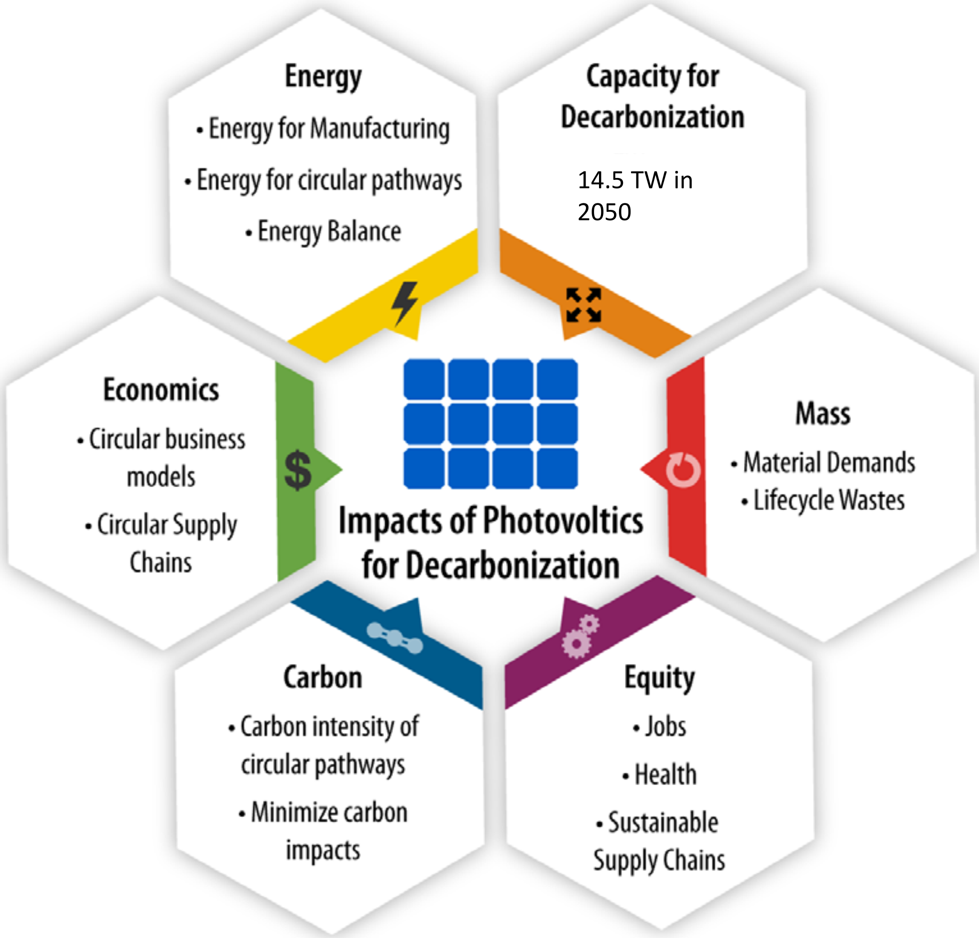


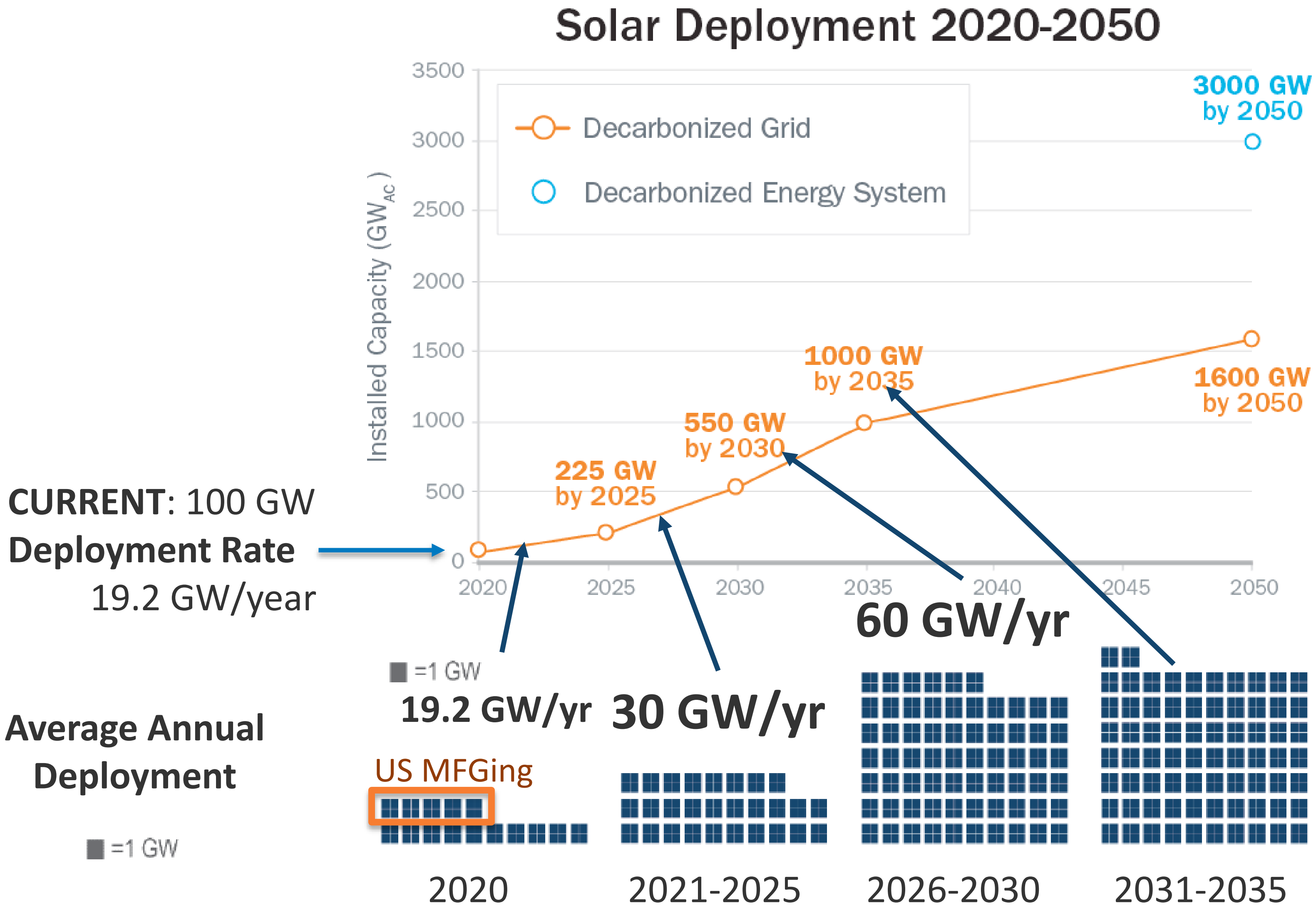
Analyzing Terawatt Scale Sustainability with PV ICE tool

Silvana Ovaitt, Heather Mirletz,
Macarena Mendez-Ribo, and **Teresa M. Barnes**

SETO Solar Colloquium, March 23, 2023

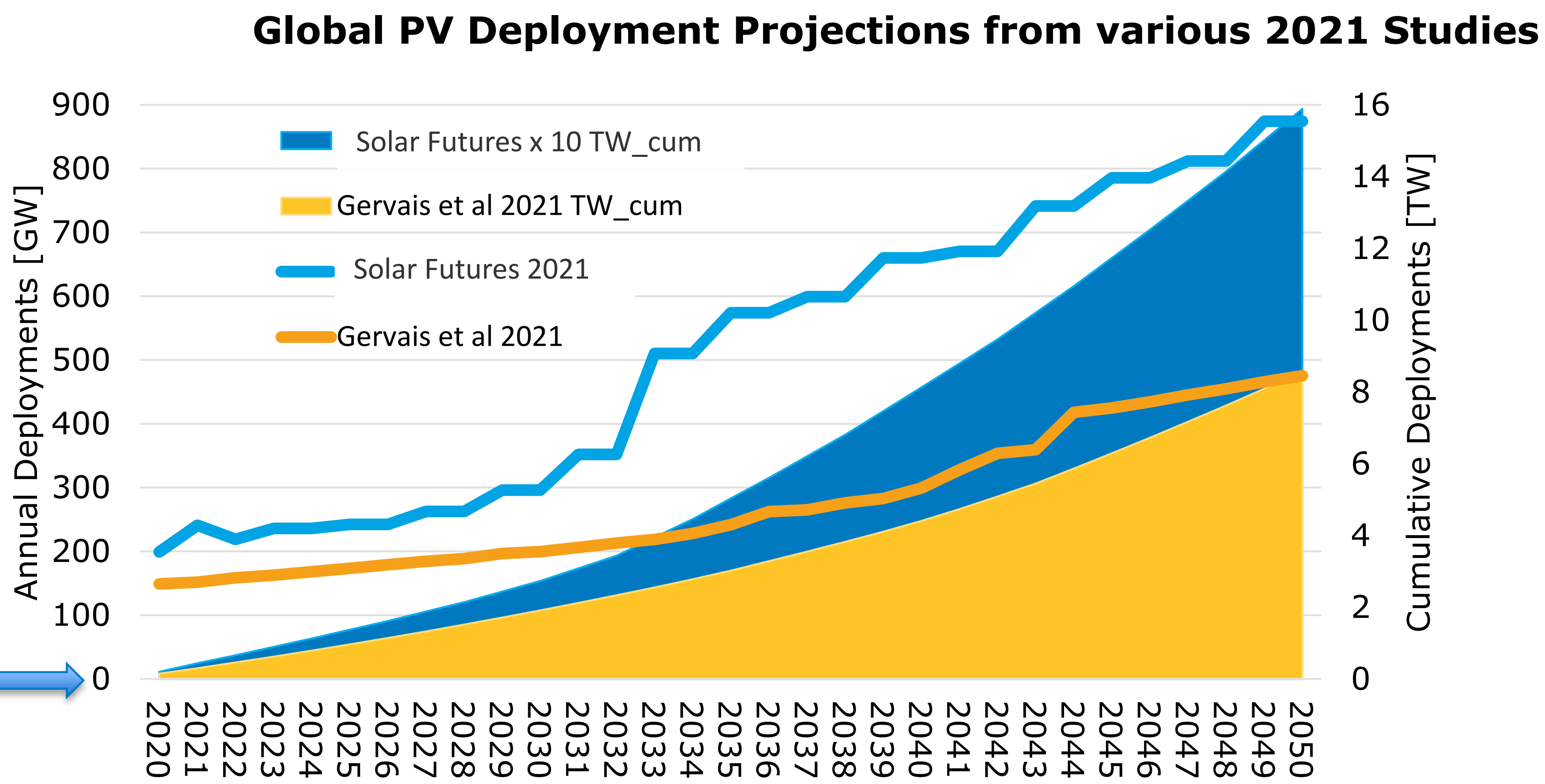
Contents

Decarbonization Goals
>90% Clean Electricity by 2035



DOE, Solar Futures Study 2021

World Decarbonization Goals and PV Deployment Rates



CURRENT: 1 TW

Deployment rate

~130 GW/yr

Deployment Goals

-US x 10 (Solar Futures): 16 TW

-Gervais: 9 TW

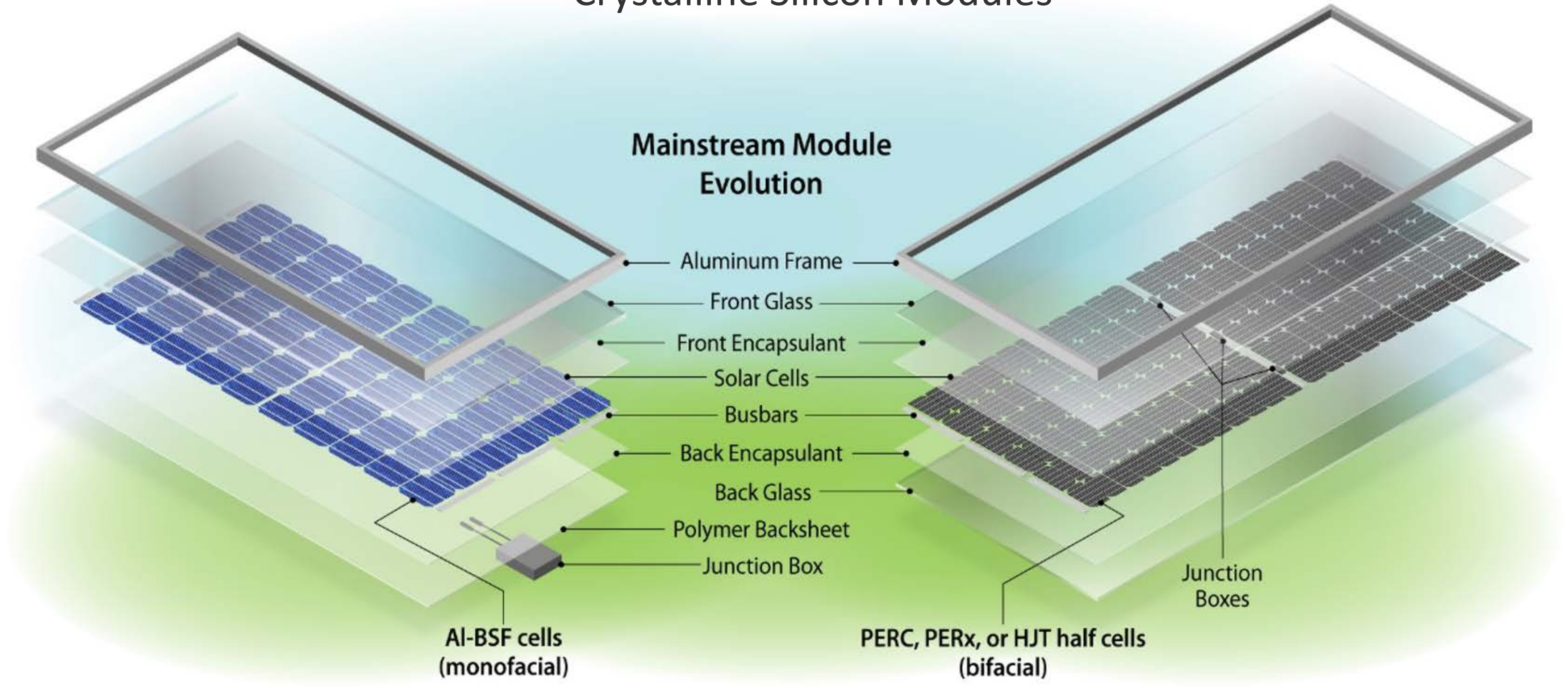
-IEA Net Zero: 15 TW

-Zhang, Breyer & others: 70 TW**+**

Deployment Rate Projected by 2030	*Scaling current by*
-US x 10 (Solar Futures): 600 GW/year	*(x4.6)*
-Gervais: 200 GW/year	*(x1.5)*
-IEA Net Zero: 630 GW/year	*(x4.8)*
-Zhang: 3000 GW/year	*(x23)*

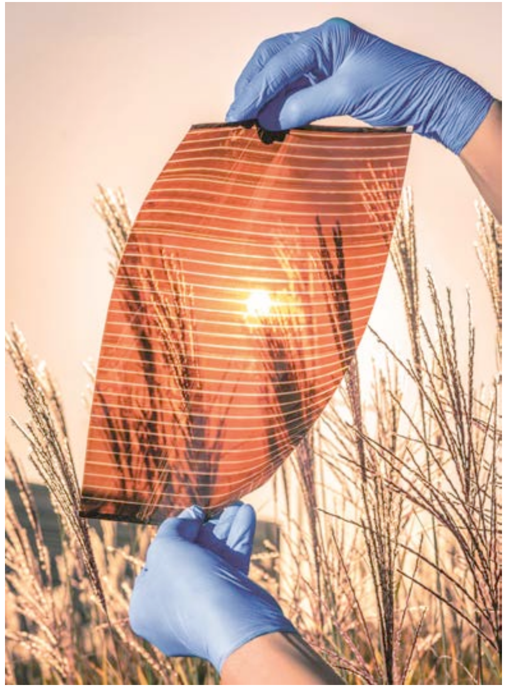
Modules Continuously Evolve

Crystalline Silicon Modules



Pre-2015 module, 20-25 year life

2022 module, 35 year life

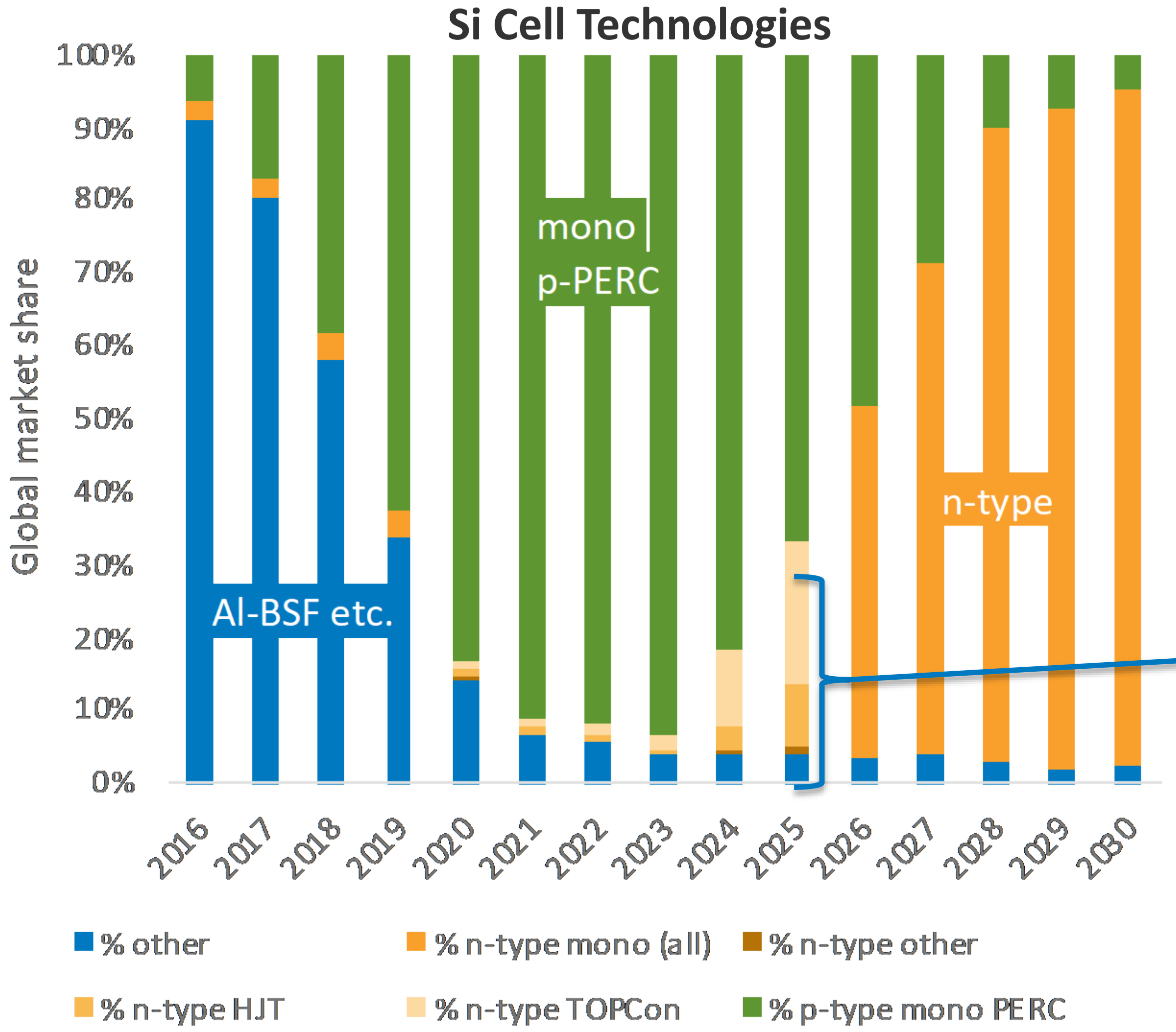


Emerging Products – flexible, non-CdTe thin film, BIPV, Etc.

Ovaitt & Mirletz et al, 2022. "PV in the Circular Economy, A Dynamic Framework Analyzing Technology Evolution and Reliability Impacts." *ISCIENCE* https://doi.org/10.1016/j.isci.2021.103488.

New Technology + Explosive Growth

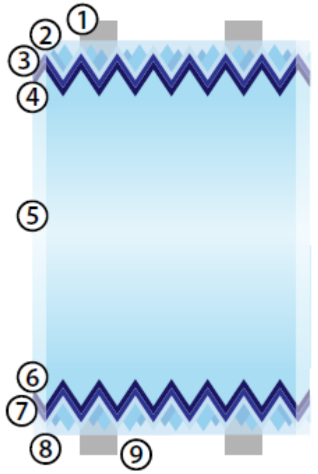
Module bifaciality factor $\phi = \frac{P_{Rear}}{P_{Front}}$



HJT

23-25% cell efficiency

ϕ ~0.85 – 0.95

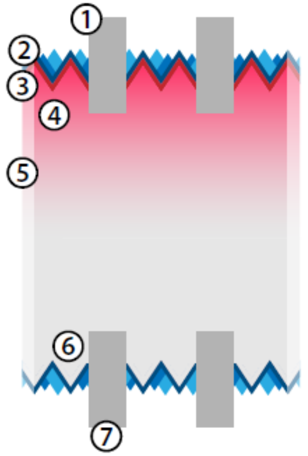


1. Frontside fingers (busbars optional) compromised of low-temperature screen-printed Ag pastes or electroplated Ni/Cu/Sn/Ag
2. TCO by PVD (typically ITO for high optical transmission and low sheet resistance)
3. p^+ doping and full-area emitter formation by PECVD of a-Si:H
4. Intrinsically doped a-Si:H by PECVD
5. High lifetime n-type base wafer
6. Intrinsically doped a-Si:H by PECVD
7. n^+ doping and full-area BSF formation by PECVD of a-Si:H
8. TCO by PVD (typically ITO for high optical transmission and low sheet resistance)
9. Backside fingers (busbars optional)

TOPCon

21-23% by SP, 21-26% by PVD

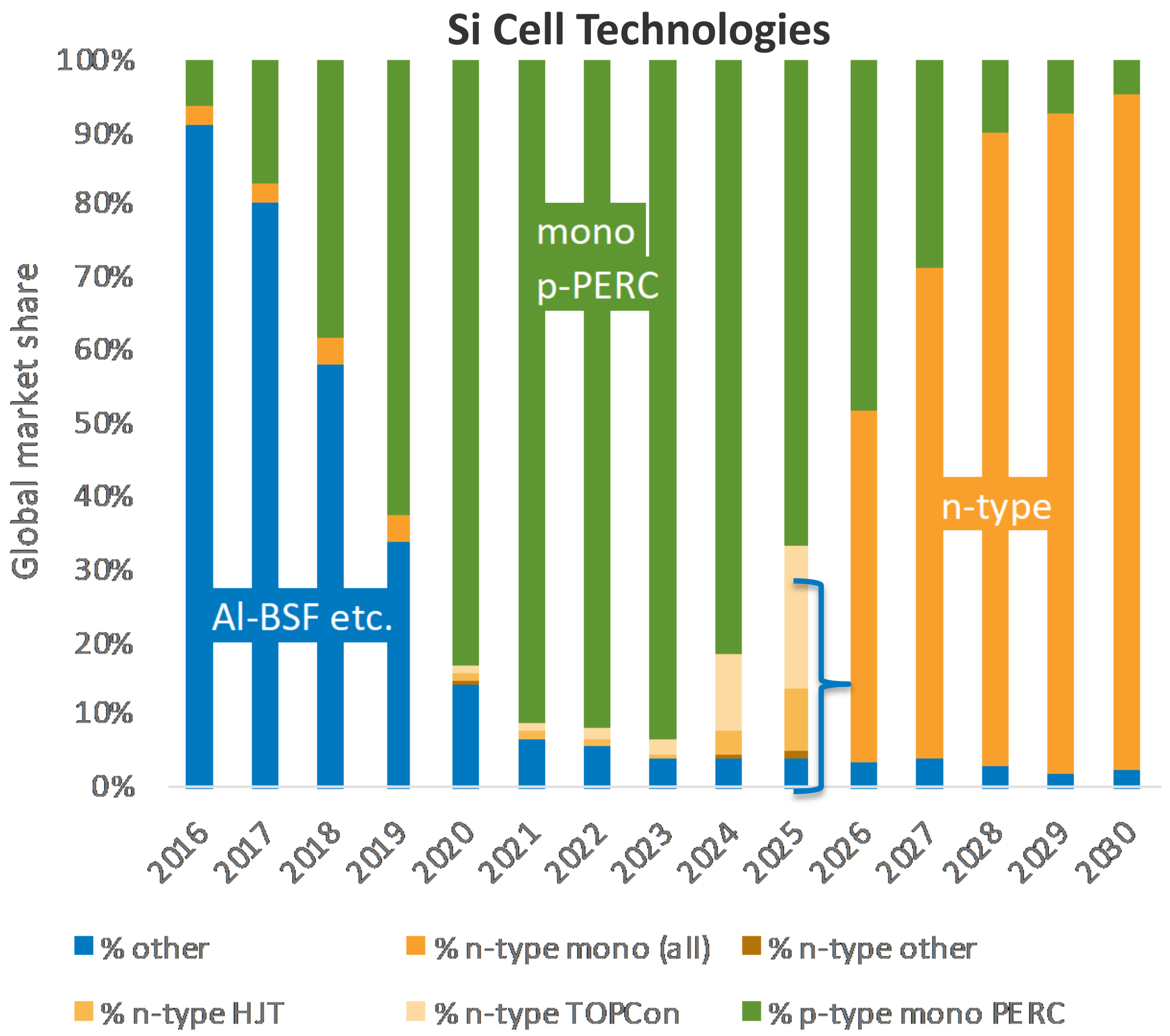
ϕ ~0.8



1. Ag and Al front metallization by screen-printing or PVD
2. SiN_x ARC and passivation layer by PECVD
3. PECVD or ALD of AlO_x surface passivation layer
4. p^+ doping and full-area emitter formation by ion implantation or BBr_3 diffusion
5. High lifetime n-type base wafer
6. Tunnel oxide passivated contact (TOPCon) layer formed by PECVD or LPCVD of doped a-Si or poly-Si layers
7. Ag rear metallization (sometimes full-area) by screen-printing or PVD

Jarett Zuboy. DuraMAT Tech Scouting 2022

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

<u>Policies:</u>

- Uyghur Forced Labor Prevention Act
- Defense Production Act
- **Inflation Reduction Act**

<u>Market Dynamics</u>

- Supply shortages, i.e. polysilicon price shocks

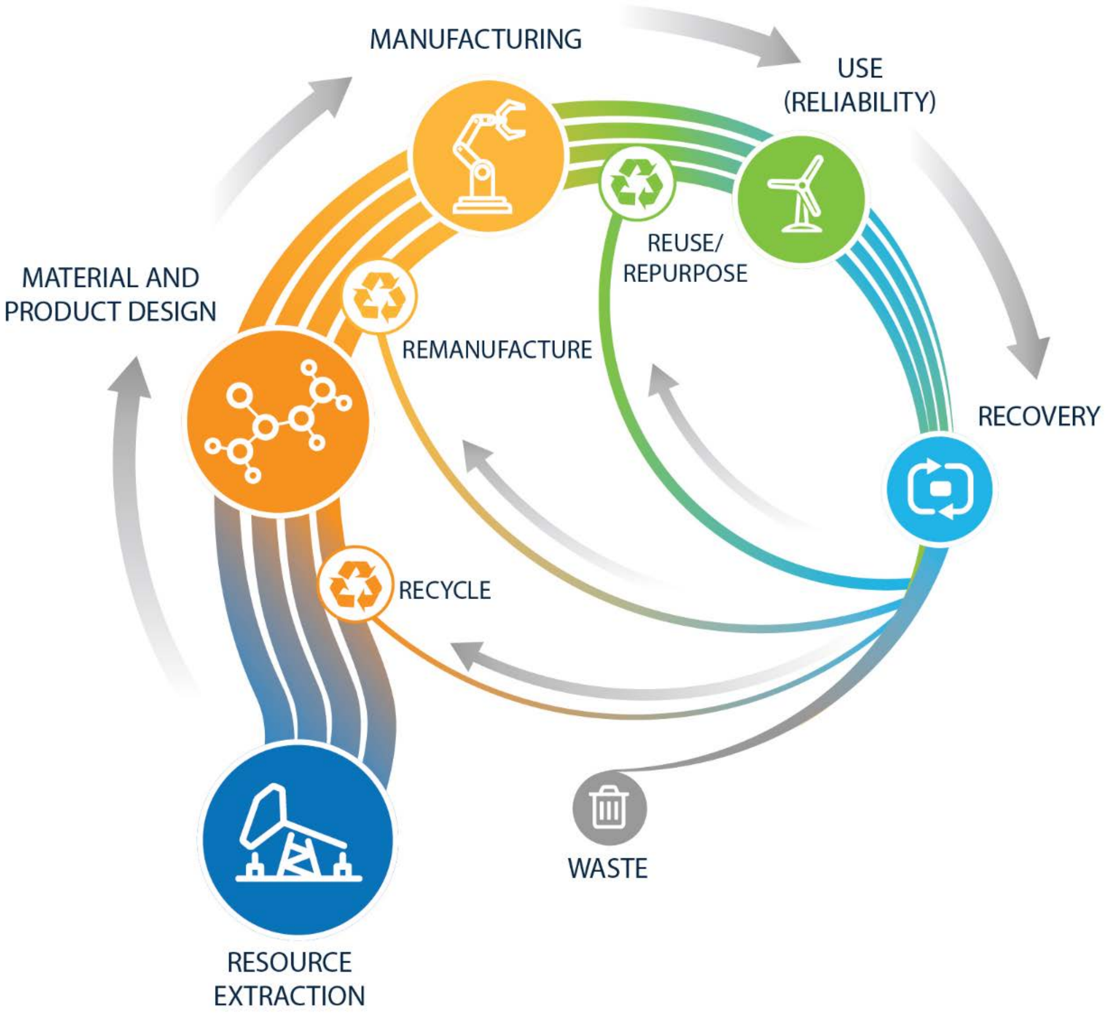
<u>DEI & Sustainability Goals:</u>

- Reduction of Increased negative environmental and social impacts. i.e. forced labor in polysilicon production, poorly regulated or illegal sand mining

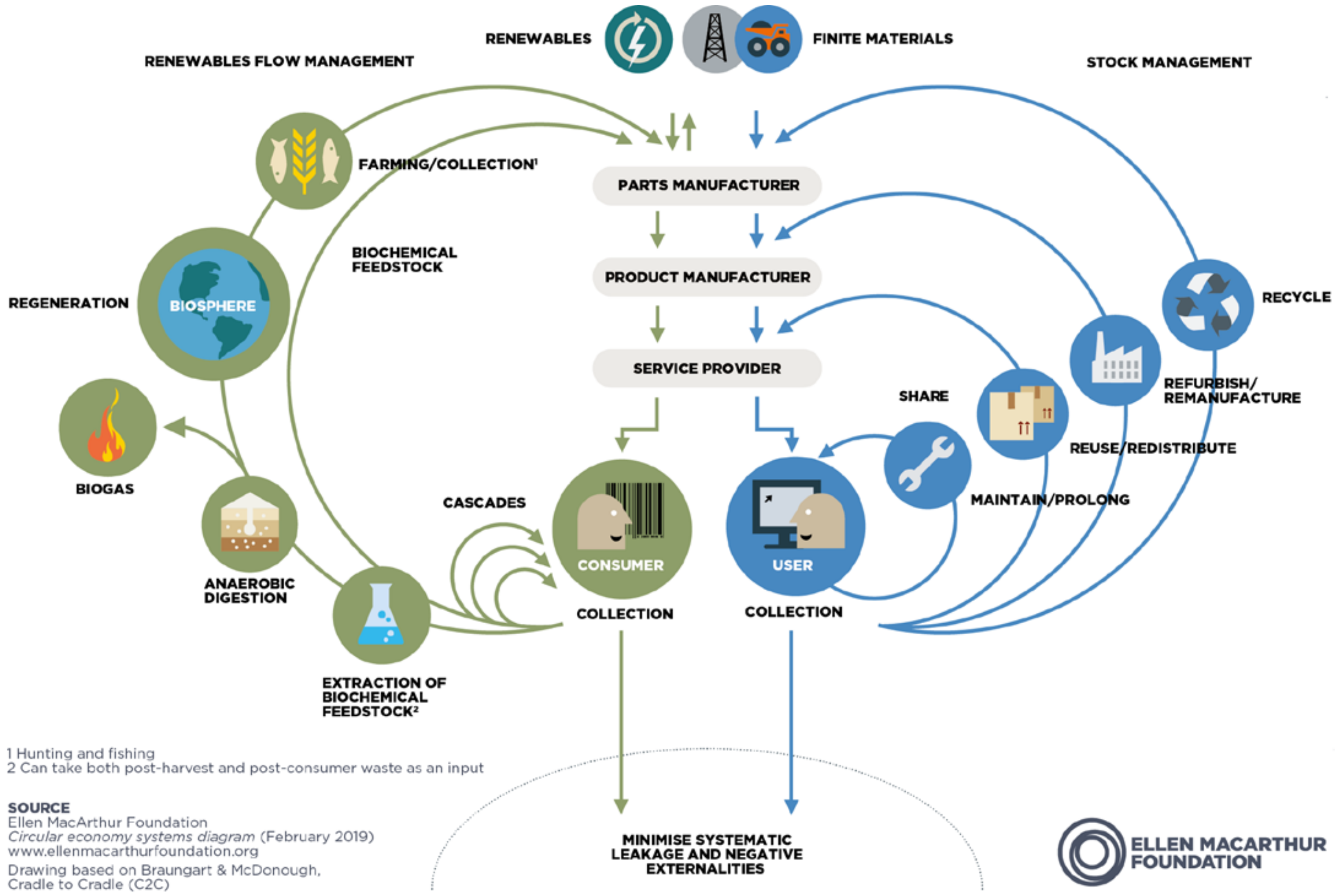
Jarett Zuboy. DuraMAT Tech Scouting 2022

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

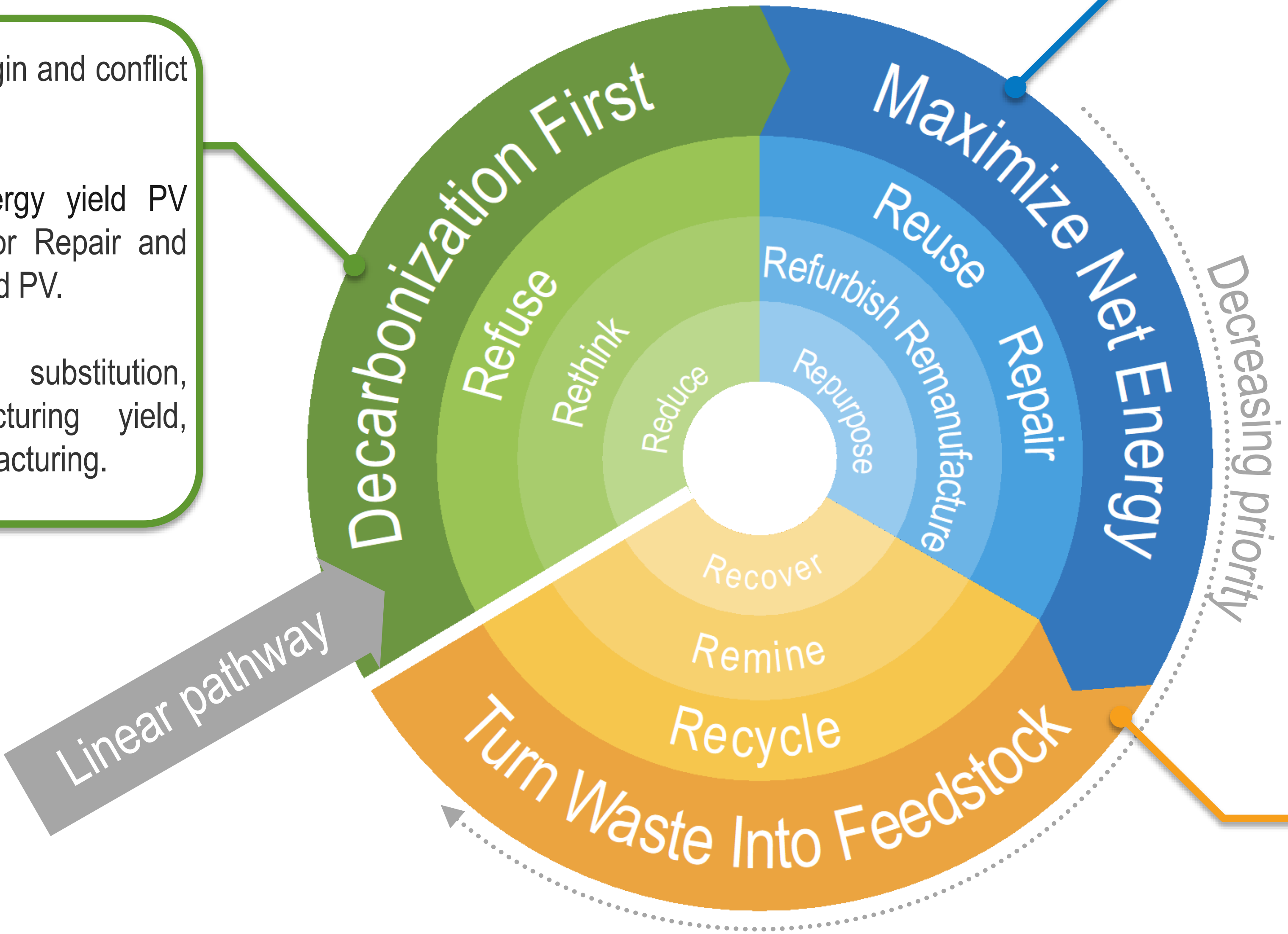
- Good metric for decarbonization
- Depends on the grid mix for manufacturing and EoL, and **use** offsets it

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

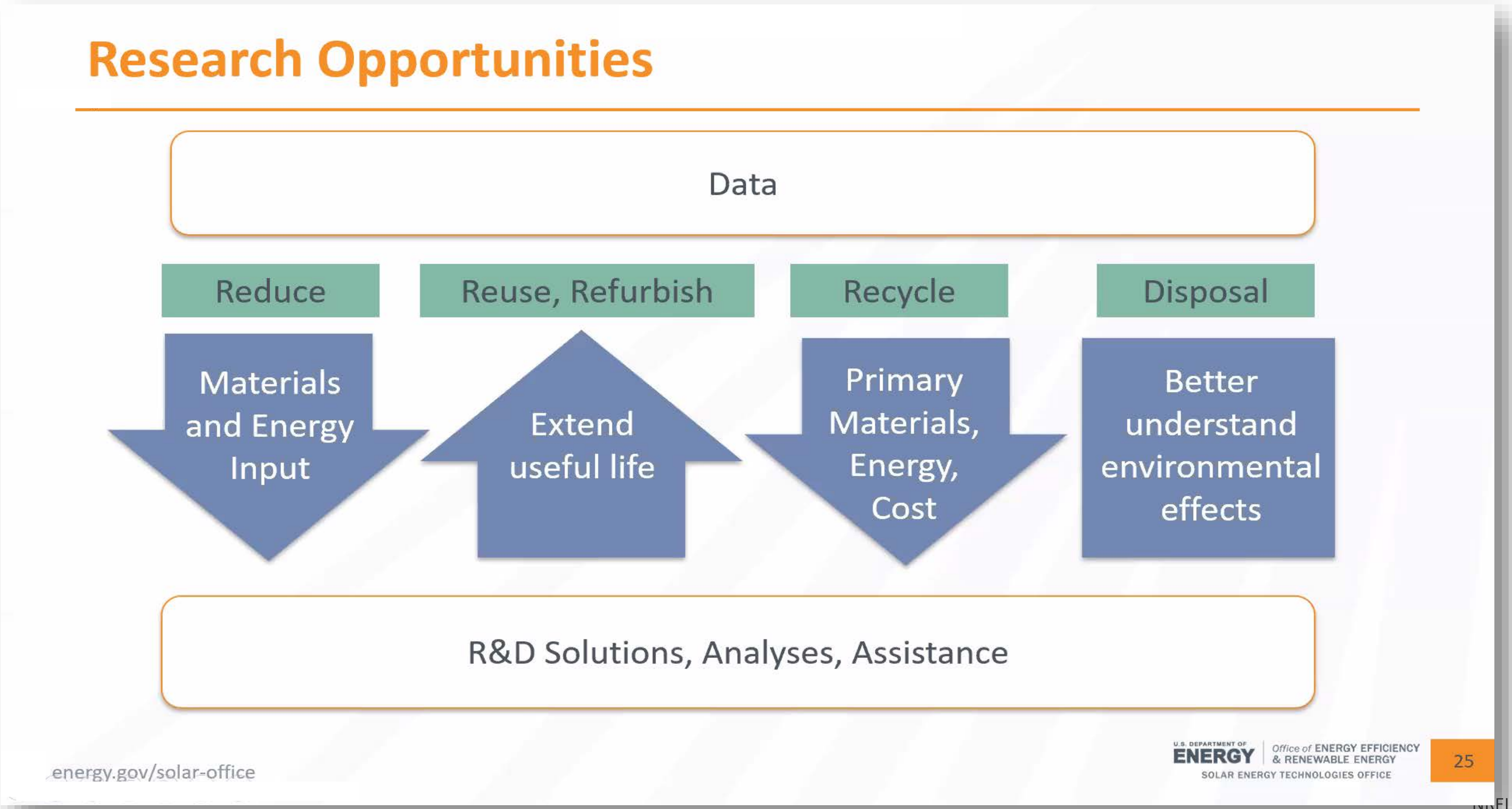
Recycle: Separate modules and components, reclaim materials.

Remine: Mine input materials from landfills, refine.

Recover: Burn component materials for energy generation.

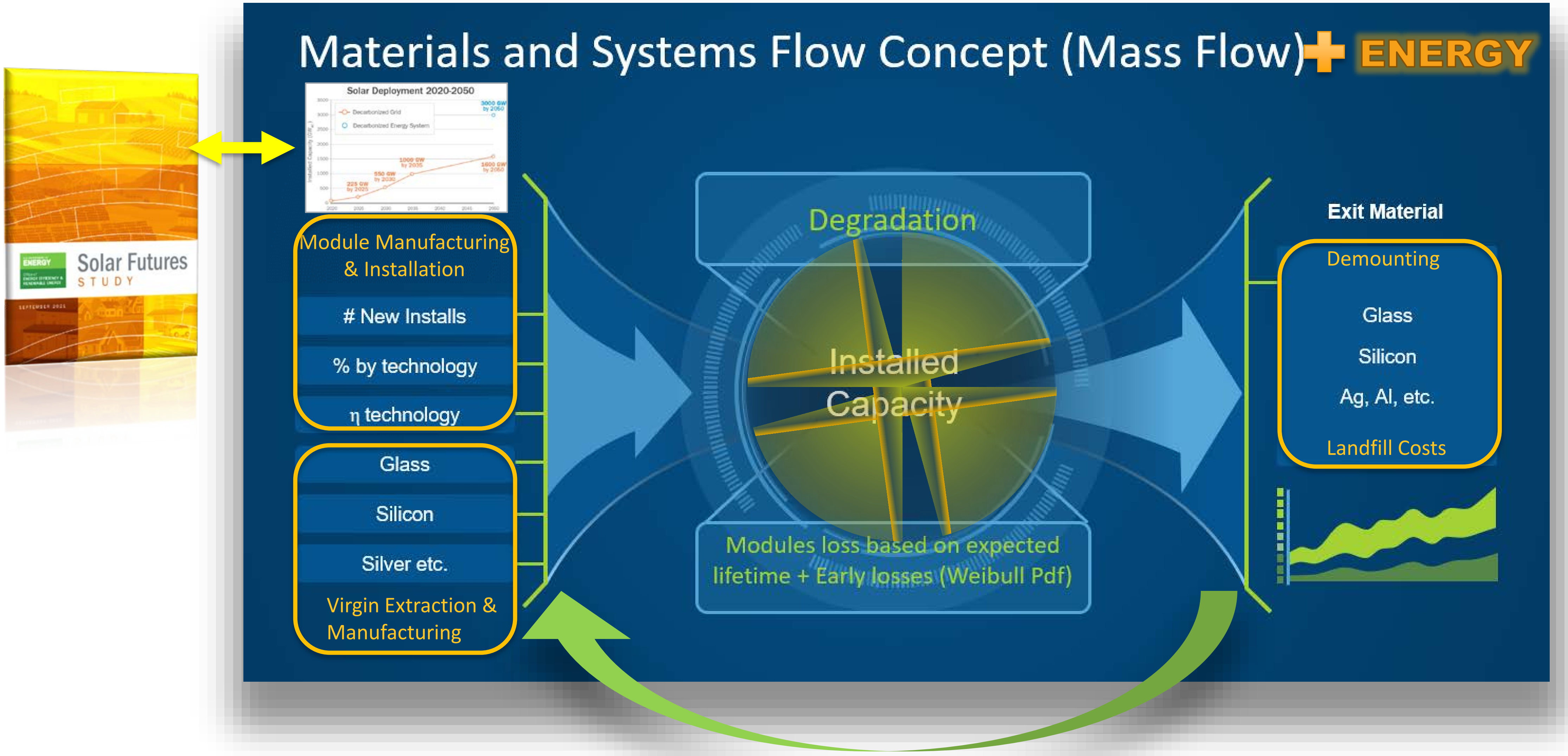
Mirletz, Ovaitt, Barnes, 2022 "Quantifying Energy flows in PV Circular Processes" PVSC Proceedings. Best Student Paper Area 8 Award
Graphic design: Macarena Mendez Ribo

From SETO CE & EoL Webinar, 2021:



PV ICE: an open-source tool evaluating circular paths for PV

nrel.gov/pv/pv-ice-tool.html

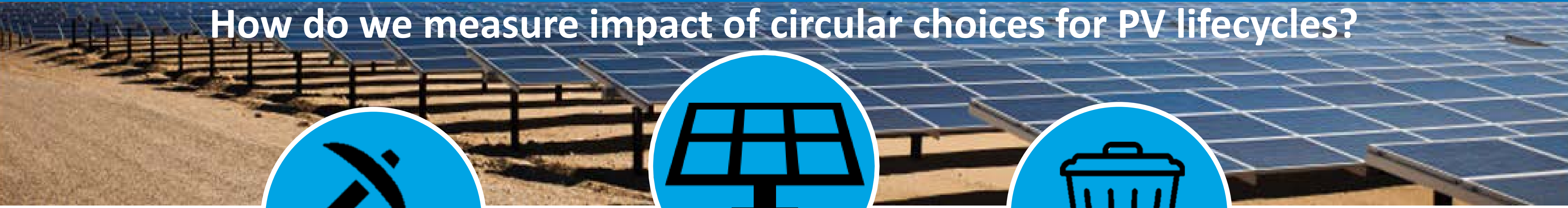


Includes pathways for circularity of materials and **Energy**

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

Installed Capacity
Maintain PV Capacity to meet Energy Transition

Waste
Reduce Wastes throughout PV lifecycle

Energy In
Minimize Energy demands of processes and materials

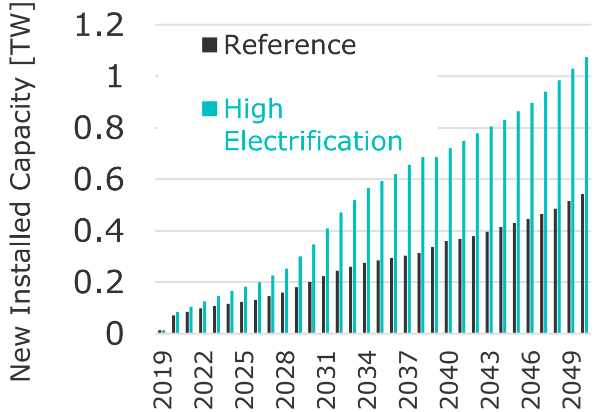
Energy Out
Maximize PV Yield for Energy Transition

Energy Balance
Maximize EROI, EPBT, Net Energy

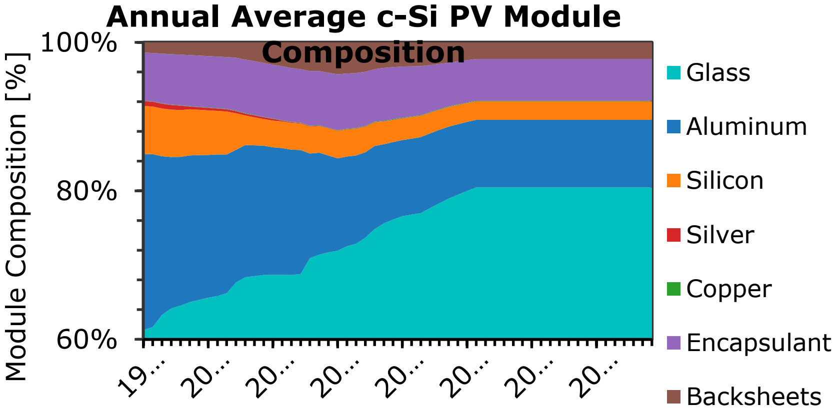
Supply Chain Security
Just and Reliable sourcing of materials

Features

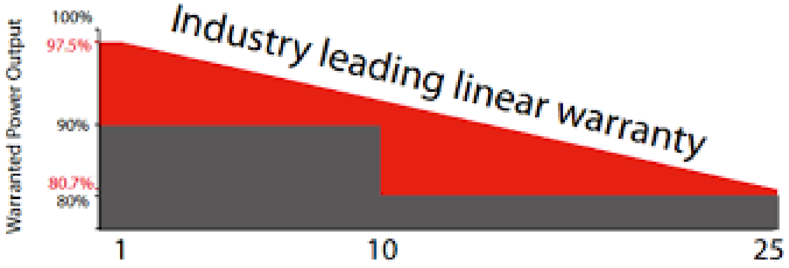
Bringing PV and Sustainability communities together, Interdisciplinary



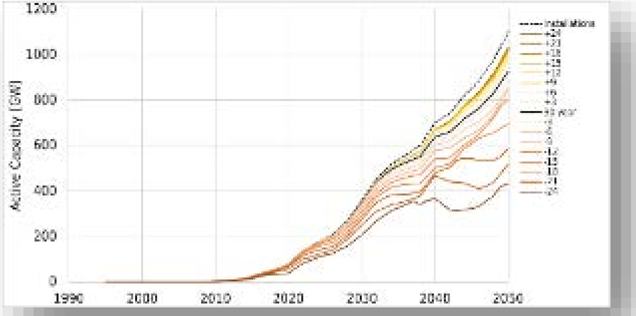
Able to use ANY deployment forecast (county, US, other countries, world, or by specific technology)



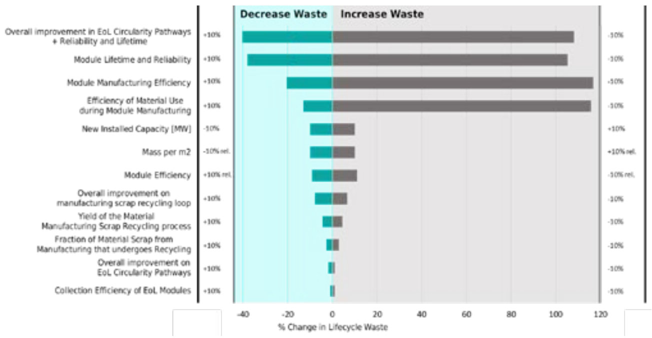
Historic and projected baselines Virgin Material Needs consider MFG Efficiencies, all as open-data!



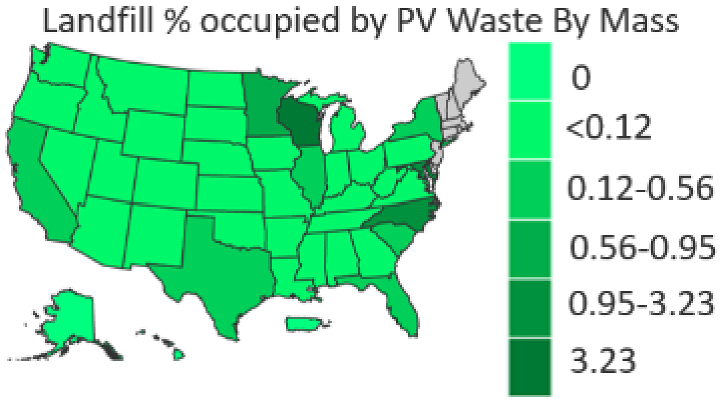
Service Life definitions (project lifetime, degradation, and improved failures and reliability approach)



Accurate Installed Capacity Calculated with degradation, and bifaciality corrections



Framework that allows easy scenarios comparison Sensitivity Analysis



Flexible Spatial and Temporal analysis

PV ICE's Integrated NREL Circular Approach

NEW INSTALLS

MANUFACTURING

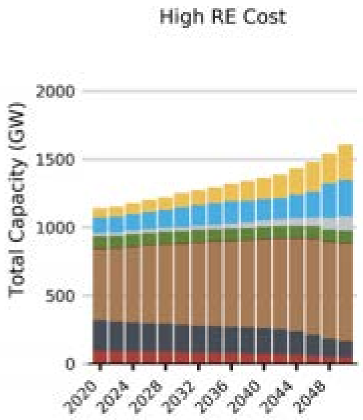
INSTALLED CAPACITY AND EXTENDED USEFUL LIFE

EOL MODES

CIRCULAR PATHWAYS

OpenEI

open source

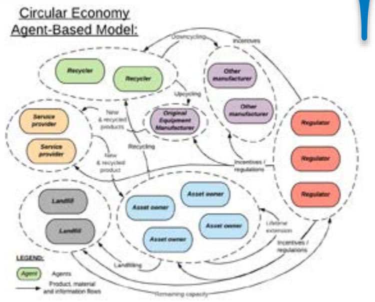


ReEDS

MFI

PV Reliability Group

DuraMAT
Durable Module Materials Consortium



Walzberg's Agent-Based Model

CELAVI Landfill calculation approach

Siting Optimization & EJ

ANL-CEEESA RELOG

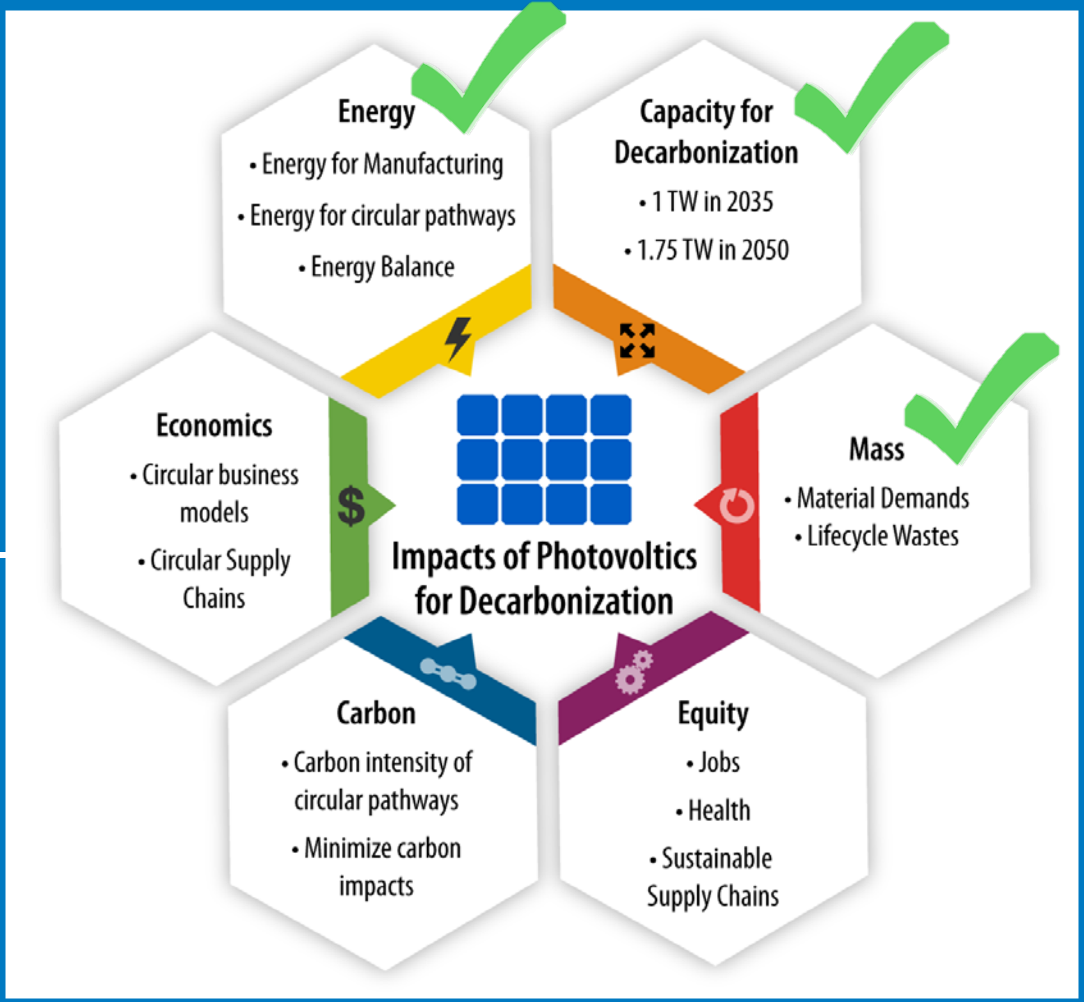
EJScreen

Upcoming Carbon Footprint

FEDERAL LCA COMMONS

Brightway

Some results



How much Virgin Material do we need for this?

Virgin Material

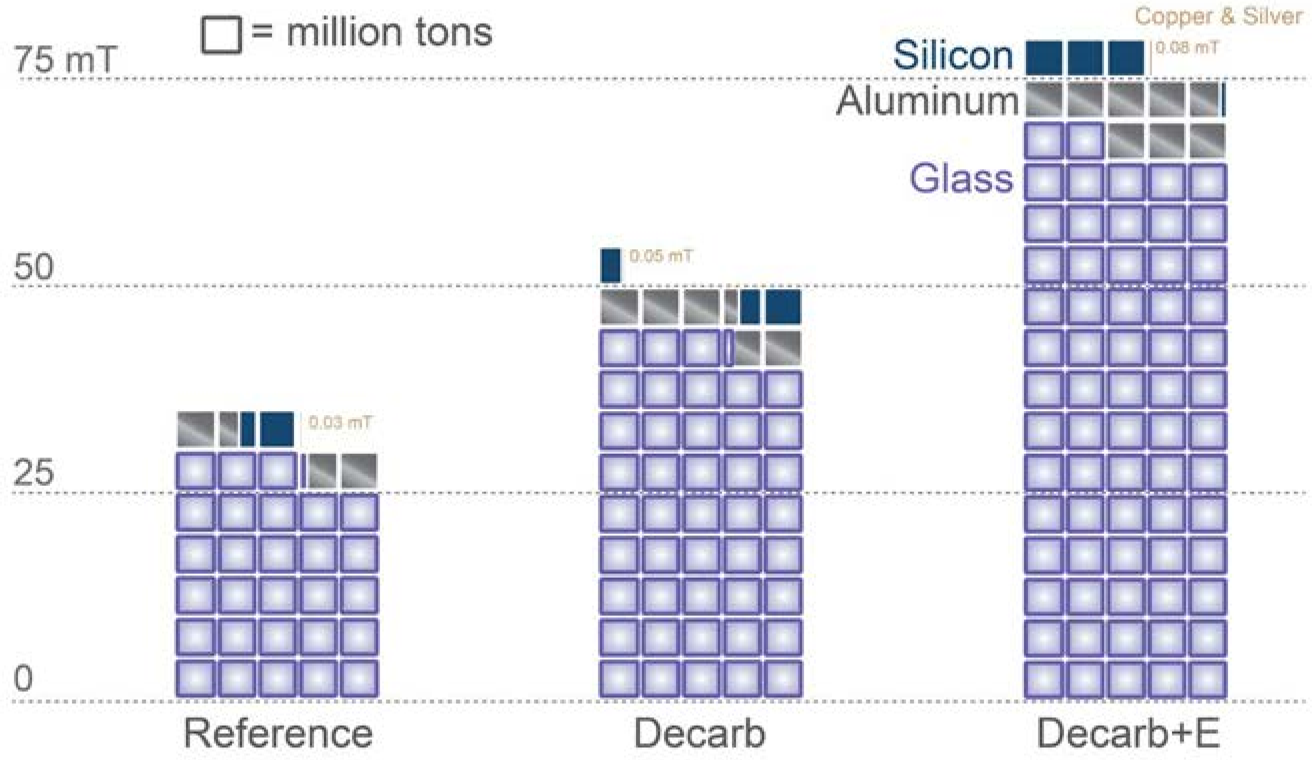


Figure 8 - 2. Comparison of virgin material demands for each silicon-based PV material cumulatively (2020–2050) across the three scenarios

In perspective: 40 MT of electronic waste yearly Worldwide NOW

US. DOE EERE "Solar Futures Study" 2021. Contributed by Ovaitt et al with PV ICE

Is there enough Virgin Material?

Virgin Material

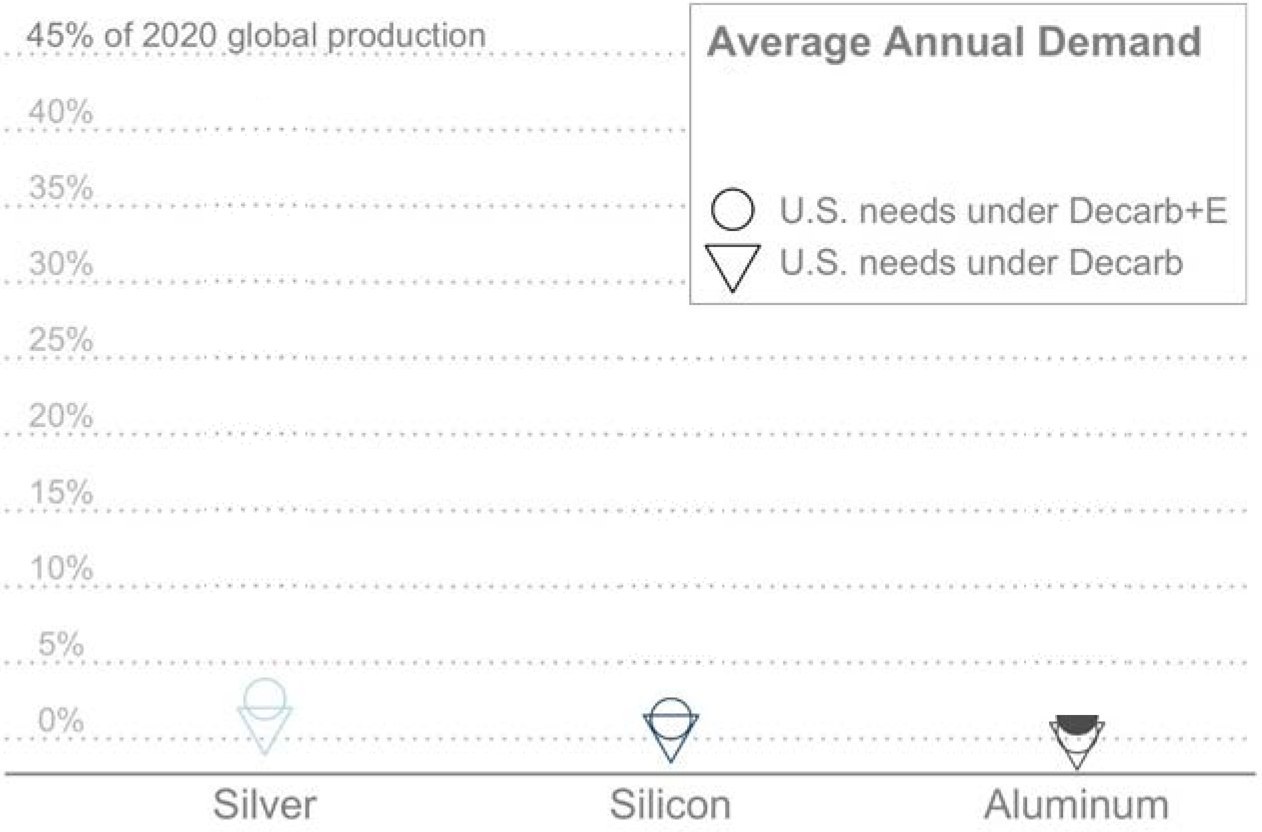


Figure 8 - 3. Percentage of 2020 global production of various materials needed to supply annual average virgin materials demand for c-Si PV

US. DOE EERE "Solar Futures Study" 2021. Contributed by Ovaitt et al with PV ICE

Is there enough Virgin Material?

Virgin Material

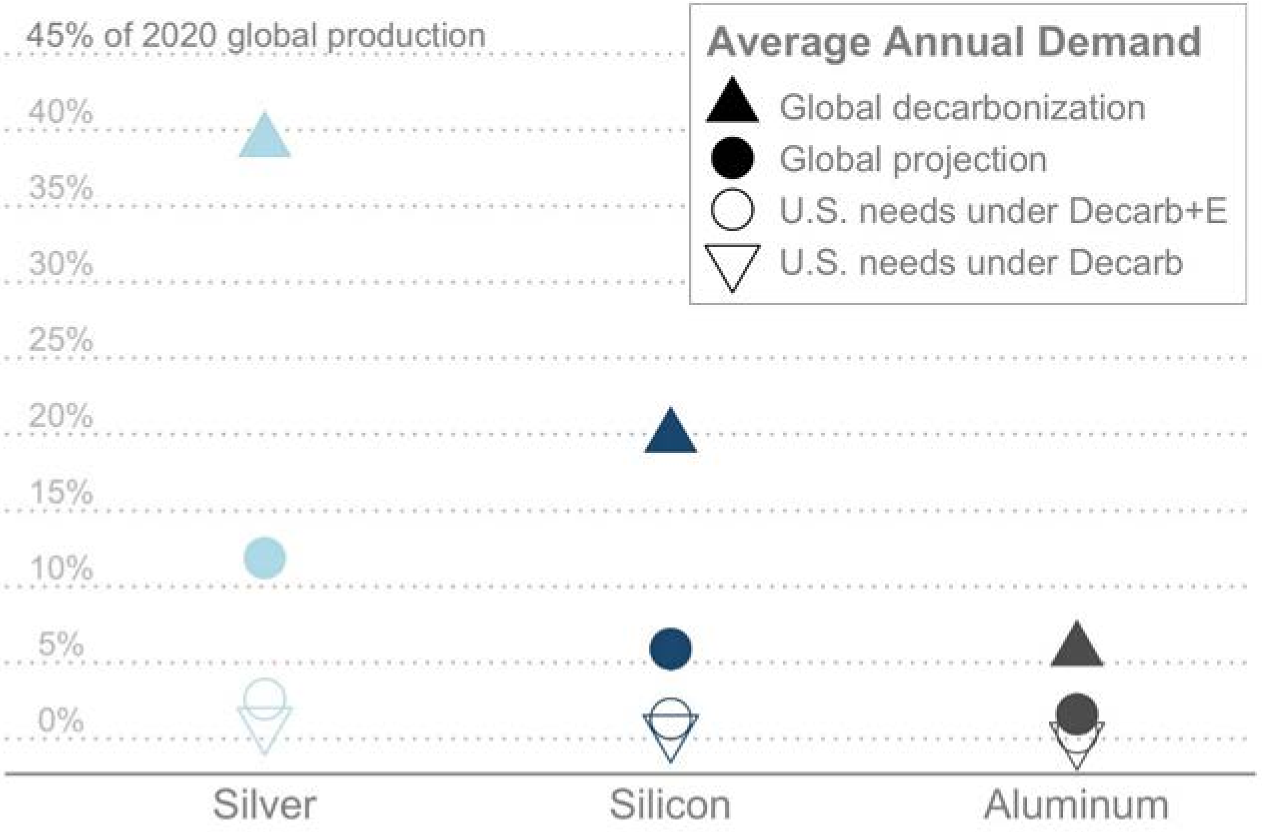


Figure 8 - 3. Percentage of 2020 global production of various materials needed to supply annual average virgin materials demand for c-Si PV

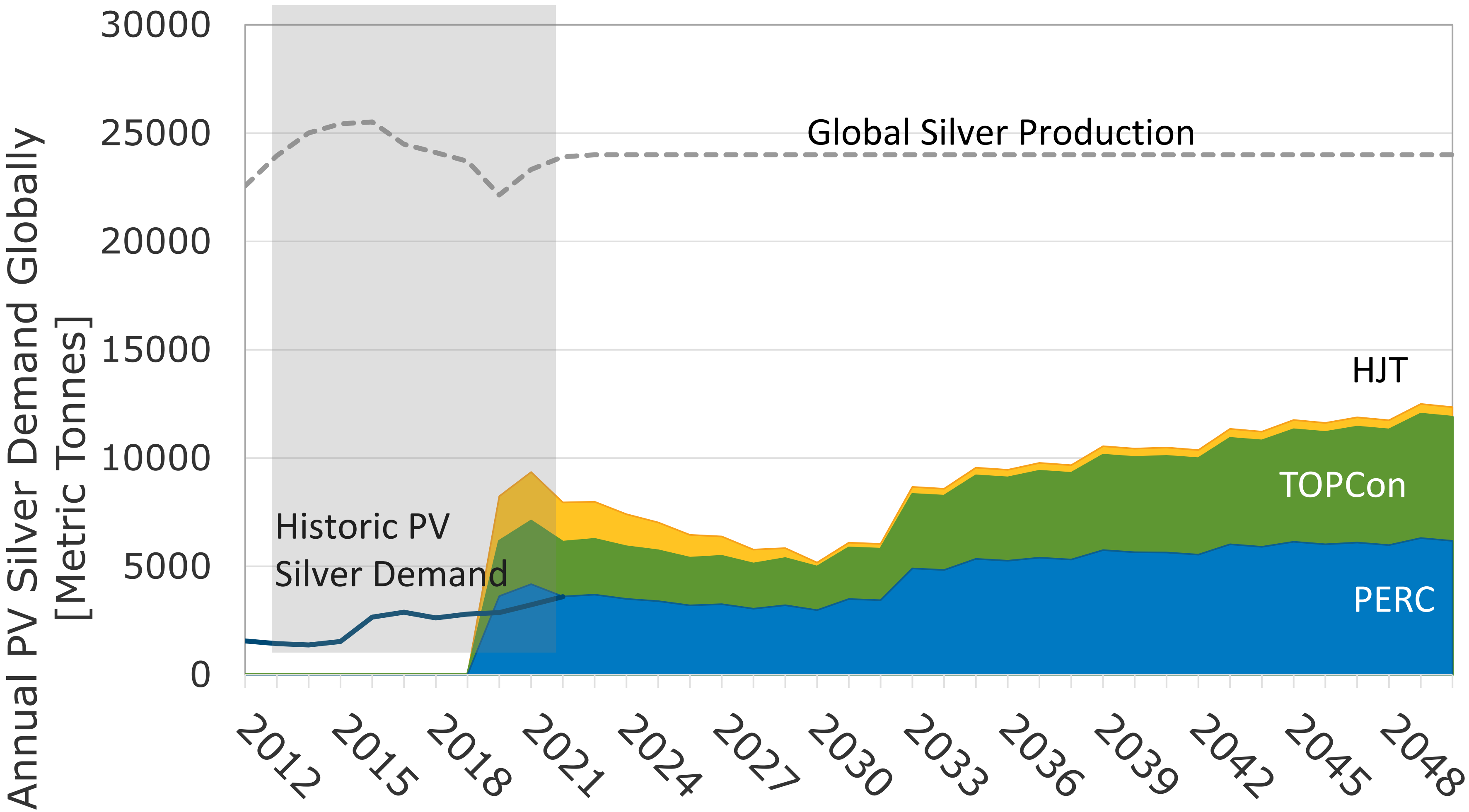
US. DOE EERE "Solar Futures Study" 2021. Contributed by Ovaitt et al with PV ICE

Is there enough Silver?

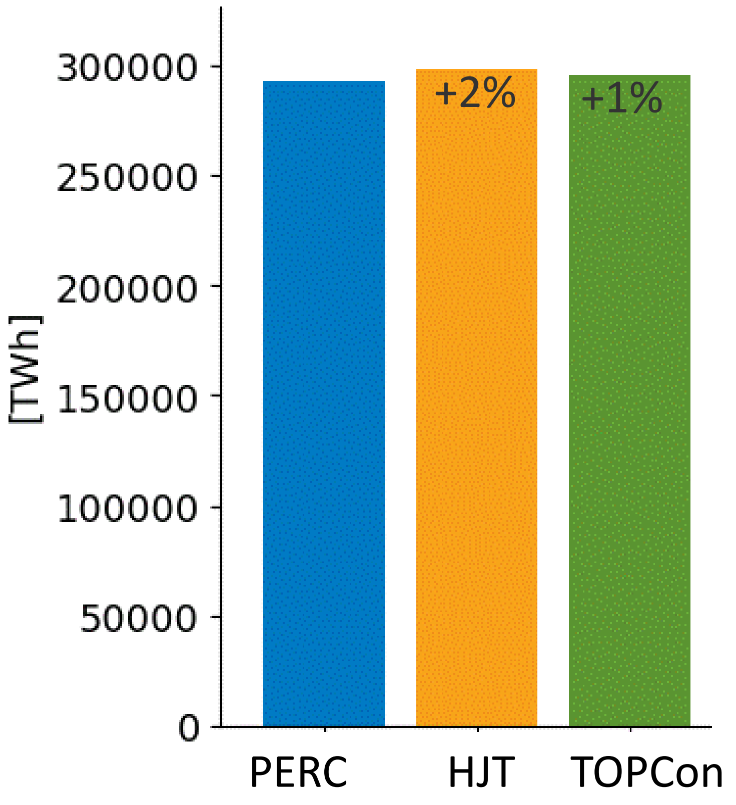
Virgin Material

Energy In

Energy Out



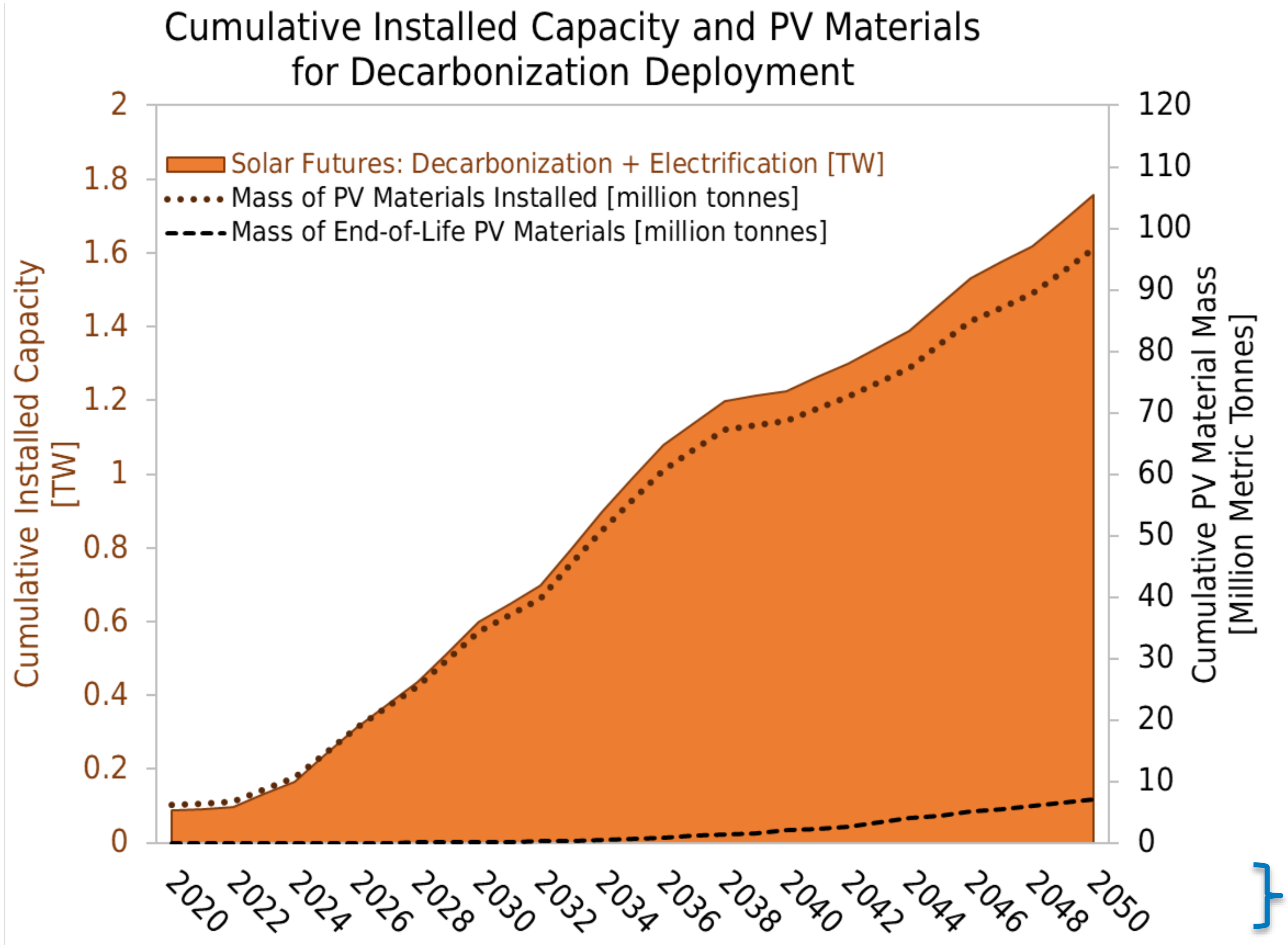
Cumulative Energy Generated

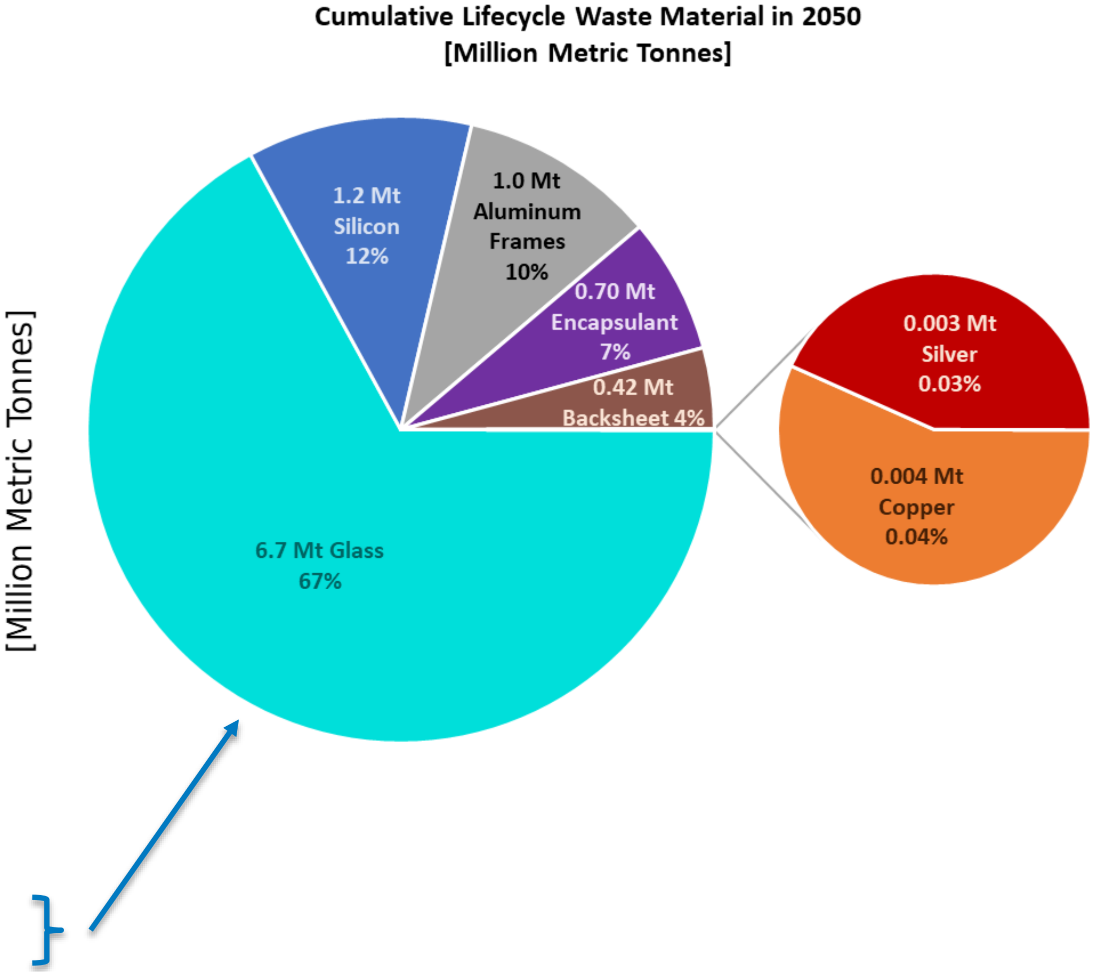


Barnes, et al. 5th International SHJ Workshop, CEA-INES 2022

Waste

Waste



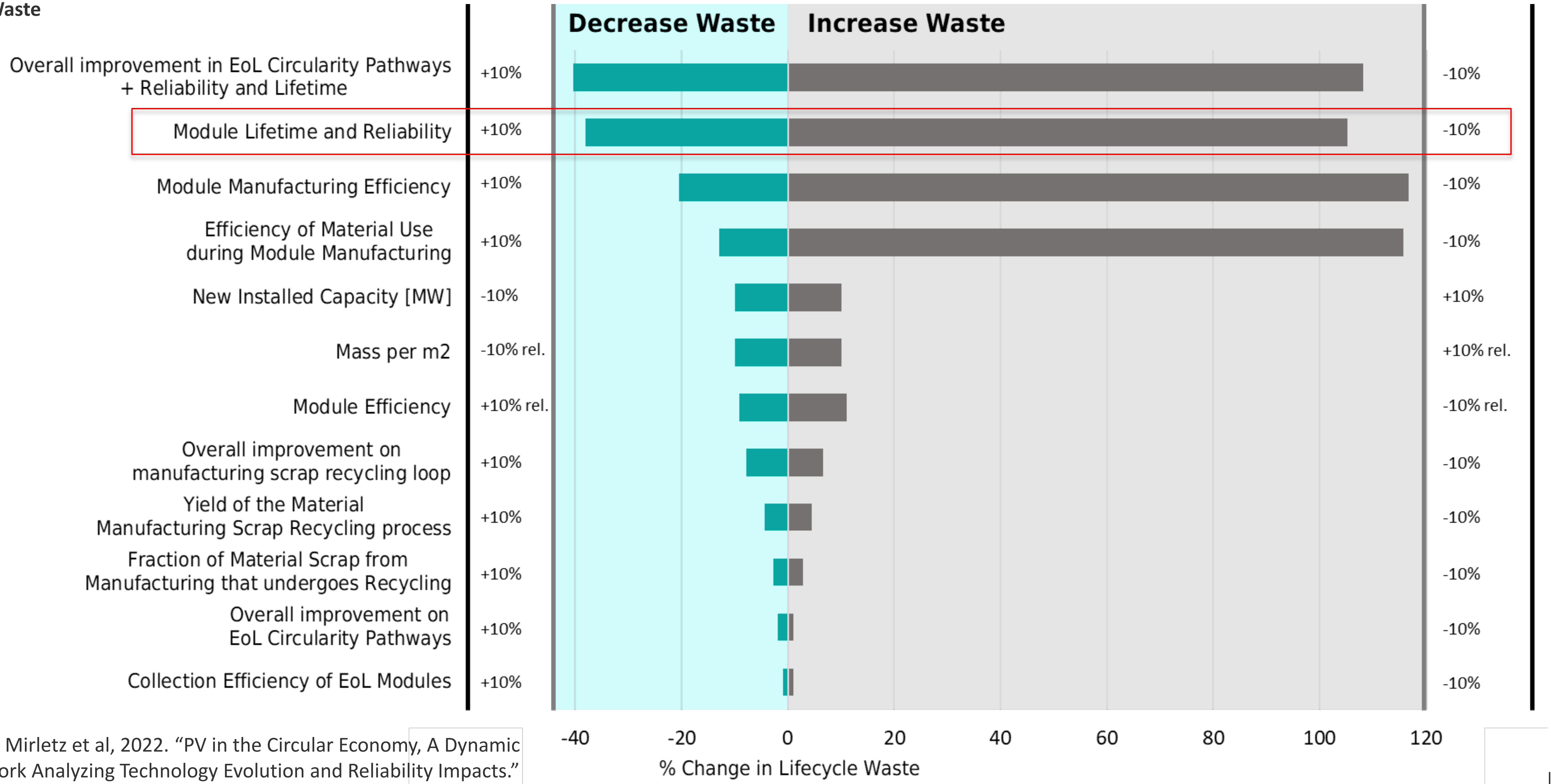


Mirletz, Silvana Ovaitt, et al 2022. "Circular Economy Priorities for Photovoltaics in the Energy Transition." PLOS ONE https://doi.org/10.1371/journal.pone.0274351

Ovaitt & Mirletz et al, 2022. "PV in the Circular Economy, A Dynamic Framework Analyzing Technology Evolution and Reliability Impacts." *ISCIENCE* https://doi.org/10.1016/j.isci.2021.103488.

How can we reduce Waste?

Waste



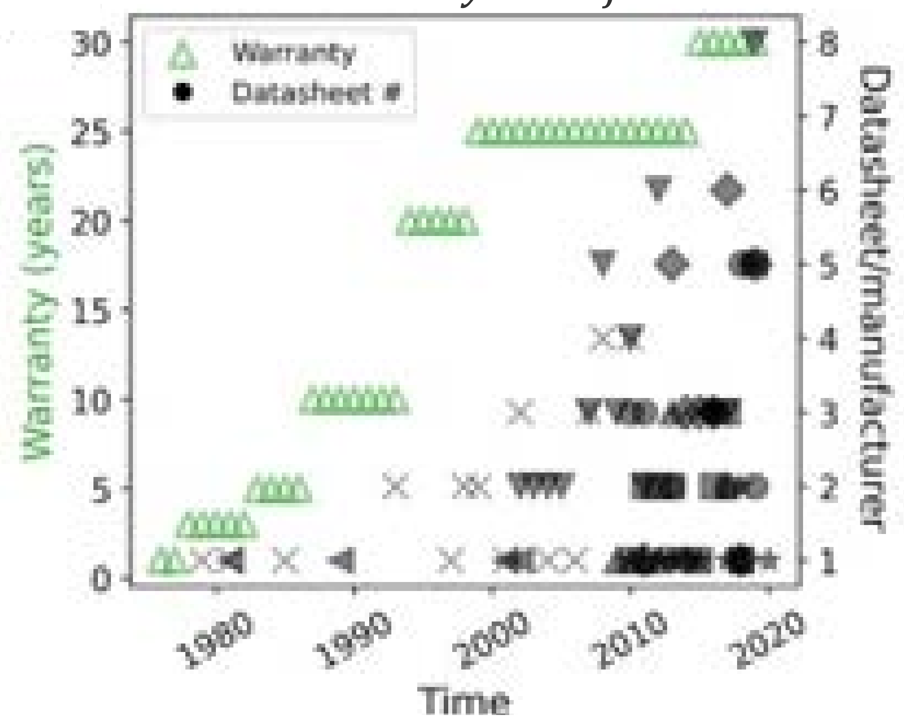
Ovaitt & Mirletz et al, 2022. "PV in the Circular Economy, A Dynamic Framework Analyzing Technology Evolution and Reliability Impacts." *ISCIENCE* https://doi.org/10.1016/j.isci.2021.103488.

Module Lifetime & Reliability

32 Years
-0.5% Degradation Rate

Waste

$Warranty \neq Lifetime$



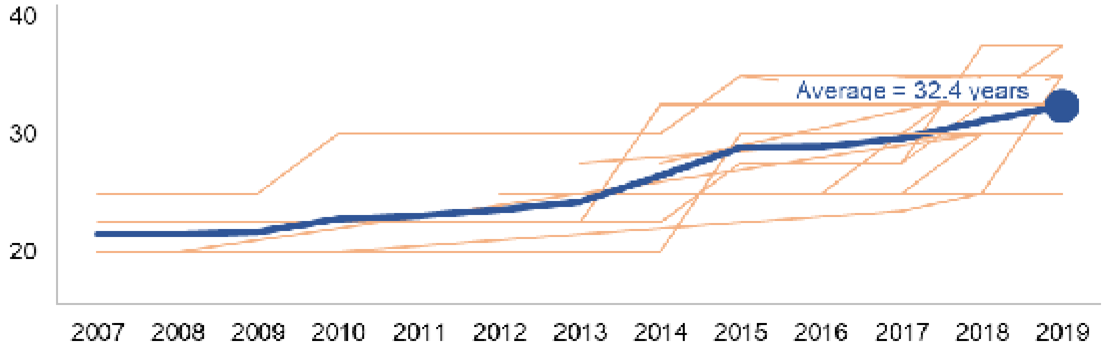
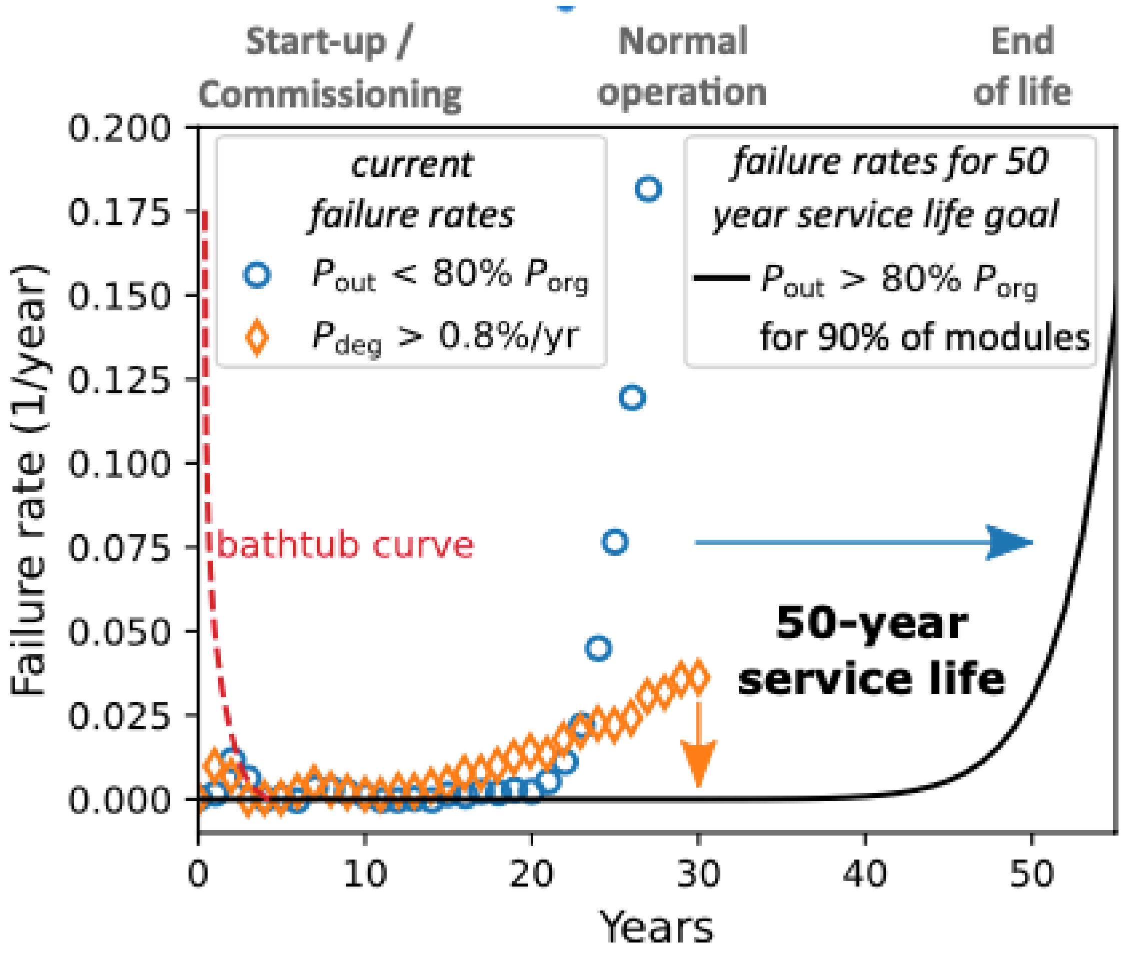


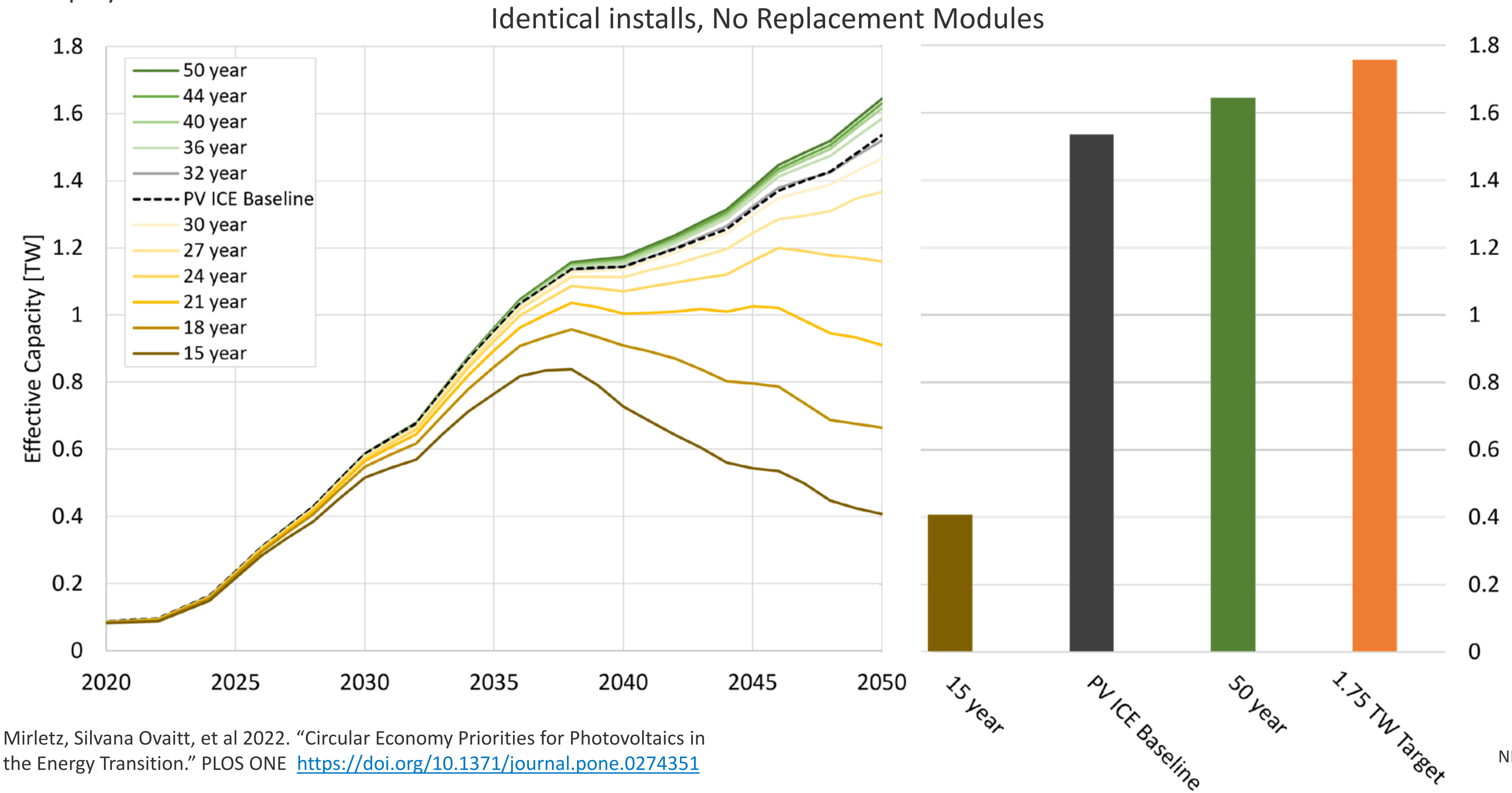
Figure 2. Project Life Expectations for Utility-Scale PV, over Time



[1]Figures from D. Jordan, Photovoltaic Module Reliability for the TW Age, Progress in Energy 2022, 10.1088/2516-1083/ac6111 [2] Wiser, LBL, 2020
[3] M. Springer, Future-proofing photovoltaics module reliability through a unifying predictive modeling framework. PinPV 2022, 10.1002/pip.3645

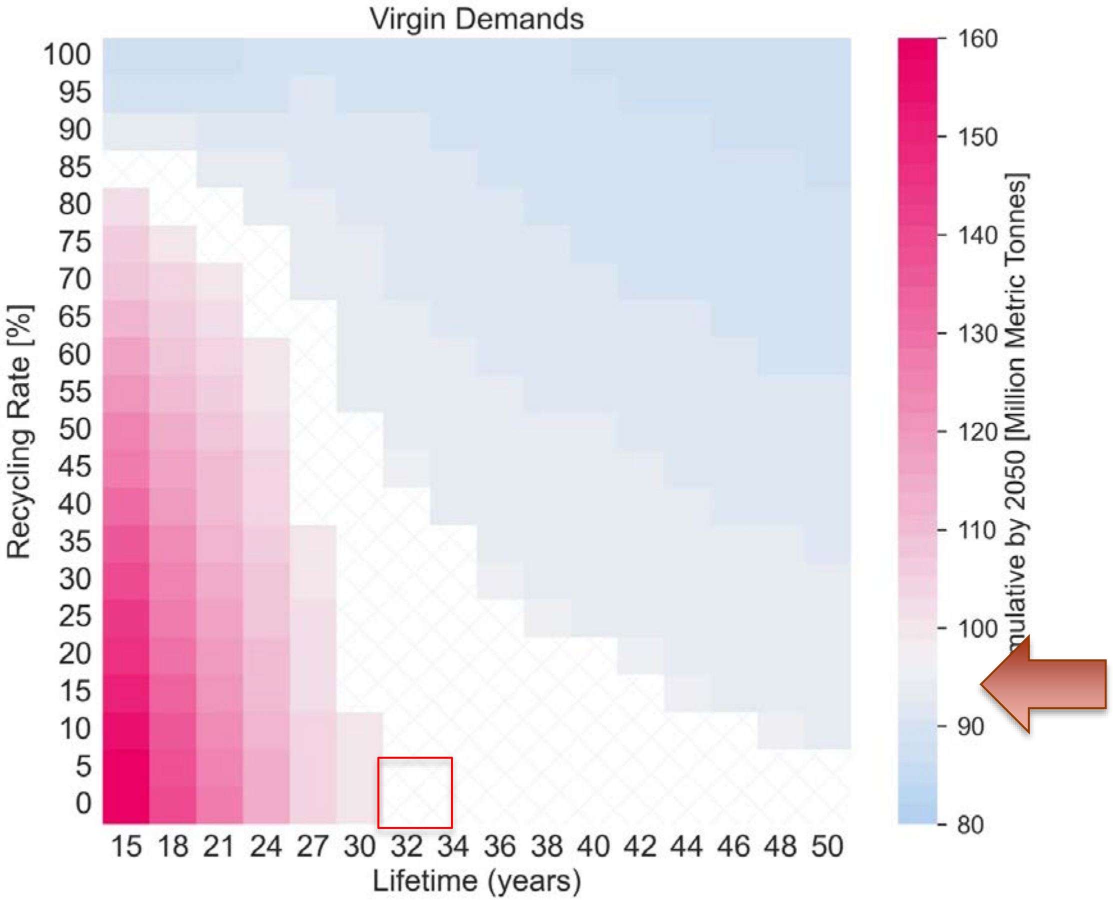
The concept of Installs vs Effective Capacity

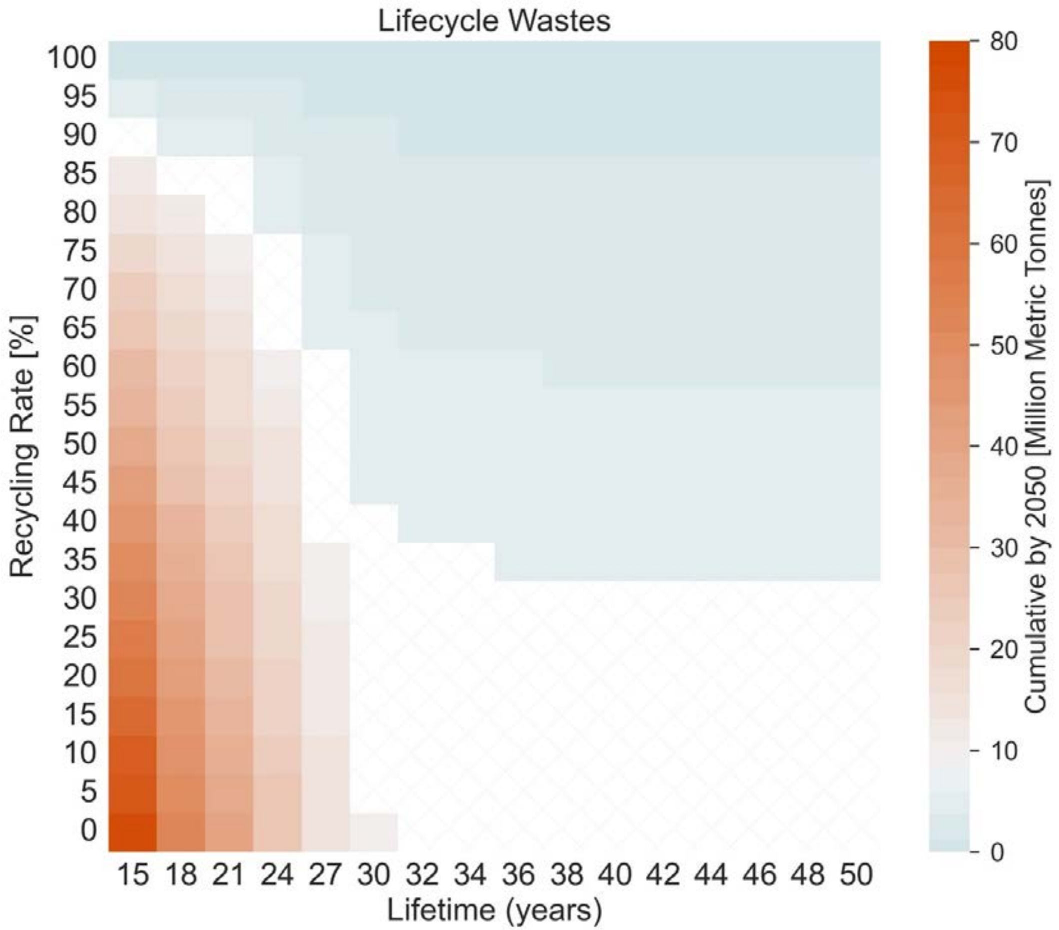
Installed Capacity



Mirletz, Silvana Ovaitt, et al 2022. "Circular Economy Priorities for Photovoltaics in the Energy Transition." PLOS ONE https://doi.org/10.1371/journal.pone.0274351

What about Recycling?



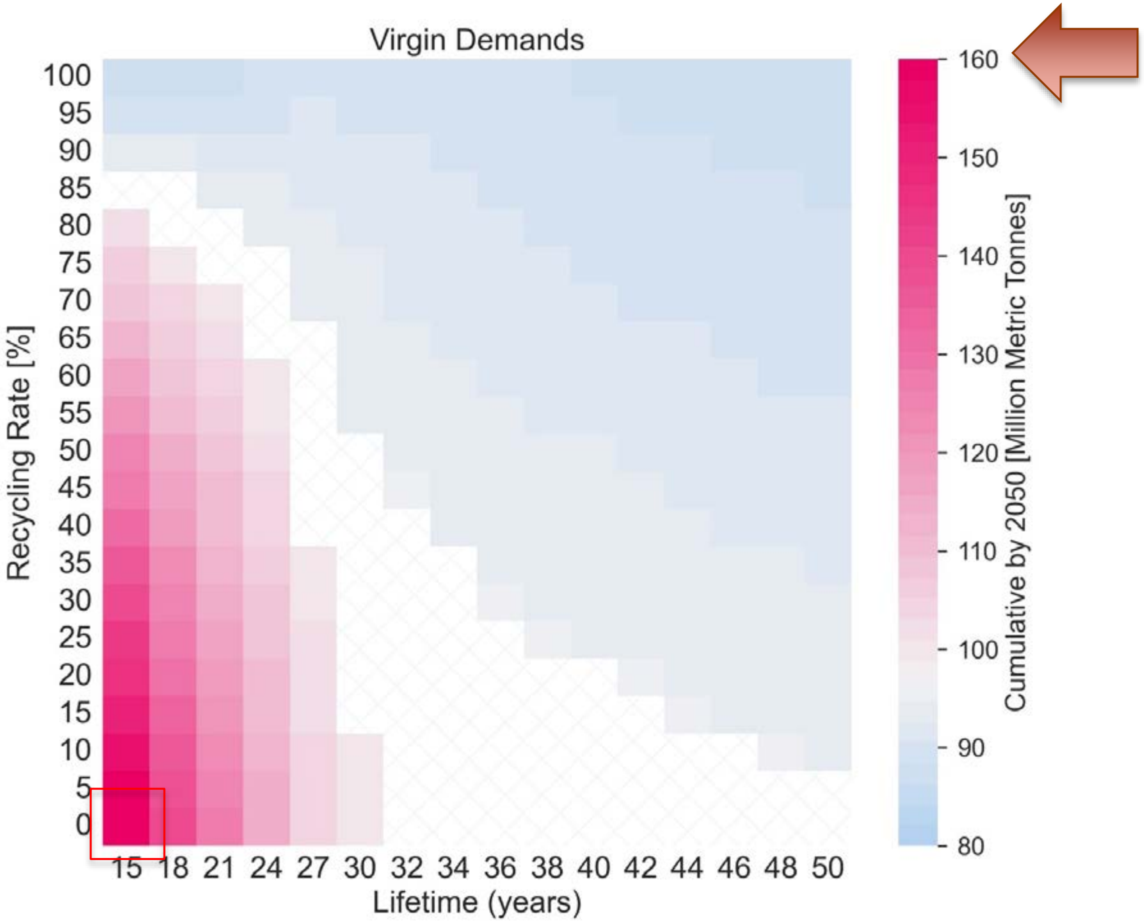


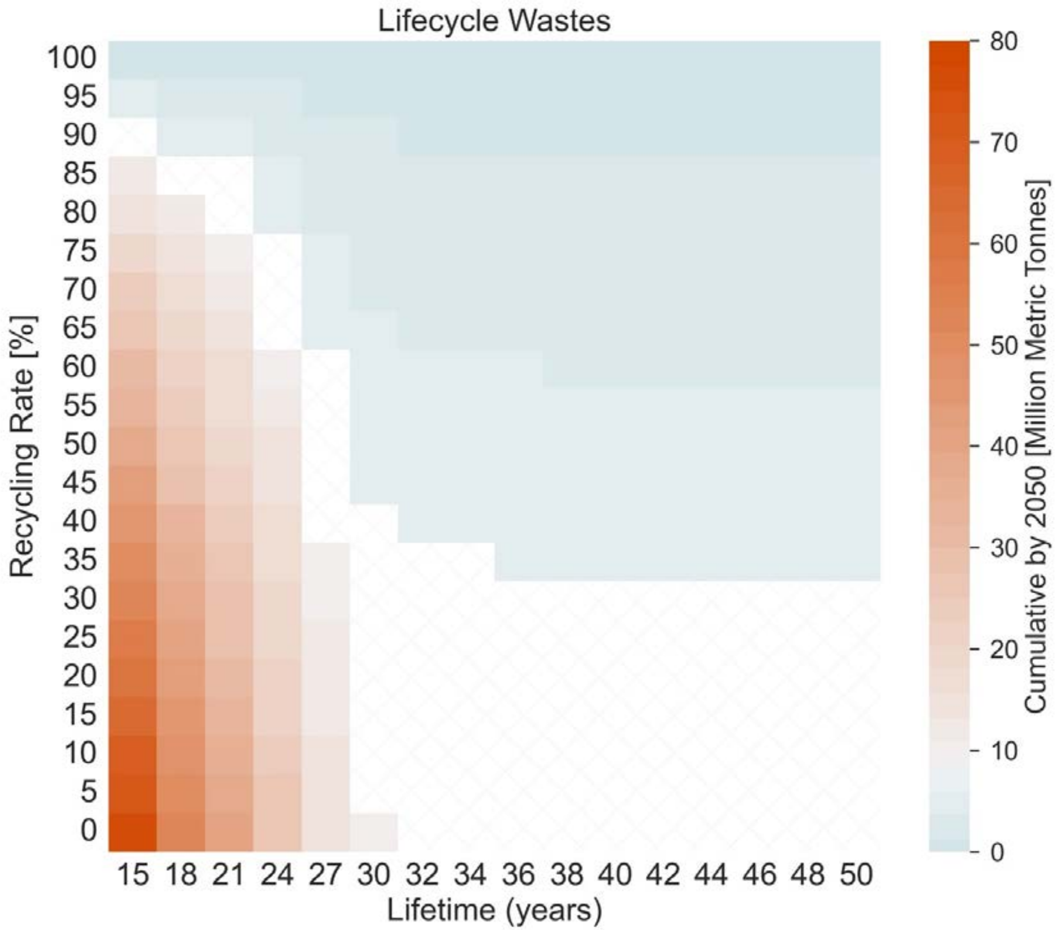
Mirletz, Silvana Ovaitt, et al 2022. "Circular Economy Priorities for Photovoltaics in the Energy Transition." PLOS ONE https://doi.org/10.1371/journal.pone.0274351

But Silvana, what about Recycling?

Virgin Material

Waste





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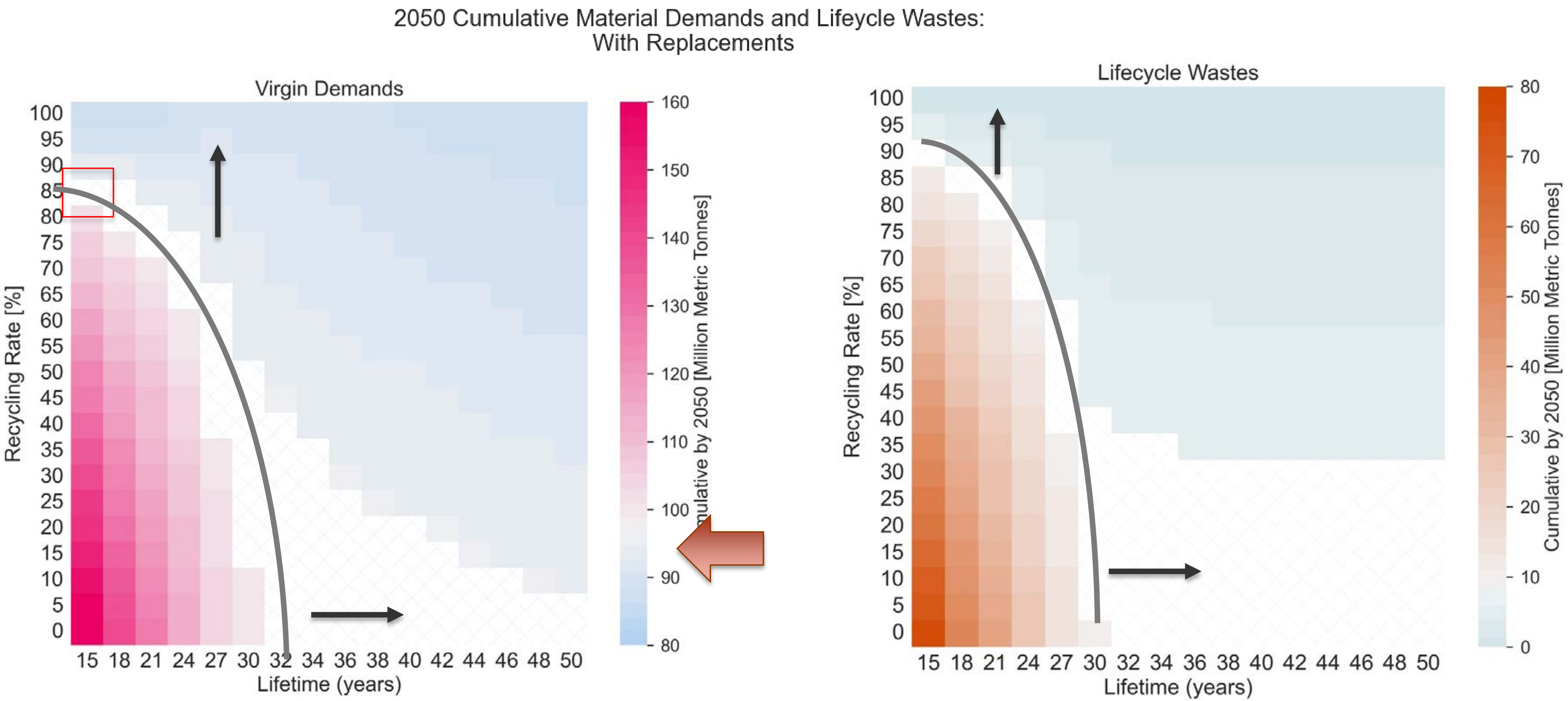


Mirletz, Silvana Ovaitt, et al 2022. "Circular Economy Priorities for Photovoltaics in the Energy Transition." PLOS ONE https://doi.org/10.1371/journal.pone.0274351

Energy Demand for different Pathways

Energy In

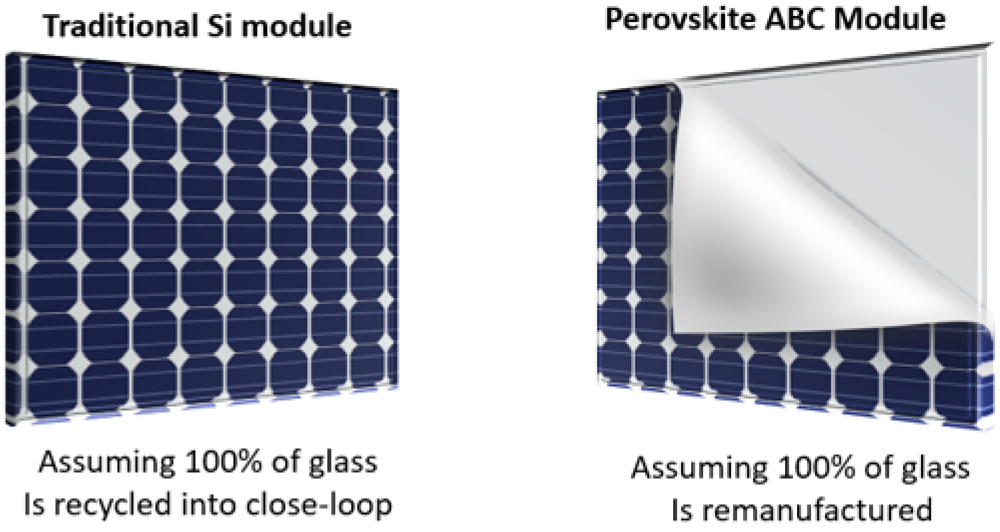
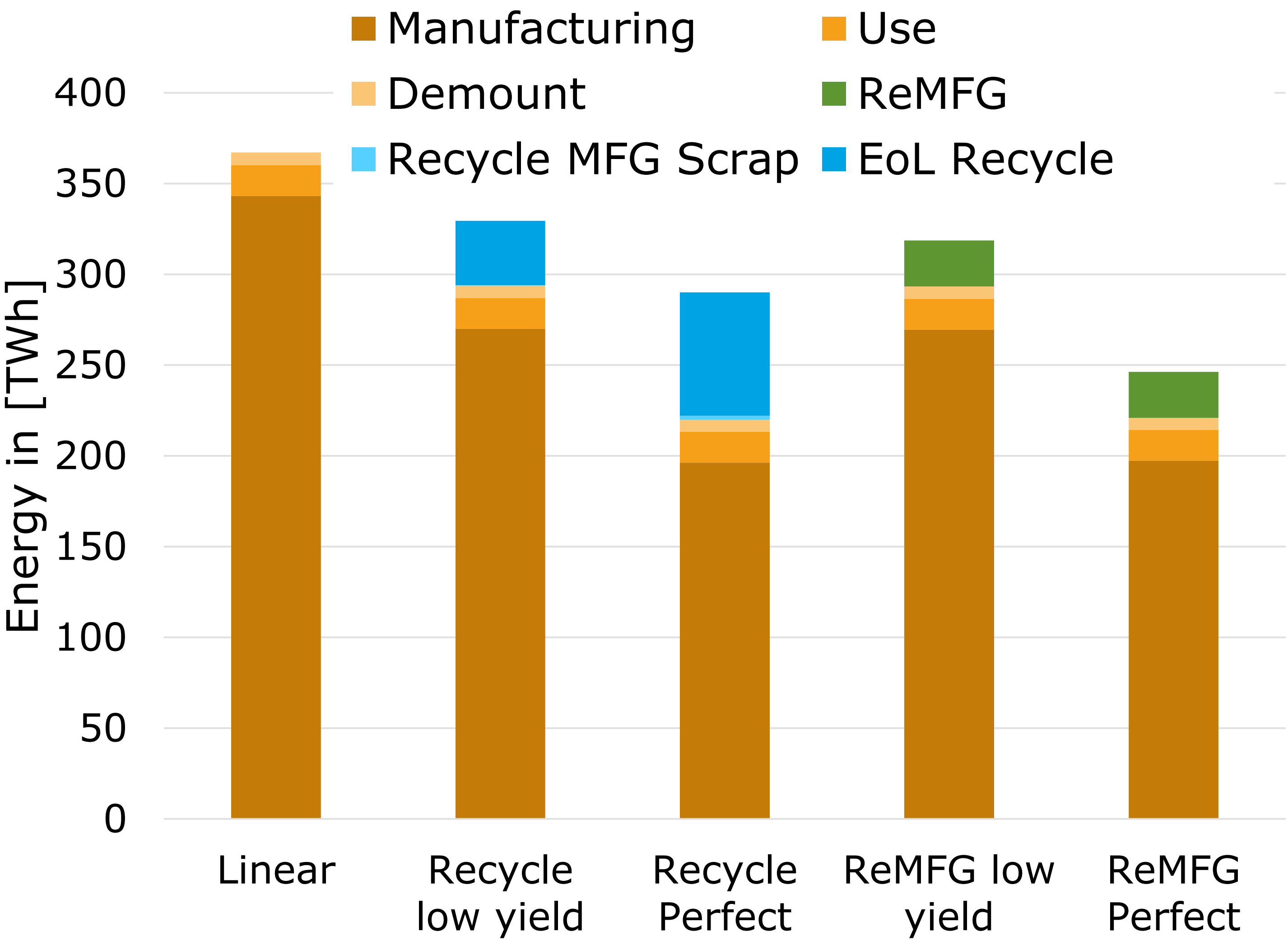
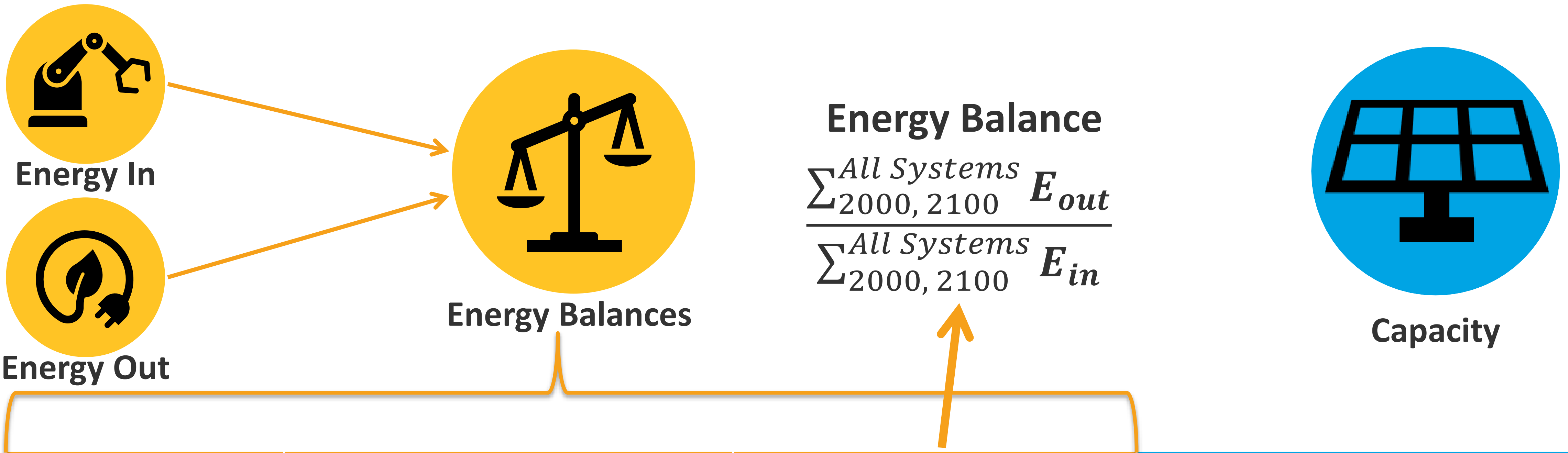


Fig. 2 Diagram of the two evaluated scenarios: 100% recycled modules, vs 100% remanufactured modules. Glass remanufacture is potentially enabled by technology designs such as the perovskite all-back-contact architectures. Scenarios are evaluated on material and energy flows of glass.



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

Energy Metrics Overview



Net Energy	EPBT	EROI	Effective Capacity
$E_{out} - E_{in}$	Energy Pay Back Time	Energy Return on Investment	Effective Capacity
	Year in which Net Energy goes positive	$\frac{E_{out}}{E_{in}}$	$\text{Installs} + \text{replacements} - \text{degradation} - \text{failures} - \text{EoL}$
Maximize ↑	Minimize ↓	Maximize ↑	Maximize ↑

Raugei, M. *Methodological Guidelines on Net Energy Analysis of Photovoltaic Electricity, 2nd Edition 2021*.
Murphy et al. *Energy Return on Investment of Major Energy Carriers: Review and Harmonization*, 2022.

Measuring Sustainability of PV in Energy Transition: Mass, Energy, Circularity, and Carbon

		PV ICE Baseline	50-year PERC Perfect Longevity	SHJ Perfect Efficiency	TOPCon High Efficiency	Idealized Perovskite Si-Tandem 4T Perfect Circularity	Recycled PERC High Circularity	Low Quality PERC
Mass	Virgin Material Demand	0	+	-	-	++	-	--
Mass	Lifecycle Material Losses	0	+	-	-	++	--	--
	Replacements	0	+	-	-	--	-	-
Energy	Net Energy	0	++	++	++	-	+	-
Energy	Energy Balance	0	+	-	-	--	--	--

Benefit ← → Detriment

Mirletz et al. PVSC 2023 (To be presented)

Siting Optimization of PV Recycling and Manufacturing Plants for Supply Chain Security & Critical Material Recovery (aka RICE)

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

RELOG

OPEN-SOURCE SOFTWARE PACKAGE FOR REVERSE LOGISTICS OPTIMIZATION

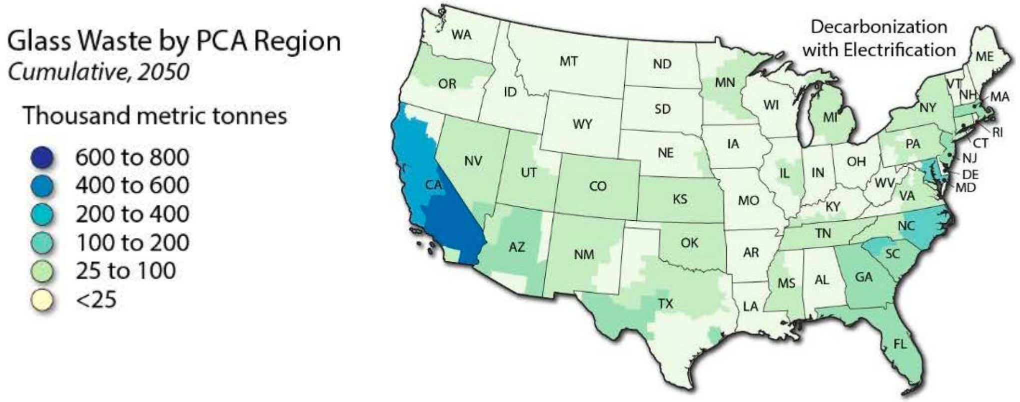
PV ICE

Open-Source Software Package for Evaluating Circular Paths for PV

A Systematic Analysis of the Costs and Environmental Impacts of Critical Materials Recovery from Hybrid Electric Vehicle Batteries in the U.S (2022) (https://doi.org/10.1016/j.isci.2022.104830)

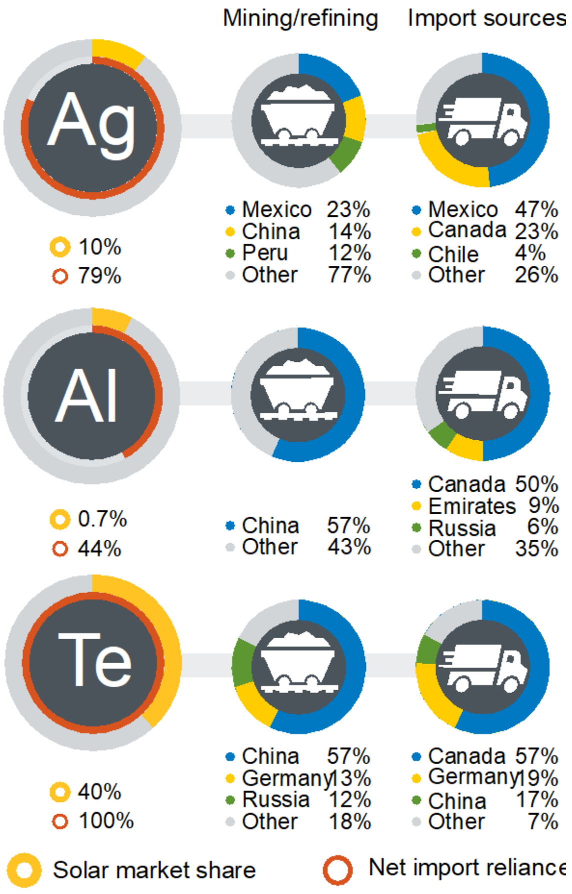
Analysis & visualization

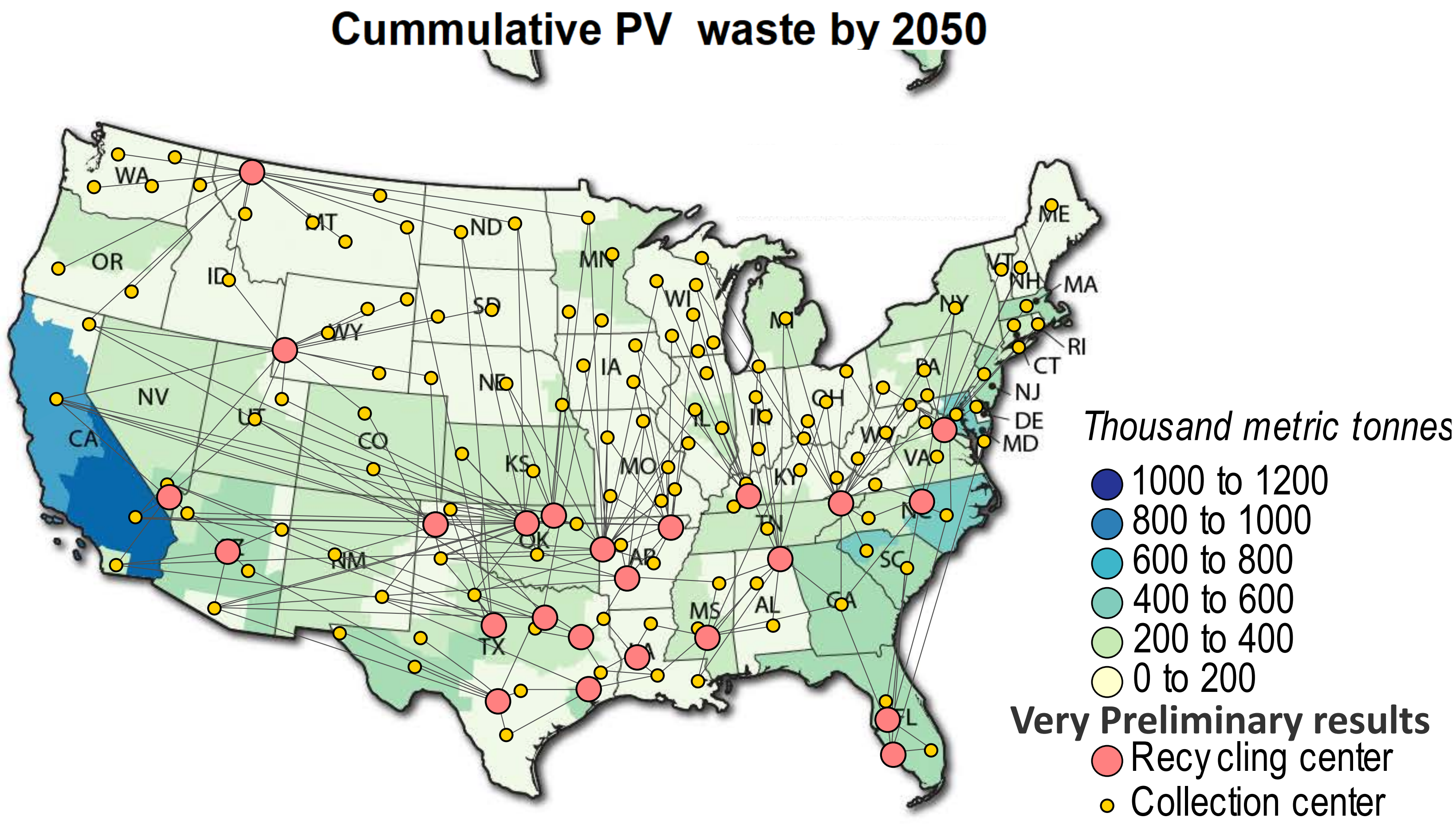
ANL-CEEESA RELOG



NREL Transforming ENERGY

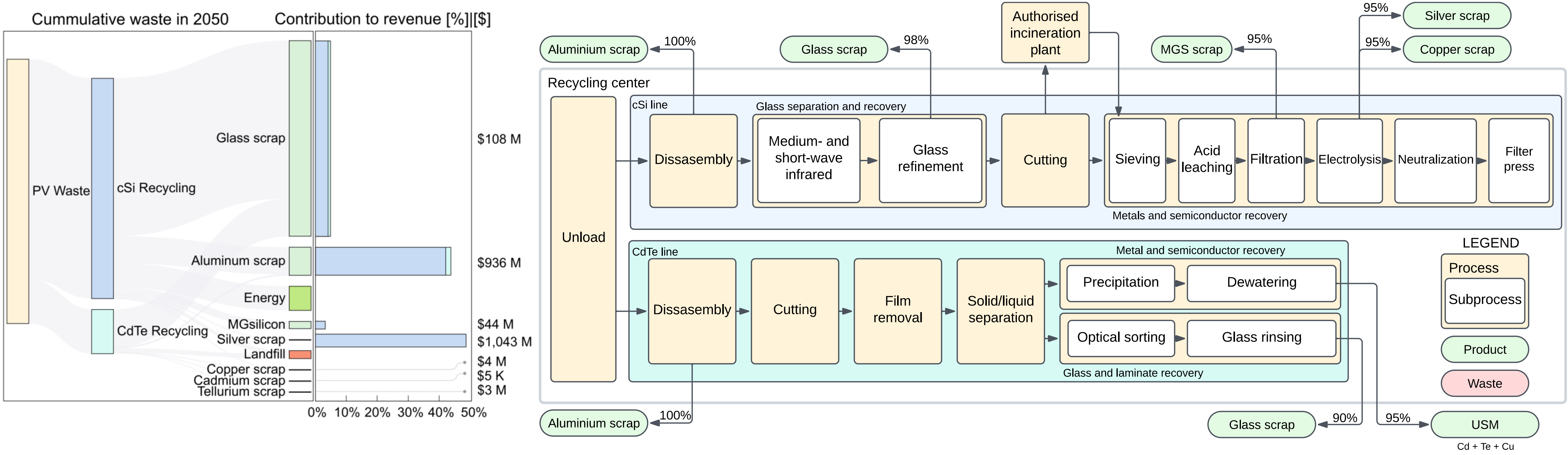
RICE Project Status





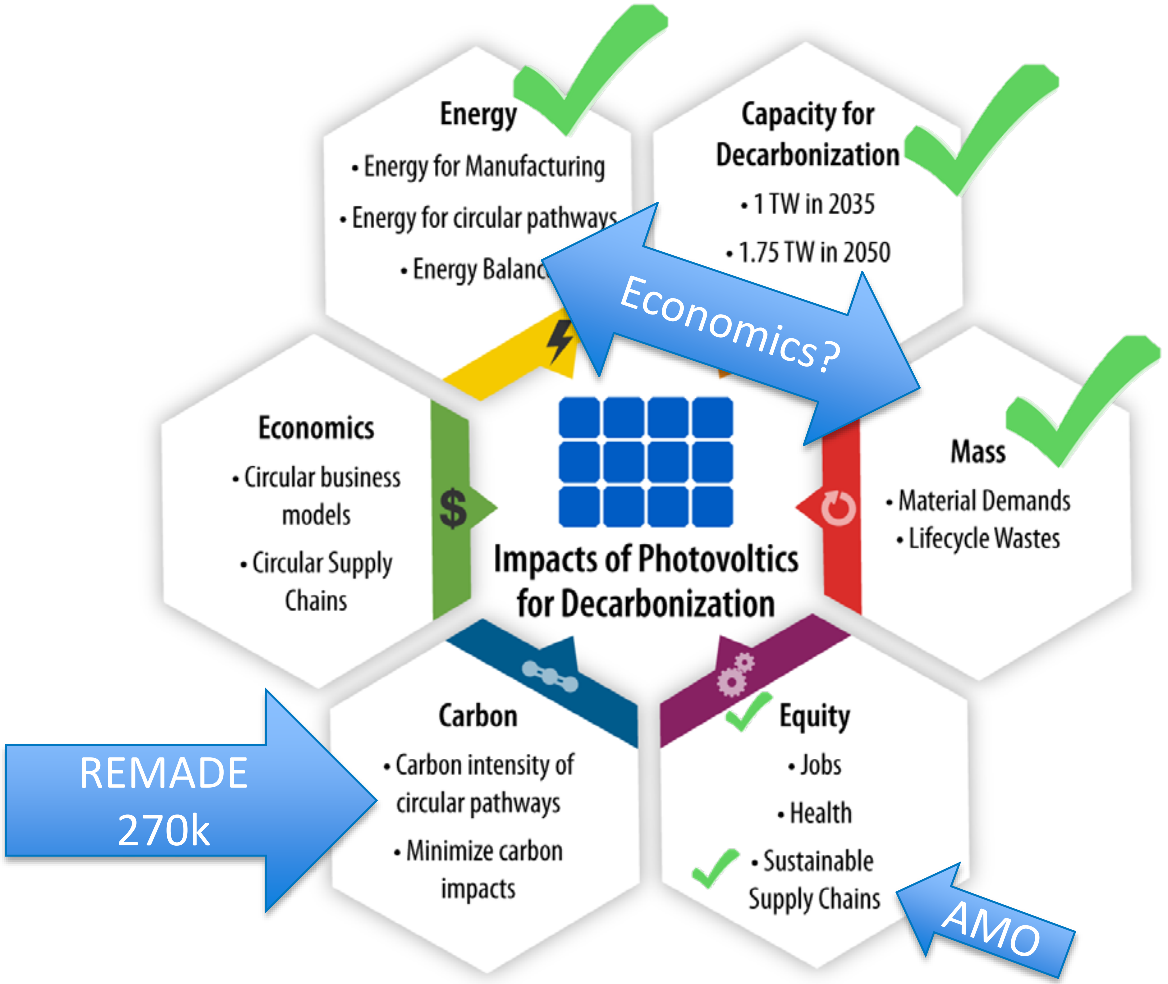
Macarena Mendez-Ribo, et al. PVSC 2023 (To be presented)

RICE Project Status



Macarena Mendez-Ribo, et al. PVSC 2023 (To be presented)

Shooting for the sun

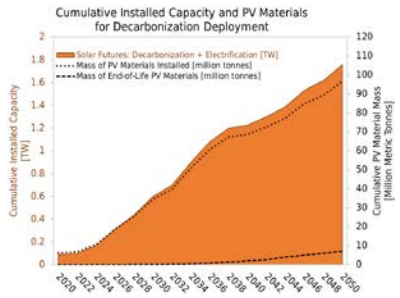


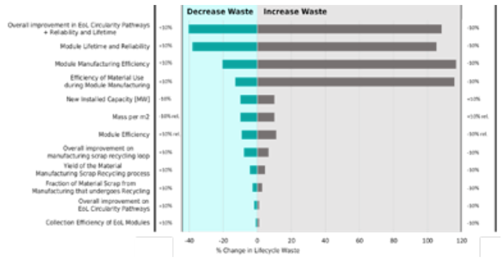
FEDERAL LCA COMMONS

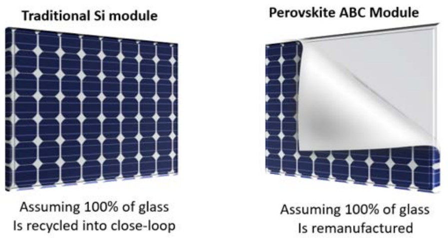
Brightway

- 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?

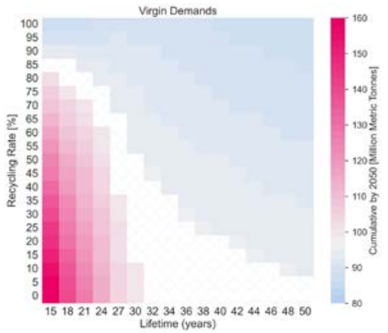
Conclusions

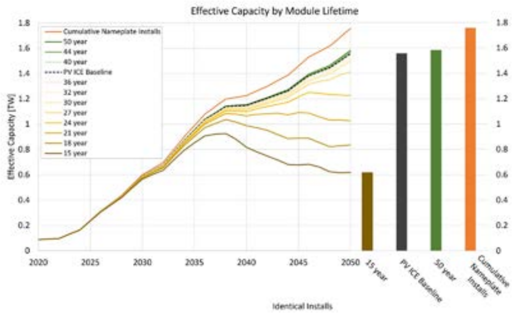






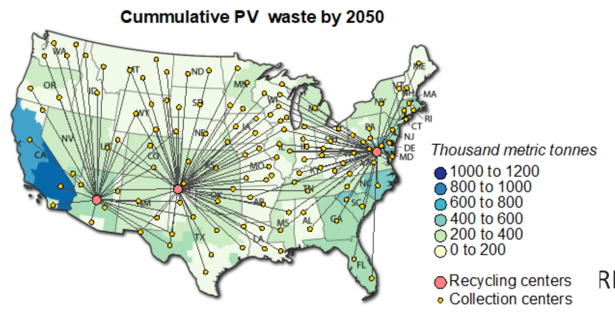
1. We have a tool that is flexible to all new deployment scenarios, that considers technology evolution and PV-specific circular paths.
2. We have used PV ICE to calculate virgin material demands, waste production with yearly geospatial resolution, and conduct a sensitivity analysis to the decision points 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





		PV ICE Baseline	50-year PERC Perfect Longevity	SHJ Perfect Efficiency	TOPCon High Efficiency	Idealized Perovskite Si-Tandem 4T Perfect Circularity	Recycled PERC High Circularity	Cheap Crap Cheap
Mass	Virgin Material Demand	0	+	-	-	++	-	--
Mass	Lifecycle Material Losses	0	+	-	-	++	--	--
	Replacements	0	+	-	-	--	-	-
Energy	Net Energy	0	++	++	++	-	+	-
Energy	Energy Balance	0	+	-	-	--	--	--

Benefit — Detriment



Team

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PhD candidate est. Fall 2023

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Postdoctoral Researcher

RICE Siting Optimization

DTU PhD

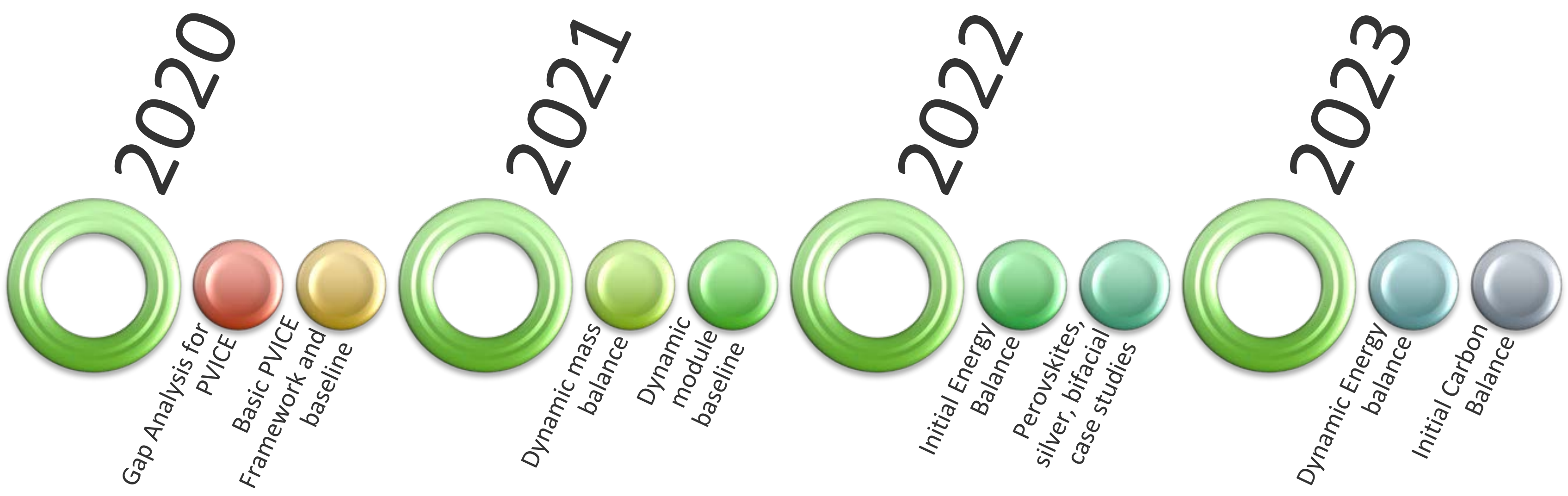
Teresa Barnes

Duramat Lead

CEEM leader at NREL

Field Performance & Reliability Group at NREL

Timeline and Funding



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

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nrel.gov/pv/pv-ice-tool.html

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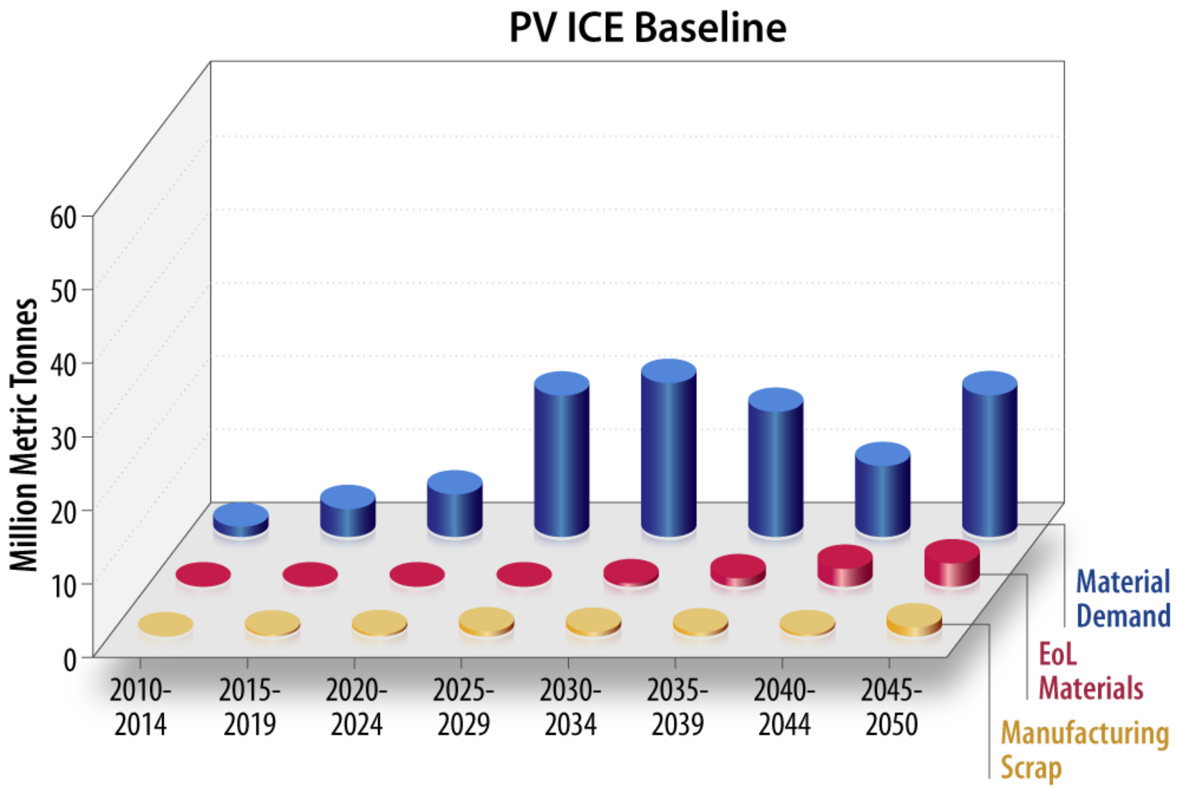
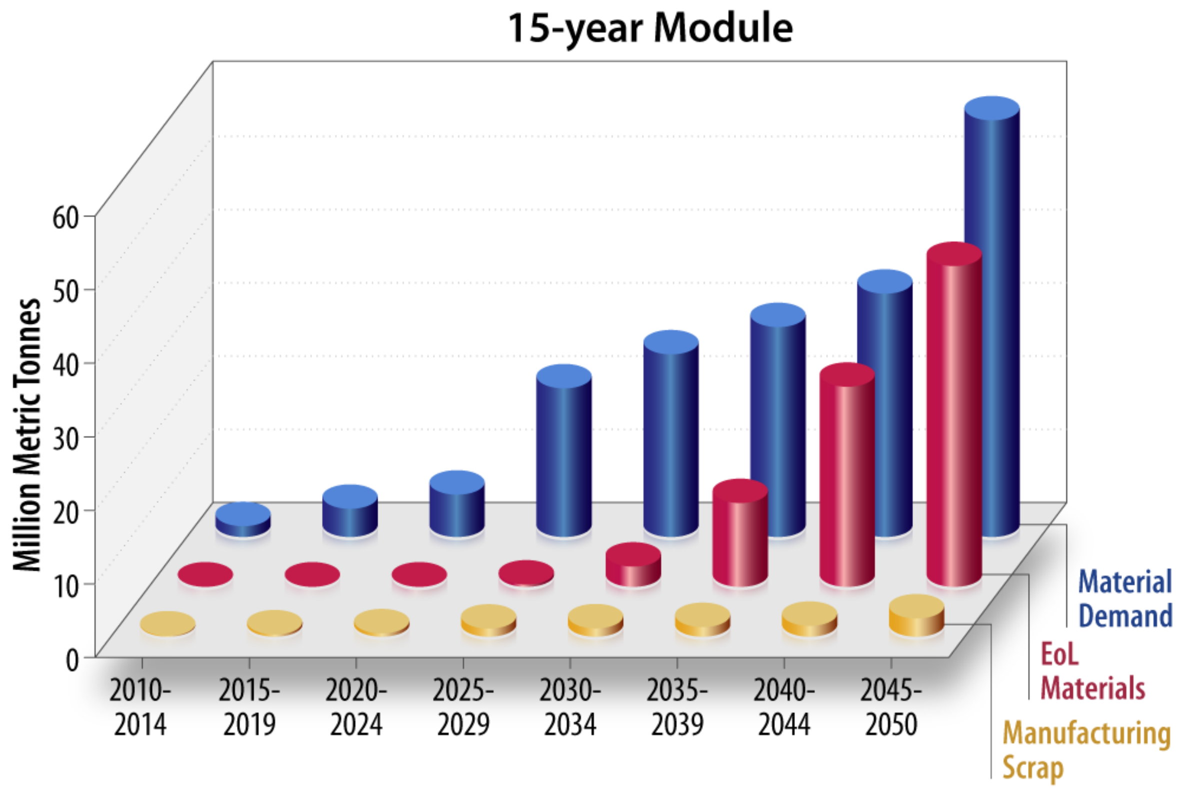
Extra Slides

Mass Flows – EoL and Manufacturing





- 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

Mirletz, Silvana Ovaitt, et al 2022. “Circular Economy Priorities for Photovoltaics in the Energy Transition.” PLOS ONE https://doi.org/10.1371/journal.pone.0274351

PV ICE Diagram

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