Conversion of solar photons into electricity: Silicon PV

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NREL Transforming ENERGY

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Energy Efficiency & Renewable Energy

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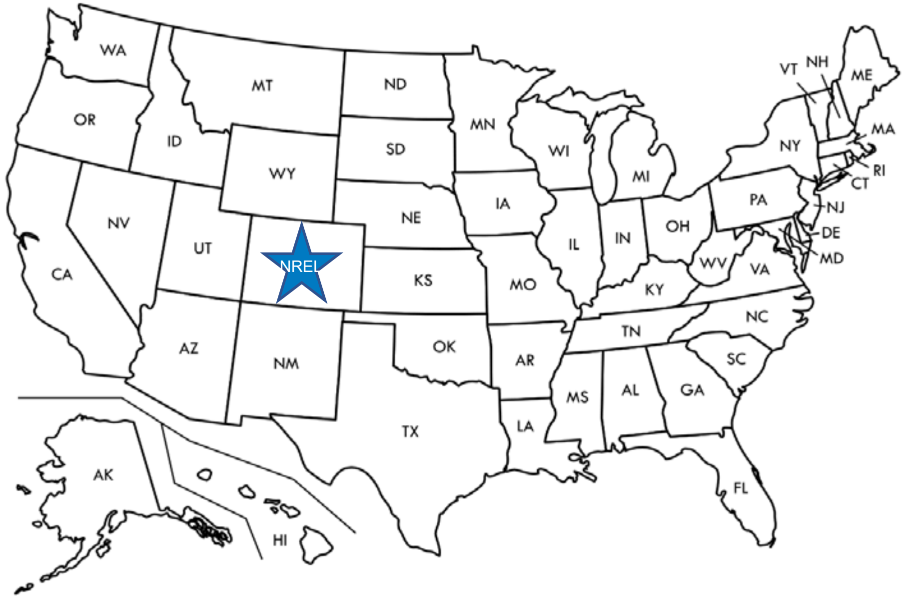

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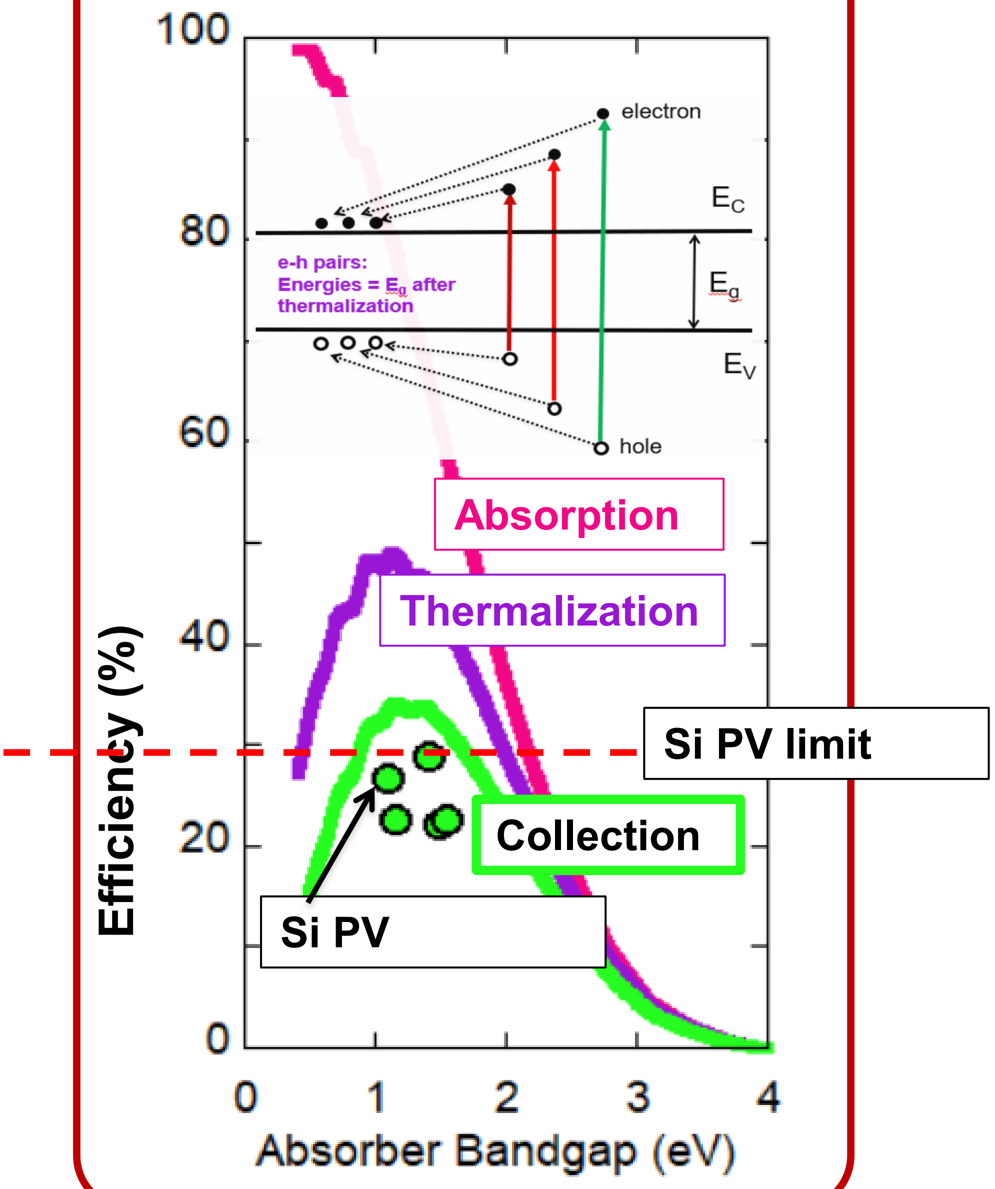
Ref: NREL. “Mission-Focused Materials,” 2022.

Outline

- Solar energy rapidly becoming one of the dominant energy sources
- Silicon PV dominates and now massively expands to US manufacturing
- NREL Core Si PV team addresses main challenges of Si PV:
  - Efficiency: novel device architectures for next generation PV
  - Cost: industrially relevant, high throughput processes
  - Reliability: defects responsible for long-term performance loss

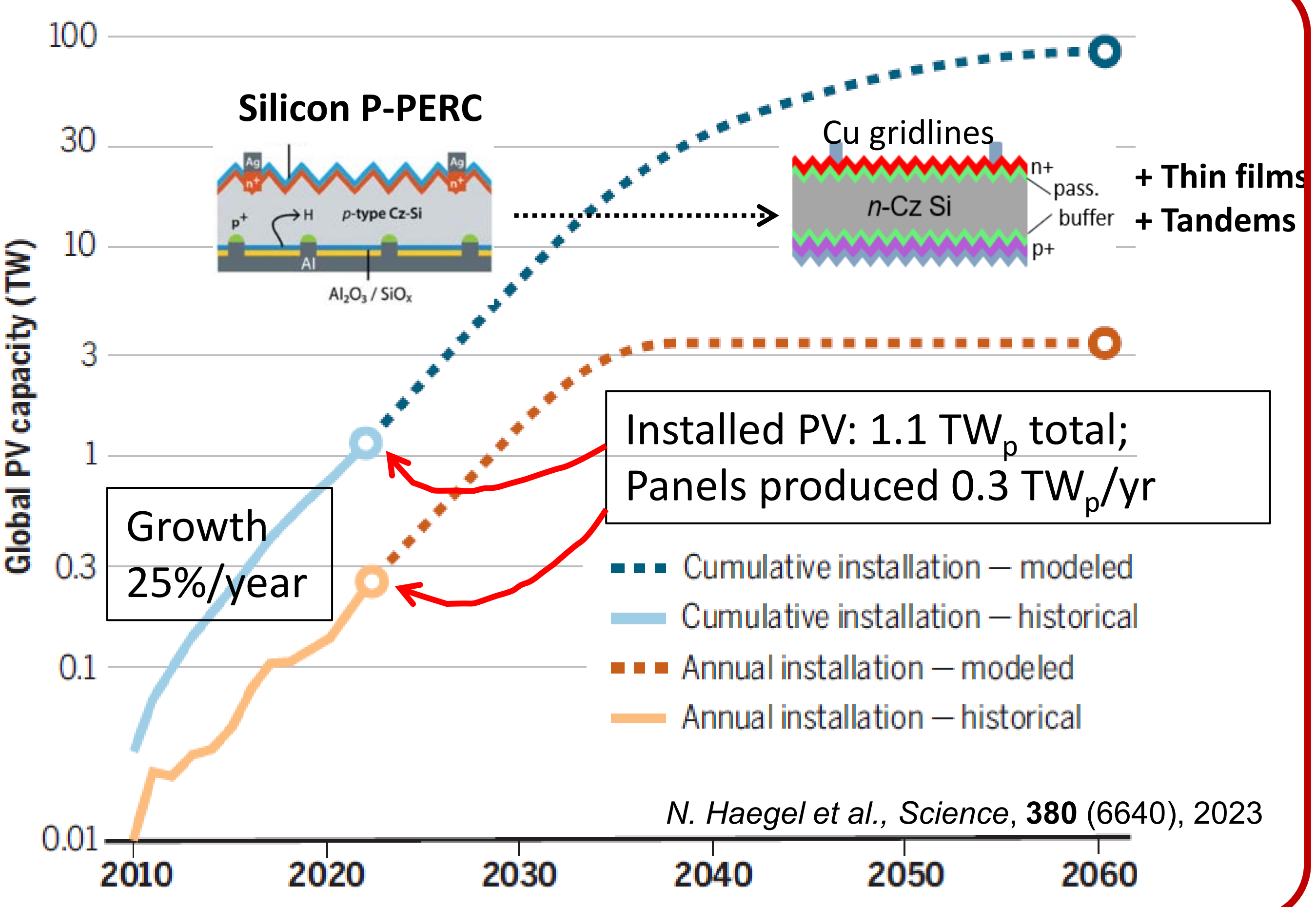
Fundamental efficiency limit: single junction solar cell ~ 30%



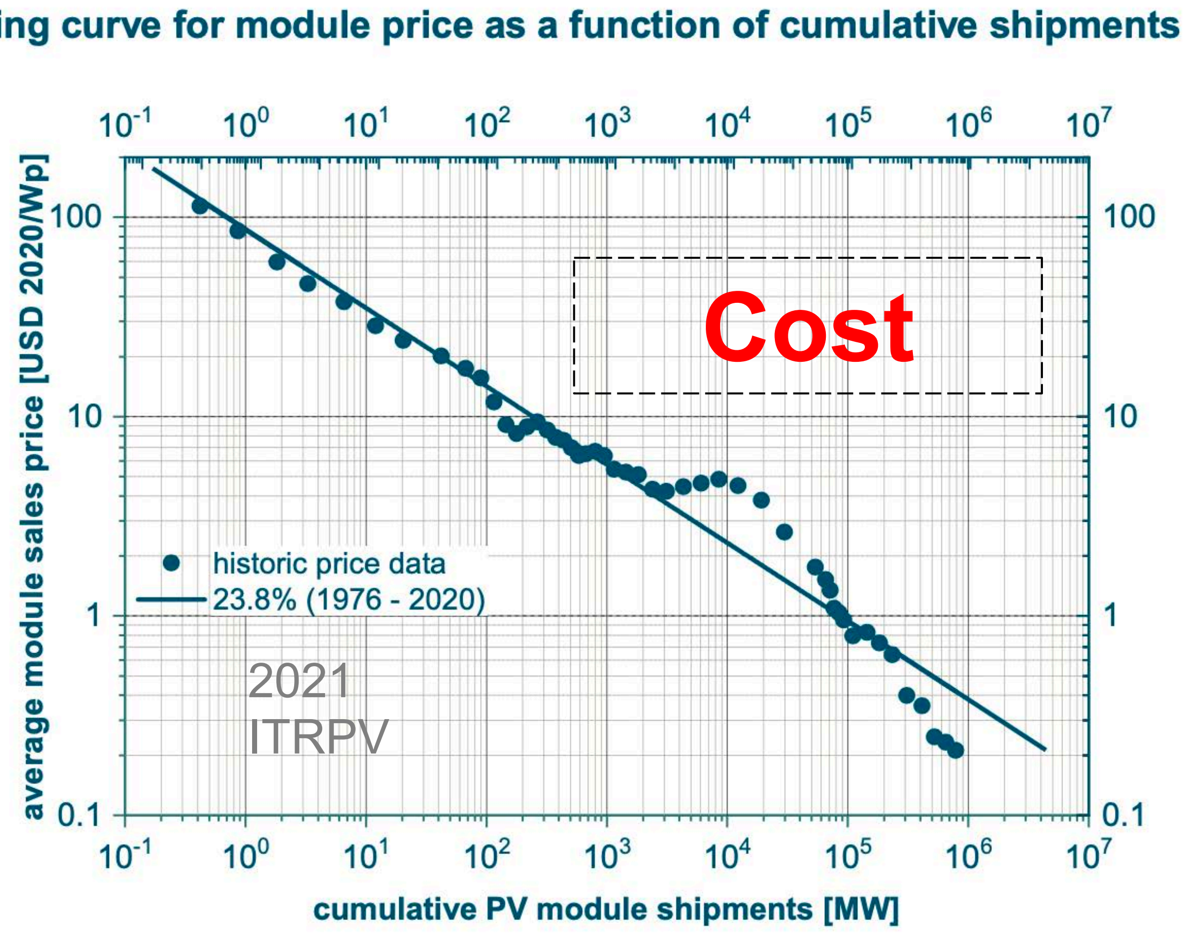
Energy today: (mostly fossil)

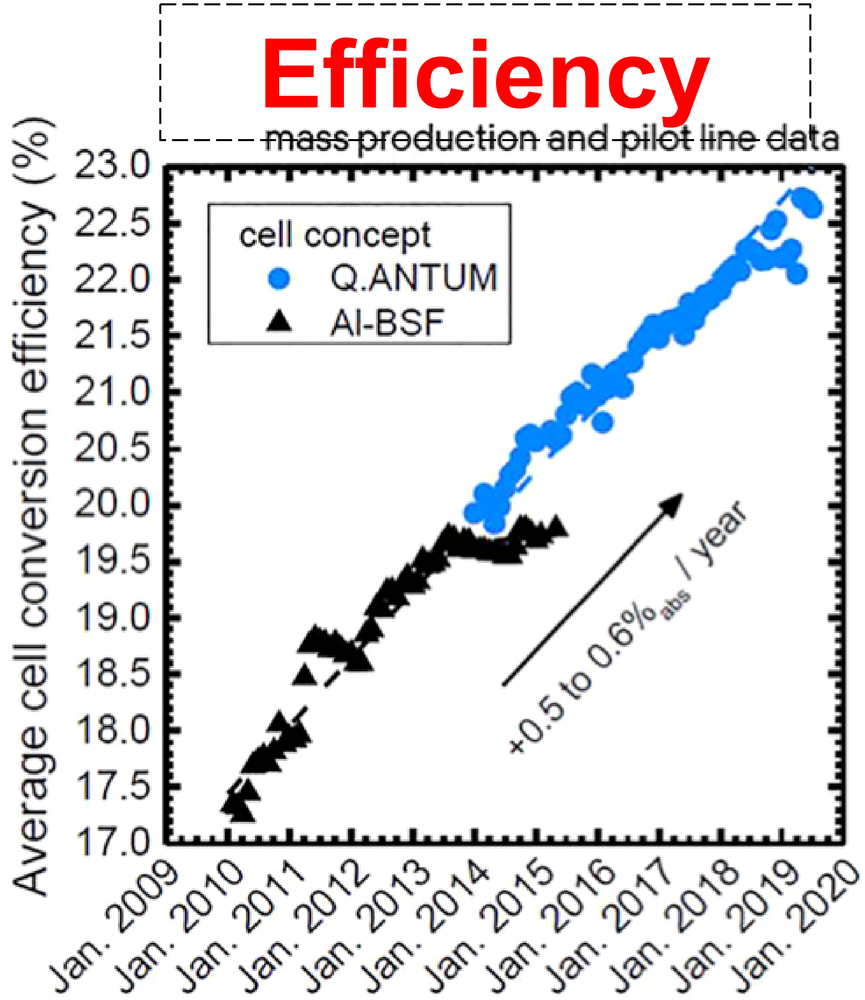
Primary energy consumption: 16 TW avg. power
Used for electricity generation: 6.8 TW
Electricity generated: 2.8 TW

Future with PV as the main energy source:



Si PV leads the PV world market at ≥ 95%; Efficiency rises ~ 0.5abs%/year





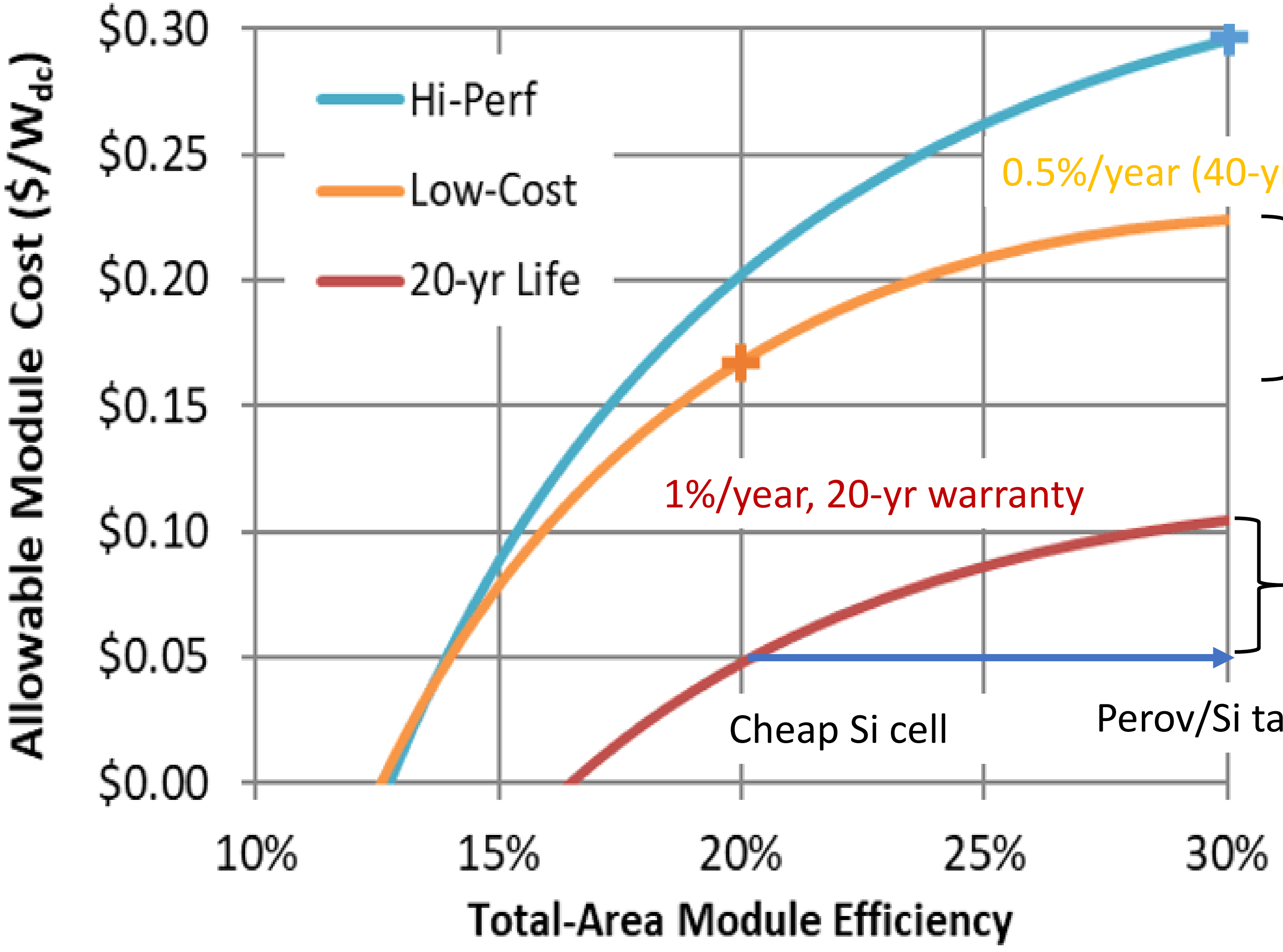
Fertig, F. et al., *2019 AsiaChem*.

Silicon-based solar cells hold 95% of the world market share [2021 ITRPV].

LCOE (Cost, Efficiency, **Reliability,** CO_2, Energy, Recyclability, Equity) = $0.02/ kWh

0.4%/year (50-yr warranty)

0.5%/year (40-yr warranty)

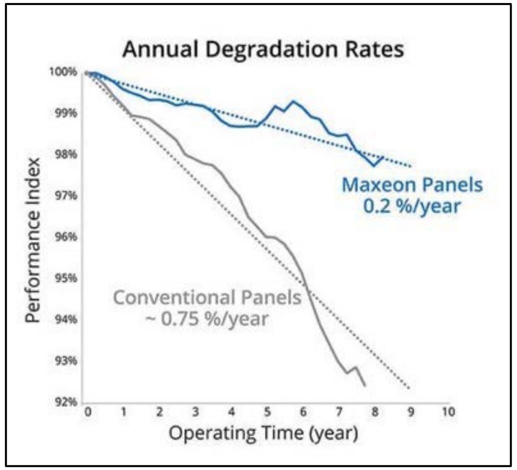


0.1% decrease in degradation rate is worth more than a 5% efficiency gain

smaller degradation rate allows more $ for cells

$0.06/W_{dc}$ available for top cell.

Maxeon/Sunpower: World record modules 40-year warranty

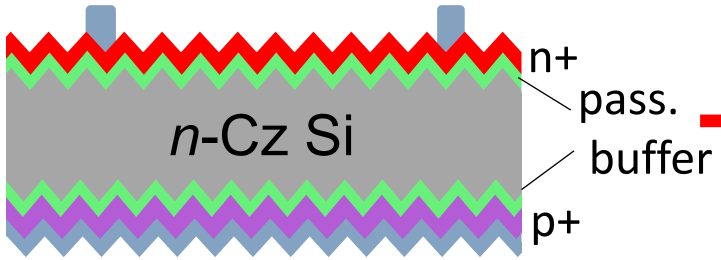


Citation: Mirletz H, Ovaitt S, Sridhar S, Barnes TM (2022) Circular economy priorities for photovoltaics in the energy transition. PLoS ONE 17(9): e0274351. https://doi.org/10.1371/journal.pone.0274351

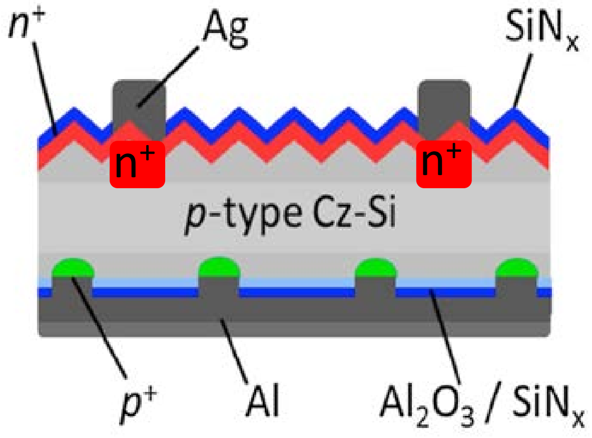
Wikoff et al., Joule 6, 1–16
July 20, 2022 ª 2022 Elsevier Inc.
https://doi.org/10.1016/j.joule.2022.06.006

Silicon PV Evolution: approaching 29.4% efficiency limit

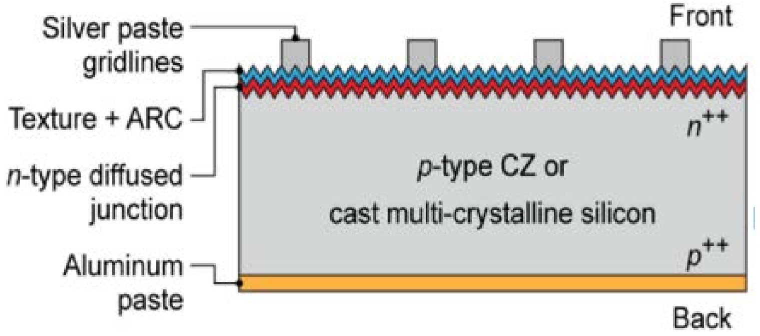
Future:
Passivated contact cell > 25%
Buffer = a-Si or tunnel SiO_2
High bulk lifetime, surface passivation, low-rec. contacts



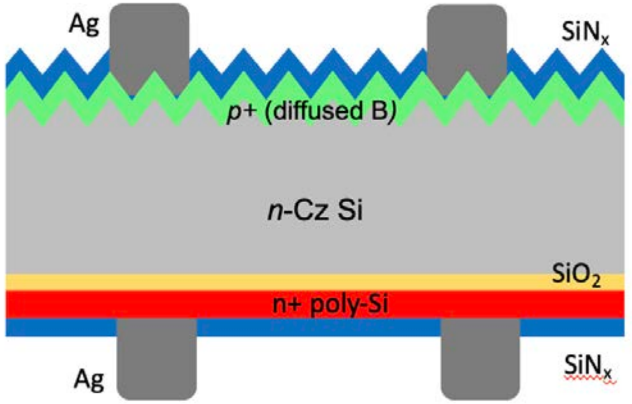
Present: P-PERC
> 24% efficiency potential
Local Al-BSF ~ 1% area fraction
Selective front emitter
SP/metal recombination minimized
Can be bifacial



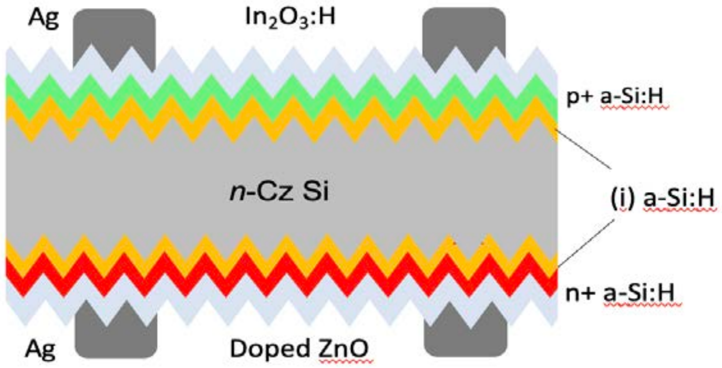
Al Back Surface Field cell, 20%
Al-diffused non-passivated BSF (high-low junction) limits efficiency

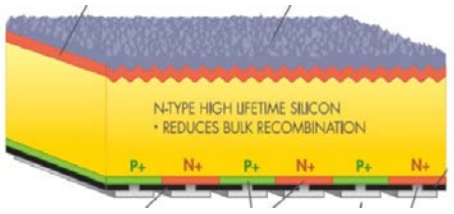


TOPCon cell 26% - less expensive



Silicon Heterojunction (SHJ) cell 27%

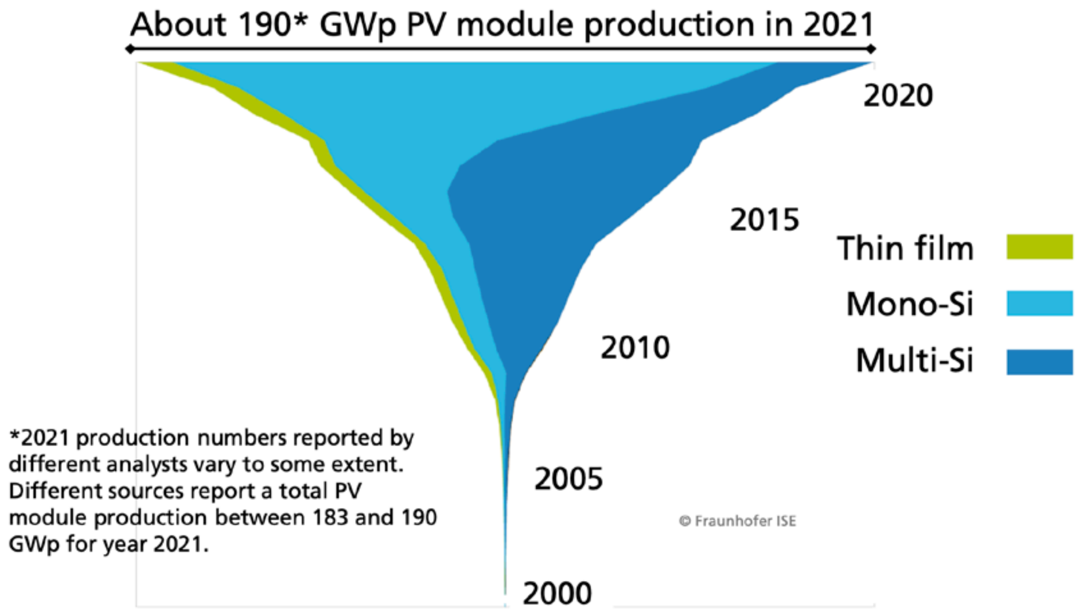




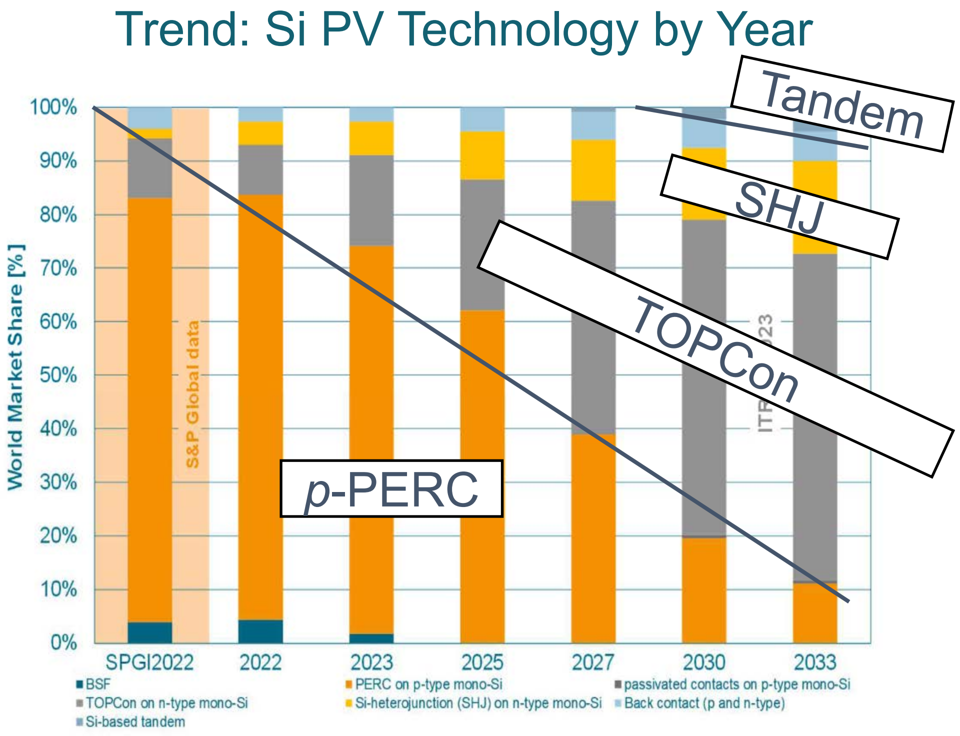
IBC cell

http://lvsum.blogspot.com/2011/12/current-cell-structures-of-commercial-c.html

Evolution of Si PV Technologies: TOPCon taking over the PV market



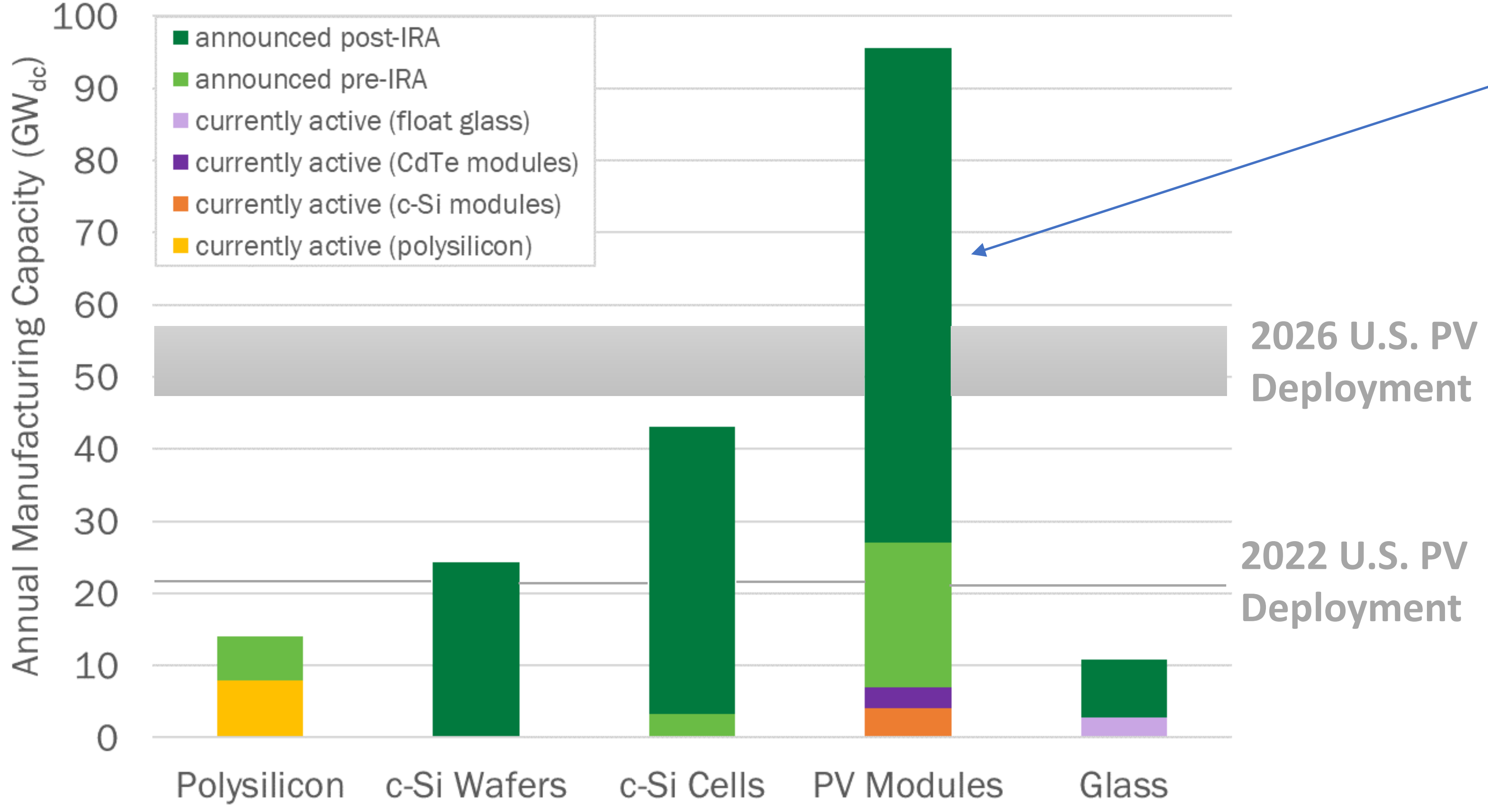
Source: Photovoltaic Report, Fraunhofer Institute for Solar Energy Systems; Feb 21, 2023



Reproduced from ITRPV 2022

- Solar energy is one of the fastest growing renewable energy markets
- *c*-Si occupies > 95% PV market with increasing *n*-type mono *c*-Si share

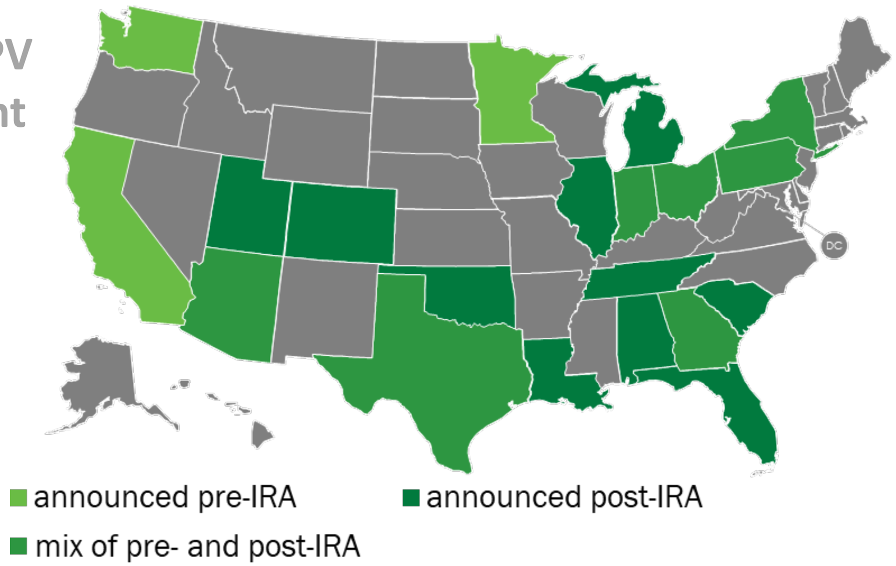
Anticipated Growth in US Solar Manufacturing Capacity: Value chain



Estimated: 2023 2025 2024 2024 2025

Maxeon, Q-cells, Convalt, Enel

With IRA tax incentives, the United States is expected to have enough module production capacity to meet domestic demand, but many of the production tools, components, and materials will likely be imported



-Thanks to Paul Basore for the graphics

2.2 GW integrated (ingot-wafer-cell-module) factory in full operation since 2021

Utilities: Di Water, CDA, Special Gases and Bulk Gases

Areas	Total area (m^2)
Main building	ca. 80,000
Utility building	ca. 11,000
Waste water treatment	ca. 7,000
Others	ca. 3,000

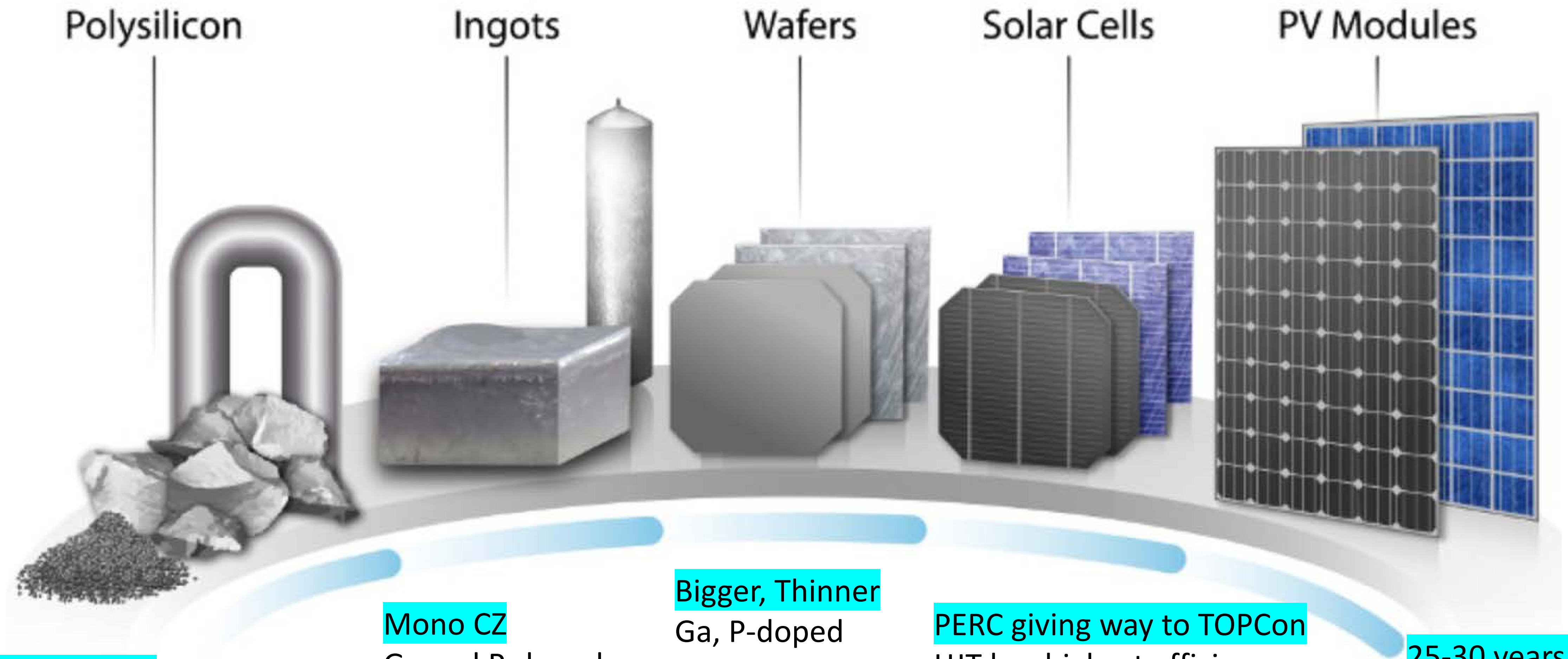
25 Acres/2.2 GW

Ankara, Turkey

Mono PERC, bifacial

Si PV Factory built in 12 months

Thanks to Peter Fath, RCT solutions, for this slide



“9-11 9-s” pure
High embedded energy/CO_2
Billion-dollar plants
Need cheap/clean energy

Mono CZ
Ga and P-doped
faster, larger pulls
China dominates
(Longi)

Bigger, Thinner
Ga, P-doped
Require gettering
20 ms lifetimes

PERC giving way to TOPCon
HJT has highest efficiency
but smaller market
Ag is an issue
27% is achievable
26.5% manufacturable

25-30 years; up to
40 years warranty
Bifacial for utility
Not recyclable
Some degradation

Image: A. Hicks, NREL

NREL Si Core Team Addresses Challenges of Si PV Technology

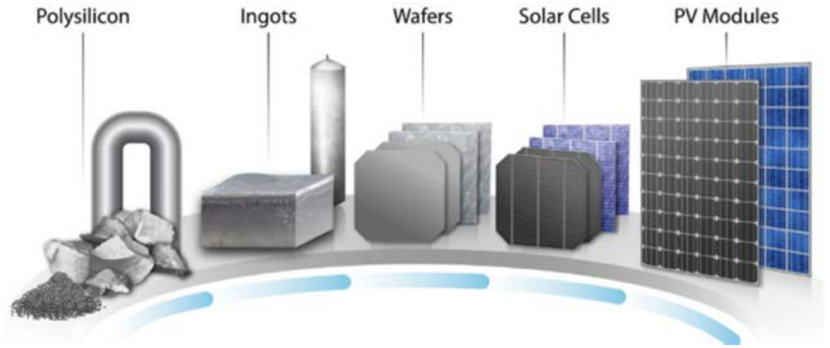
- **Efficiency:**
  - Advanced passivated contacts to enable > 25% cells (excellent passivation and transport, transparent) ✓
  - High efficiency device architectures implementing passivated contacts ✓
  - Very high bulk lifetime: perfect crystal growth, no process- or light induced defects ✓
- **Cost:**
  - Low cost, Earth abundant metallization – Ag screen print (reduce >4x), replace with Cu ✓
  - Replacing In in TCOs (for HJ cells) with other elements (only 3 nm ITO allowed)
  - Low-cost cell architectures, few process steps ✓
- **Reliability:**
  - No bulk degradation in p-Cz Si wafer bulk: LID, LeTID, no mechanism revealed ✓
  - Mitigate Potential Induced Degradation (PID)
  - No other degradation modes, even in n-Cz cells ✓

- **Recyclability:** modules (and kerf) ✓
- **Future** hybrid technologies: Si-based tandem ✓

✓ Core expertise activity
✓ New recent activity

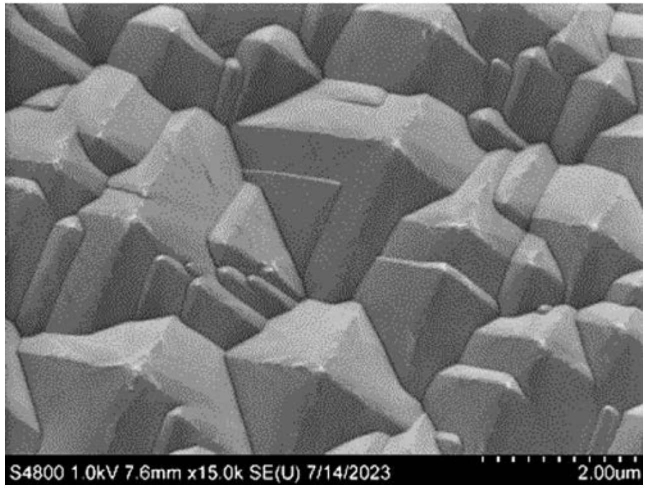
Silicon program at NREL: Main Achievements

1. Introduced to mainstream Si PV, poly-Si passivated contacts with FhISE and GIT (2013 – 2015), now known as TOPCon cells, with global production outcompeting HJ cells.
2. High-efficiency, stacked III-V/Si tandem cells (2015)
3. Concepts of 3-terminal tandem cell and transparent conductive adhesive, IPs (2015); initiated stand-alone tandem program at NREL (2015)
4. Bulk defect mitigation in n-Cz Si by *Tabula Rasa* (2014)
5. Hydrogen passivation of poly-Si contacts by solid H source, IP (2014)
6. Trap-assisted dopant compensation for IBC cells (2018 - 2020)
7. Nickel silicide barrier stability for Cu metallization (2015- 2018)
8. Si battery anode research - SEISTa consortium: role of oxide barrier, in situ surface-enhanced Raman (2017 – 2019)
9. Electron Paramagnetic Resonance to reveal mechanisms of LID and LeTID degradation in mainstream p-Cz Si, and performance-degrading defect detection in n-Cz Si (2018 – present)
10. Engineered nanopinhole contacts for high-efficiency Si cells, IP (2019 – present)
11. Ga hyperdoping for passivated contact cells IP (2015 – present)
12. New projects and industry collaborations on modules, Cu-metallization, poly-Si, power beaming, PhD level workforce for PV industry (2022, 2023)

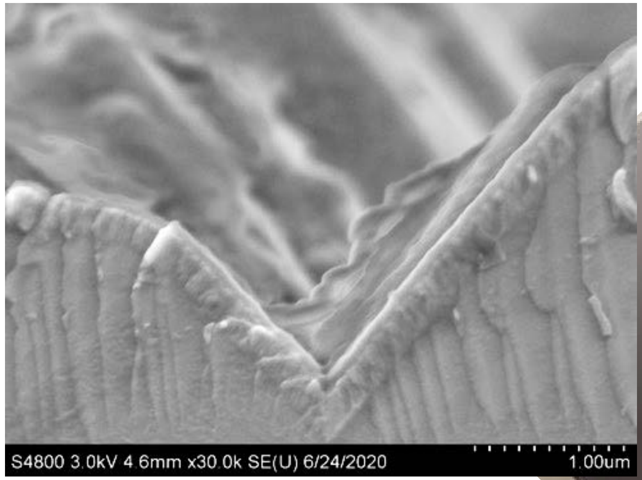


- Licensed patent: Flash QE tester (2012) R&D100; 11 patents and applications; numerous inventions 2021-2023.

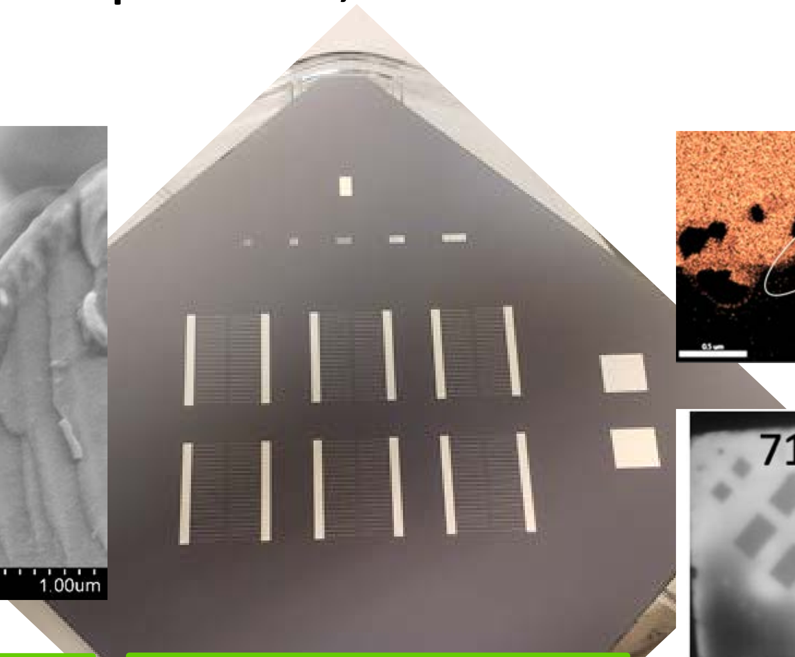
PV workforce training on the whole Si PV process, and new directions enabled with new cleanroom tools



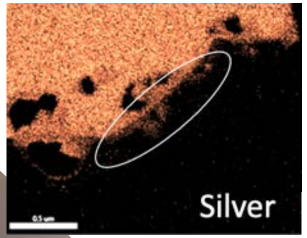
Front-end wet cleanroom chemistry (Singulus)

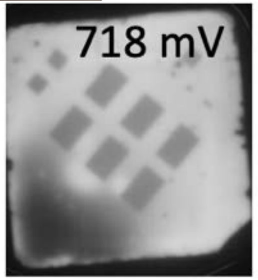


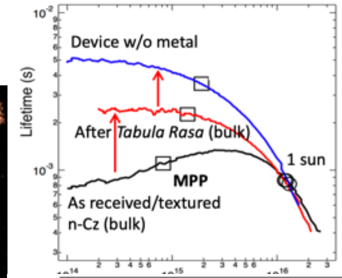
Depositions + Thermal (LPCVD, P, B, SiO_2, SiN_x – Tempress, Thermco; a-Si:H, ALD Al_2O_3 in cluster)

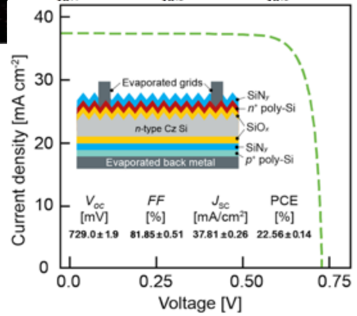


Back-end metallization:
Screen printing
Evaporation





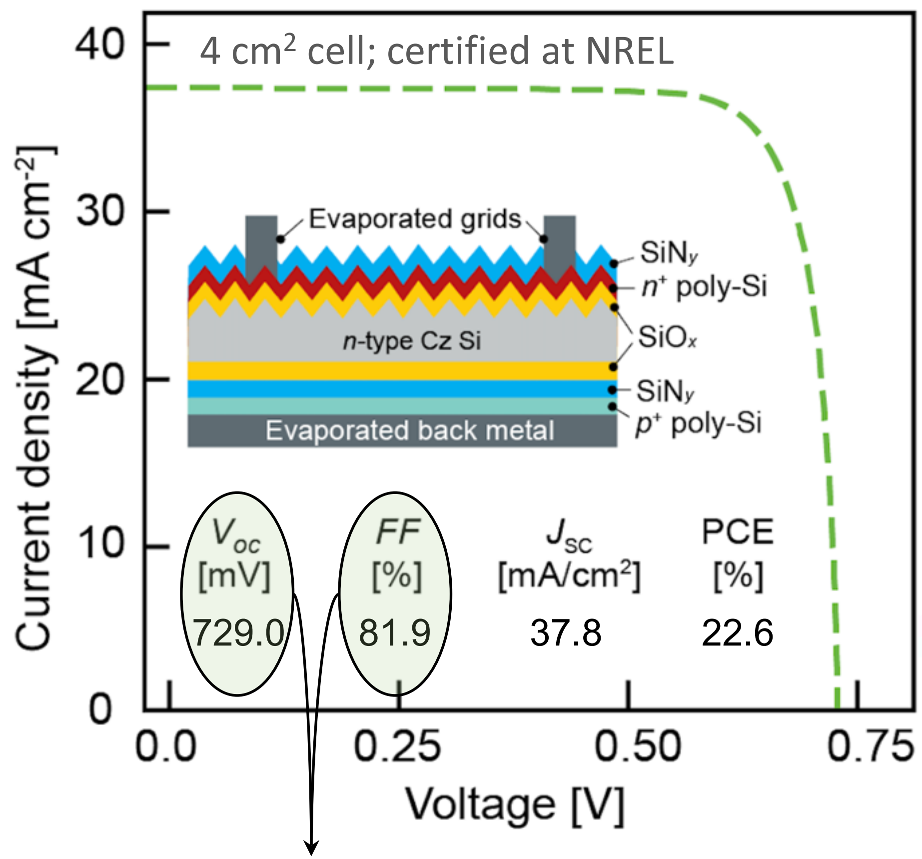




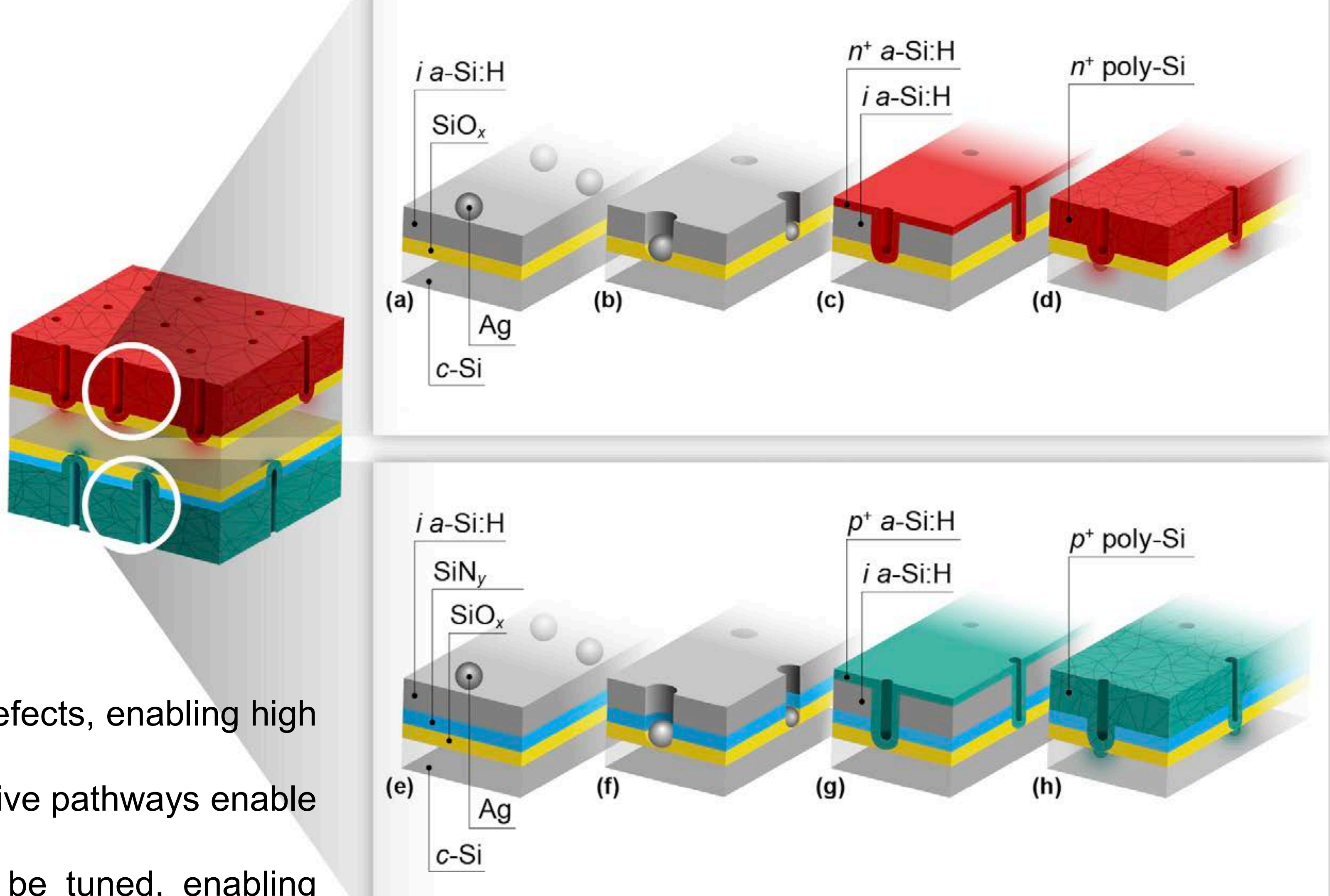
Advanced Characterization:
PL, Sinton, JV, QE, SEM, TEM, EBIC

- Next generation Si PV: novel passivated contacts, devices, reliability/defects, metallization (Ag to Cu)
- Industry engagement
- **Workforce training** on industrially relevant Si PV tools with highest cleanroom standards (students, engineers, interns)

Poly-crystalline silicon on locally etched insulators: electrical contacts for high-efficiency silicon solar cells



Patent application filed in 2021. USPTO app. No. 17/516,533



C. L. Anderson et al. Advanced Energy Materials, 2023, 13, 2203579

note: few additional processing omitted for simplicity

- Insulating layers mitigate inherent surface defects, enabling high open-circuit voltage
- Within 1 cm^2, millions of nanoscale, conductive pathways enable current transport through insulating layers
- Area density of conductive pathways can be tuned, enabling solar cells with high open-circuit voltage and high fill-factor

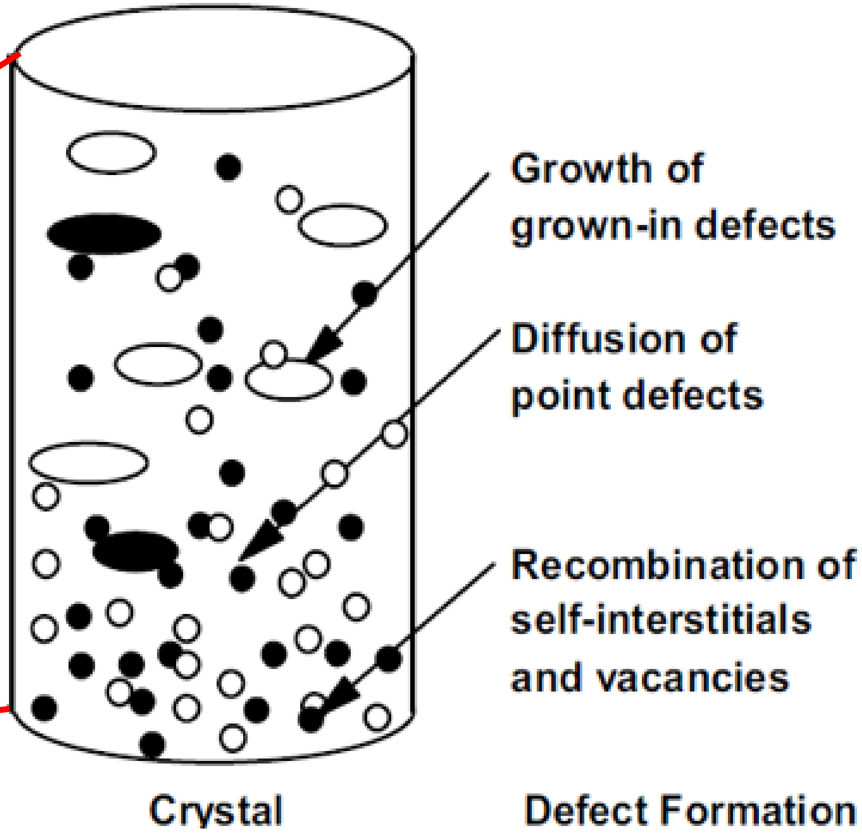
The fabrication process applies galvanic corrosion principles to create nanoscale, conductive pathways

Today, most Si for electronics and PV is Cz–Si. The Cz growth process introduces small amounts of impurities and defects in the bulk.

NREL Si team: identify microscopic origins and mitigate these bulk defects.

Fig. 1.2: Photograph of a silicon CZ puller with 200 mm crystal (Wacker Siltronic AG).

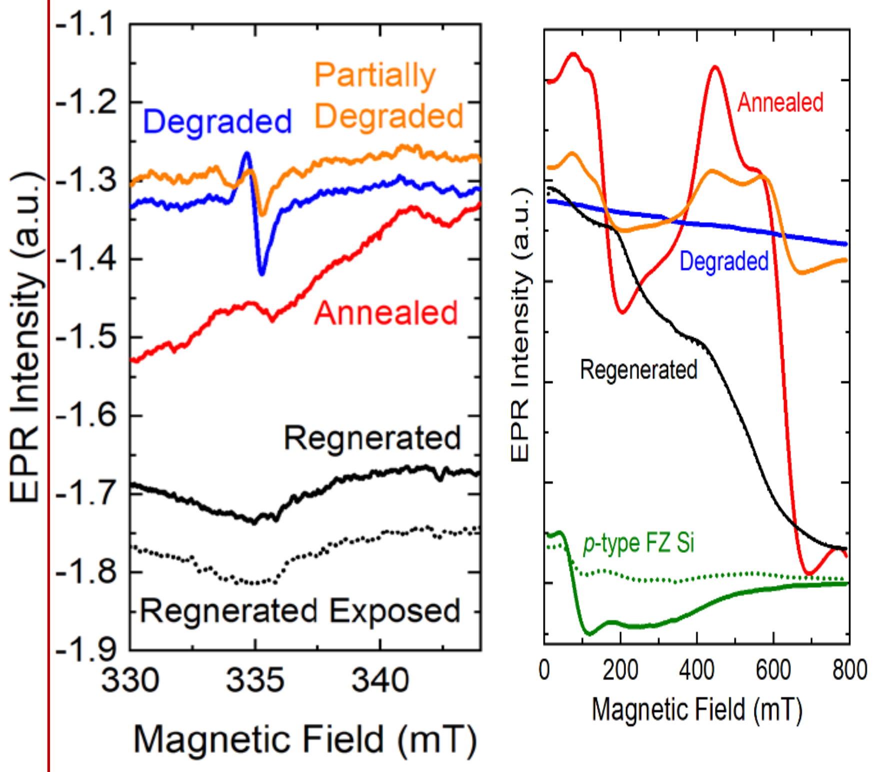
E. Dornberger, PhD thesis 1997

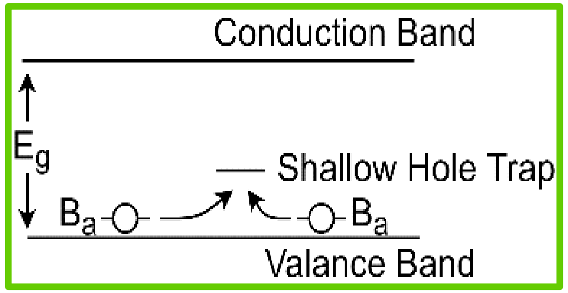


Dopants (P, B, Ga) – only partial segregation into solid.
Oxygen – solid solubility, precipitation with vacancies.
Metal impurities – self purification due to small $K_{segr} \sim 10^{-5}$

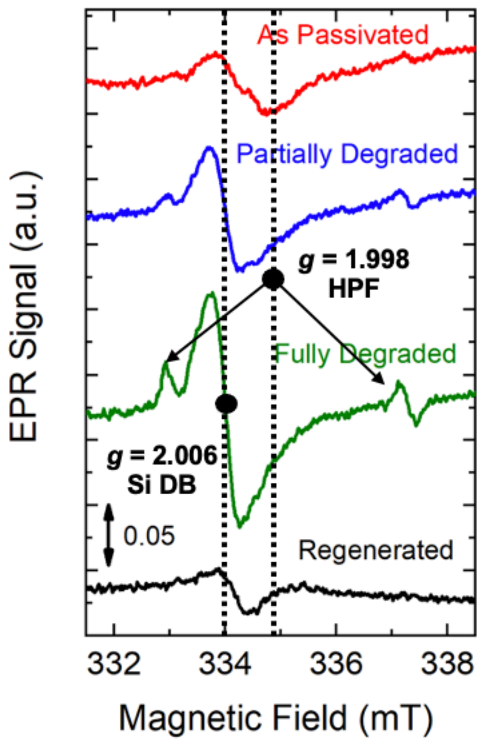
Electron Paramagnetic Resonance + EDMR for degradation mechanisms in p-Cz Si

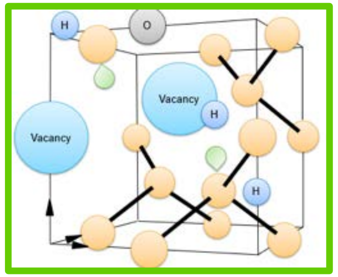
LID in Cz-Si:B – numerous, shallow hole traps created by light + deep defects



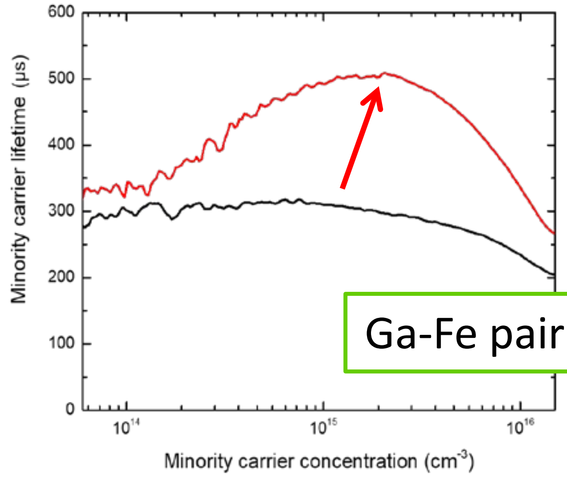


LeTID in Cz-Si:Ga Si dangling bond in partially hydrogenated vacancy





Light-induced P-hyperfine signals in LeTID sample; DFT theory



Ga-Fe pair dissociation

A. Meyer *et al.*, *Energy Env. Science* 2021; *Cell Reports* 2023

Future Outlook

- NREL Si team's orientation towards high-quality science and innovation.
- Given the IRA support, a massive revival of Si PV across the whole value chain is expected in the next few years. We contribute to this by:
  - Industrially relevant innovative basic research addressing long term issues:
    - Cu metallization to replace Ag
    - Novel, industrially relevant passivated contacts (firable, transparent, nanopinhole)
    - EPR, EDMR, and electronic techniques for very low-level defect identification and mitigation
  - Expanded, wide-spectrum industry collaborations on shorter term issues:
    - Modern, flexible, compact baseline cell process capability at NREL for industry testing (*e.g.*, new wafers, device processes, Cu metallization)
    - Advanced characterization on ingot, wafer, cell, module level
    - Reliability - integrate cells with modules
  - Preparing the future industry leaders, PhD level workforce for the US PV industry.