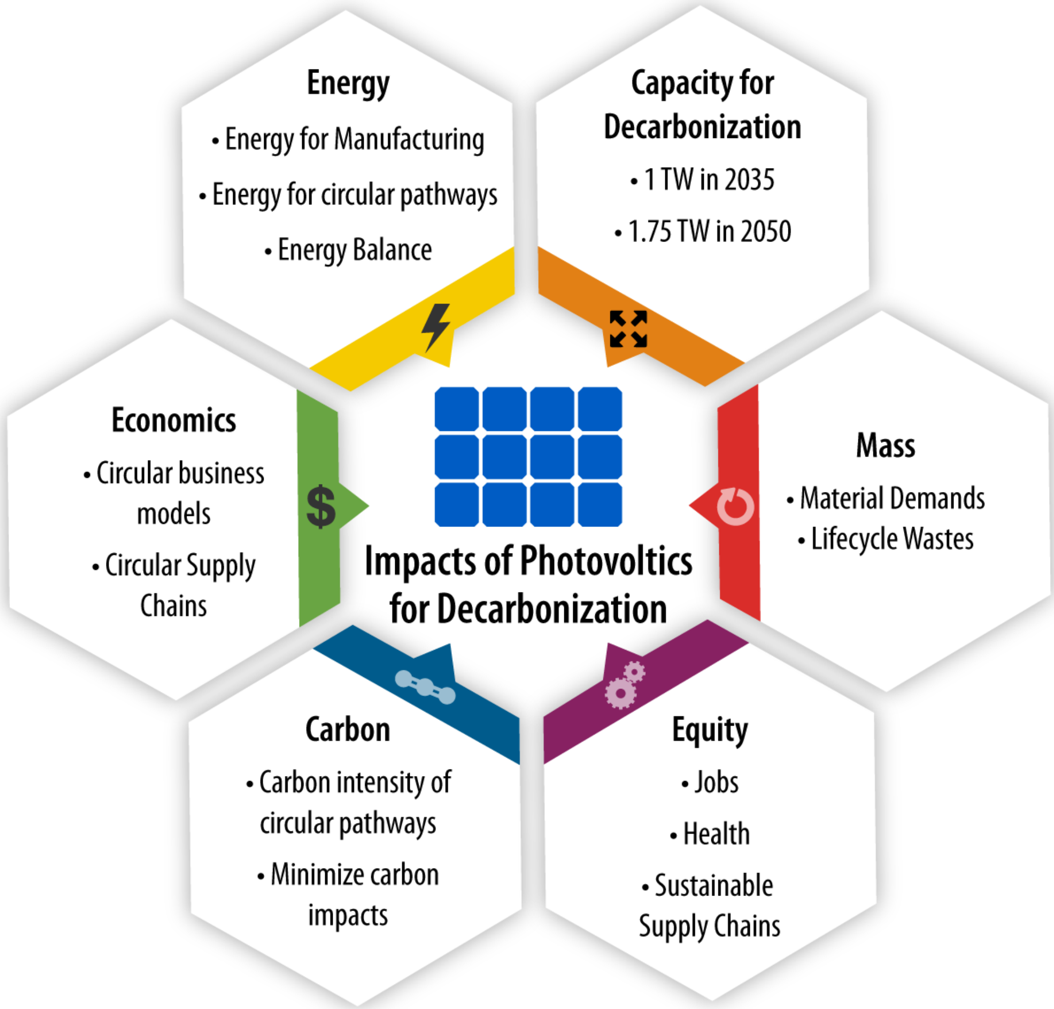
More than recycling: The importance of multiple metrics for a Circular Economy for PV in the Energy Transition



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40th EU PVSEC, 5CO.6.6

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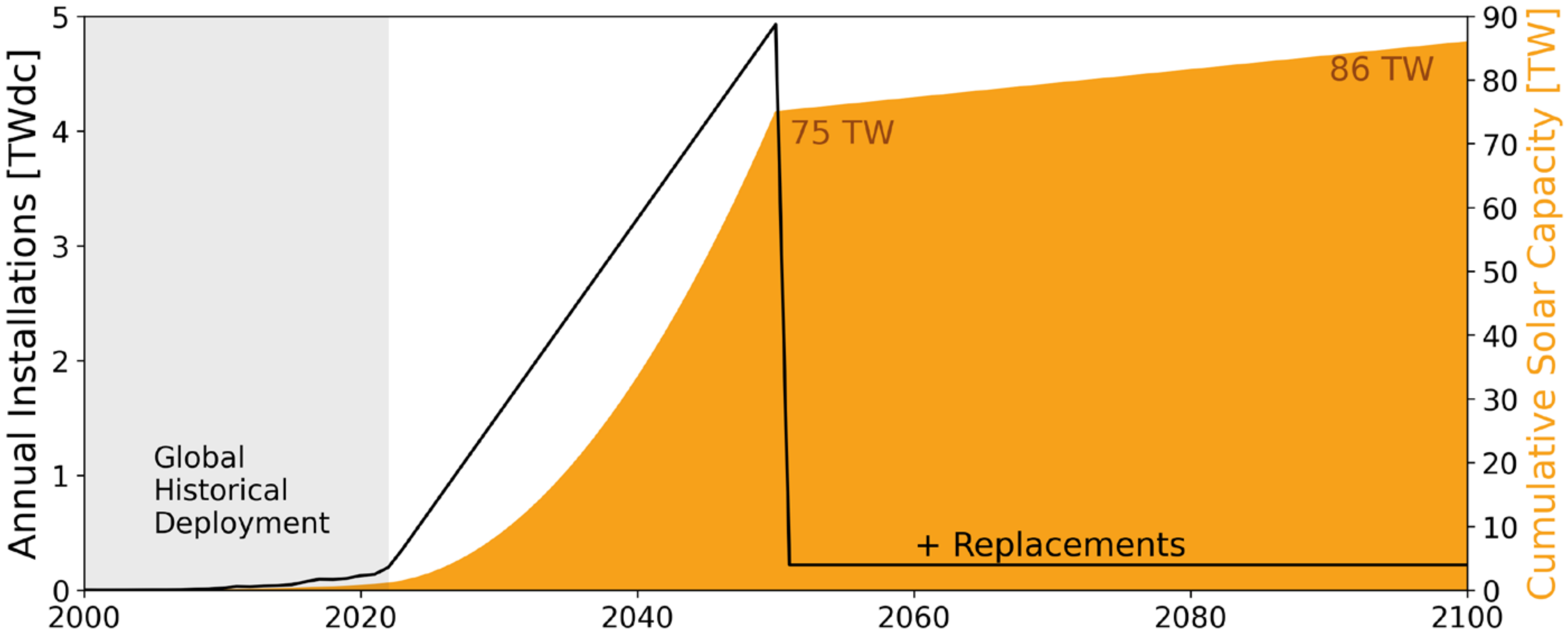
Best Student Presentation Nominee

World Decarbonization Goals & PV Deployment Rates

Current Capacity: 1.2 TWdc

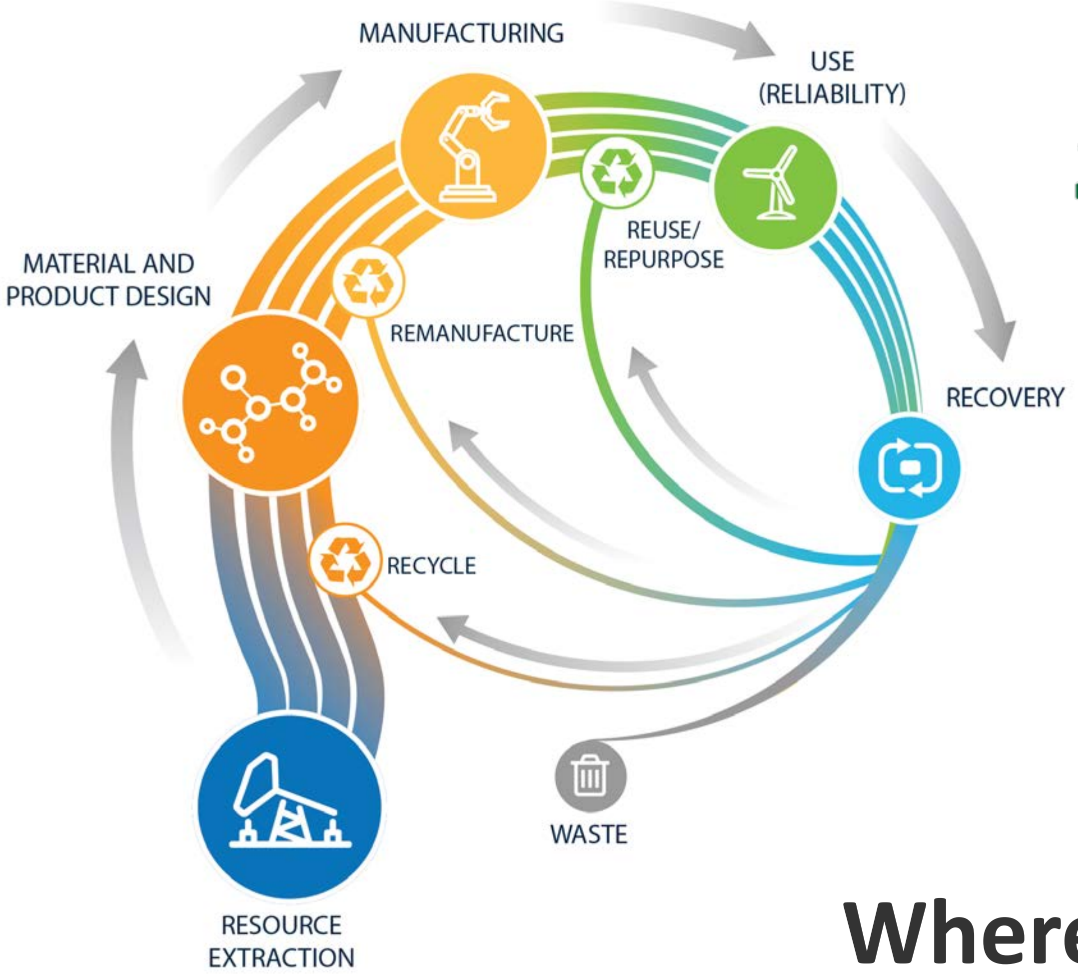
Deployment 2022: 240+ GWdc



Source	Deployment Goals	Deployment Rate by 2030	Scaling vs 2022
2019 IEA Net Zero	15 TW	630 GW/year	x2.6
2021 US Solar Futures	16 TW	600 GW/year	x2.5
2021 Zhang et al, *Energy & Env. Sci.*	70+ TW	3000 GW/year	x12.5
2023 Haegel et al. *Nature*	75 TW	1500 GW/year	x6.3

Masson et al. Snapshot of Global PV Markets - 2023. IEA PVPS Task 1; 2023.

Circular Economy for PV Sustainability



$$CI = 1 - \frac{V + W}{2M + \sum_x \frac{W_{F(x)} - W_{R(x)}}{2}}$$

Virgin Material (V)
Waste (W)
Mass of the product (M)
Waste from Feedstock & Manufacturing ($W_{F(x)}$)
Waste from recycling process ($W_{R(x)}$)

Where's the Energy?

Saidani et al. A taxonomy of circular economy indicators. *J. of Cleaner Production.* 2019.
Smith and Jones. "Circularity Indicators: An Approach to Measuring Circularity: Methodology." Ellen MacArthur Foundation. 2019.

Multiple Metrics

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

Virgin Material
Reduce Extraction of Virgin Materials

Waste
Reduce Wastes throughout PV lifecycle

Energy Demand
Minimize Energy demands of processes and materials

Carbon Intensity
Minimize carbon intensity of lifecycle

Installed Capacity
Maintain PV Capacity to meet Energy Transition

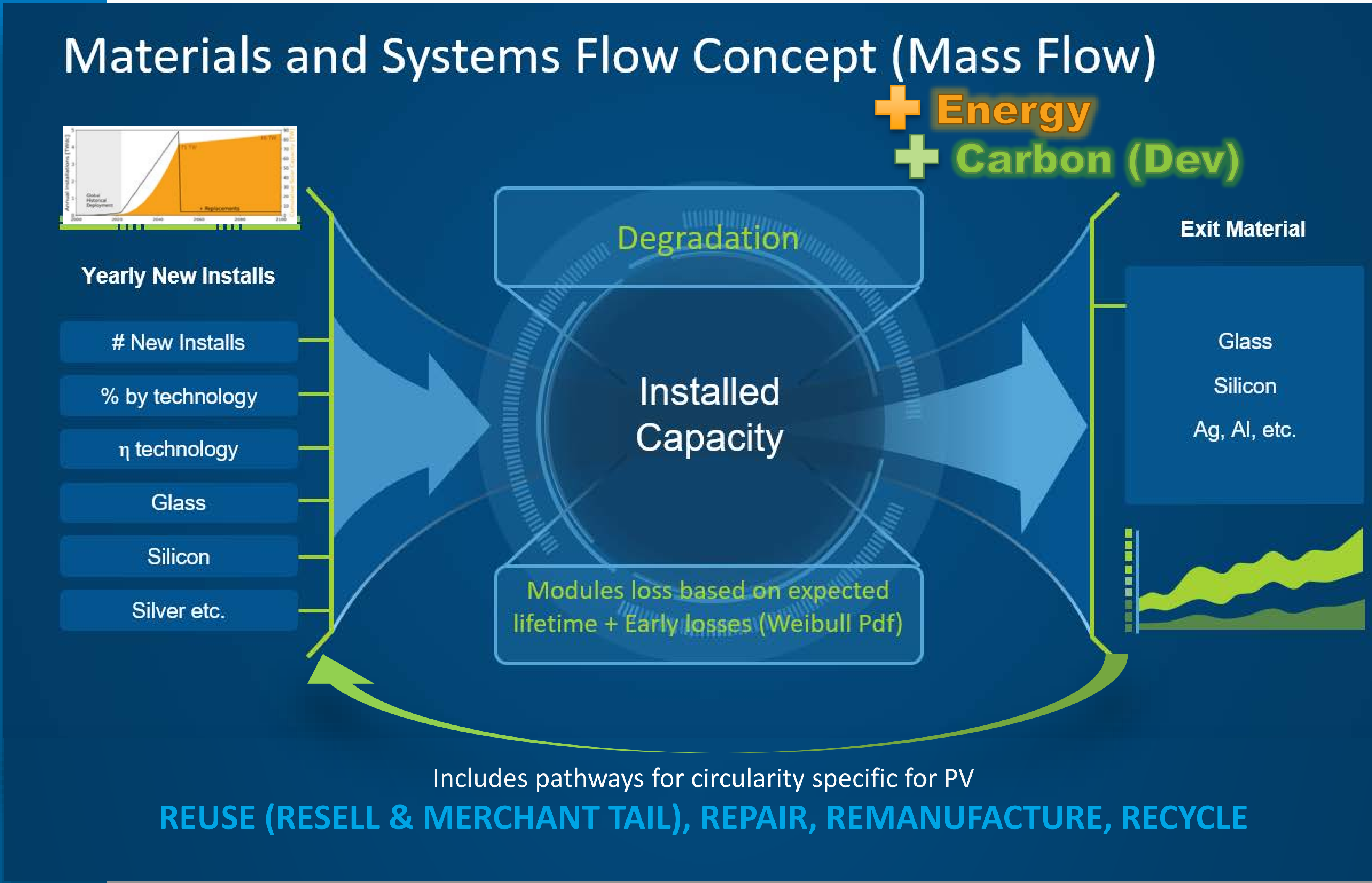
Net Energy
Energy Generated minus Energy Demand

Energy Balance
Energy Generated divided by Energy Demand

Supply Chain Security
Just and Reliable sourcing of materials

PV in Circular Economy Tool PV ICE

System-dynamics, geospatial, open-source model that evaluates the material, energy and carbon viability of the PV manufacturing, deployment, reuse, and recycling industries across the Energy Transition, allowing exploration of supply chains with varying degrees and types of circularities.



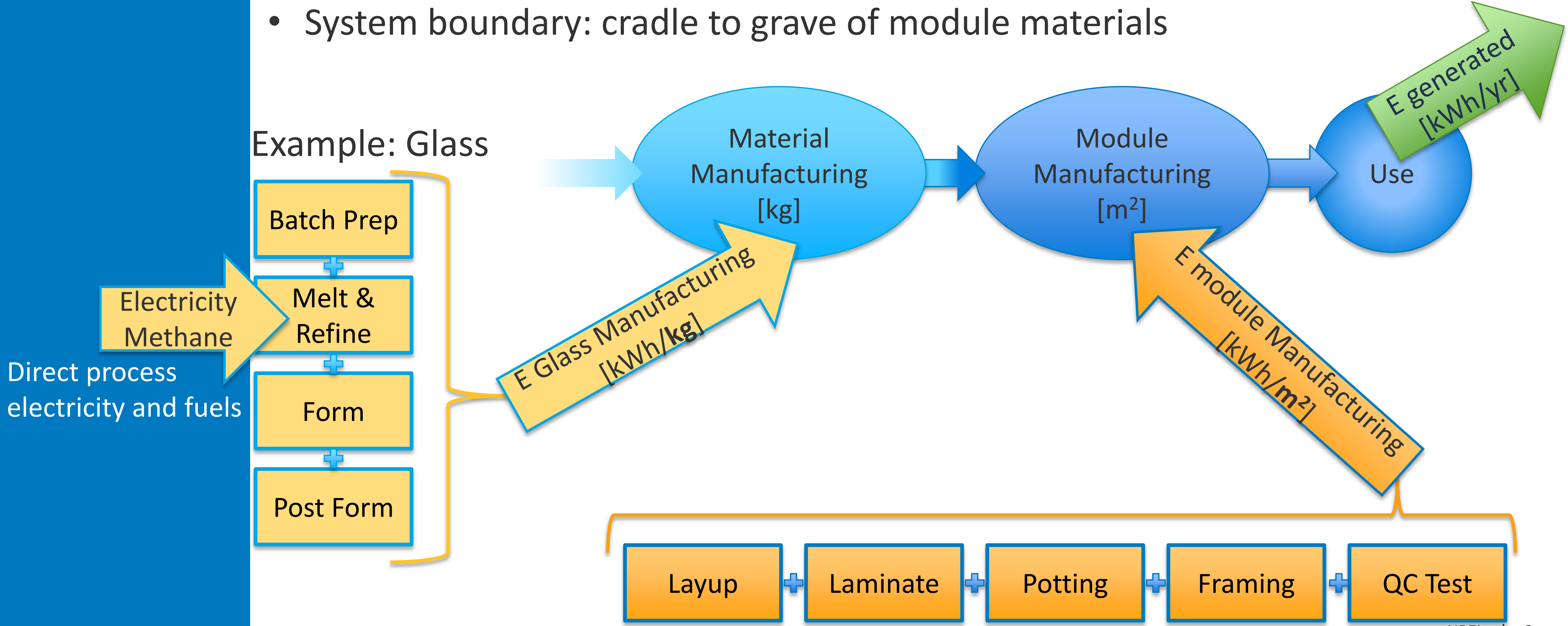
https://www.nrel.gov/pv/pv-ice-tool.html

Mass and Energy in PV ICE

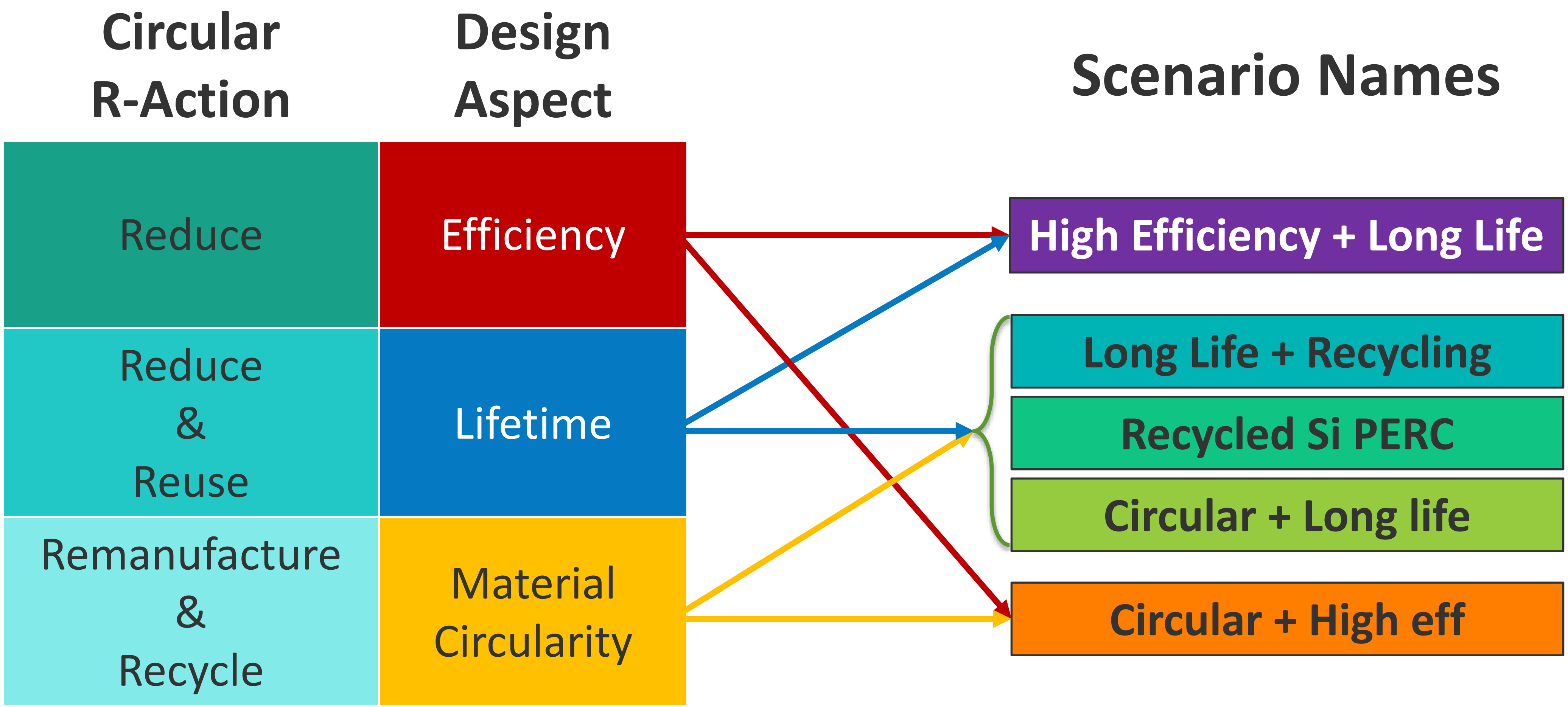
Dynamic with time, accounting for:

- PV module evolution
- process improvements
- historical market shares
- System boundary: cradle to grave of module materials

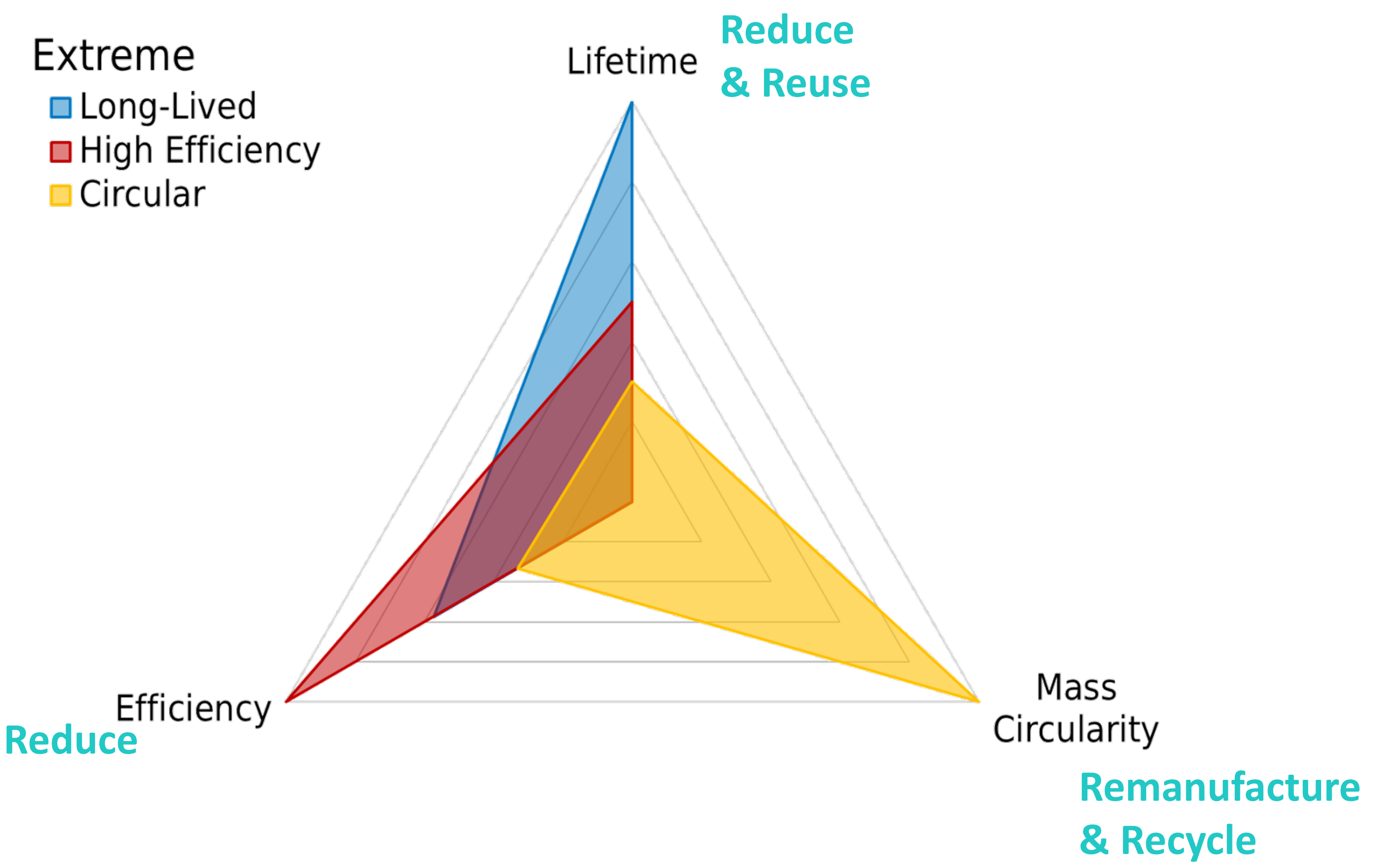
Example: Glass



Explore 3 PV Module Design Aspects



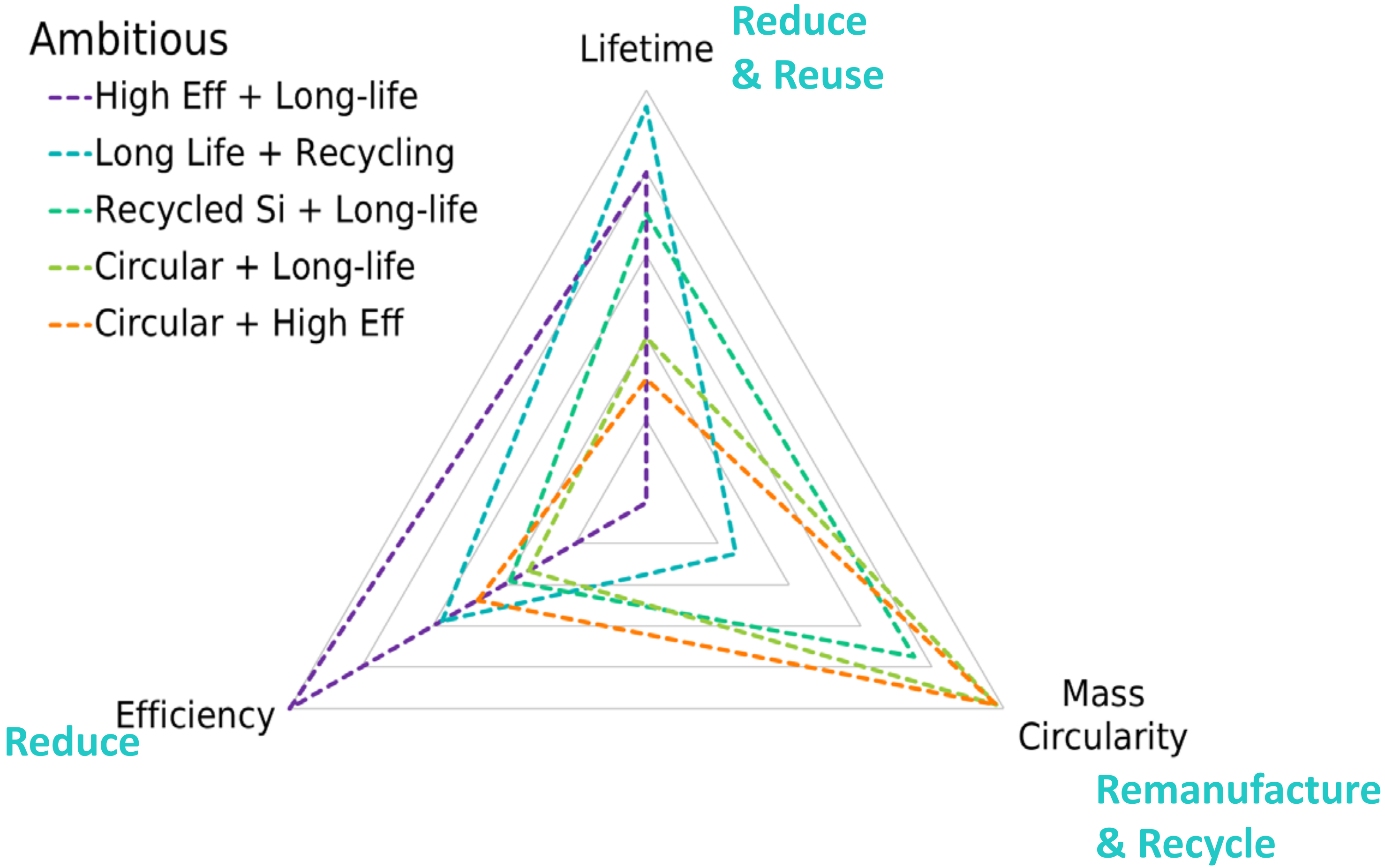
What if…
we prioritized one aspect at the expense of the other two?



"Extreme" Scenarios

What if…
2/3 design aspects could be improved by 2050, to a less perfect level?

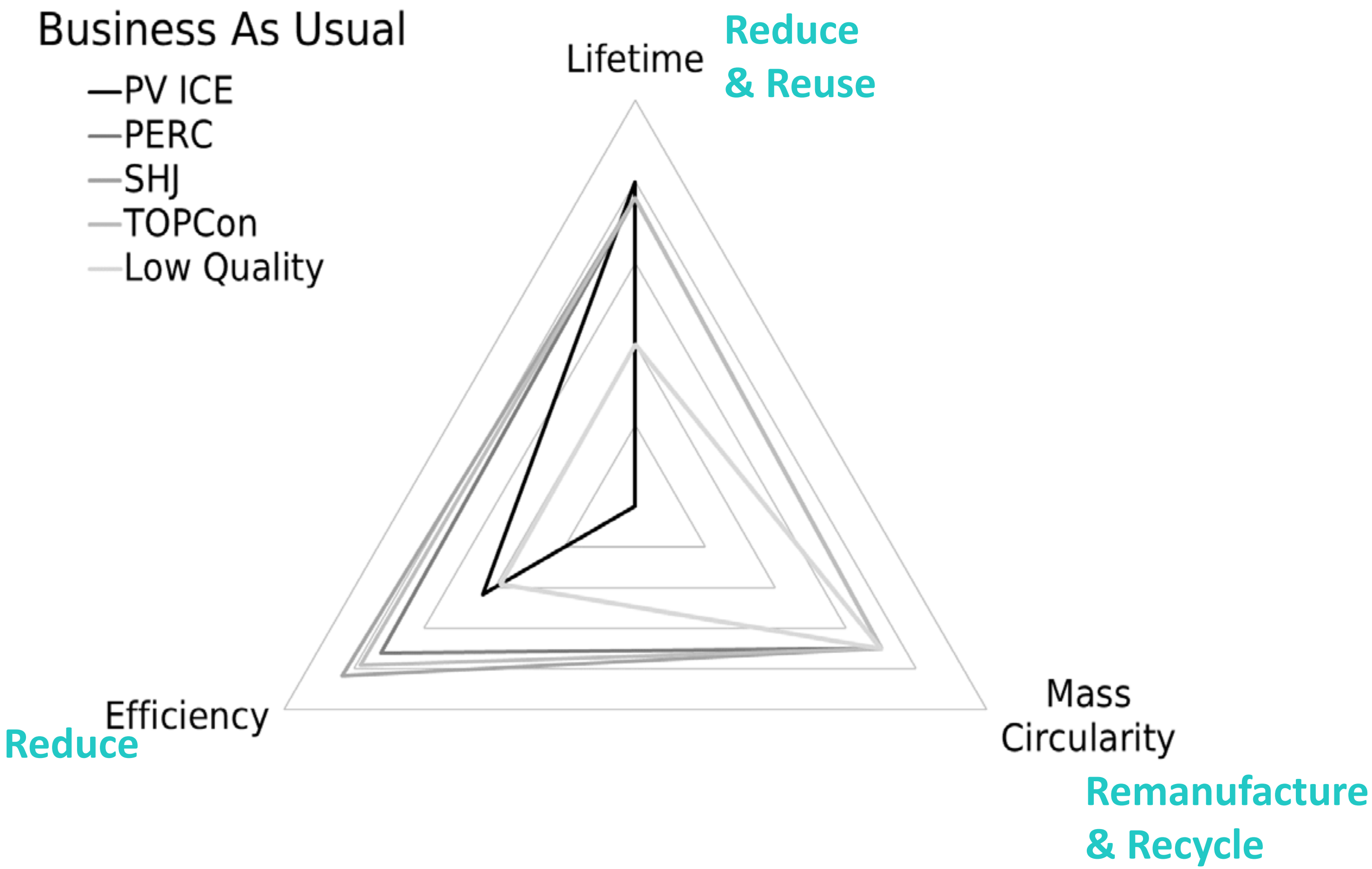
"Ambitious" Scenarios



Baselines

Currently commercialized Technologies and their expected improvements

“Business as Usual” Scenarios



Takeaways

Full manuscript submitted to EPJ for peer-reviewed publication:

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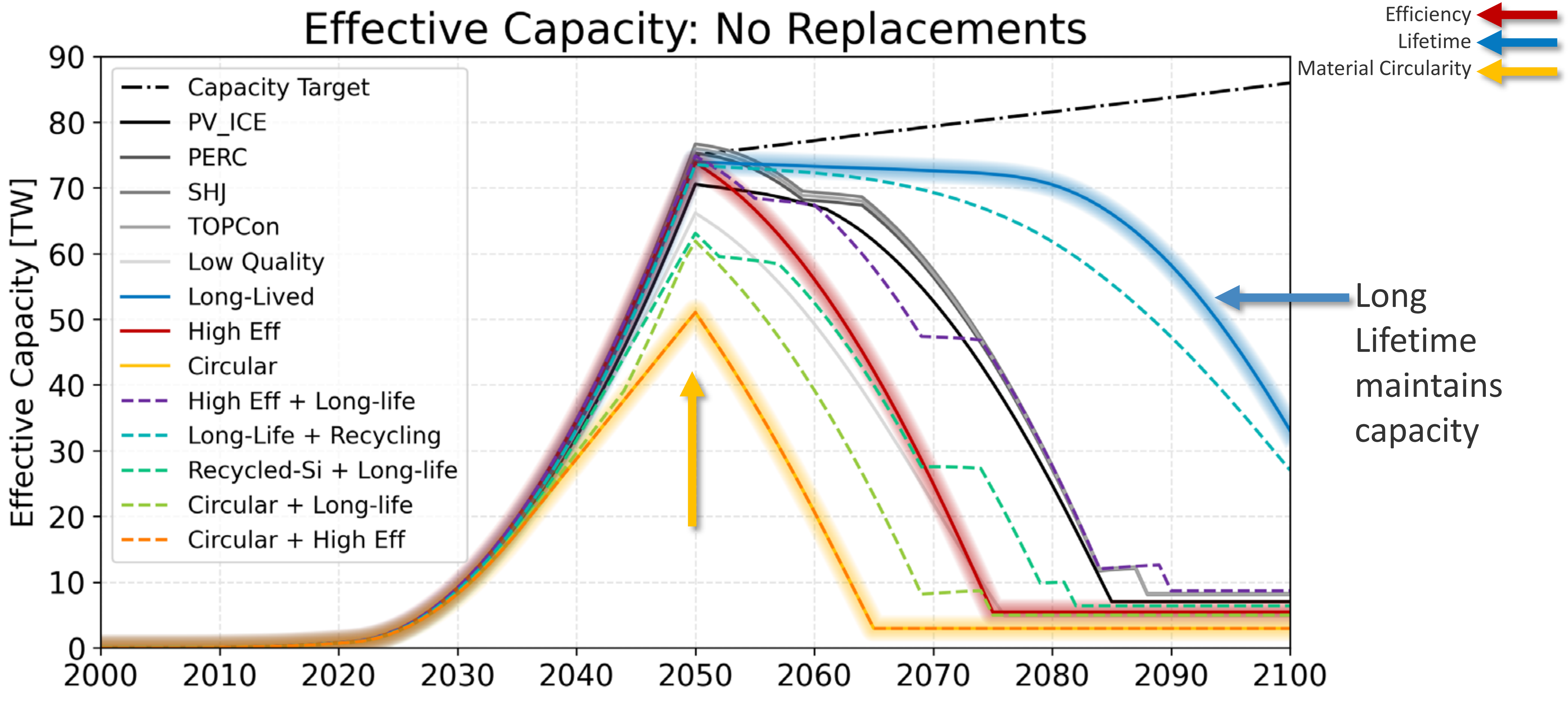
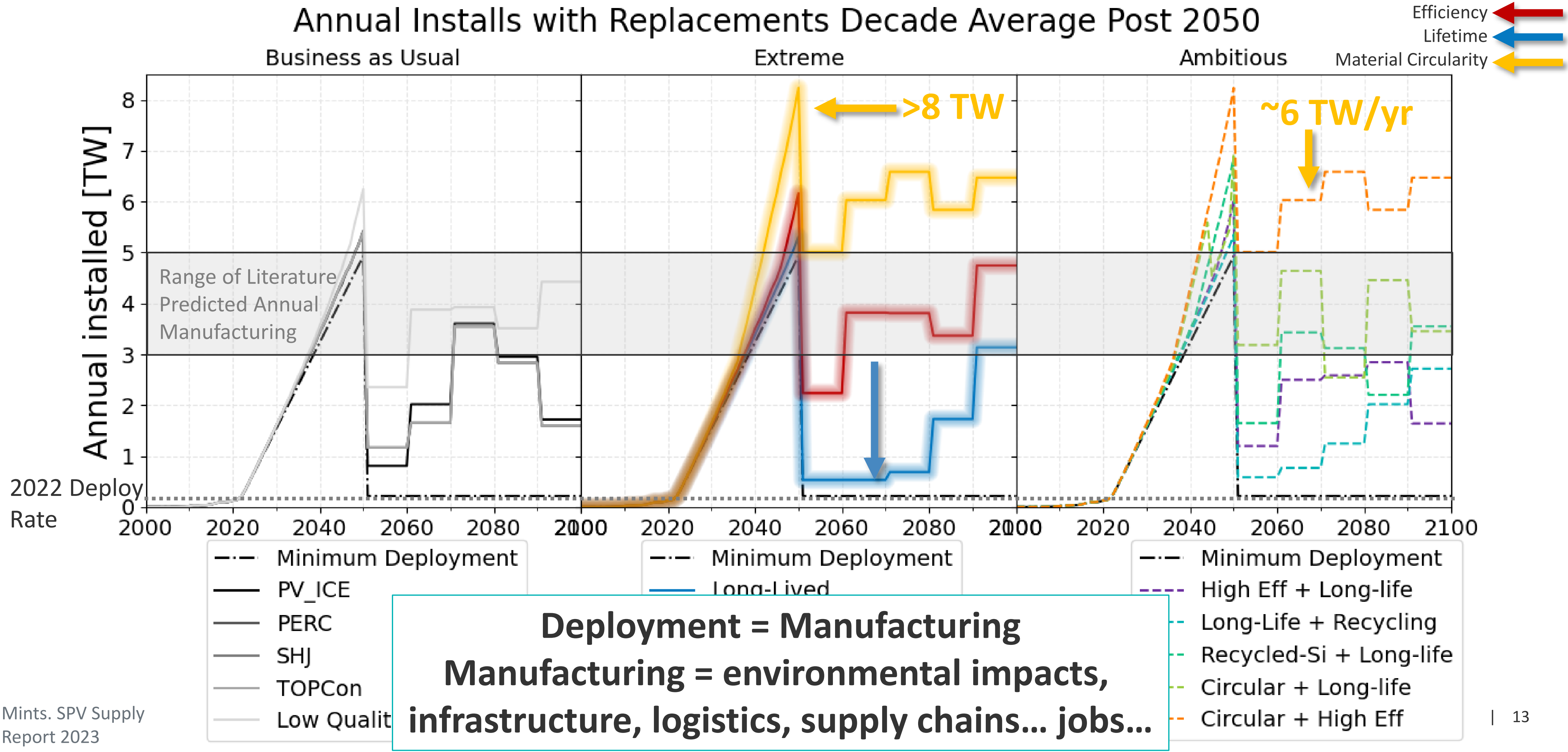
All Scenarios Require Replacements by 2100



Long Lifetime maintains capacity

Short lifetimes (15 yrs) do not meet capacity targets without replacements pre-2050

Annual Manufacturing and Deployment with Replacements

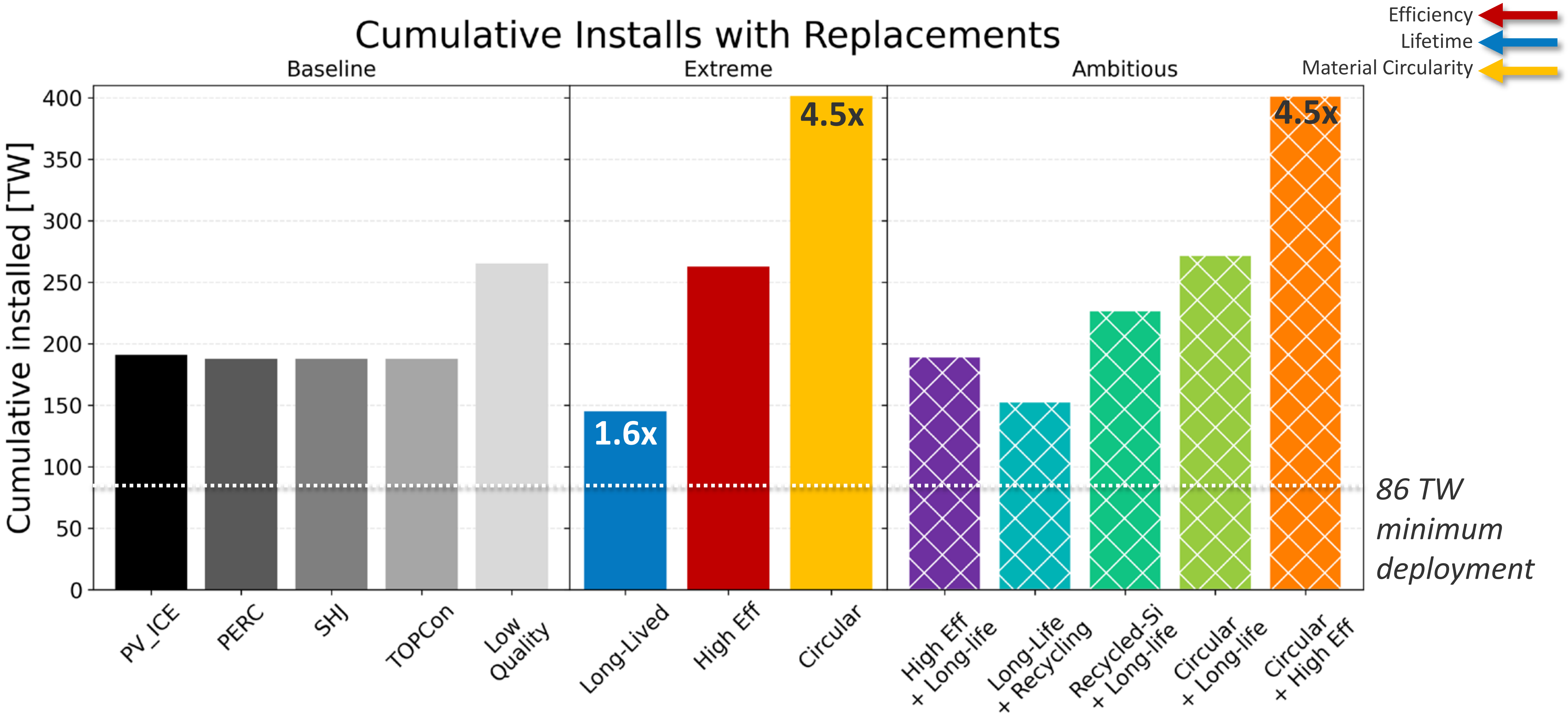


Deployment = Manufacturing

Manufacturing = environmental impacts, infrastructure, logistics, supply chains… jobs…

Mints. SPV Supply Report 2023

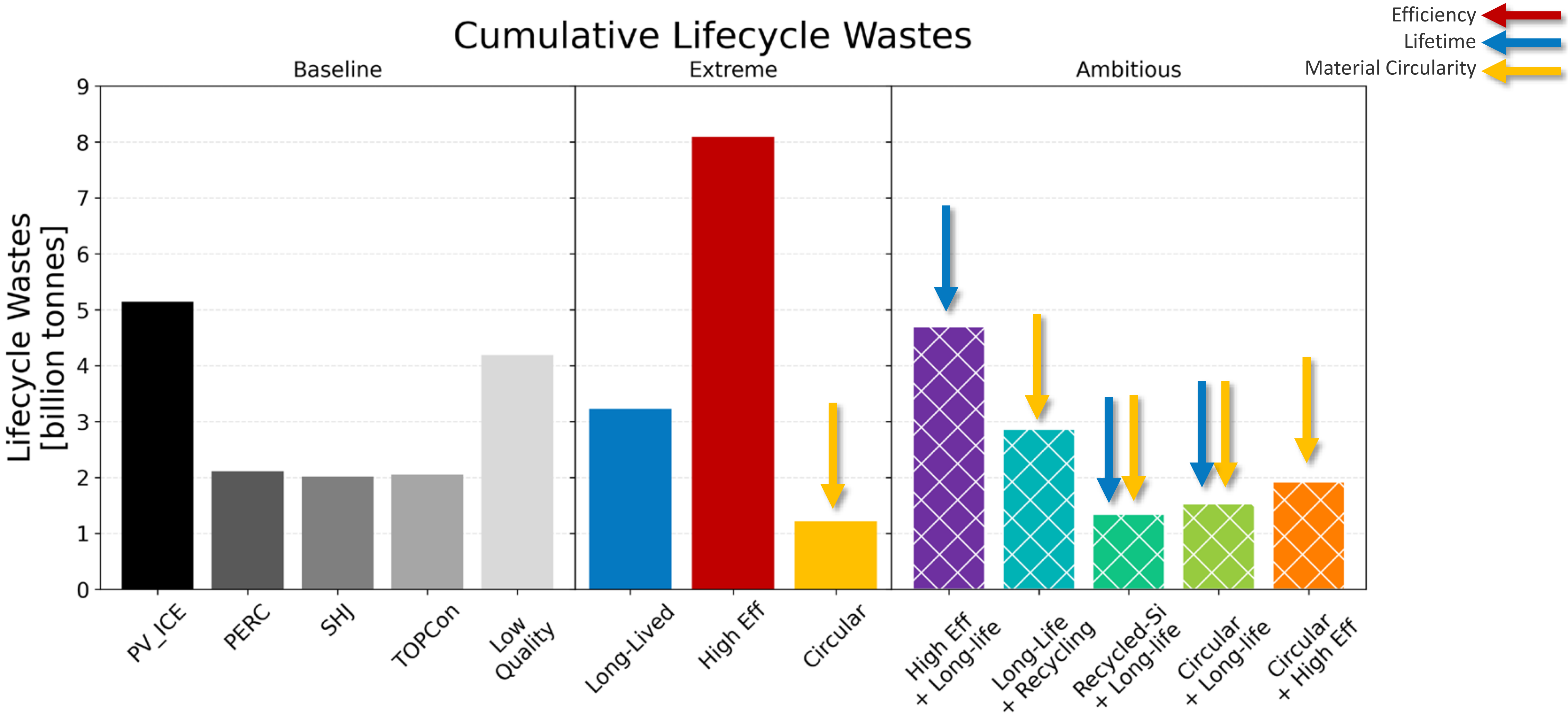
Cumulative Deployment 2000-2100 with Replacements



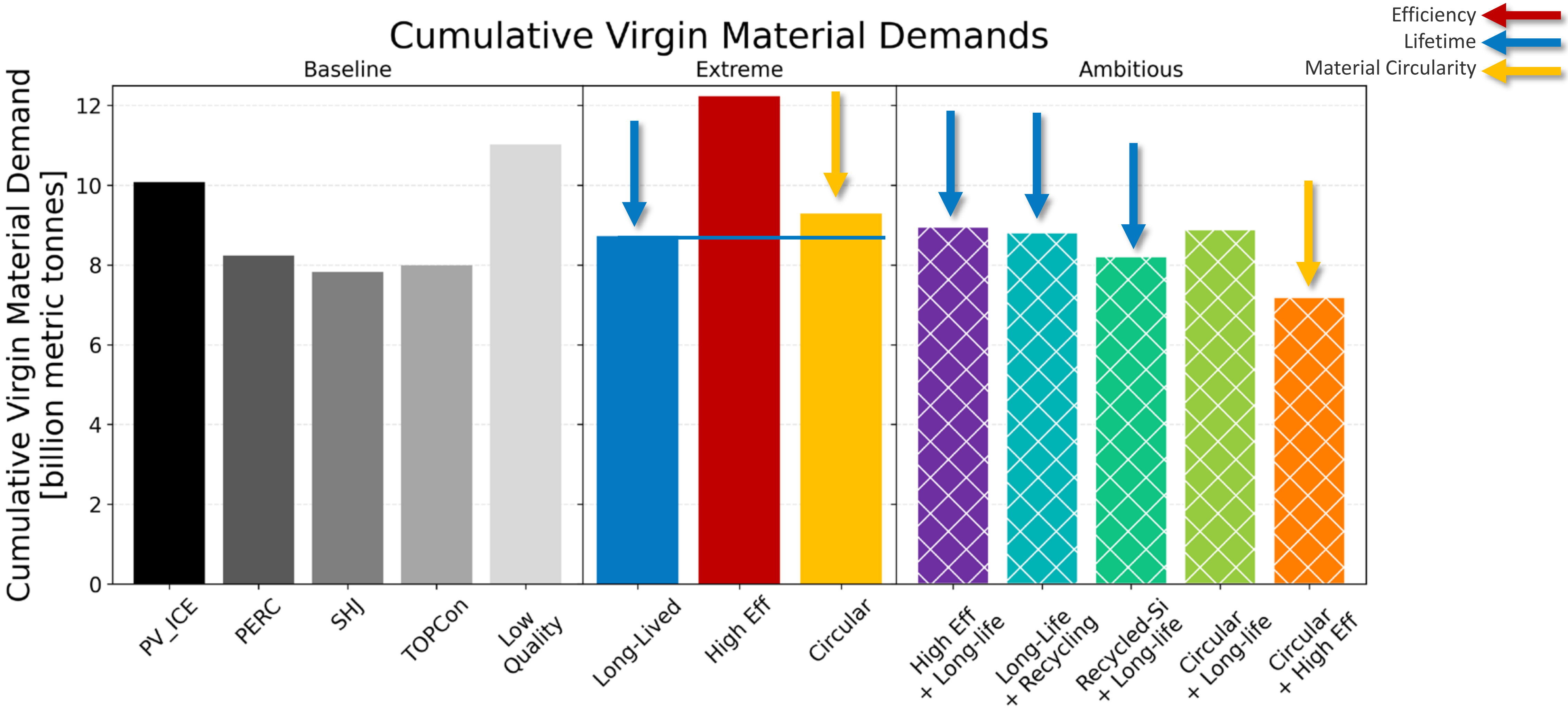
Short lifetimes = 4.5x min deployment

Long lifetimes = 1.6x min deployment

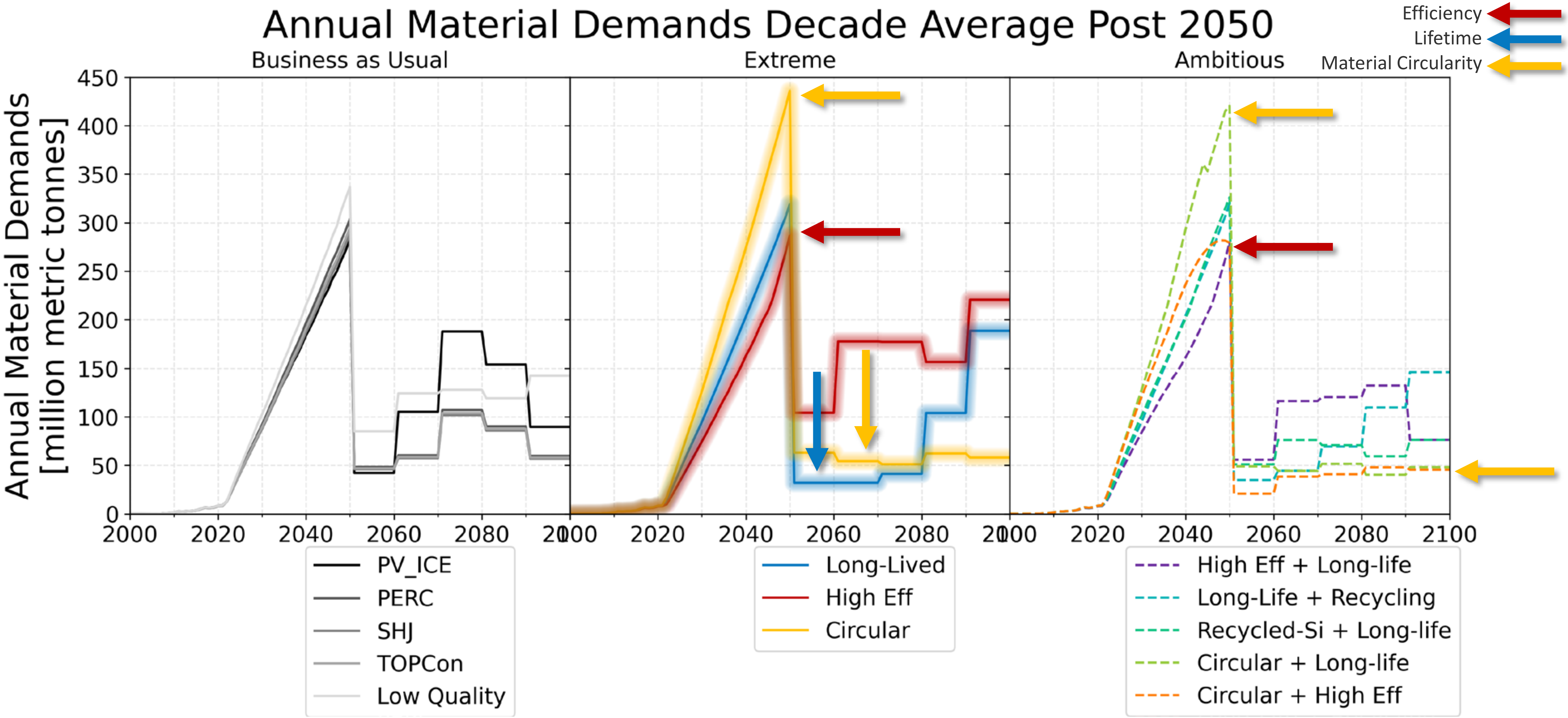
Material Circularity: Great at Waste Minimization



Material Circularity: Reduces Virgin Material Demand



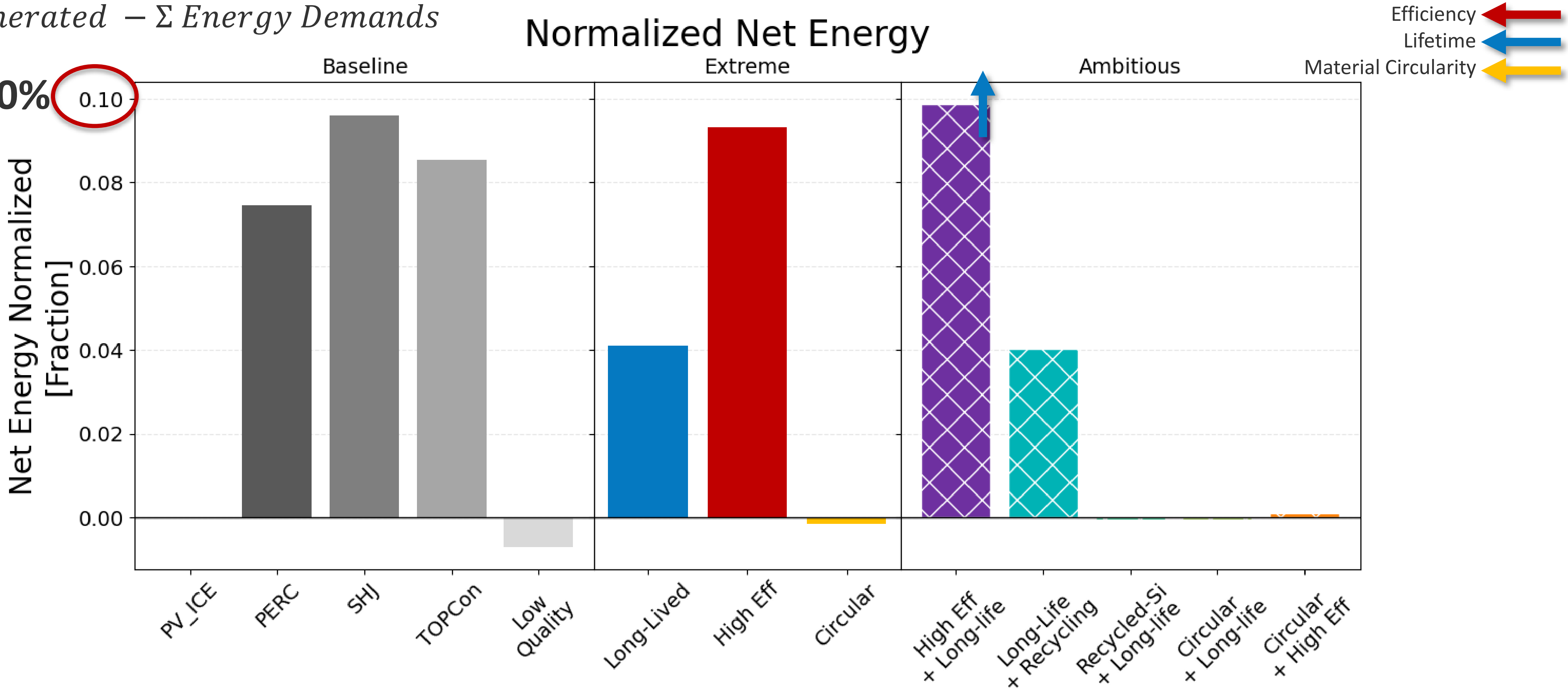
But no matter how Circular, Virgin material demand is not eliminated



Bifaciality: Improves Net Energy

$\Sigma\ Energy\ Generated\ - \Sigma\ Energy\ Demands$

But, only 10%

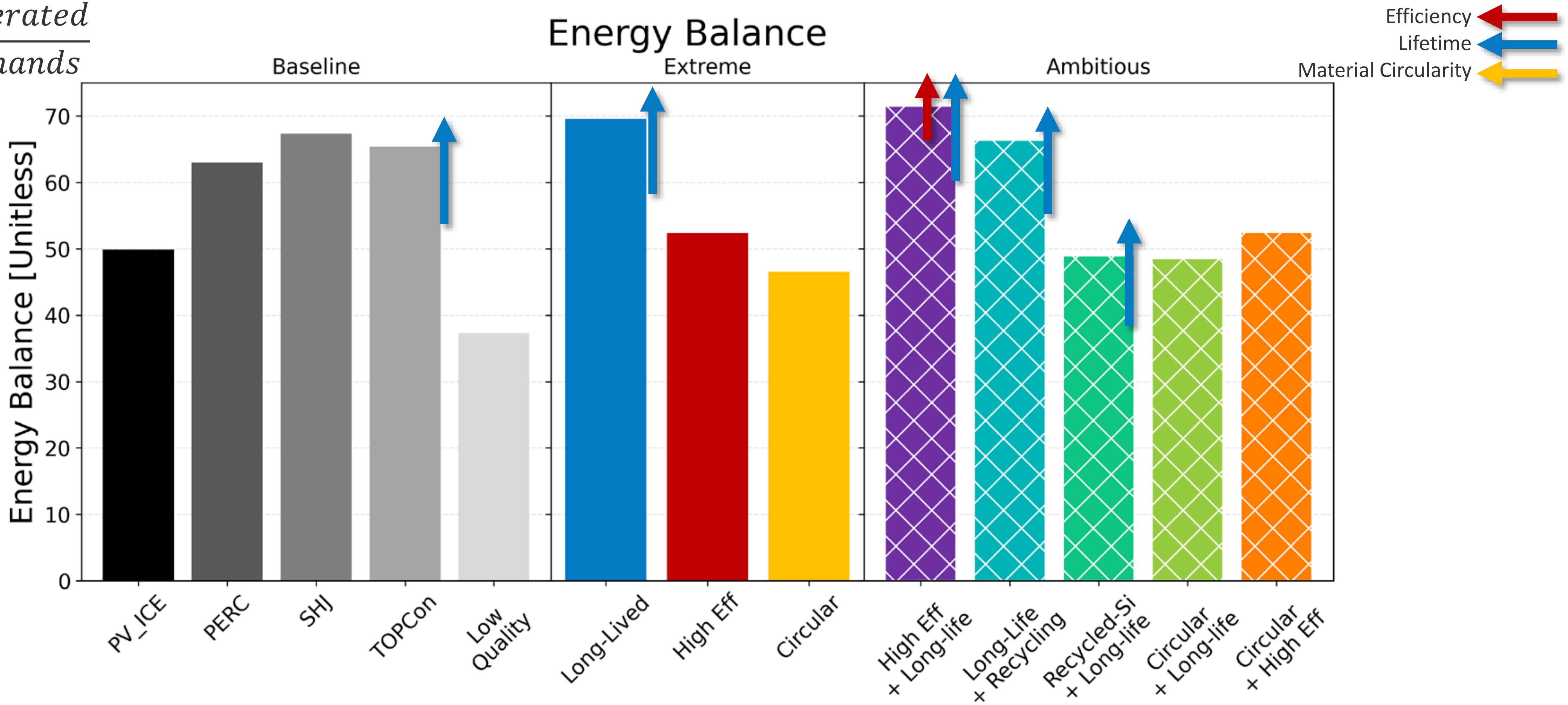


Bifaciality improves net energy

Bifaciality + Lifetime *Maximizes* net energy

Lifetime: Maximizes Energy Balance

$$\frac{\sum Energy\ Generated}{\sum Energy\ Demands}$$



Lifetime improves energy balance

Lifetime +Reuse OR +Efficiency maximizes energy balance

Multi Metric Performance

	Scenario	Total Deployment (TW)	Material Demand (bmt)	Lifecycle Wastes (bmt)	Energy Demands (TWh)	Net Energy (TWh)	Energy Balance (Unitless)
Business as Usual	PV ICE	191	10.1	5.1	144,000	7,044,000	50
	PERC	188	8.2	2.1	122,000	7,569,000	63
	SHJ	188	7.8	2.0	116,000	7,719,000	67
	TOPCon	188	8.0	2.1	119,000	7,644,000	65
	IRENA reg. loss	265	11.0	4.2	193,000	6,995,000	37
Extreme	Long-Lived	145	8.7	3.2	107,000	7,333,000	70
	High Efficiency	263	12.2	8.1	150,000	7,699,000	52
	Circular	401	9.3	1.2	154,000	7,034,000	47
Ambitious	High Eff + Long-life	189	9.0	4.7	110,000	7,740,000	71
	Long Life + Recycling	152	8.8	2.9	112,000	7,328,000	66
	Recycled Si + Long-life	227	8.2	1.3	147,000	7,041,000	49
	Circular + Long-life	272	8.9	1.5	148,000	7,040,000	49
	Circular + High Eff	401	7.2	1.9	137,000	7,051,000	52
			Minimize	*Minimize*	*Minimize*	*Maximize*	*Maximize*

bmt = billion metric tonnes

Benefit — Harm

Multi Metric Performance

	Scenario	Total Deployment *TW*	Material Demand *bmt*	Lifecycle Wastes *bmt*	Energy Demands *TWh*	Net Energy *TWh*	Energy Balance *Unitless*	Benefits	Harms
Business as Usual	PV ICE	191	10.1	5.1	144,000	7,044,000	50	0	2
	PERC	188	8.2	2.1	122,000	7,569,000	63	4	0
	SHJ	188	7.8	2.0	116,000	7,719,000	67	4	0
	TOPCon	188	8.0	2.1	119,000	7,644,000	65	4	0
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	Circular + High Eff	401	7.2	1.9	137,000	7,051,000	52	2	2
		Minimize				*Maximize*		*Maximize*	*Minimize*

bmt = billion metric tonnes

Benefit — Harm

Takeaway Messages

1) Material Circularity (Remanufacture, Recycle)

- Minimizes waste (76%)
- Can reduce cumulative virgin material demands (up to 29%)

2) No scenario eliminates virgin material demands

- Speed of energy transition
- Source materials sustainably
  - Manufacturing yields and short circular pathways preferred

3) Efficiency and bifaciality (Reduce)

- alone improves net energy (9%) and reduces peak material demands (30%)
- need to combine with other design aspects to improving more metrics

4) Lifetime Extension (Reliability and Reuse)

- Minimizes material and Energy Demands, maximizes energy balance
- Plays well with others, minimizes harms, maximizes benefits

No matter what else you do, don't forget to make it last.

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Thank you!

Questions?

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PV ICE Tool: https://www.nrel.gov/pv/pv-ice-tool.html, https://github.com/NREL/PV_ICE

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