Analyzing Terawatt Scale Sustainability with PV ICE tool

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5 Conclusions (What can PV ICE do)
Decarbonization Goals
>90% Clean Electricity by 2035

Solar Deployment 2020-2050

- Decarbonized Grid
- Decarbonized Energy System

CURRENT: 100 GW Deployment Rate
19.2 GW/year

Average Annual Deployment
19.2 GW/yr 30 GW/yr

US MFGing

2020 2021-2025 2026-2030 2031-2035

DOE, Solar Futures Study 2021
World Decarbonization Goals and PV Deployment Rates

Global PV Deployment Projections from various 2021 Studies

**Deployment Goals**
- US x 10 (Solar Futures): 16 TW
- Gervais: 9 TW
- IEA Net Zero: 15 TW
- Zhang, Breyer & others: 70 TW+

**Deployment Rate Projected by 2030**
- US x 10 (Solar Futures): 600 GW/year
- Gervais: 200 GW/year
- IEA Net Zero: 630 GW/year
- Zhang: 3000 GW/year

**Scaling current by**
- (x4.6)
- (x1.5)
- (x4.8)
- (x23)

CURRENT: 1 TW
Deployment rate
~130 GW/yr
Modules Continuously Evolve

Crystalline Silicon Modules

Mainstream Module Evolution

- Aluminum Frame
- Front Glass
- Front Encapsulant
- Solar Cells
- Busbars
- Back Encapsulant
- Back Glass
- Polymer Backsheet
- Junction Box

Pre-2015 module, 20-25 year life

Emerging Products – flexible, non-CdTe thin film, BIPV, Etc.

2022 module, 35 year life

New Technology + Explosive Growth

Si Cell Technologies

Global market share

- 100%
- 90%
- 80%
- 70%
- 60%
- 50%
- 40%
- 30%
- 20%
- 10%
- 0%

- 2015
- 2016
- 2017
- 2018
- 2019
- 2020
- 2021
- 2022
- 2023
- 2024
- 2025
- 2026
- 2027
- 2028
- 2029
- 2030

- Al-BSF etc.
- mono
- p-PERC
- n-type

Module bifaciality factor $\phi = \frac{P_{\text{Rear}}}{P_{\text{Front}}}$

HJT
23-25% cell efficiency
$\phi \sim 0.85 - 0.95$

TOPCon
21-23% by SP, 21-26% by PVD
$\phi \sim 0.8$
**New Technology + Explosive Growth**

Expect somewhat disruptive technology changes requiring new fabs every few years

Current events illustrate benefits of increased geographic diversity for new plants, and of sustainable planning

Policies:
- Uyghur Forced Labor Prevention Act
- Defense Production Act
- Inflation Reduction Act

Market Dynamics
- Supply shortages, i.e. polysilicon price shocks

DEI & Sustainability Goals:
- Reduction of increased negative environmental and social impacts, i.e. forced labor in polysilicon production, poorly regulated or illegal sand mining
How do we deploy TWs Sustainably?

• 630 GW/Year by 2030 (currently ~130 GW/yr)
  – Manufacturing demands and impacts

• Do we make them:
  – More efficient?
  – More recyclable?
  – Long lasting?
  – Less material intensive?
Big Questions About Circularity

- Circular Economy concepts are well defined and studied for consumer products
- Should we think about them differently for renewable energy?
ENG 101 and Thermo Still Apply

Accumulation = In − Out + Generation − Consumption

Mass Balance
- Minimize waste out OR virgin material in
- Required starting point

Energy Balance
- Very different from a consumer product because it makes clean energy over time
- Embedded energy, transportation, energy produced

Carbon Balance
- Good metric for decarbonization
- Depends on the grid mix for manufacturing and EoL, and use offsets it
Circular R-strategies for PV in the Energy Transition

Refuse: Refuse virgin and conflict materials.

Rethink: High energy yield PV systems, design for Repair and Reliability Integrated PV.

Reduce: Material substitution, increase manufacturing yield, decarbonize manufacturing.

Reuse: Merchant tail, resell in secondary markets.

Repair: Onsite repair of modules and components.

Refurbish: Demount and transport modules for repairs Replace storm-damaged modules on site.

Remanufacture: Disassemble, replace cells, relaminate.

Repurpose: Repower system with new components

Recycle: Separate modules and components, reclaim materials.

Remine: Mine input materials from landfills, refine.

Recover: Burn component materials for energy generation.
Research Opportunities

Data

Reduce
- Materials and Energy Input

Reuse, Refurbish
- Extend useful life

Recycle
- Primary Materials, Energy, Cost

Disposal
- Better understand environmental effects

R&D Solutions, Analyses, Assistance

From SETO CE & EoL Webinar, 2021:
PV ICE: an open-source tool evaluating circular paths for PV

Includes pathways for circularity of materials and energy

REUSE (RESELL & MERCHANT TAIL), REPAIR, REMANUFACTURE, RECYCLE
Metrics of Success

How do we measure impact of circular choices for PV lifecycles?

- **Virgin Material**: Reduce Extraction of Virgin Materials
- **Energy In**: Minimize Energy demands of processes and materials
- **Energy Out**: Maximize PV Yield for Energy Transition
- **Energy Balance**: Maximize EROI, EPBT, Net Energy
- **Installed Capacity**: Maintain PV Capacity to meet Energy Transition
- **Waste**: Reduce Wastes throughout PV lifecycle
- **Supply Chain Security**: Just and Reliable sourcing of materials
Features

Bringing PV and Sustainability communities together, Interdisciplinary

Accurate Installed Capacity Calculated with degradation, and bifaciality corrections

Able to use ANY deployment forecast (county, US, other countries, world, or by specific technology)

Historic and projected baselines
Virgin Material Needs consider MFG Efficiencies, all as open-data!

Framework that allows easy scenarios comparison Sensitivity Analysis

New Installed Capacity [TW]

Industry leading linear warranty

Service Life definitions (project lifetime, degradation, and improved failures and reliability approach)

Landfill % occupied by PV Waste By Mass

Flexible Spatial and Temporal analysis
PV ICE’s Integrated NREL Circular Approach

NEW INSTALLS

- High RE Cost

MANUFACTURING

- PV Reliability Group

INSTALLED CAPACITY AND EXTENDED USEFUL LIFE

- DuraMAT

EOL MODES

- Walzberg’s Agent-Based Model

CIRCULAR PATHWAYS

- CELAVI Landfill calculation approach

ReEDS

- MFI

Upcoming Carbon Footprint

- Siting Optimization & EJ

- ANL-CEEESA

- RELOG

- EJScreen

- FEDERAL COMMONS

- Brightway
Some results
How much Virgin Material do we need for this?

In perspective: 40 MT of electronic waste yearly Worldwide NOW

Figure 8 - 2. Comparison of virgin material demands for each silicon-based PV material cumulatively (2020–2050) across the three scenarios
Is there enough Virgin Material?

Figure 8 - 3. Percentage of 2020 global production of various materials needed to supply annual average virgin materials demand for c-Si PV
Is there enough Virgin Material?

Figure 8 - 3. Percentage of 2020 global production of various materials needed to supply annual average virgin materials demand for c-Si PV
Is there enough Silver?

Virgin Material

Energy In

Energy Out

Annual PV Silver Demand Globally

[Metric Tonnes]

Historic PV Silver Demand

Global Silver Production

Cumulative Energy Generated

Barnes, et al. 5th International SHJ Workshop, CEA-INES 2022
Cumulative Installed Capacity and PV Materials for Decarbonization Deployment

- Solar Futures: Decarbonization + Electrification [TW]
- Mass of PV Materials Installed [million tonnes]
- Mass of End-of-Life PV Materials [million tonnes]

Cumulative Lifecycle Waste Material in 2050
[Million Metric Tonnes]

- 6.7 Mt Glass 57%
- 1.2 Mt Silicon 12%
- 1.0 Mt Aluminum Frames 10%
- 0.70 Mt Encapsulant 7%
- 0.42 Mt Backsheet 4%
- 0.004 Mt Copper 0.04%
- 0.003 Mt Silver 0.03%


### How can we reduce Waste?

<table>
<thead>
<tr>
<th>Decrease Waste</th>
<th>Increase Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall improvement in EoL Circularity Pathways + Reliability and Lifetime</td>
<td>+10%</td>
</tr>
<tr>
<td>Module Lifetime and Reliability</td>
<td>+10%</td>
</tr>
<tr>
<td>Module Manufacturing Efficiency</td>
<td>+10%</td>
</tr>
<tr>
<td>Efficiency of Material Use during Module Manufacturing</td>
<td>+10%</td>
</tr>
<tr>
<td>New Installed Capacity [MW]</td>
<td>-10%</td>
</tr>
<tr>
<td>Mass per m2</td>
<td>-10% rel.</td>
</tr>
<tr>
<td>Module Efficiency</td>
<td>+10% rel.</td>
</tr>
<tr>
<td>Overall improvement on manufacturing scrap recycling loop</td>
<td>+10%</td>
</tr>
<tr>
<td>Yield of the Material Manufacturing Scrap Recycling process</td>
<td>+10%</td>
</tr>
<tr>
<td>Fraction of Material Scrap from Manufacturing that undergoes Recycling</td>
<td>+10%</td>
</tr>
<tr>
<td>Overall improvement on EoL Circularity Pathways</td>
<td>+10%</td>
</tr>
<tr>
<td>Collection Efficiency of EoL Modules</td>
<td>+10%</td>
</tr>
</tbody>
</table>

% Change in Lifecycle Waste

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Module Lifetime & Reliability

Warranty ≠ Lifetime

Figure 2. Project Life Expectations for Utility-Scale PV, over Time

32 Years
-0.5% Degradation Rate

Wiser, LBL, 2020

M. Springer, Future-proofing photovoltaics module reliability through a unifying predictive modeling framework. PinPV 2022, 10.1002/pip.3645
The concept of Installs vs Effective Capacity

What about Recycling?

Virgin Material

Waste

But Silvana, what about Recycling?

But Silvana, what about Recycling?

**Energy Demand for different Pathways**

Fig. 2  Diagram of the two evaluated scenarios: 100% recycled modules, vs 100% remanufactured modules. Glass remanufacture is potentially enabled by technology designs such as the perovskite all-back-contact architectures. Scenarios are evaluated on material and energy flows of glass.

Mirletz, Ovaitt, Barnes, 2022 "Quantifying Energy flows in PV Circular Processes"  
PVSC Proceedings. Best Student Paper Area 8 Award
## Energy Metrics Overview

### Energy Balance

\[
\sum_{2000, 2100} \frac{E_{\text{out}}}{\sum_{2000, 2100} E_{\text{in}}}
\]

### Energy In vs. Energy Out

<table>
<thead>
<tr>
<th>Net Energy</th>
<th>EPBT</th>
<th>EROI</th>
<th>Effective Capacity</th>
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</thead>
<tbody>
<tr>
<td>(E_{\text{out}} - E_{\text{in}})</td>
<td>Energy Pay Back Time</td>
<td>Energy Return on Investment</td>
<td>Effective Capacity</td>
</tr>
<tr>
<td>Year in which Net Energy goes positive</td>
<td>Maximize ↑</td>
<td>Minimize ↓</td>
<td>Maximize ↑</td>
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<tr>
<td>Installs + replacements − degradation − failures − EoL</td>
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# Measuring Sustainability of PV in Energy Transition: Mass, Energy, Circularity, and Carbon

<table>
<thead>
<tr>
<th></th>
<th>PV ICE Baseline</th>
<th>50-year PERC</th>
<th>SHJ Perfect Longevity</th>
<th>SHJ High Efficiency</th>
<th>TOPCon</th>
<th>Idealized Perovskite Si-Tandem 4T</th>
<th>Recycled PERC</th>
<th>Recycled High Circularity</th>
<th>Recycled Low Quality PERC</th>
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<tbody>
<tr>
<td><strong>Mass</strong></td>
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<tr>
<td>Virgin Material Demand</td>
<td>0</td>
<td>+</td>
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<td>-</td>
<td>++</td>
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<tr>
<td>Lifecycle Material Losses</td>
<td>0</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>++</td>
<td>-</td>
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<tr>
<td>Energy</td>
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<tr>
<td>Replacements</td>
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<tr>
<td>Net Energy</td>
<td>0</td>
<td>++</td>
<td>++</td>
<td>++</td>
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<td>+</td>
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<td>-</td>
</tr>
<tr>
<td>Energy Balance</td>
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</table>

**Benefit** | **Detriment**


RELOG
OPEN-SOURCE SOFTWARE PACKAGE FOR REVERSE LOGISTICS OPTIMIZATION

PV ICE
Open-Source Software Package for Evaluating Circular Paths for PV

OBJECTIVES
Assess techno economic and life-cycle impacts of large-scale PV recycling
Help identify locations and speed at which a recycling industry needs to grow in the US to meet target recycling rates, accounting for cost of transport, warehousing, and capital costs
Inform strategies for incentivizing collection and recycling

Glass Waste by PCA Region Cumulative, 2050
Thousand metric tonnes
- 600 to 800
- 400 to 600
- 200 to 400
- 100 to 200
- 25 to 100
- <25

Analysis & visualization
RICE Project Status

Macarena Mendez-Ribo, et al. PVSC 2023 (To be presented)
Shooting for the sun

- More US MFG and supply chain security decision support, including Critical materials?
- Economic layer?
- Full LCA integration?
- Energy justice in PV evaluations?
- Other countries / USAID?
- Other renewables?
- Tool for standard comparisons for FOA/prizes/SBIR?
Conclusions

1. We have a tool that is flexible to all new deployment scenarios, that considers technology evolution and PV-specific circular paths.
2. We have used PV ICE to calculate virgin material demands, waste production with yearly geospatial resolution, and conduct a sensitivity analysis to the decision points and process efficiencies governing both.
3. We have evaluated different circularity pathways enabled by novel technologies (i.e. Perovskite remanufacturing)
4. We have identified lifetime and recycling thresholds that can help us meet decarbonization goals from a Mass Perspective
5. We have detailed how poor module quality reduces Energy Balance, and how reducing degradation is a good lever to ease Energy Transition deployment.
6. We are exploring sustainable strategies for PV for Mass and Energy, finding that when evaluating a suite of metrics, module lifetime consistently scores well while other strategies have obvious tradeoffs.
7. We are exploring PV ICE geospatial and temporal results for siting optimization of recycling and manufacturing facilities of PV
8. We can use PV ICE to support US manufacturers and supply chain to make informed decisions
9. We could use PV ICE to evaluate critical materials or other materials if funded to do so
Silvana Ayala  
Researcher, sp. CE tool development

Heather Mirletz  
Colorado School of Mines  
Mass, Energy baseline curator & analysis  
PhD candidate est. Fall 2023

Macarena Mendez Ribo  
Postdoctoral Researcher  
RICE Siting Optimization  
DTU PhD

Teresa Barnes  
Duramat Lead  
CEEM leader at NREL

Field Performance & Reliability Group at NREL
# Timeline and Funding

<table>
<thead>
<tr>
<th></th>
<th>FY20</th>
<th>FY21</th>
<th>FY22</th>
<th>FY23</th>
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<tbody>
<tr>
<td><strong>PV-ICE FRAMEWORK</strong></td>
<td>NREL P&amp;A</td>
<td>NREL P&amp;A</td>
<td>NREL P&amp;A/BD DuraMAT DECS</td>
<td>AMO- RELOG</td>
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<tr>
<td>Module materials baselines and case studies</td>
<td>Colorado School of Mines</td>
<td>NREL P&amp;A, Solar Futures</td>
<td>50% NREL LDRD 50% Solar TEA</td>
<td>100% Solar TEA – data set is dual purpose for PV LCA</td>
</tr>
<tr>
<td>Technical oversight and mentoring</td>
<td>NREL P&amp;A</td>
<td>NREL P&amp;A/BD</td>
<td>NREL Strategic Planning</td>
<td>DuraMAT MGMT</td>
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<tr>
<td>Addition of thin film and other tech</td>
<td>n/a</td>
<td>n/a</td>
<td>AMO - RELOG</td>
<td>AMO- RELOG Waiting for FY22 REMADE funding</td>
</tr>
</tbody>
</table>

- **NREL** | National Renewable Energy Laboratory
- **AMO-RELOG** | Argonne National Laboratory - Research and Engineering Program for Liabilities, Operations, and Geosystems
- **LDRD** | Laboratory Directed Research and Development
- **TEA** | Technology Evaluation Assessment
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Extra Slides
• Even for fastest cycling (15-year module), EoL materials mis-aligned in time to supply decarbonization-scale material demand.

• Manufacturing Scrap happens closer to deployment and can be leveraged for material demand

PV ICE Diagram

All circles have associated yields/efficiencies
All Hexagons have associated decision points