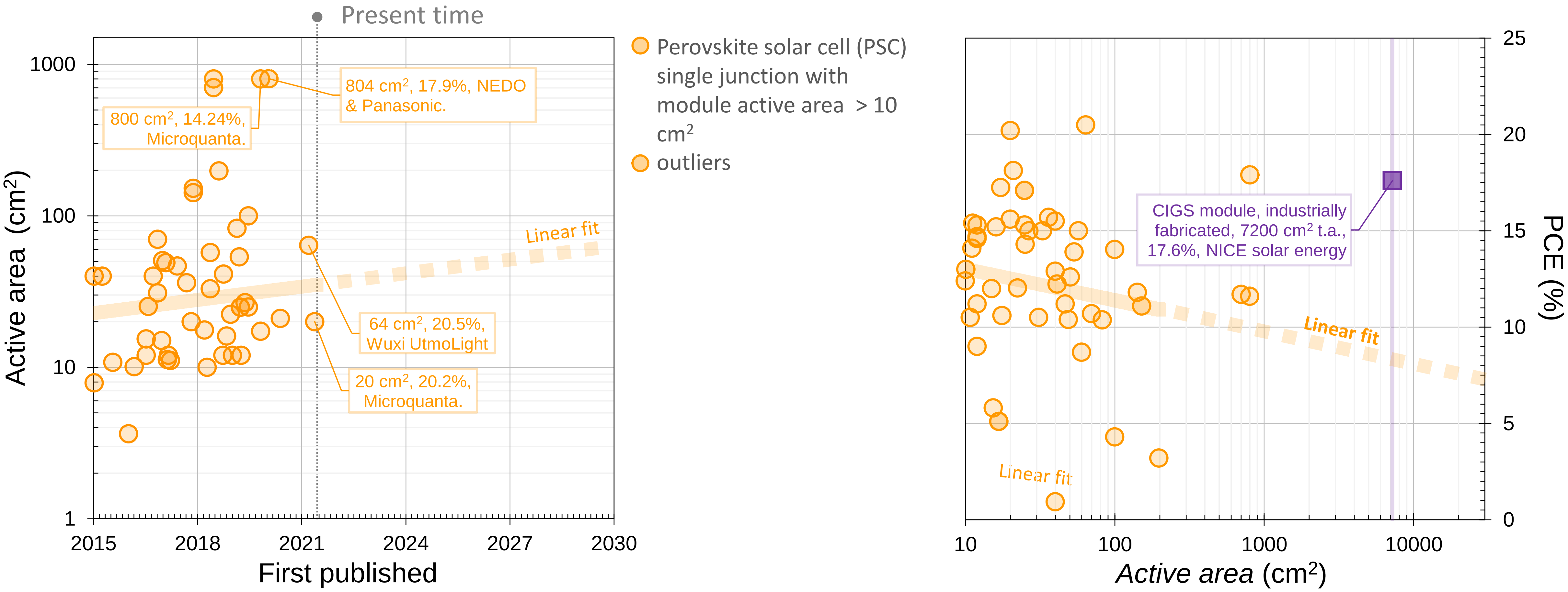

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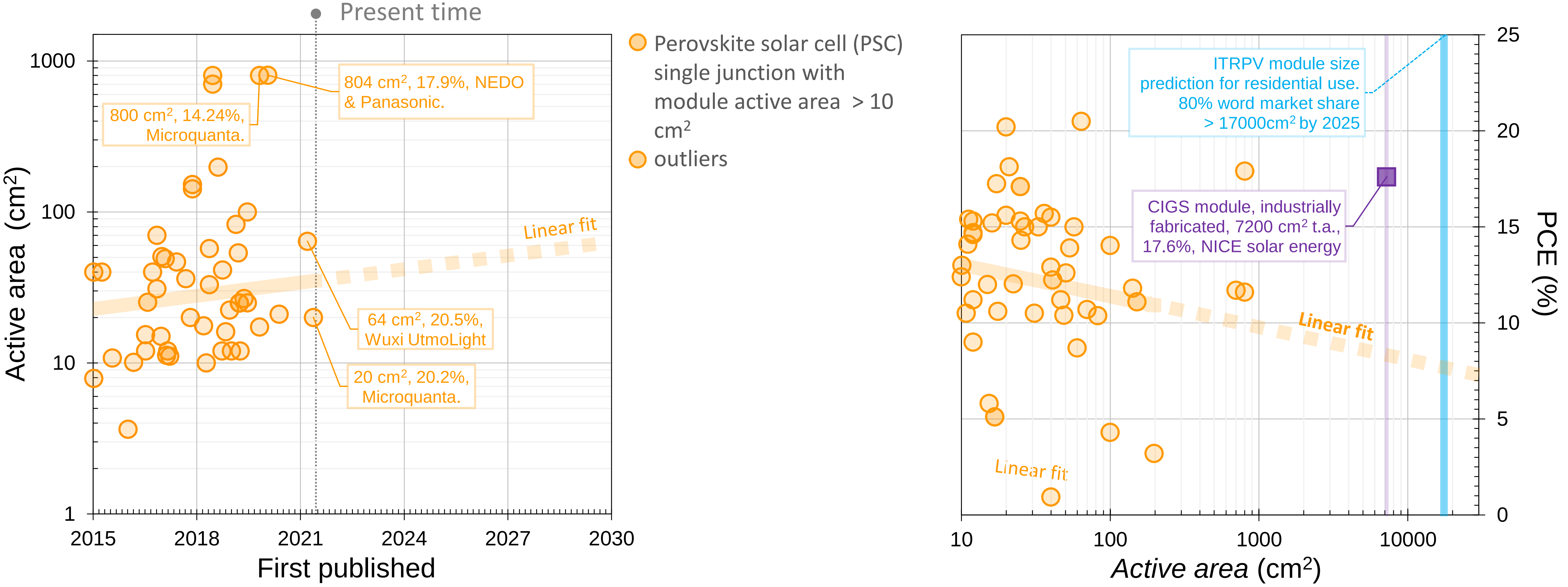

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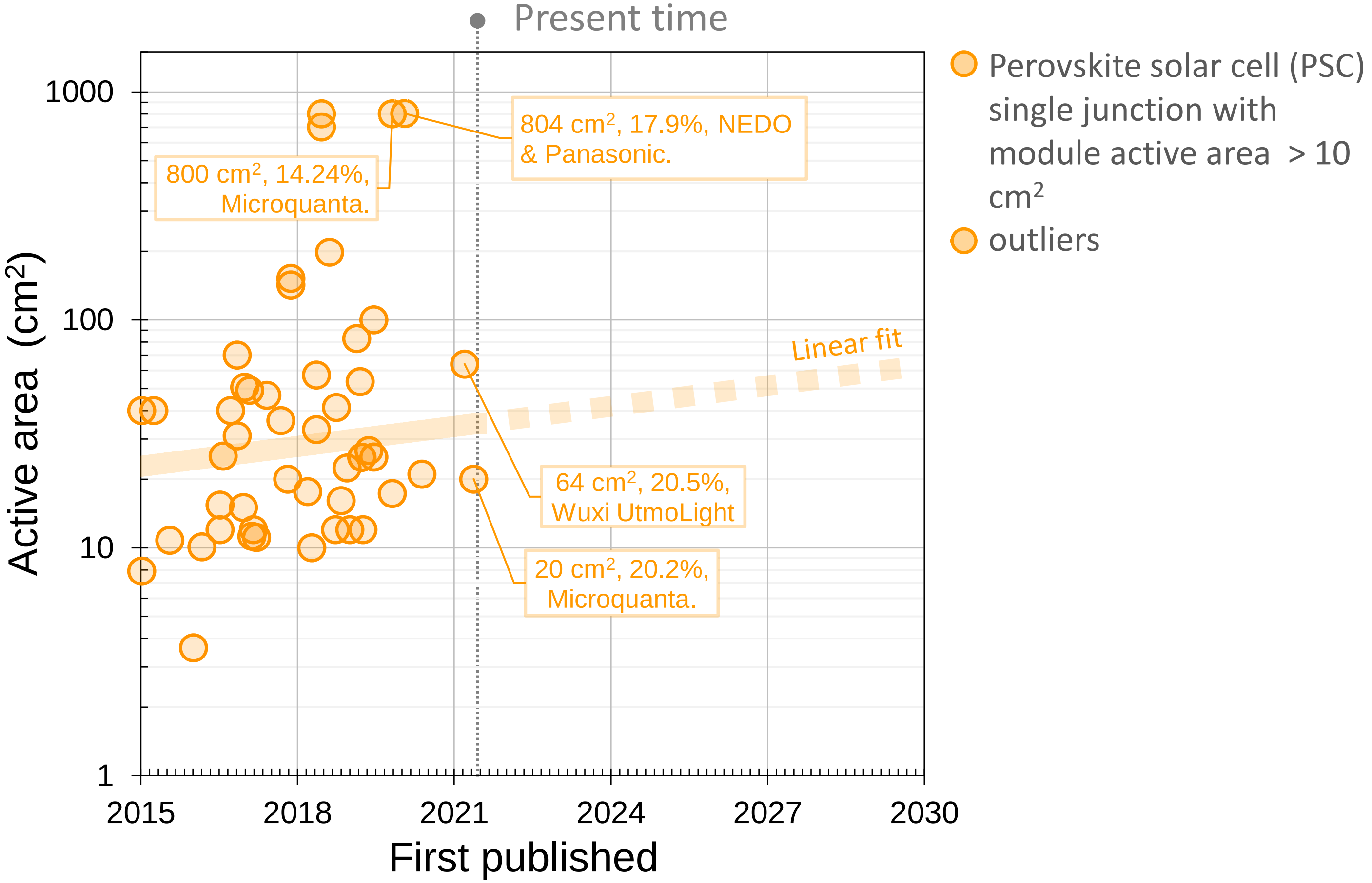

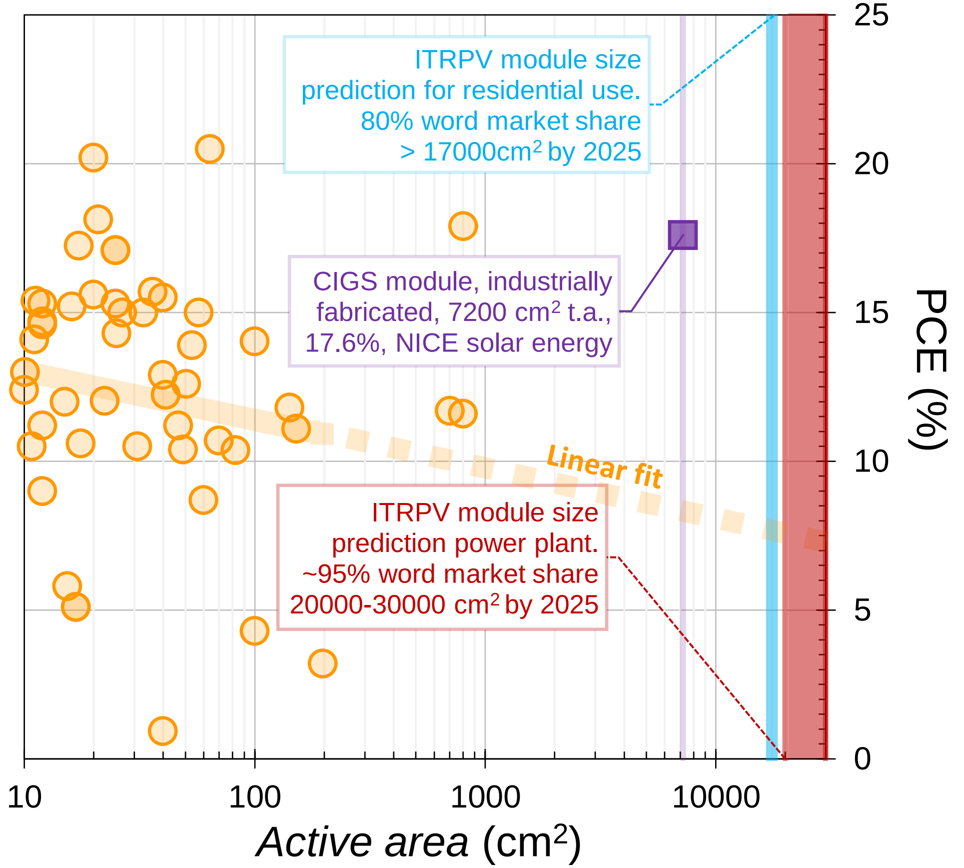

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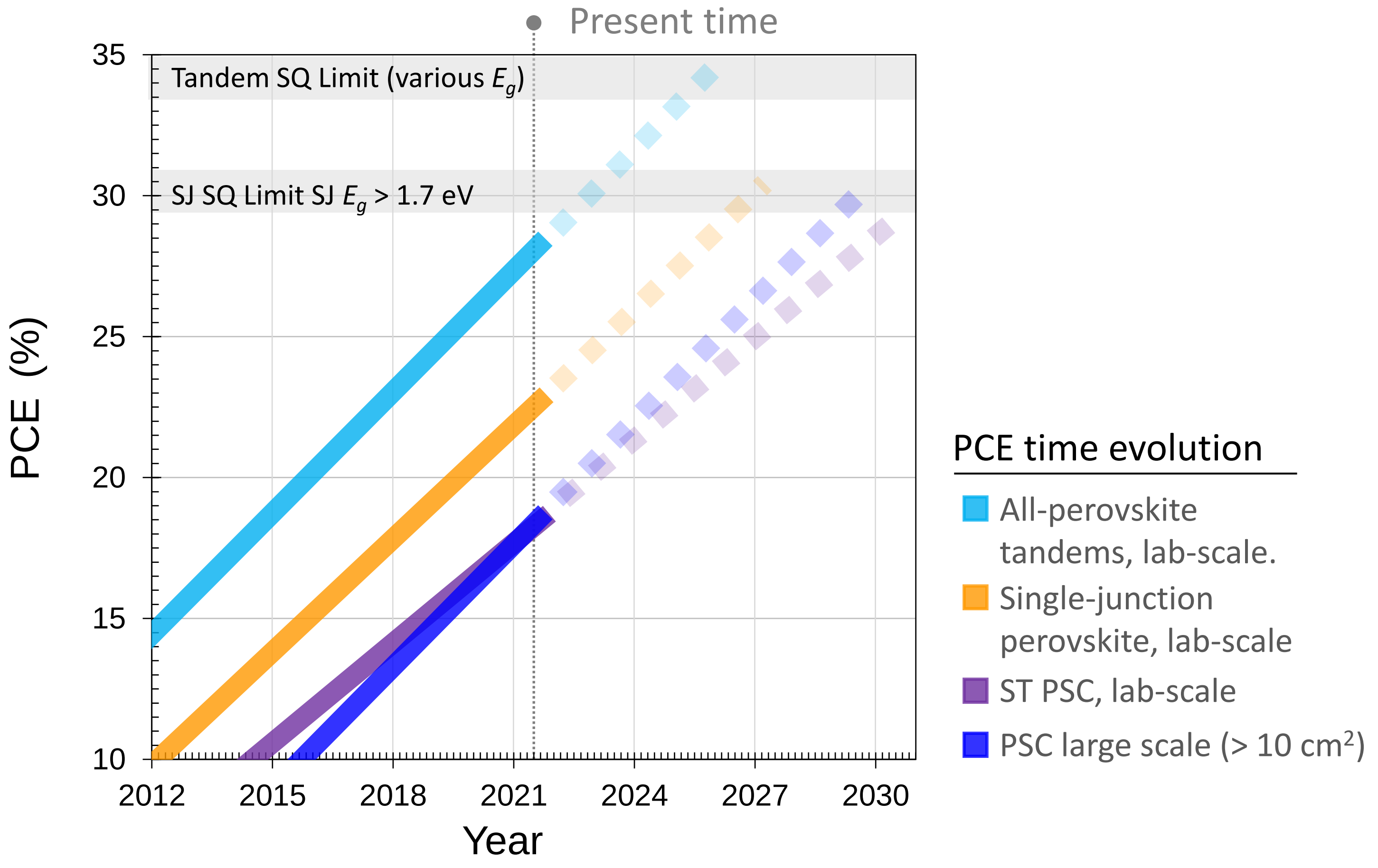
Research development *vs* ITRPV mass production predictions .

ITRPV 12th ed., (2021). predicts average stabilized efficiency values for tandem solar cells in mass production



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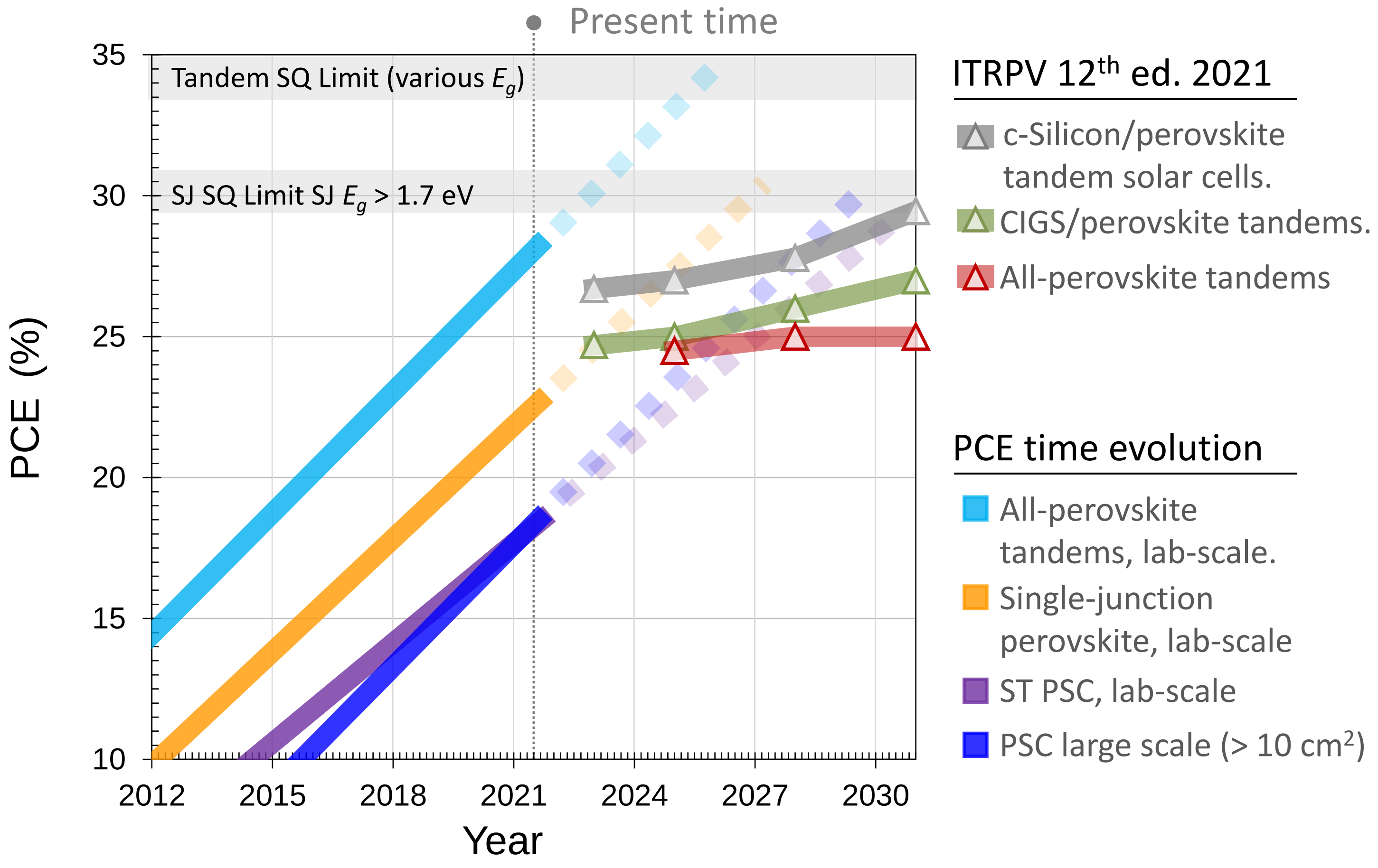

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Conclusions

Advances at lab-scale followed by scaling-up efforts reveal cell-to-module efficiency gap.

Since first reported, tandem efficiencies have reached 29.52% for 2T tandems and 28.7% 4T tandems at a laboratory scale – Although most record efficiencies use non-scalable deposition techniques.

Reports and publications show challenges for scaling up. Should be prioritized.

ITRPV 2021 ed. predicts average stabilized efficiency values for tandem solar cells in mass production

Other considerations

Size and throughput (TPT) should be ideal. Do the deposition methods meet the general TPT requirements to compete?

Product size requirements in PV (BOS driven) will define minimum size requirement for thin-film deposition equipment.

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Thank you for your attention

Contact

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CRamirez@nicesolarenergy.com

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Thank you for watching

Percistand Workshop Team