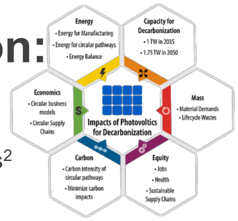
Measuring Sustainability of PV in Energy Transition: Mass, Energy, and Circularity



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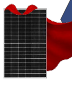
Common Sustainability Proposals for PV

These are the most common sustainability proposals for PV: Maximize Lifetime, Maximize Efficiency, Maximize Recycling. But which is really the most sustainable choice?

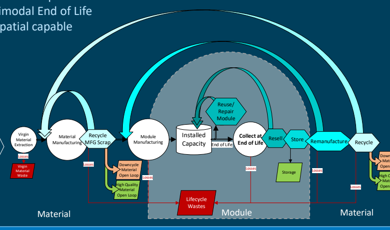


- **Perfect Longevity**: 50-year life, Avg. eff., Low Bifacial
- **Perfect Efficiency**: High Bifacial, 30-yr Life, Downcycle
- **High Efficiency**: Bifacial, 30-yr Life, Downcycle
- **Perfect Circularity**: Re-manufacture, 15-yr Life
- **High Circularity**: Recycle Si, Mid eff., 20-yr Life
- **Cheap**: Affordable, Low Quality, Low eff.
- **Baseline**: "business as usual"

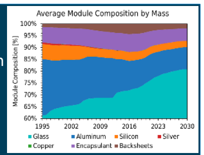
PV ICE Tool

https://github.com/NREL/PV_ICE

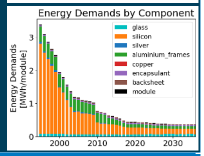
- Open-source Python Framework
- PV specific CE paths
- Multimodal End of Life
- Geospatial capable



Baseline dynamic material composition capturing historical module evolutions



Baseline dynamic energy demand capturing historical changes in process energy intensities



How do we measure impact of circular choices for PV in the context of Energy Transition?

Effective Capacity and Replacements

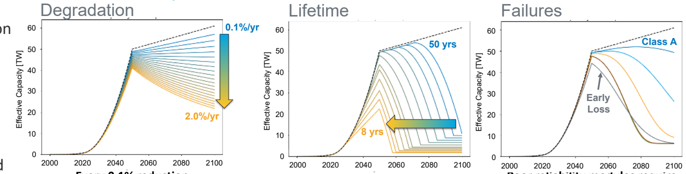
Top priority: Build and Maintain PV Capacity for Energy Transition

Goal: Minimize Replacements

Effective Capacity = installs – degradation – failures – project lifetime; represents capacity available to generate energy.

Replacements will be required before 2100, increasing annual manufacturing. Quantity of replacements depends on lifetime. Short lived modules significantly decrease effective capacity and therefore increase required replacements.

Effective Capacity with no Replacements

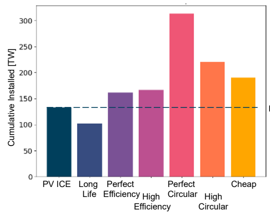


Every 0.1% reduction in degradation saves ~3 TW of replacements

Short Lifetimes require more replacements, sooner

Poor reliability modules require *double replacements* versus top tier quality modules

Cumulative Installations including Replacements



Longevity decreases deployment and replacement manufacturing

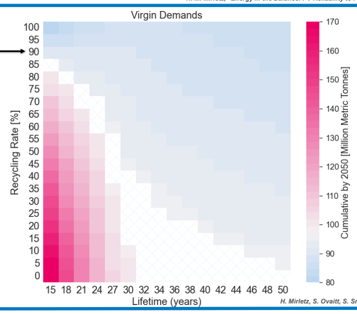
H. M. Mirletz, "Energy in the Balance: PV Reliability to Power the Energy Transition," presented at the PVRW 2023, Lakewood, CO, Feb. 28, 2023

Raw Material Demand

Goal: Minimize Extraction of Virgin Materials

Material extraction and refinement entails energy and environmental impacts. These can be minimized through increasing recycling rates or increasing lifetime. Currently, there is no closed-loop recycling for c-Si PV modules, and only the CdTe semiconductor is closed-loop in thin film technology.

Maximize Mass Circularity >95% OR increase Lifetime
Currently no modules >90% closed-loop, even CdTe

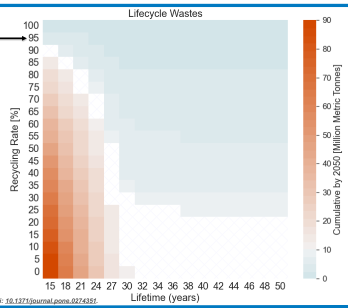


Lifecycle Wastes

Goal: Minimize Wastes throughout PV lifecycle

Wastes are generated during refinement and manufacturing as well as at end of life. This means more replacements manufacturing generates more manufacturing wastes. For long lived modules, end of life wastes will occur after 2050, therefore Long life provides "grace period" to develop circular supply chains.

Maximize Mass Circularity >90%
OR Increase Lifetime



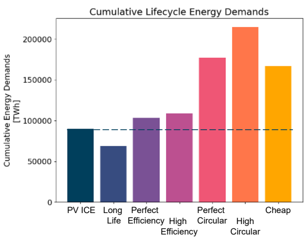
H. Mirletz, S. Ovaitt, S. Sridhar, and T. M. Barnes, "Circular economy priorities for photovoltaics in the energy transition," PLOS ONE, vol. 17, no. 9, Sep. 2022, doi: 10.1371/journal.pone.0274351.

Energy Demands

Goal: Minimize Energy demands

Energy demands can be reduced by reducing the quantity of manufacturing and/or reducing the energy intensity of processes (e.g.; recycling). If we need to manufacture more modules prior to 2050 (e.g.; short lived modules requiring replacements), then we increase energy demands while the grid is not fully decarbonized.

Energy savings from circular pathways is not sufficient to offset increased energy needs for manufacturing replacements. Long-lived modules reduce energy demands.



Energy savings of circular paths
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Energy demands of more replacements

Energy Balance

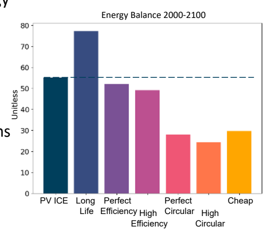
$$\frac{\sum_{2000,\,2100}^{All\ Systems} E_{out}}{\sum_{2000,\,2100}^{All\ Systems} E_{in}}$$

Goal: Maximize EROI & Net Energy

Energy Return on Investment (EROI) is energy generated over energy demands, representing energy returned to society.

We propose Energy Balance; all energy generated by all systems deployed 2000 through 2100 divided by all energy demands of those systems.

Energy Balance is increased by increasing lifetime.



Lifetime increases Energy Balance

Conclusions

		PV ICE Baseline	Perfect Longevity	SHJ	TOPCon	Perfect Circularity	High Circularity	Cheap Crap
Mass	Virgin Material Demand	0	+	-	-	++	-	--
Mass	Lifecycle Wastes	0	+	-	-	++	--	--
	Replacements	0	+	-	-	--	-	-
Energy	Net Energy	0	++	++	++	-	+	-
Energy	Energy Balance	0	+	-	-	--	--	--

Benefit — Detriment

- **Examine all metrics for holistic sustainability evaluation**

Take Aways:

- **Importance of deploying high reliability modules**
- **Designs can have tradeoffs between mass and energy**
  - Circularity scores well in mass, poorly in energy
  - Efficiency scores well in Net Energy, poorly in mass
- **Longevity shows improvement in all metrics**

Future Metrics: Carbon, Energy Justice, Supply Chains…

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