NREL
Transforming ENERGY

Circular Economy for Photovoltaics in Service of Energy Transition

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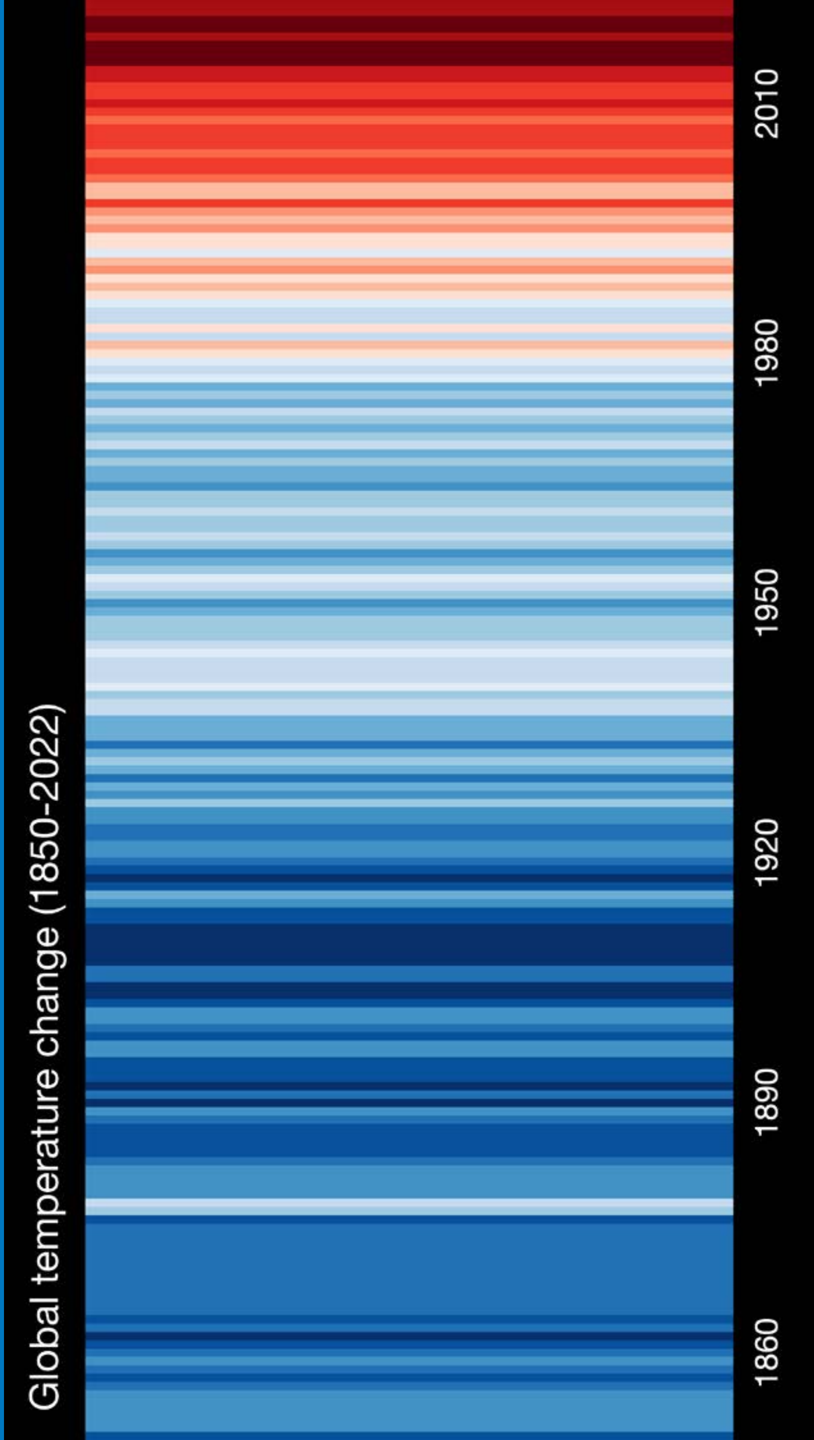
Goal: Net Zero CO_2, ASAP

Requires energy transition.

Deploying PV is essential to this goal.

Globally, we need up to 75 TW of PV.



Haegel et al 2023

Existing PV technology is ready to accomplish energy transition

Globally, in 2023:

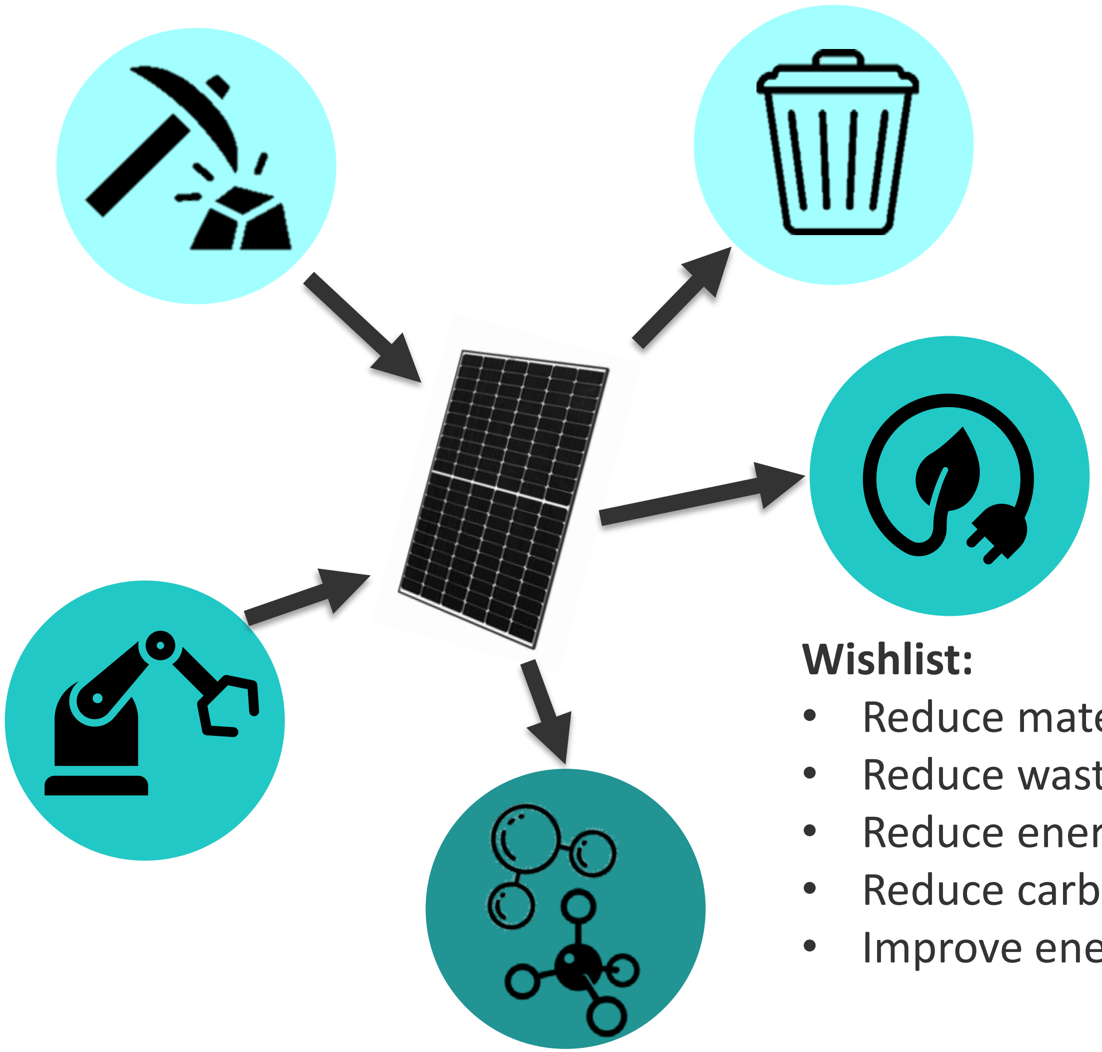
- Cumulative capacity of 1.4-1.6 TW
- Added 350-446 GW of PV capacity
  - U.S. added ~32 GW
  - E.U added ~46 GW
  - China added >200 GW

- PV is largest fraction of new capacity
- Cheapest source of electricity in most places globally

IRENA, IEA PVPS

But, PV isn’t perfect

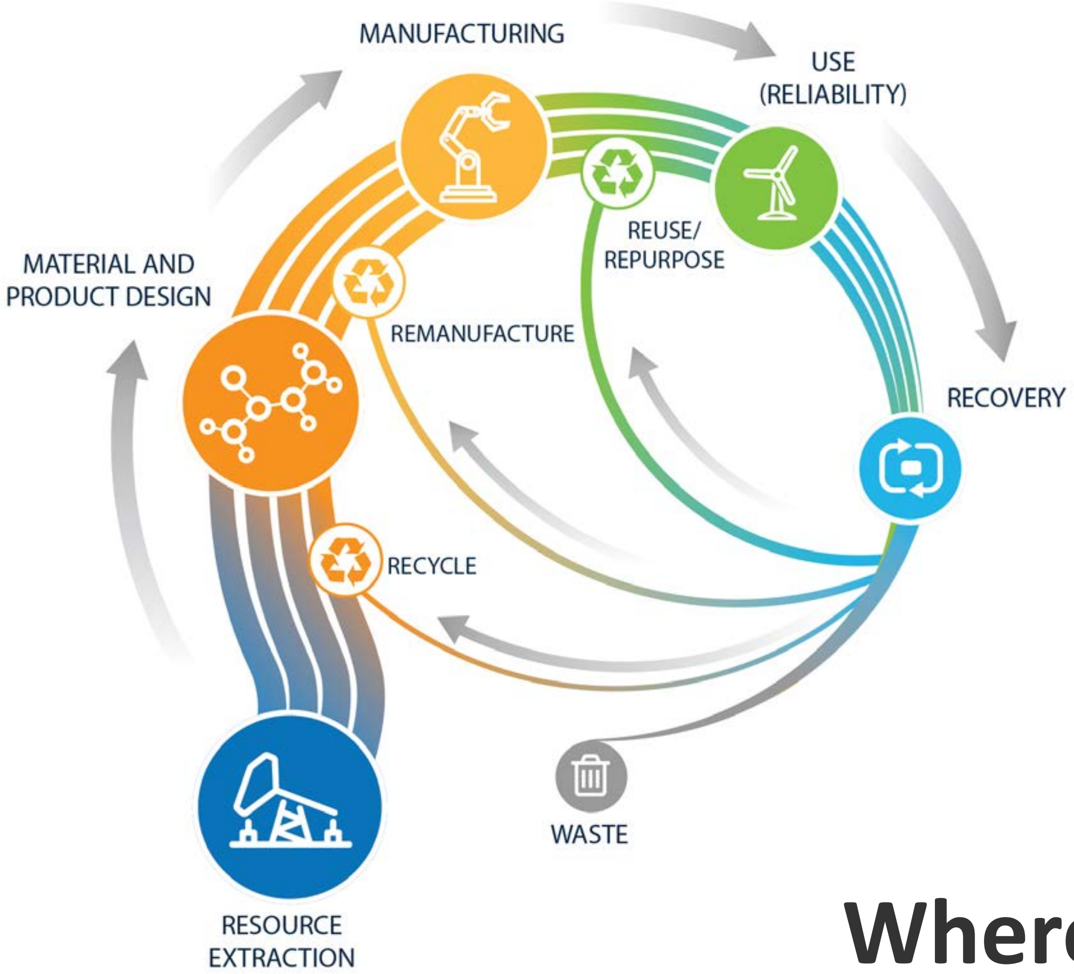
(otherwise, we wouldn’t have jobs)



Wishlist:

- Reduce material demand
- Reduce wastes
- Reduce energy demands
- Reduce carbon intensity
- Improve energy yield

Circular Economy for PV Sustainability



Virgin Material

Waste

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

Mass of the product

Waste from Feedstock & Manufacturing

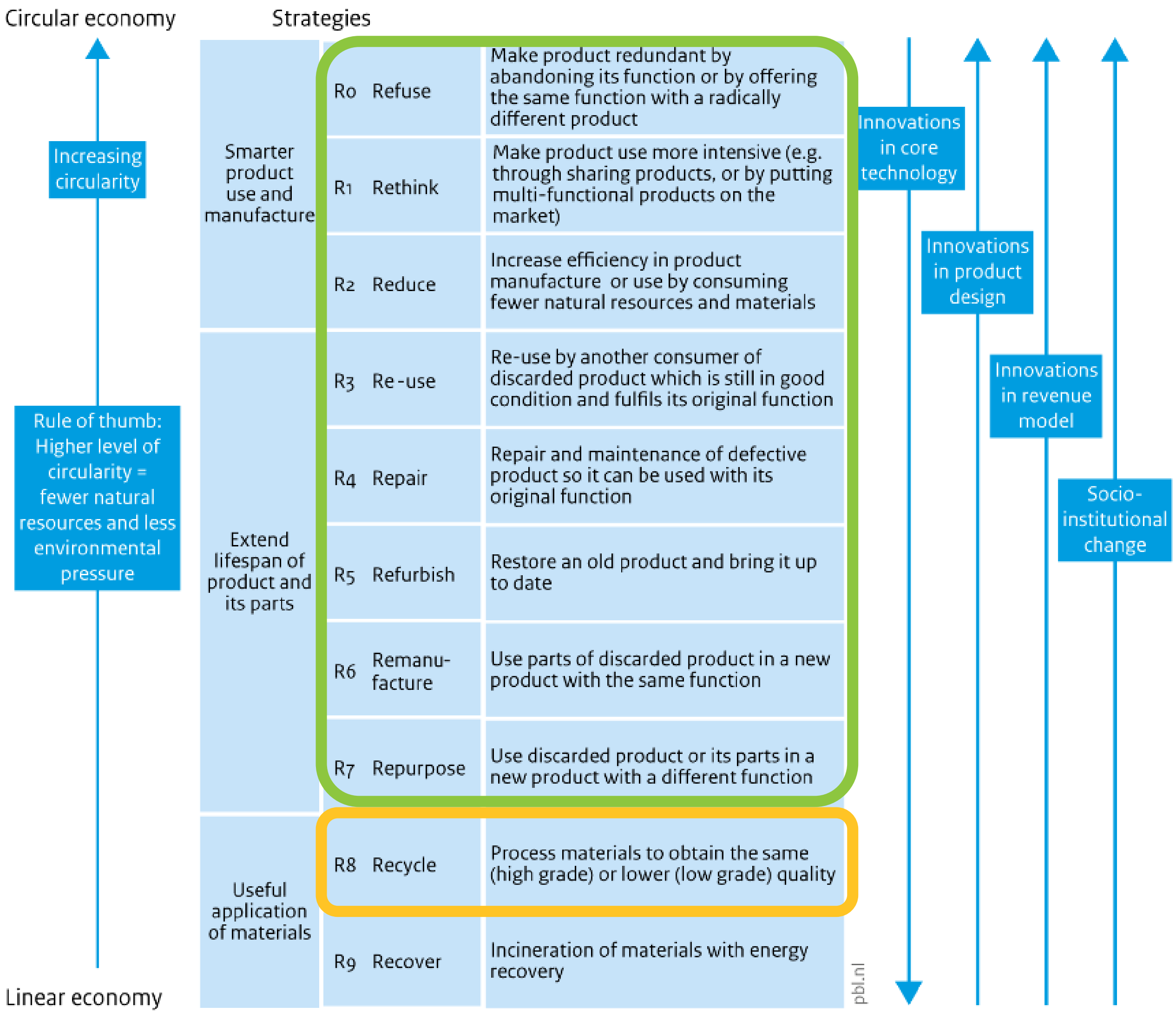
Waste from recycling process

Where's the Energy?

Saidani et al. *J. of Cleaner Production.* 2019.
Smith and Jones. Ellen MacArthur Foundation. 2019.

Circular Economy ≠ Recycling

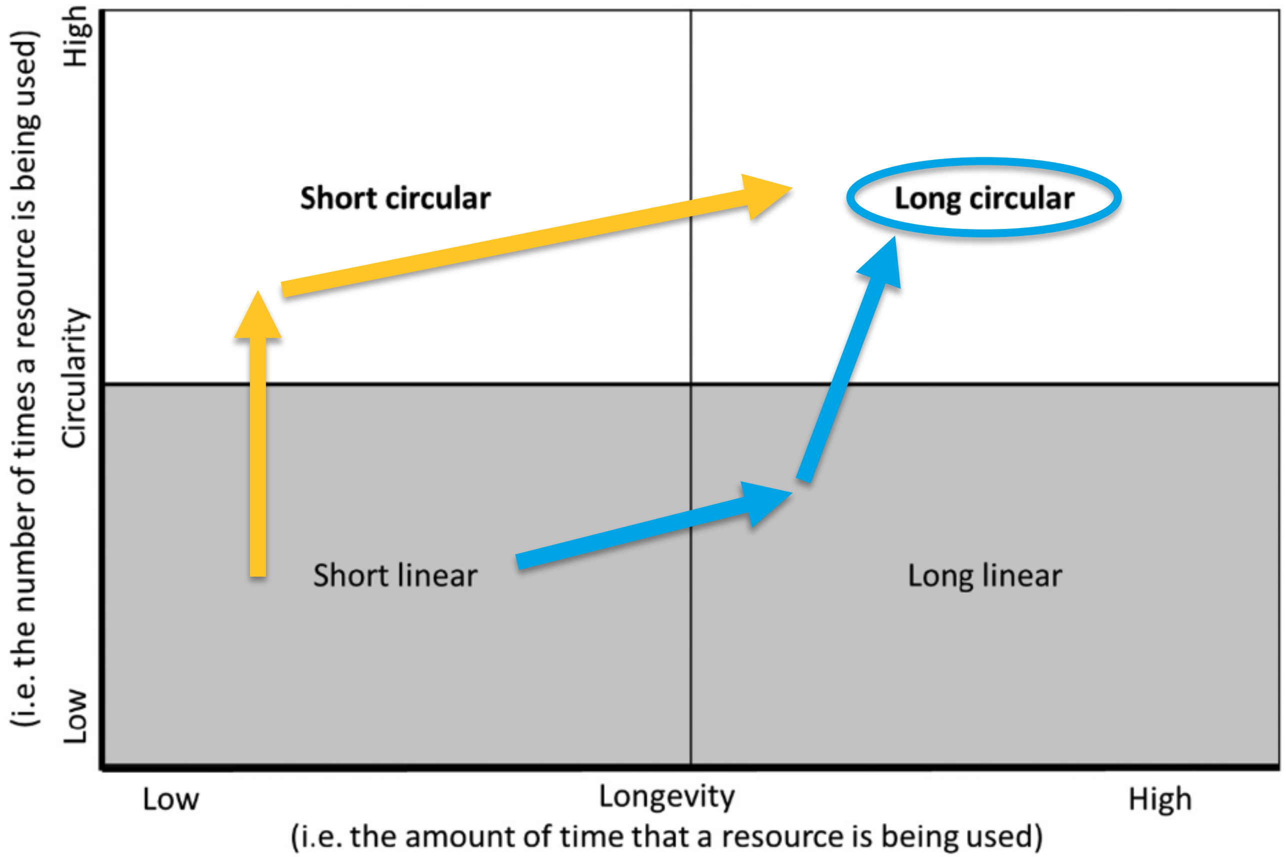
Figure 1
Circularity strategies within the production chain, in order of priority



Source: RLI 2015; edited by PBL

Potting et al. 2017

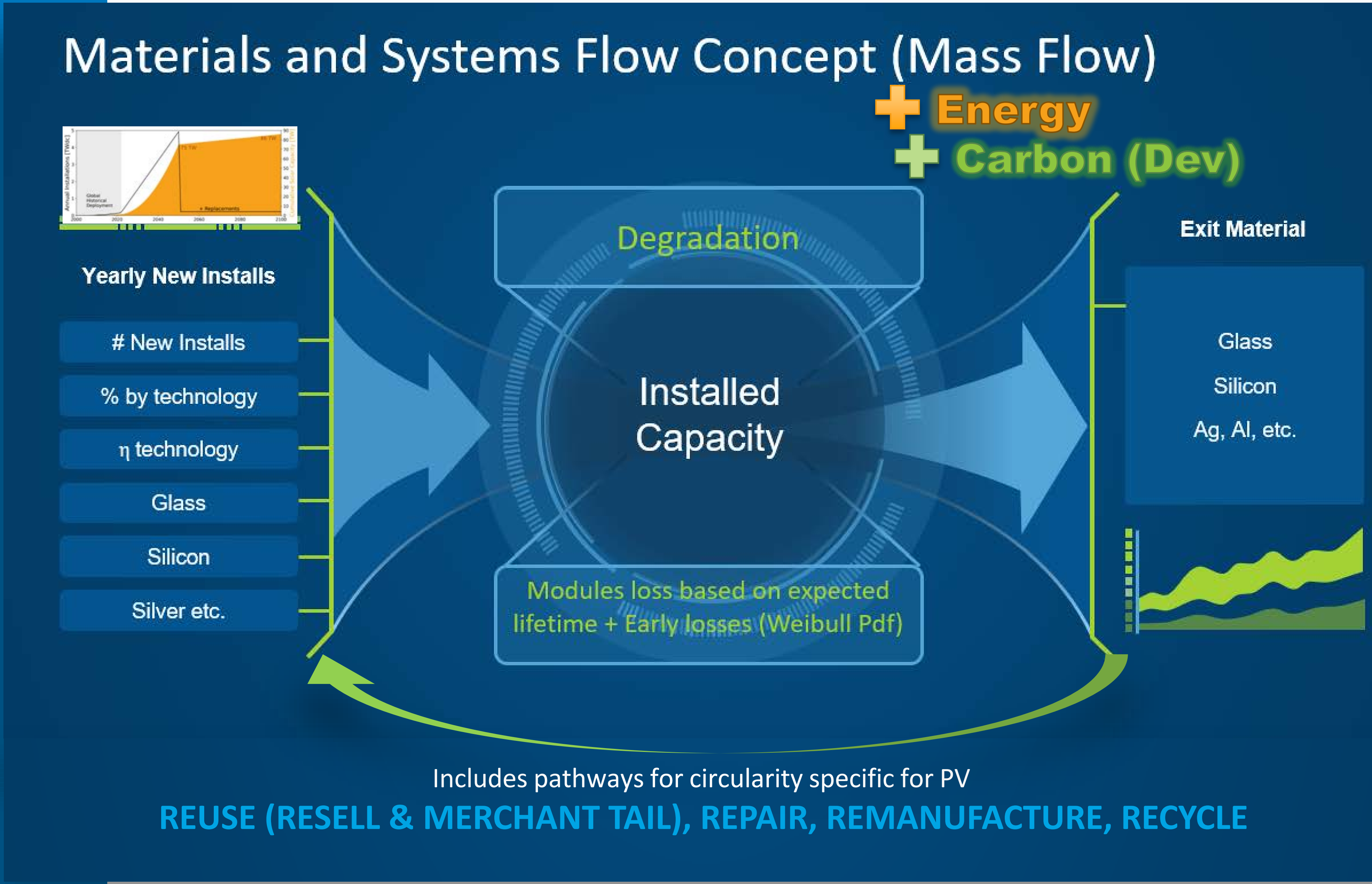
Transition from linear to circular economy
also has a time dimension
think about use phase



Figge et al. 2018

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

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

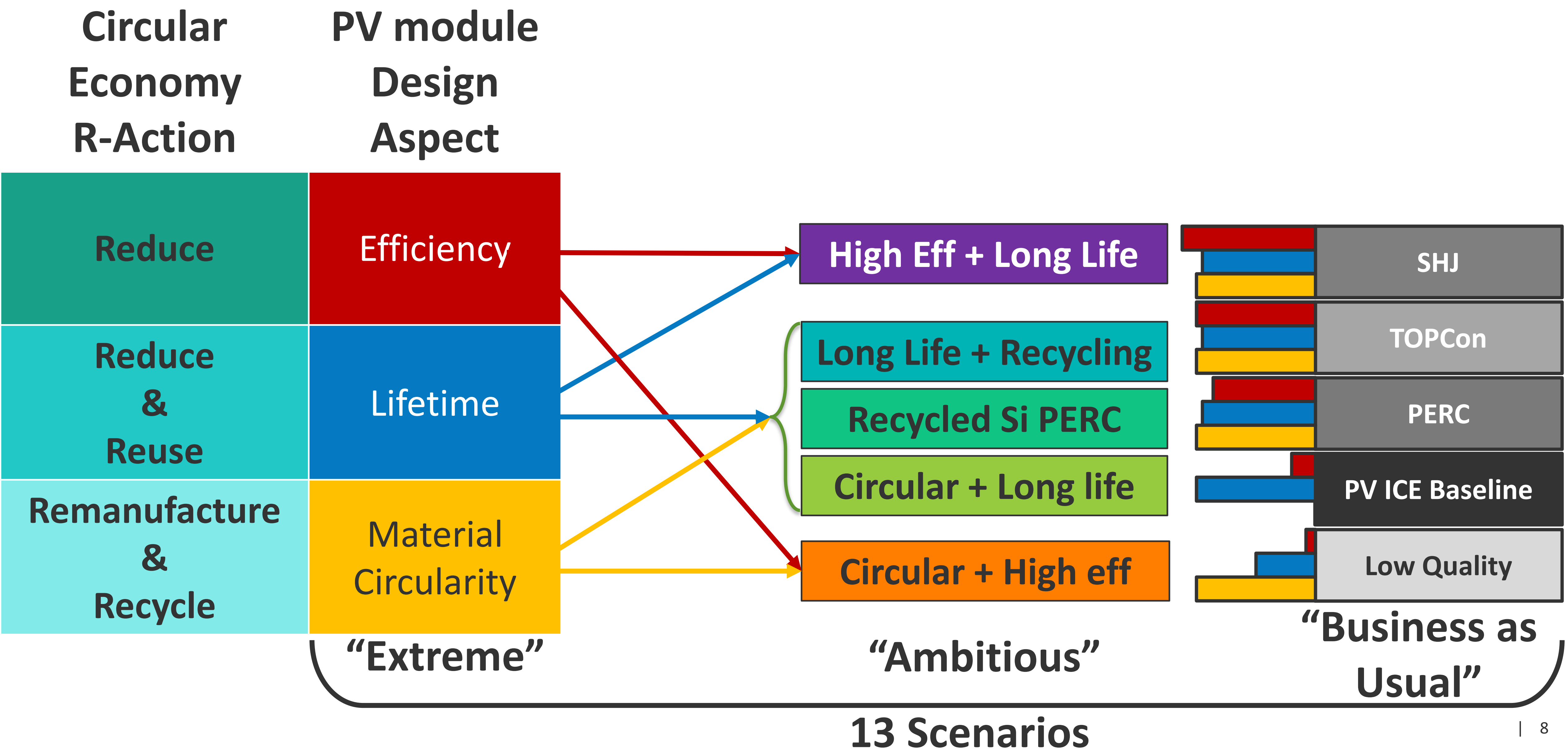
Net Energy
Energy Generated minus Energy Demand

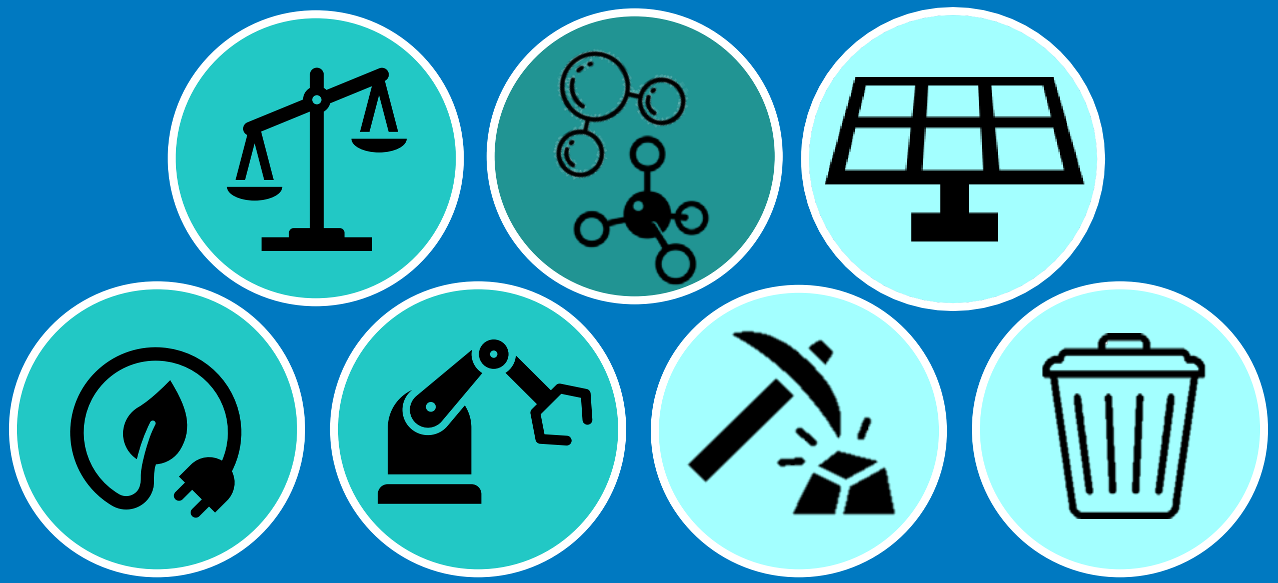
Energy Balance
Energy Generated divided by Energy Demand

More metrics!

Supply Chain Security
Just and Reliable sourcing of materials

How Circular Economy aligns to PV module design aspects





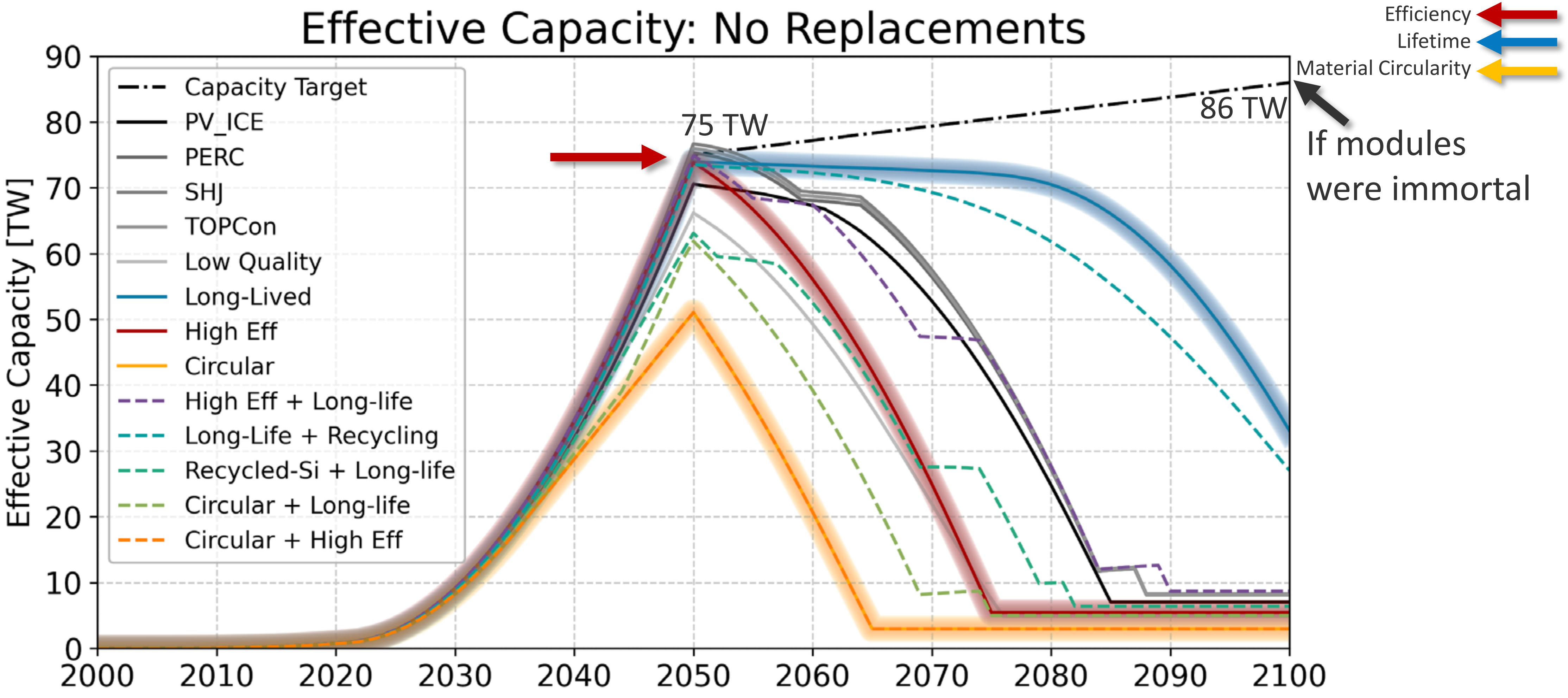
Let’s try out **Efficiency**

Efficiency is a “Reduce” Circular Economy action

Includes bifaciality.

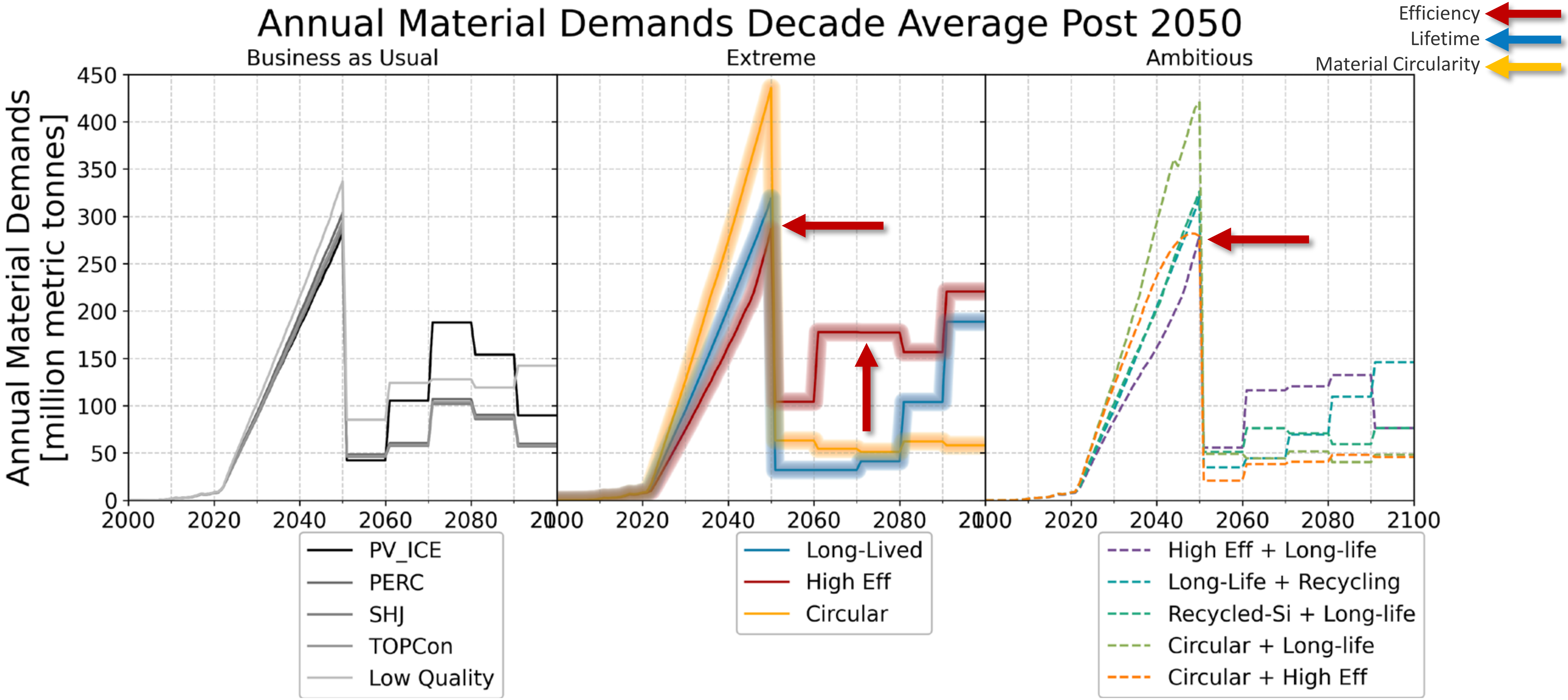
How does improving efficiency impact our metrics?

Efficiency through bifaciality is “bonus” capacity



Efficiency helps maintain higher capacities

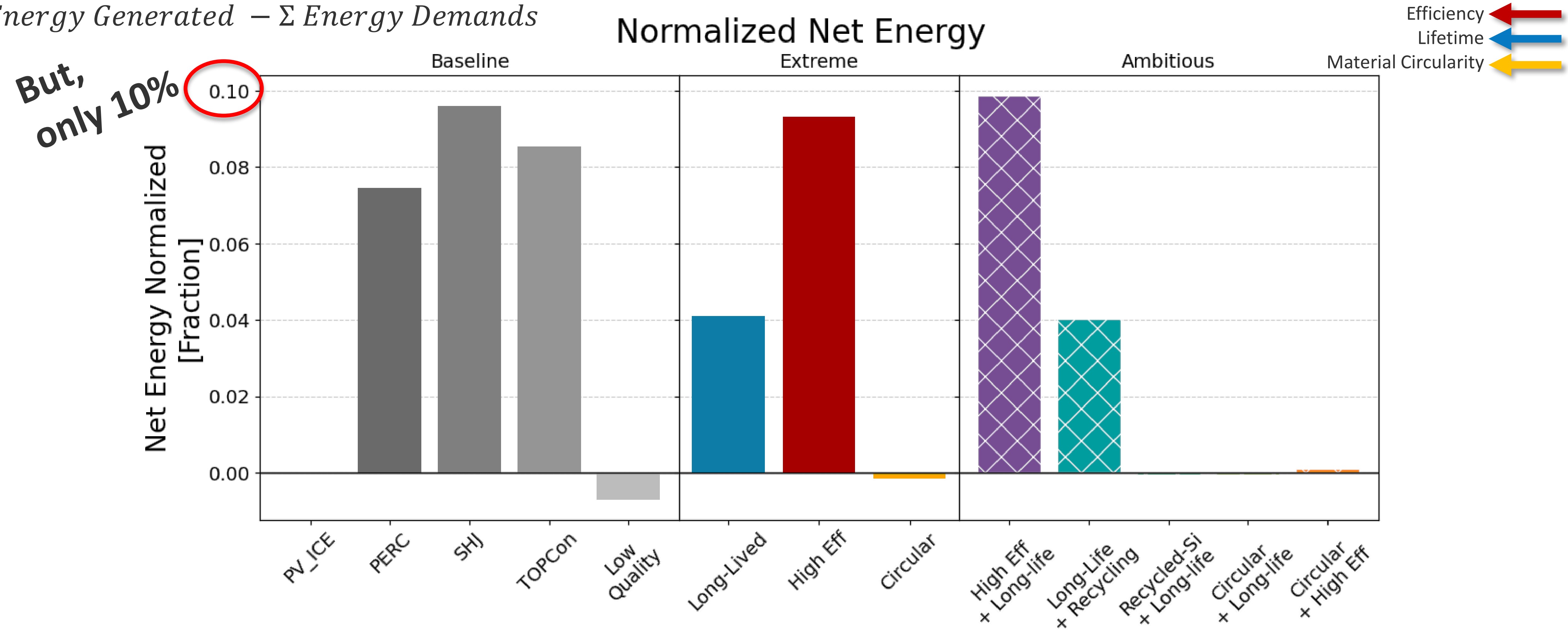
Efficiency slightly reduces peak material demand



Efficiency improves mass/power; need less material for the same power, BUT, without material circularity or lifetime, requires more material post-2050

Bifaciality: Improves Net Energy

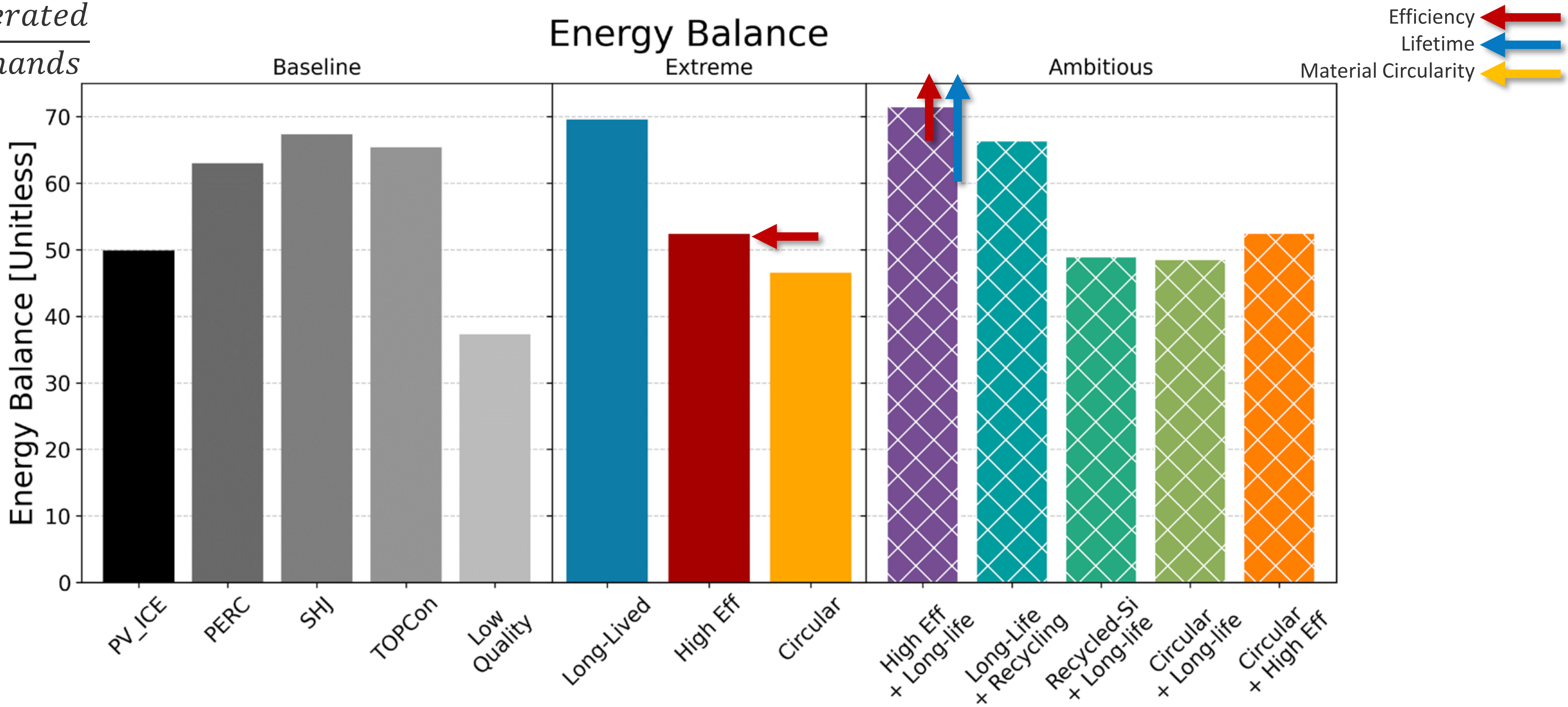
$\Sigma\, Energy\ Generated\ - \Sigma\, Energy\ Demands$



Bifaciality improves net energy; all apparent scenarios have some bifaciality

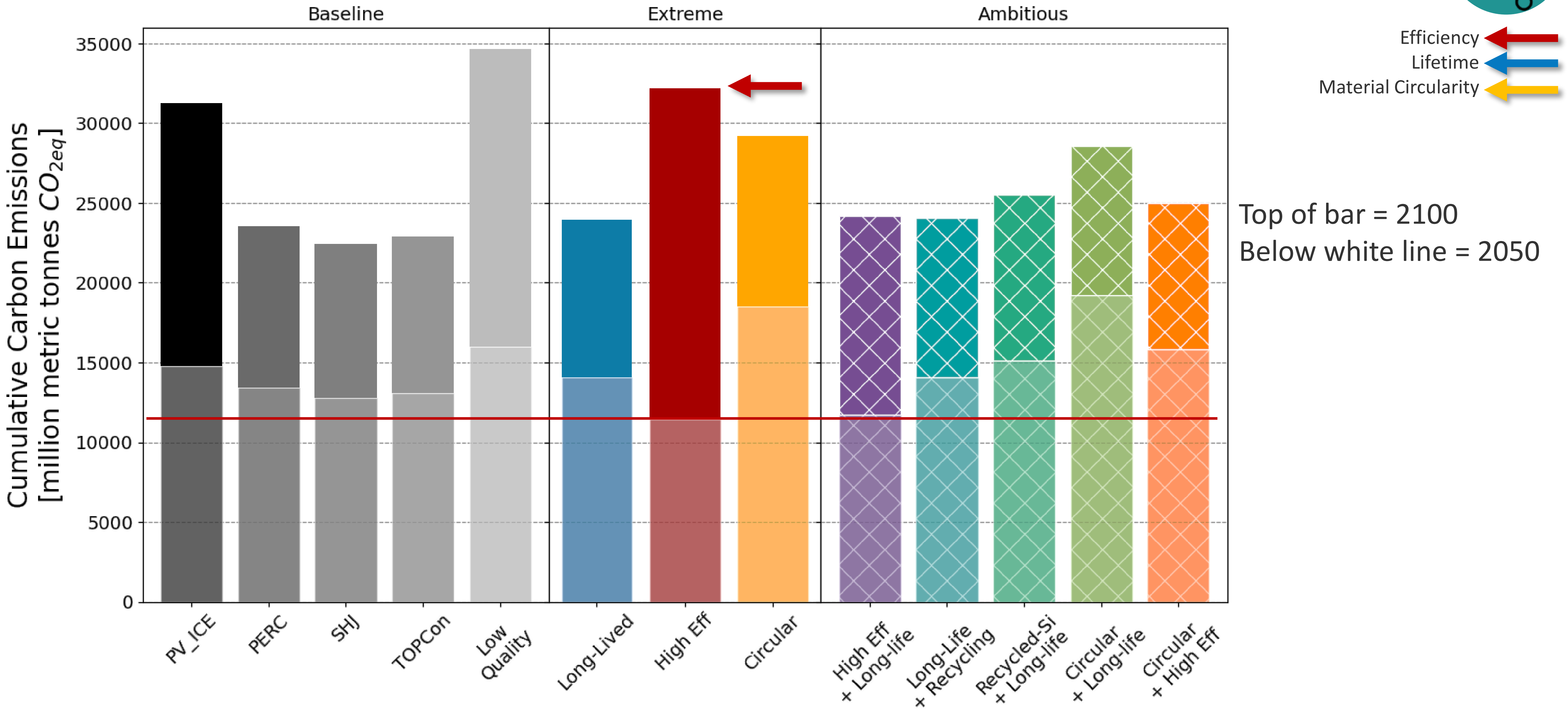
Lifetime + Efficiency Maximizes Energy Balance

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



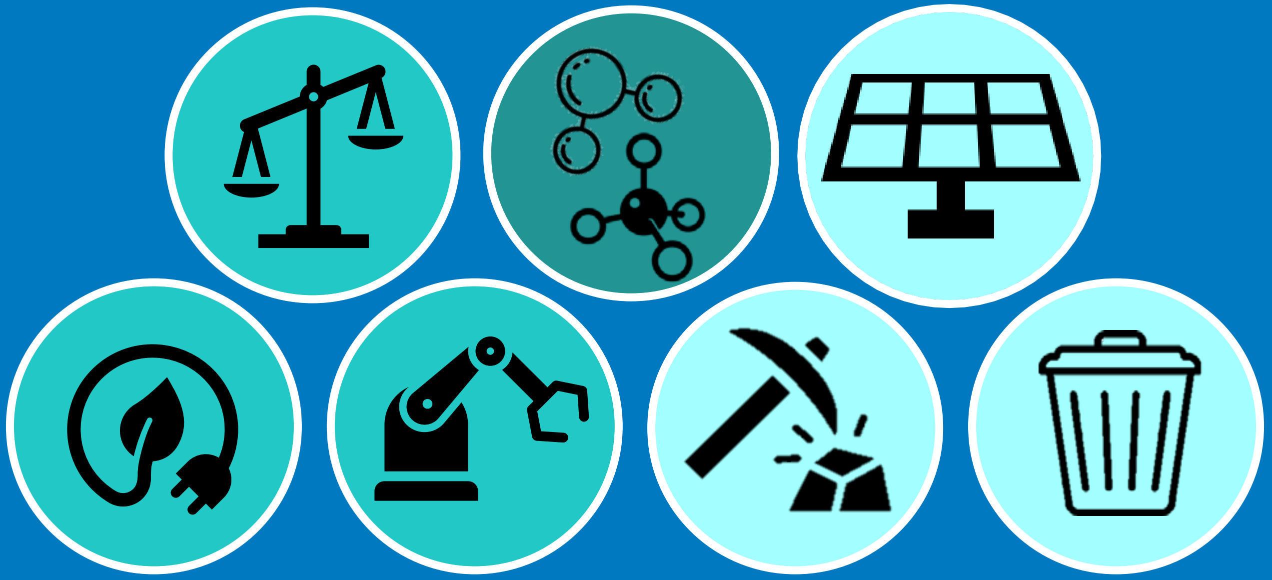
Efficiency and bifaciality alone does *not* maximize energy balance.

Cumulative Emissions in 2050, 2100



Efficiency & Bifaciality minimizes emissions pre-2050 (fewer modules to meet capacity target)

BUT 2nd largest emissions in 2100 due to large material demands later.

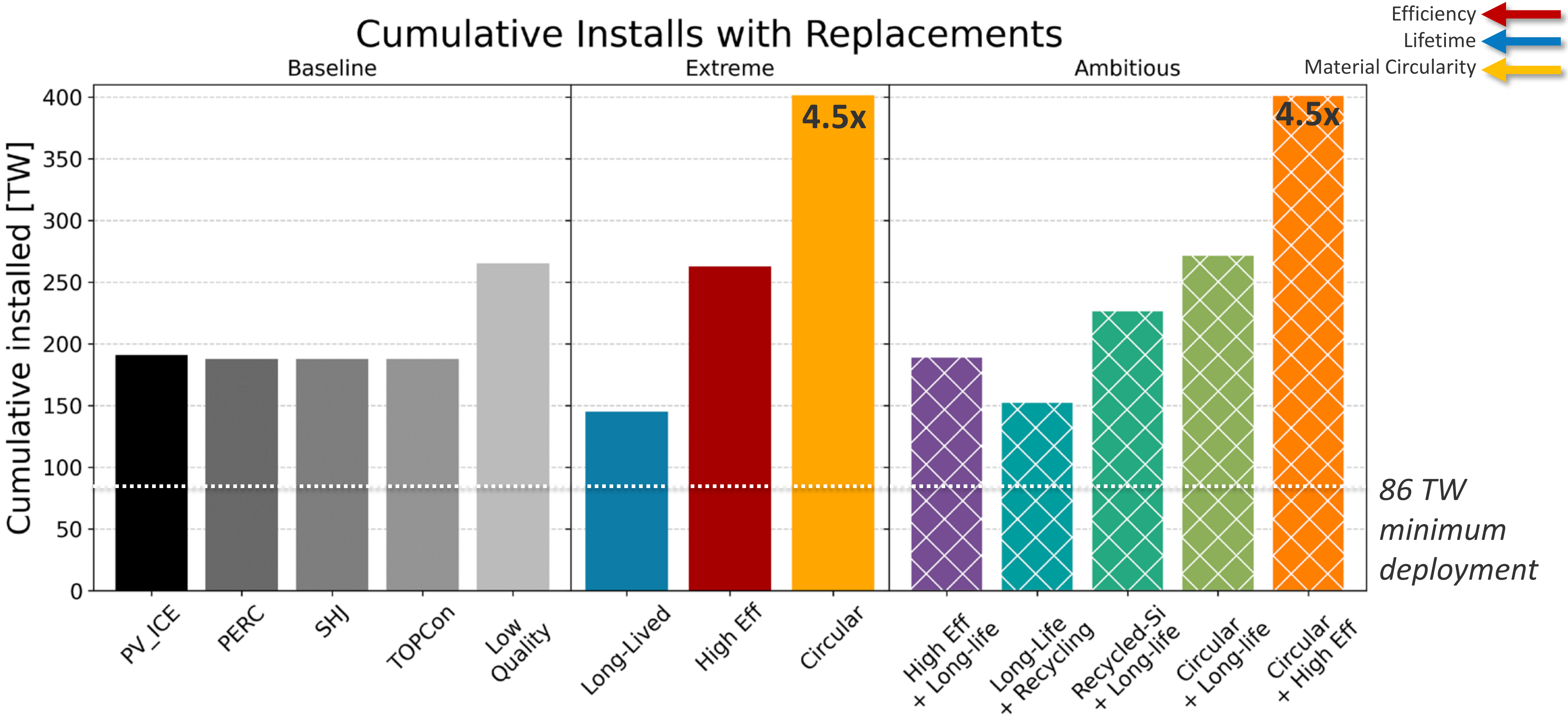


Let's try out **Material Circularity**

Material Circularity is a "Remanufacture" and "Recycle" Circular Economy action

How does improving material circularity impact our metrics?

Cumulative Deployment 2000-2100 with Replacements

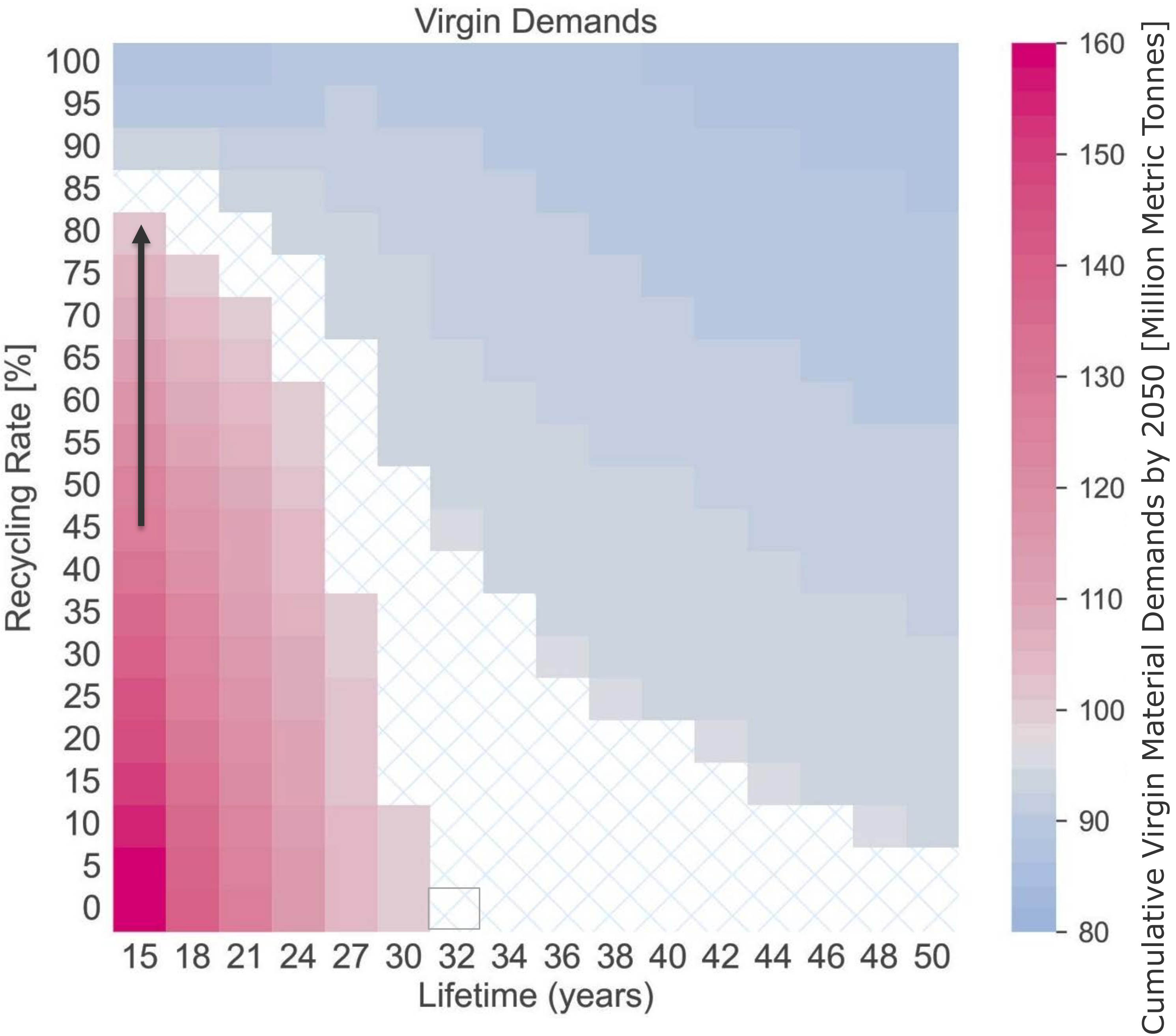


Envisioning a high material circularity with short lifetime to cycle to new tech fast

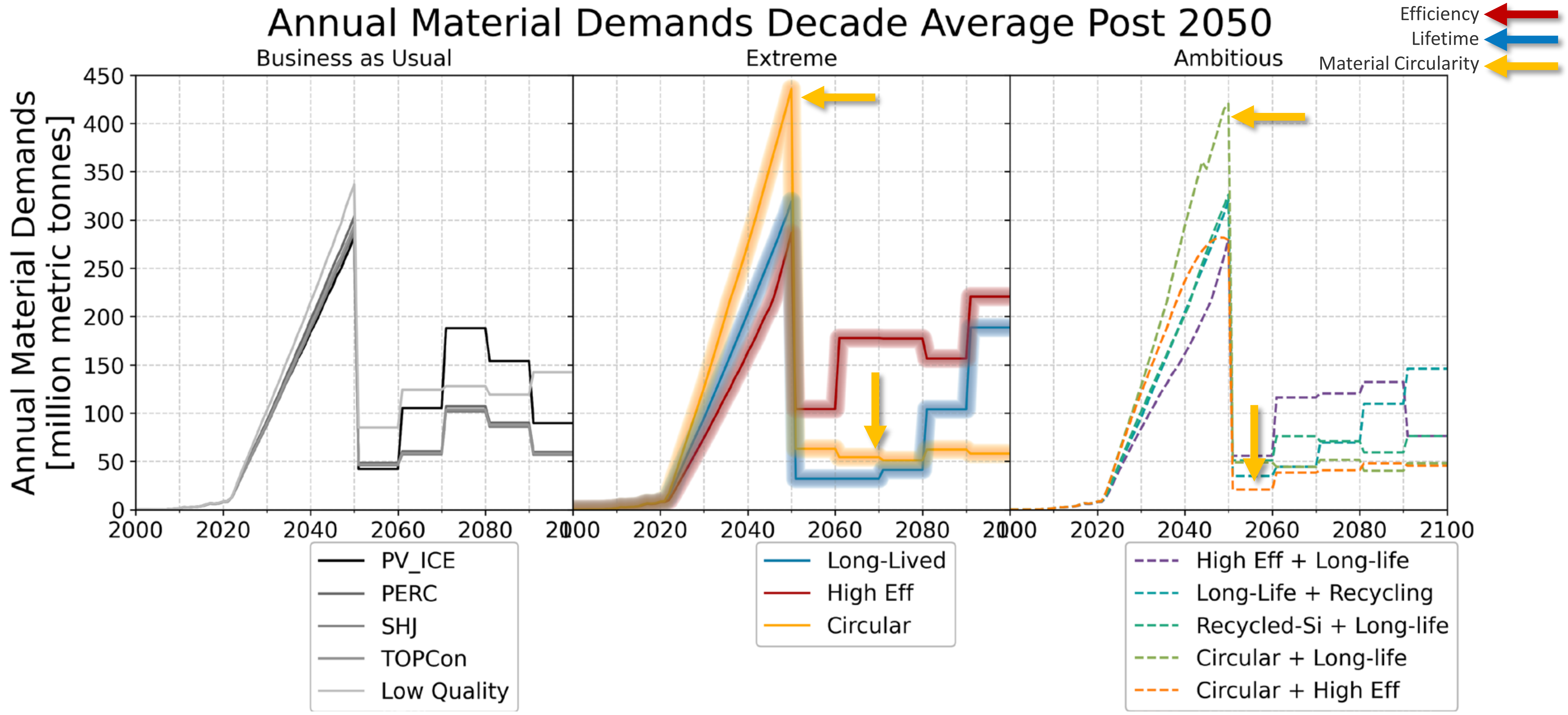
→ Requires 4.5x deployment = 4.5x manufacturing

Virgin Material Demands

- MUST be >90% closed-loop recycled for ***all component materials*** to reduce material demand
- No current PV technology achieves this

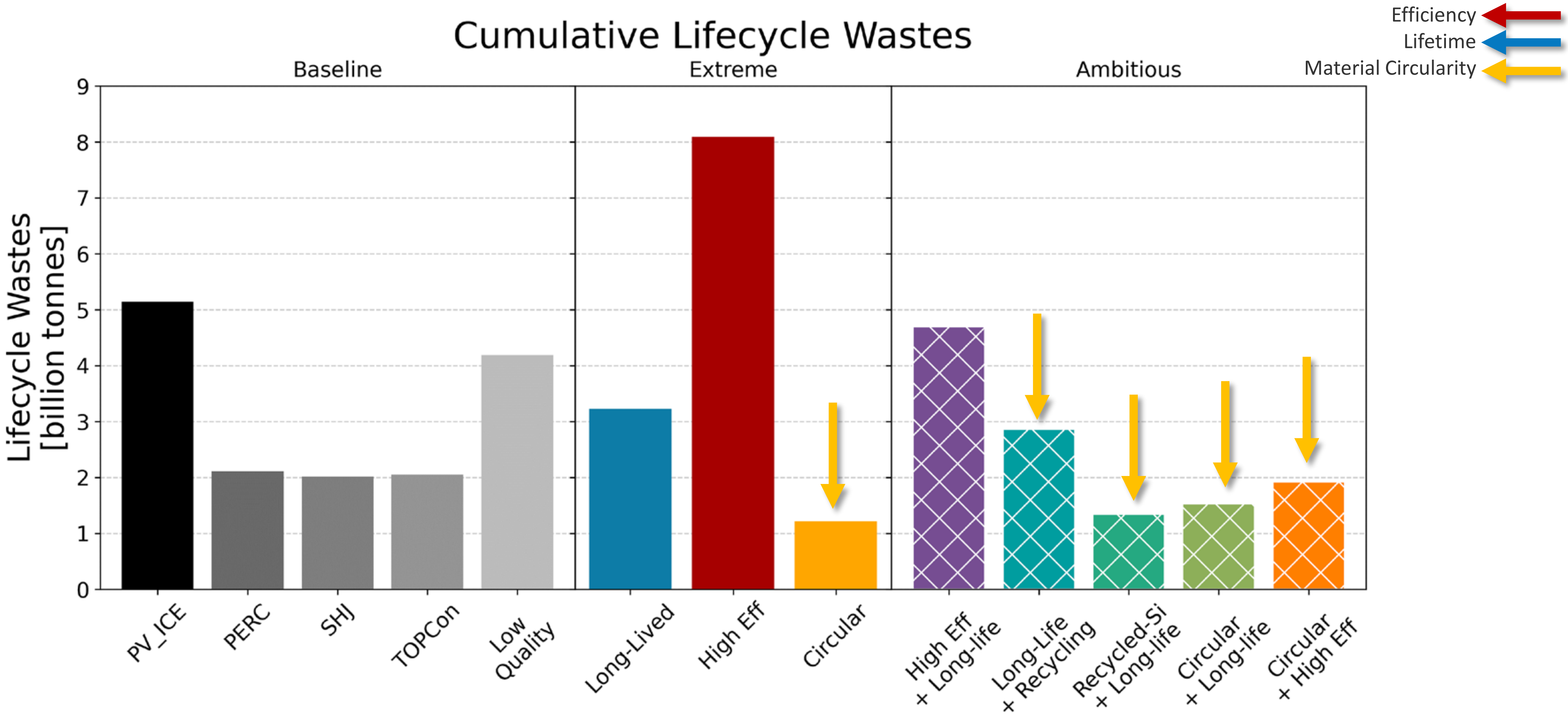


Material Circularity peaks material demand, then lowers after 2050



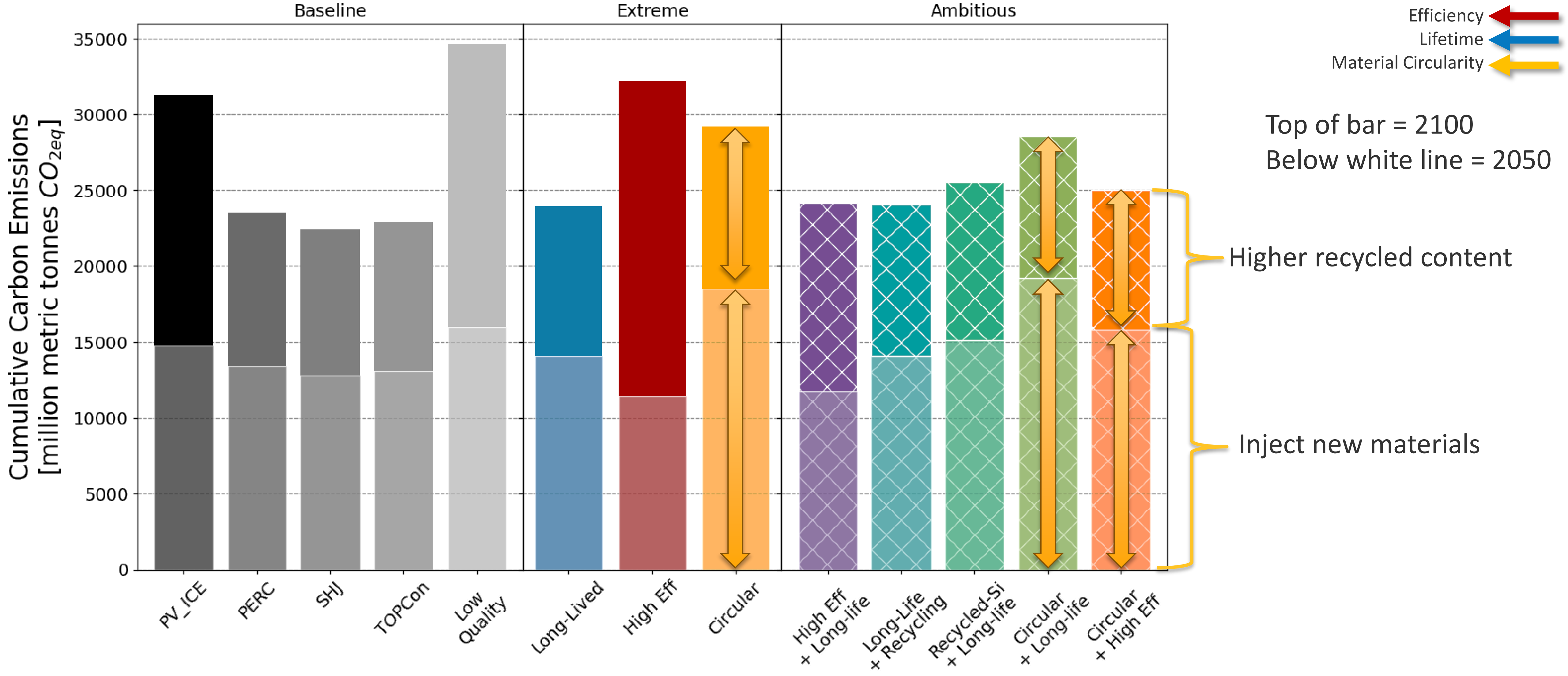
High deployment rates after 2050 don't eliminate need for non-recycled materials

Material Circularity: Great at Waste Minimization

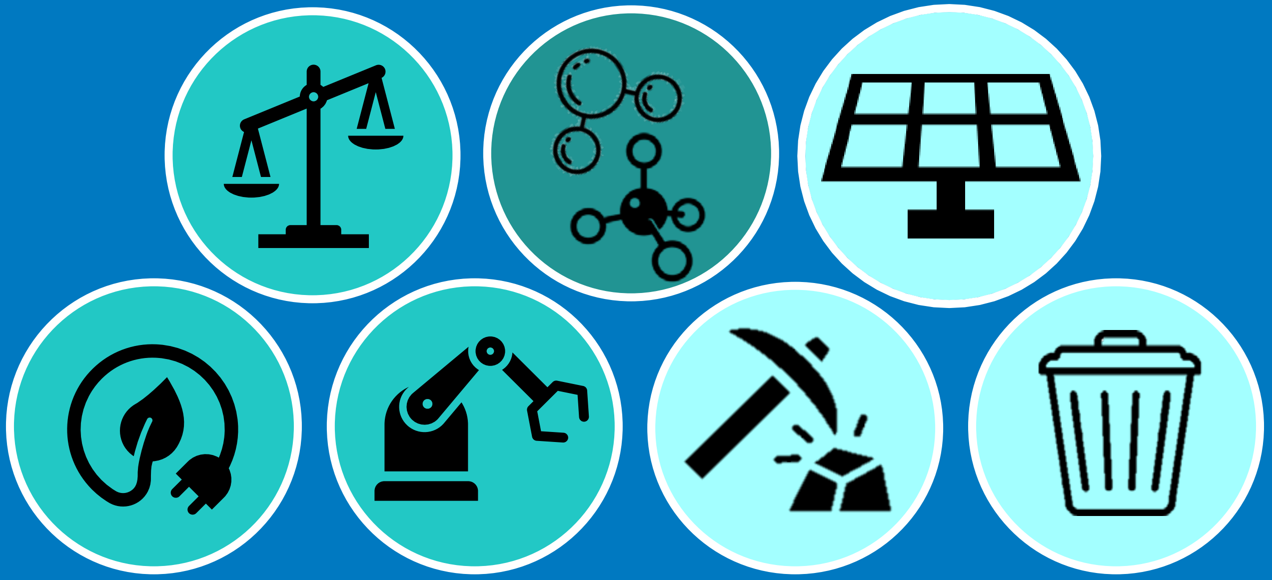


Recycling primarily keeps materials out of the landfill

Cumulative Emissions in 2050, 2100



Material circularity can help reduce carbon in second half of century

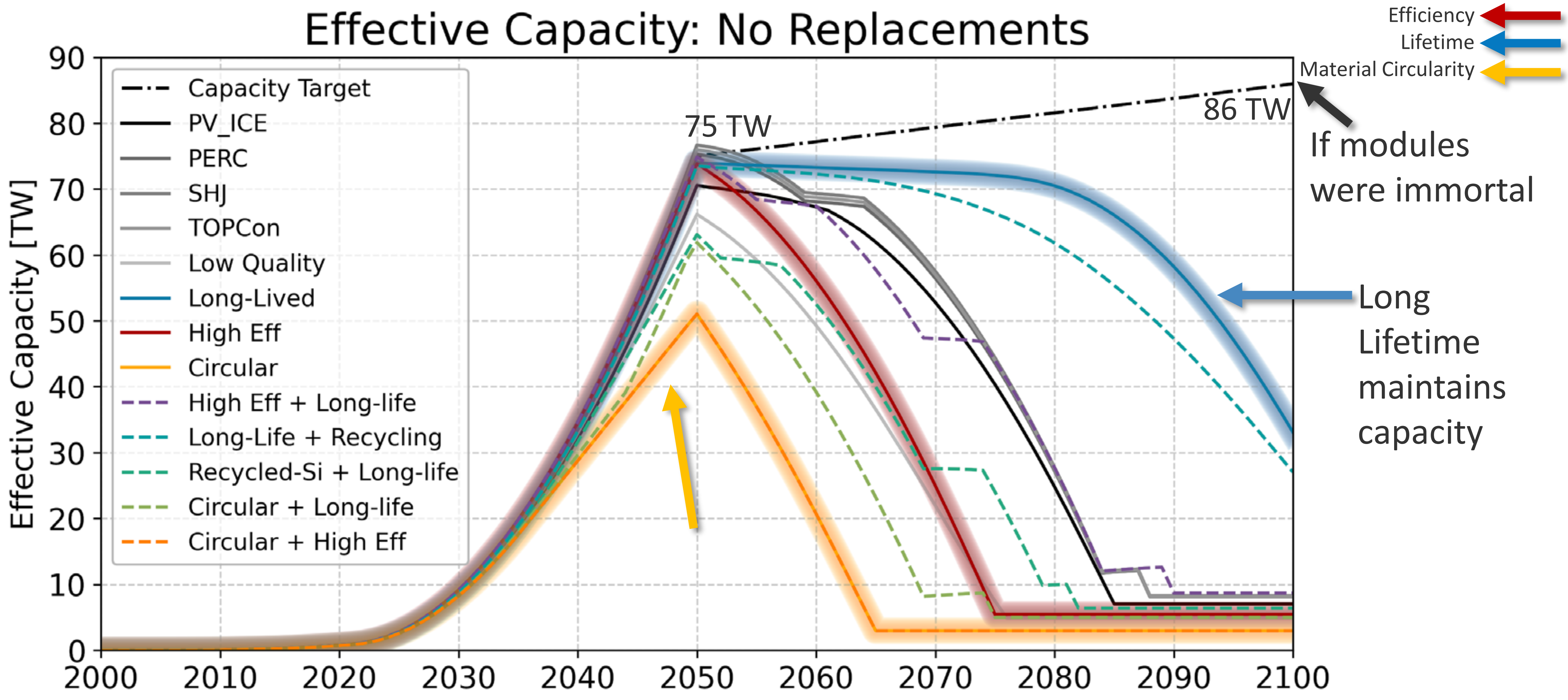


Let’s try out **Lifetime**

Lifetime is both a “Reduce” and “Reuse” Circular Economy action

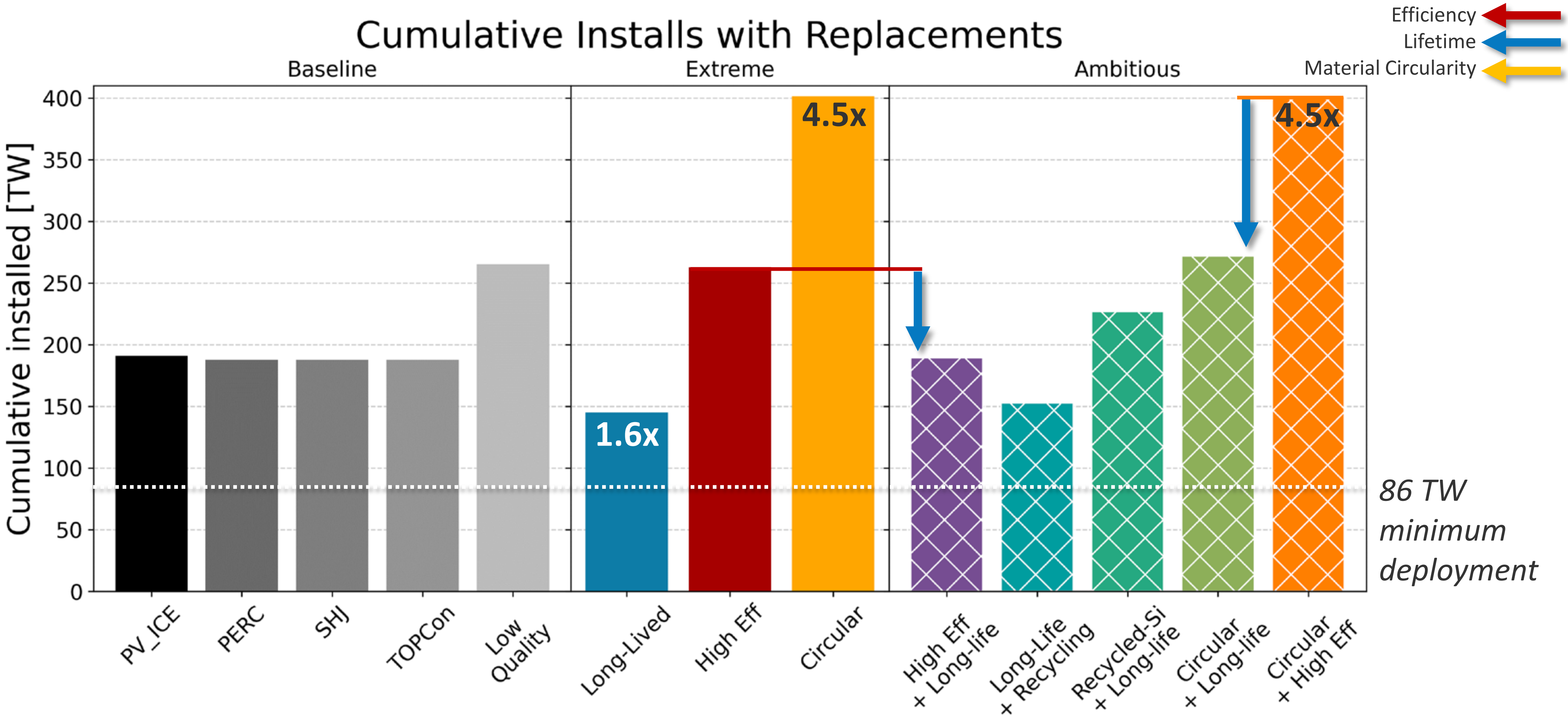
How does improving lifetime impact our metrics?

All Module Lifetimes Require Replacements by 2100



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

Cumulative Deployment 2000-2100 with Replacements



Short lifetimes = 4.5x min deployment

Long lifetimes = 1.6x min deployment

For every 0.1%/year degradation, save 2 to 3 TWs of replacements by 2050

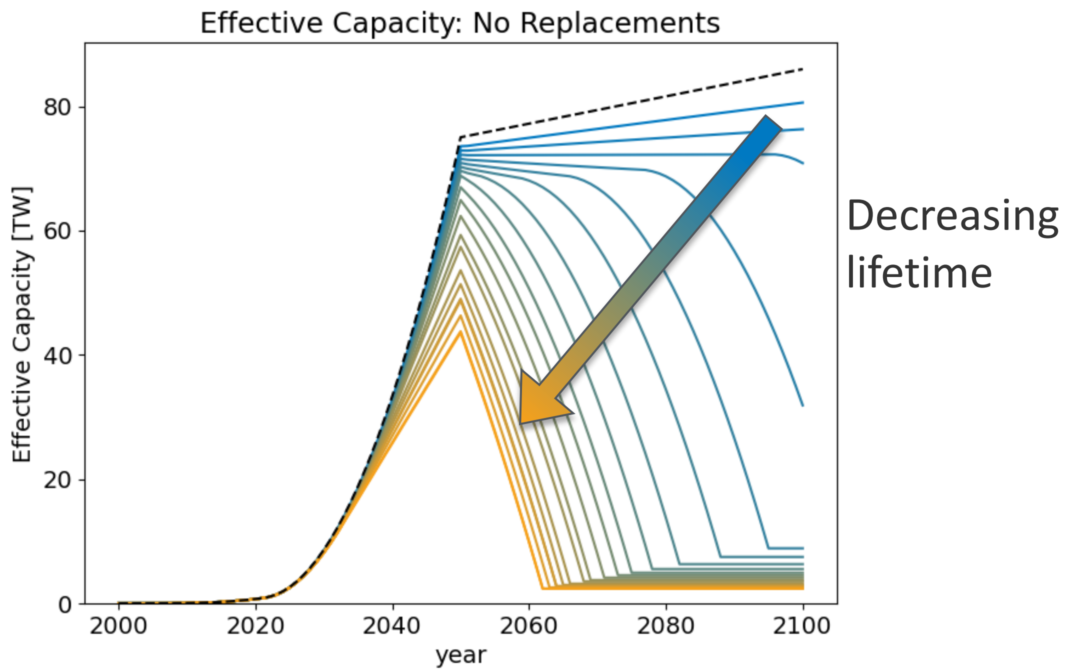
On average, save		
20 to 60 GW	2 to 3 TW	20 to 23 TW
by 2030	by 2050	by 2100

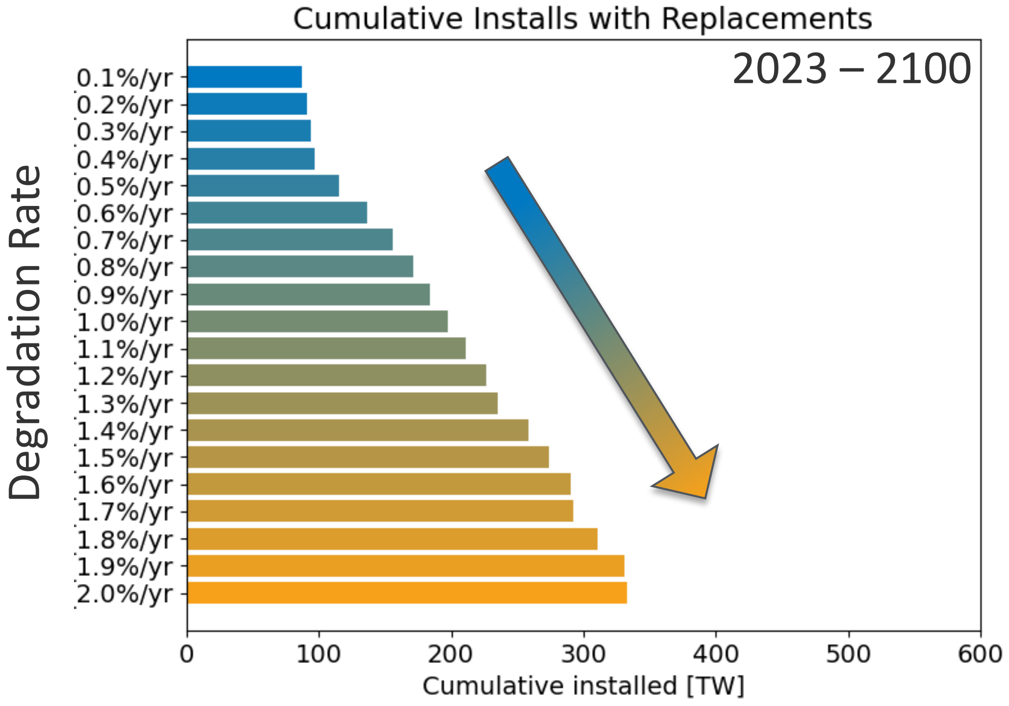
Fewer replacements =

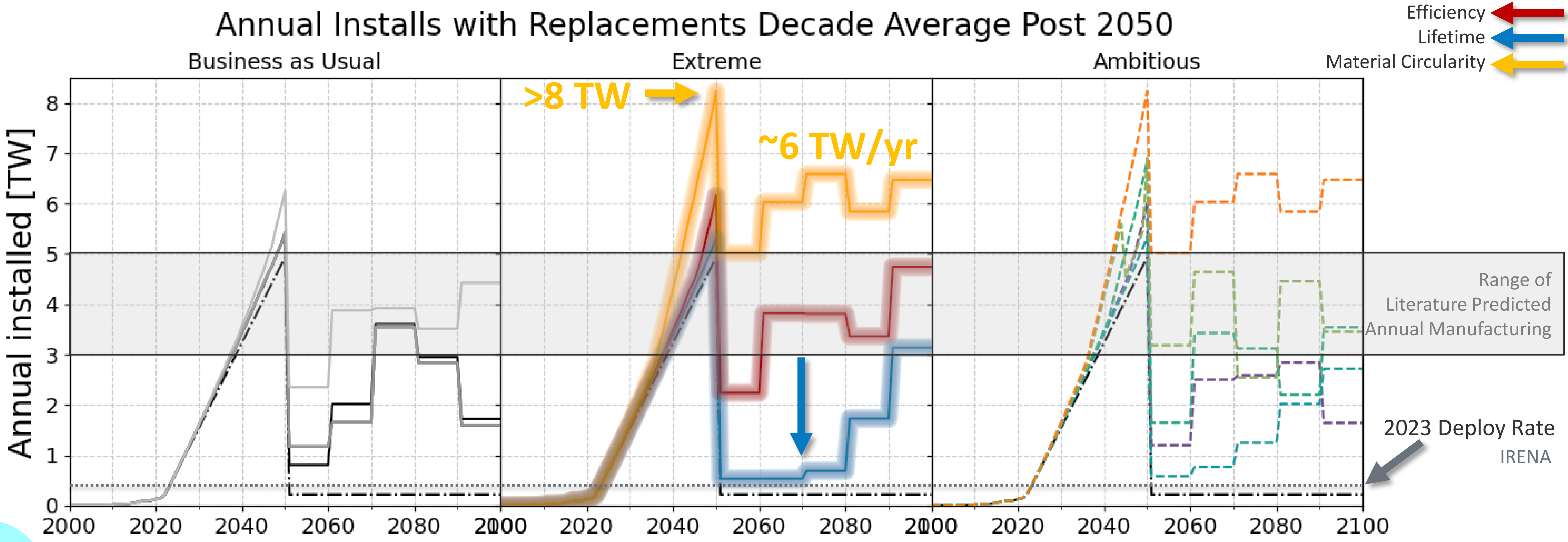
less manufacturing =

less logistics =

Reduce







Annual Deployment including replacements is highly se

Lifeti

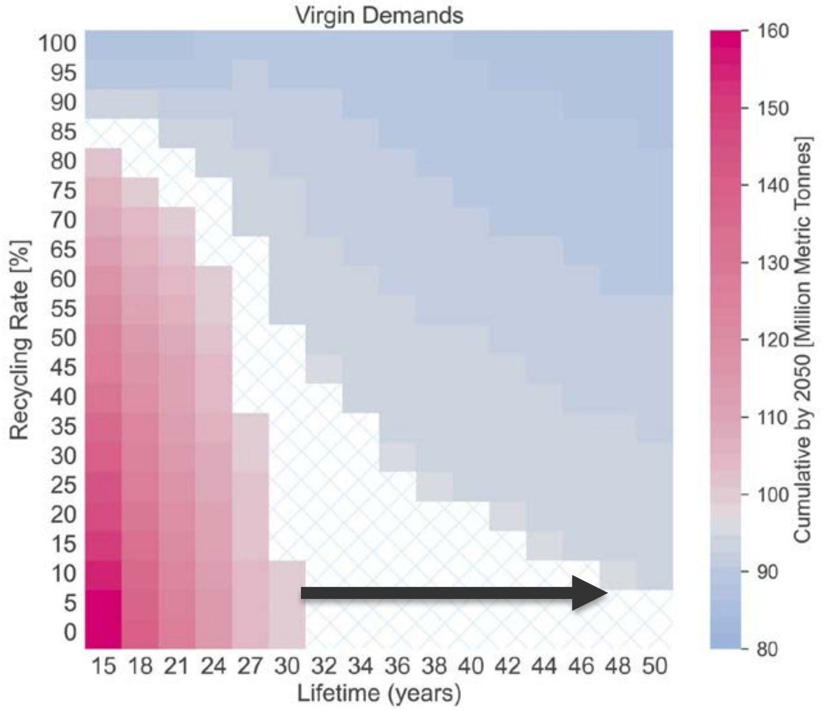
- Short-lived modules (15 years) require annual deployment rates ~6 TW through 2100
- quired annual deployment

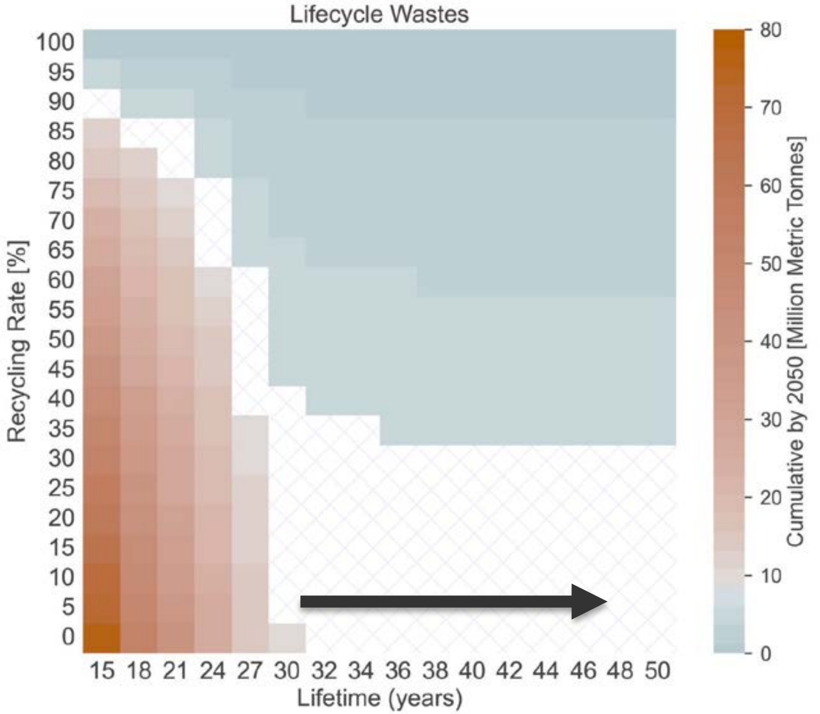
Deployment = Manufacturing
Manufacturing = environmental impacts, infrastructure, logistics, supply chains… jobs…

Virgin Material Demands & Lifecycle Wastes

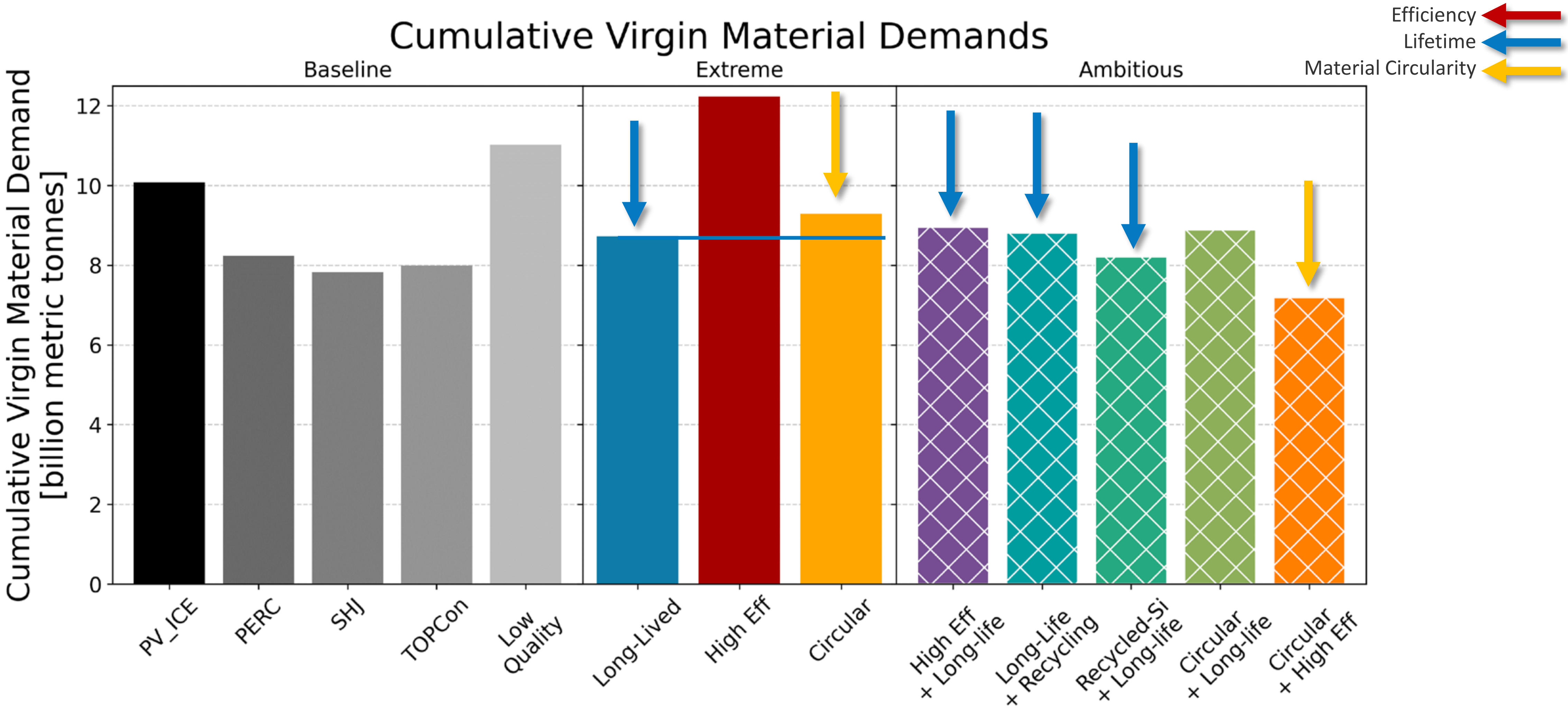
- No material demand or waste downside to lifetime extension

- Lifetime improvements lower the threshold for improving material circularity





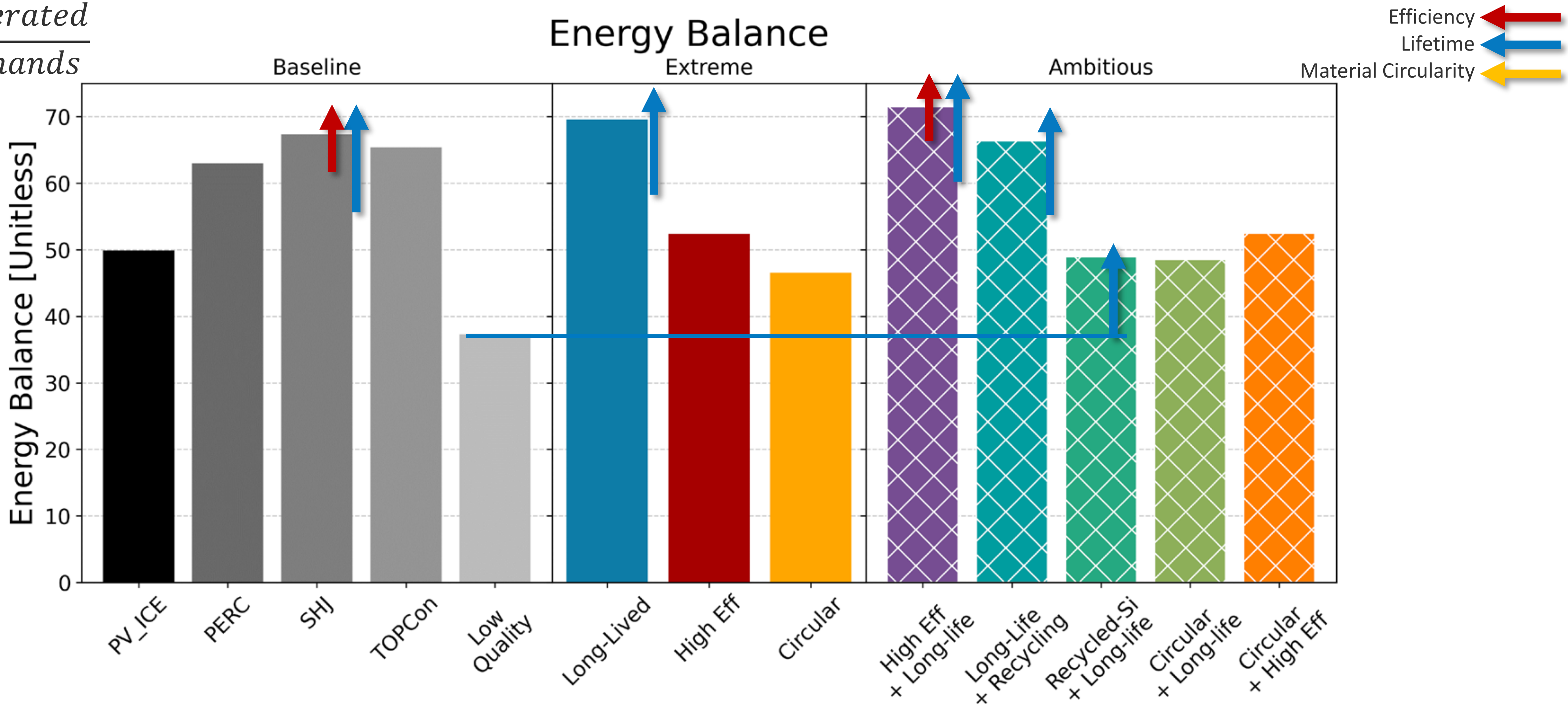
Material Circularity and Lifetime Reduce Virgin Material Demand



Short - linear to Long - circular

Lifetime: Maximizes Energy Balance

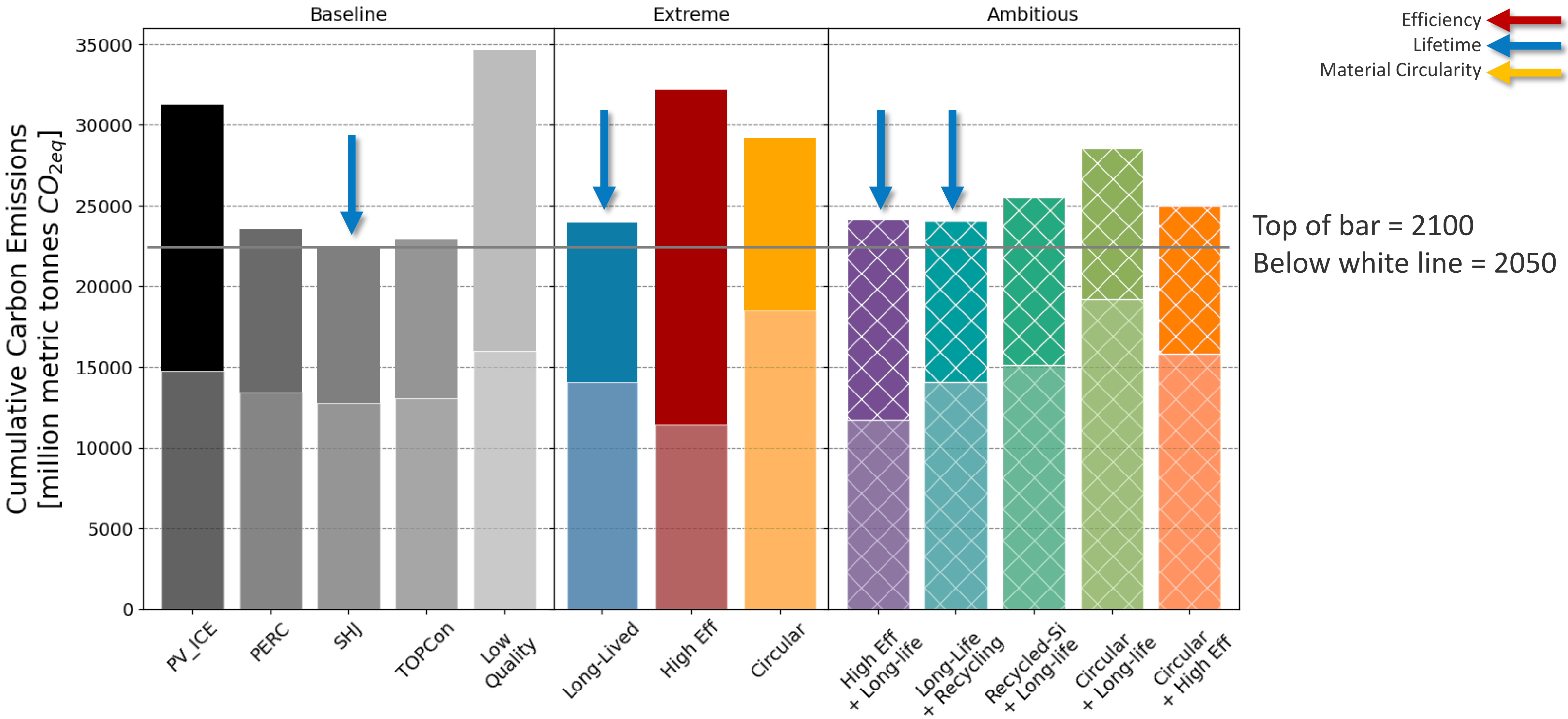
$$\frac{\sum Energy\ Generated}{\sum Energy\ Demands}$$



Lifetime improves energy balance

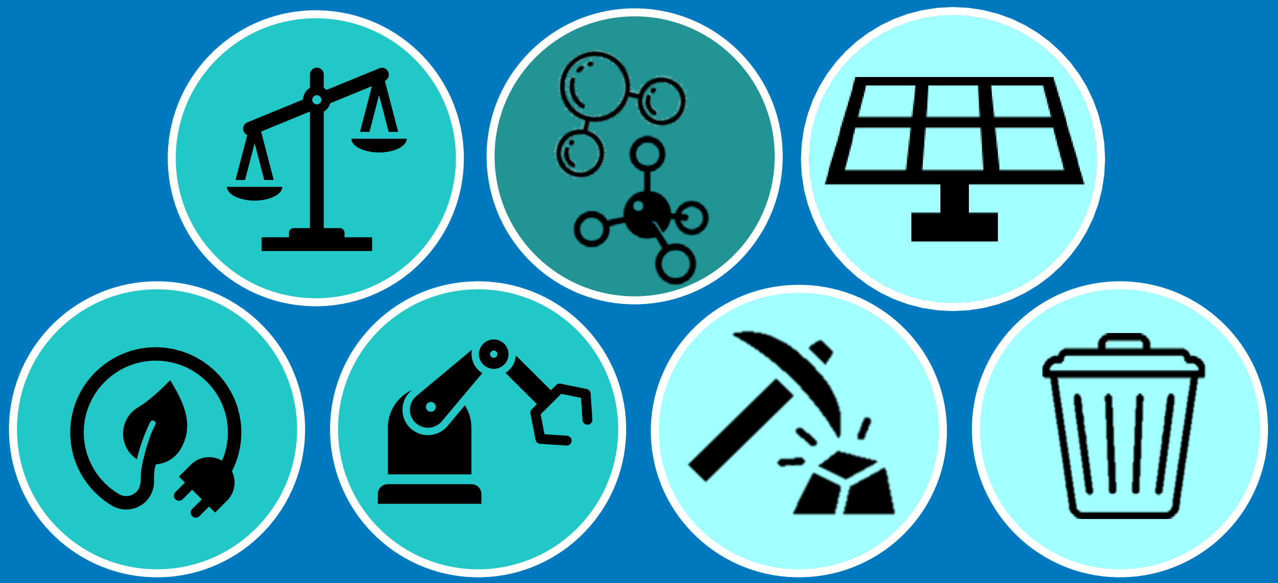
Lifetime+**Efficiency** maximizes energy balance

Cumulative Emissions in 2050, 2100



Lifetime ***now*** to minimize emissions by 2100

Deployments =
material demands =
energy demands =
carbon



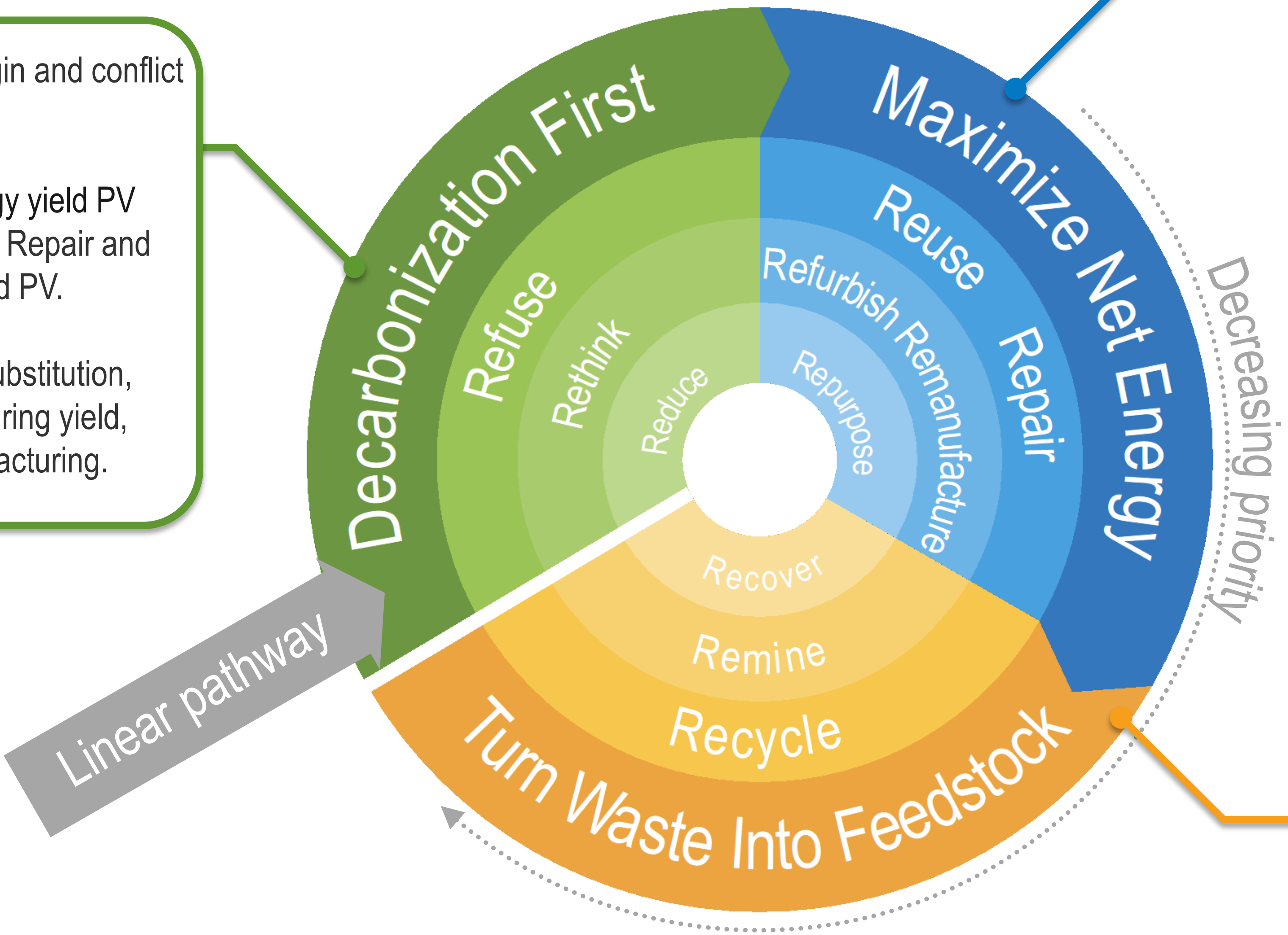
How to prioritize design improvements
where circular economy is in service to energy transition

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.



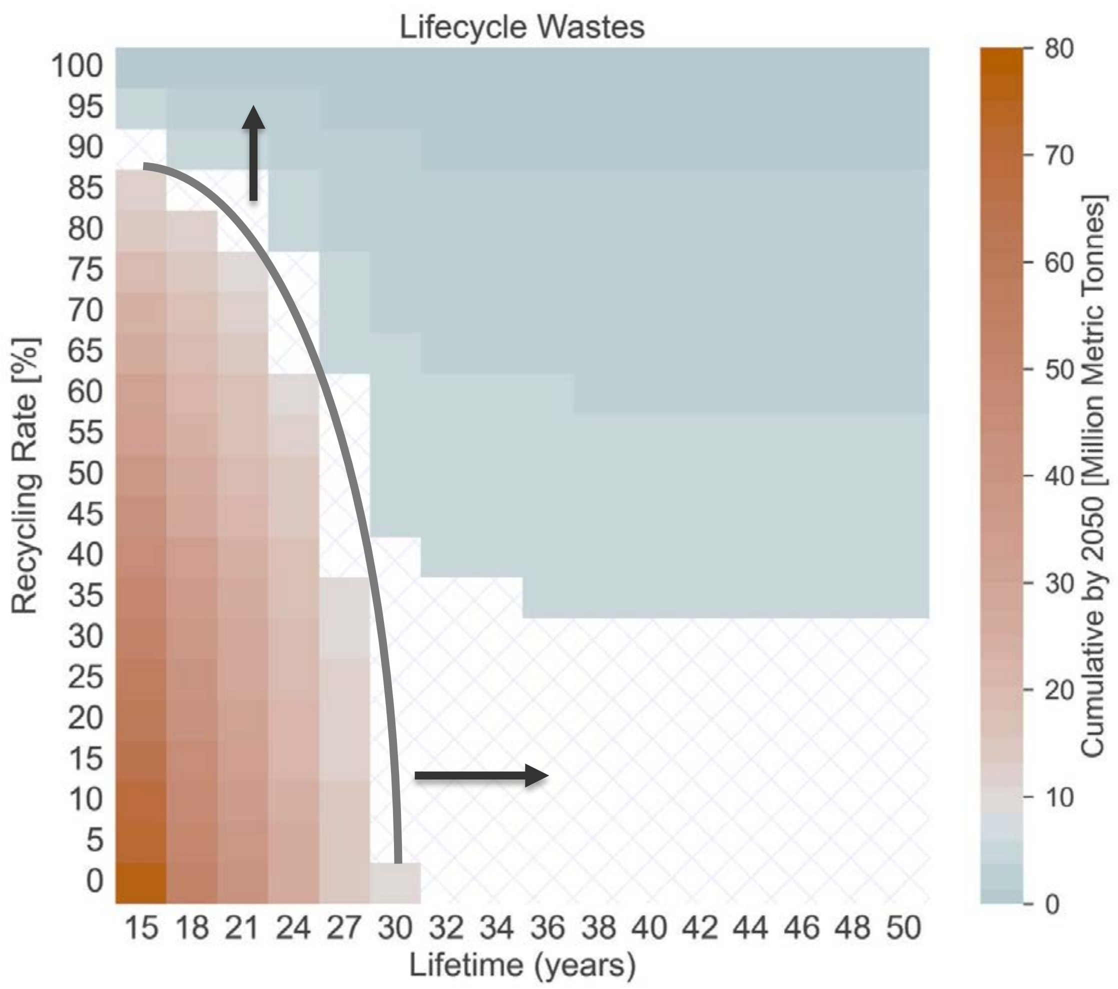
Reuse: Merchant tail, resell in secondary markets.
Repair: Onsite repair of modules and components.
Refurbish: Demount and transport modules for repairs Replace storm-damaged modules on site .
Remanufacture: Disassemble, replace cells, relaminate.
Repurpose: Repower system with new components

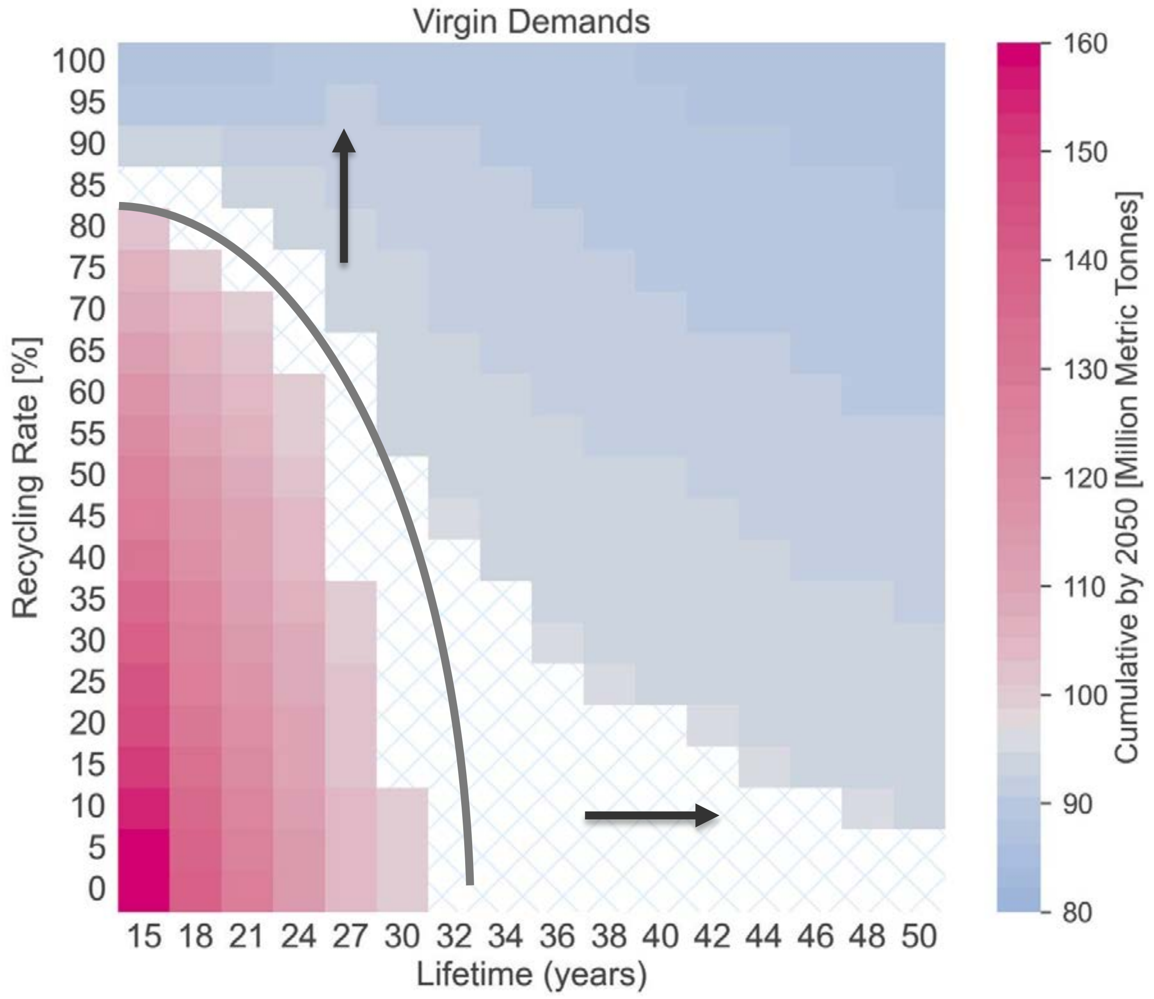
Recycle: Separate modules and components, reclaim materials.

Remine: Mine input materials from landfills, refine.

Recover: Burn component materials for energy generation.

Directions and Thresholds for Improvement





Directions for improvement of PV technology

Balance lifetime and material circularity

Mirletz et al. 2022, Plos One

Metric Table

		Capacity	Mass		Energy			Carbon			
	Scenario	**Total Deployment** *TW*	**Raw Material Demand** *bmt*	**Lifecycle Wastes** *bmt*	**Energy Demands** *TWh*	**Net Energy** *TWh*	**Energy Balance** *Unitless*	**Cumulative Emissions 2050** *CO2eq bmt*	**Cumulative Emissions 2100** *CO2eq bmt*	**Benefits**	**Harms**
Business as Usual	**PV ICE**	191	10.1	5.1	144,000	7,044,000	50	14.7	31.2	0	3
	PERC	188	8.2	2.1	122,000	7,569,000	63	13.4	23.5	6	0
	SHJ	188	7.8	2.0	116,000	7,719,000	67	12.8	22.4	6	0
	TOPCon	188	8.0	2.1	119,000	7,644,000	65	13.1	22.9	6	0
	Low Quality	265	11.0	4.2	193,000	6,995,000	37	16.0	34.6	0	5
Extreme	**Long-Lived**	145	8.7	3.2	107,000	7,333,000	70	14.1	23.9	4	0
	High Efficiency	263	12.2	8.1	150,000	7,699,000	52	11.5	32.2	2	3
	Circular	401	9.3	1.2	154,000	7,034,000	47	18.5	29.2	1	3
Ambitious	**High Eff + Long-life**	189	9.0	4.7	110,000	7,740,000	71	11.7	24.2	5	0
	Long Life + Recycling	152	8.8	2.9	112,000	7,328,000	66	14.1	24.1	3	0
	Recycled Si + Long-life	227	8.2	1.3	147,000	7,041,000	49	15.1	25.5	2	1
	Circular + Long-life	272	8.9	1.5	148,000	7,040,000	49	19.2	28.6	1	2
	Circular + High Eff	401	7.2	1.9	137,000	7,051,000	52	15.8	25.0	2	2
		Minimize				*Maximize*		*Minimize*		*Maximize*	*Minimize*

bmt = billion metric tonnes

Benefit — Harm

Lifetime improvement minimizes harms and maximizes benefits during energy transition.

But how “not perfect” are we talking?

Let’s put
current PV technology impacts in these metric categories into decarbonization context.

Wishlist:

- Reduce material demand
- Reduce wastes
- Reduce energy demands
- Reduce carbon intensity
- Improve energy yield

How much waste are we talking?

CBS MORNINGS ›

05/2023

A black eye for green energy? Renewable energy growth brings mounting waste challenge

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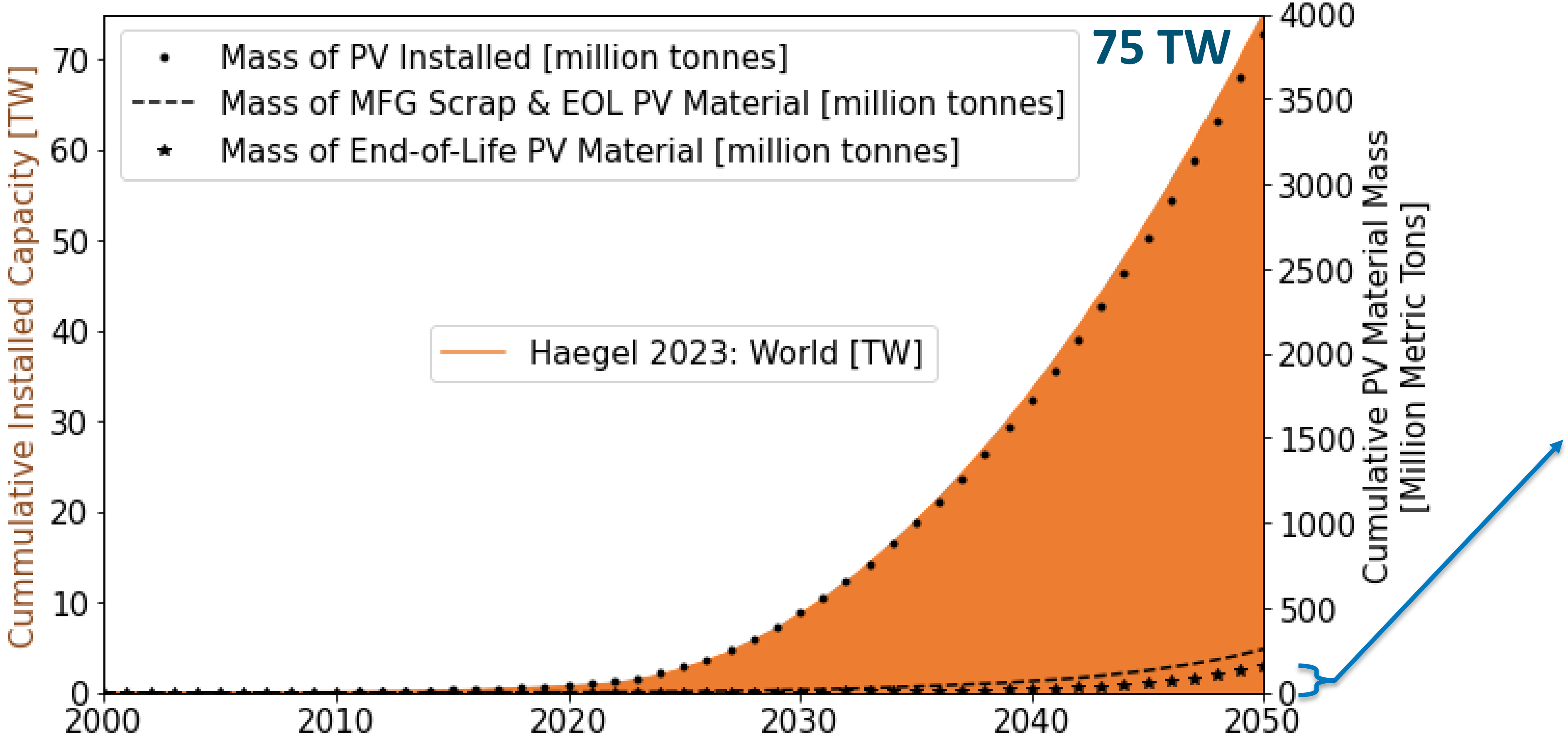
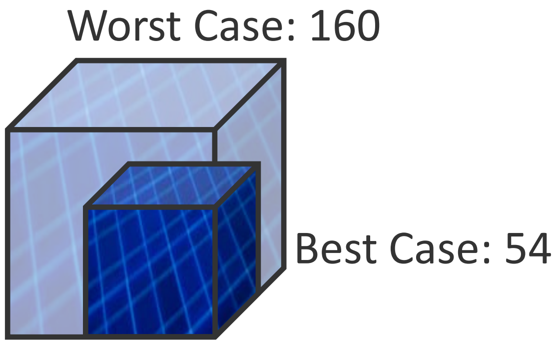
A black eye for green energy? Renewable energy growth brings mounting waste challenge

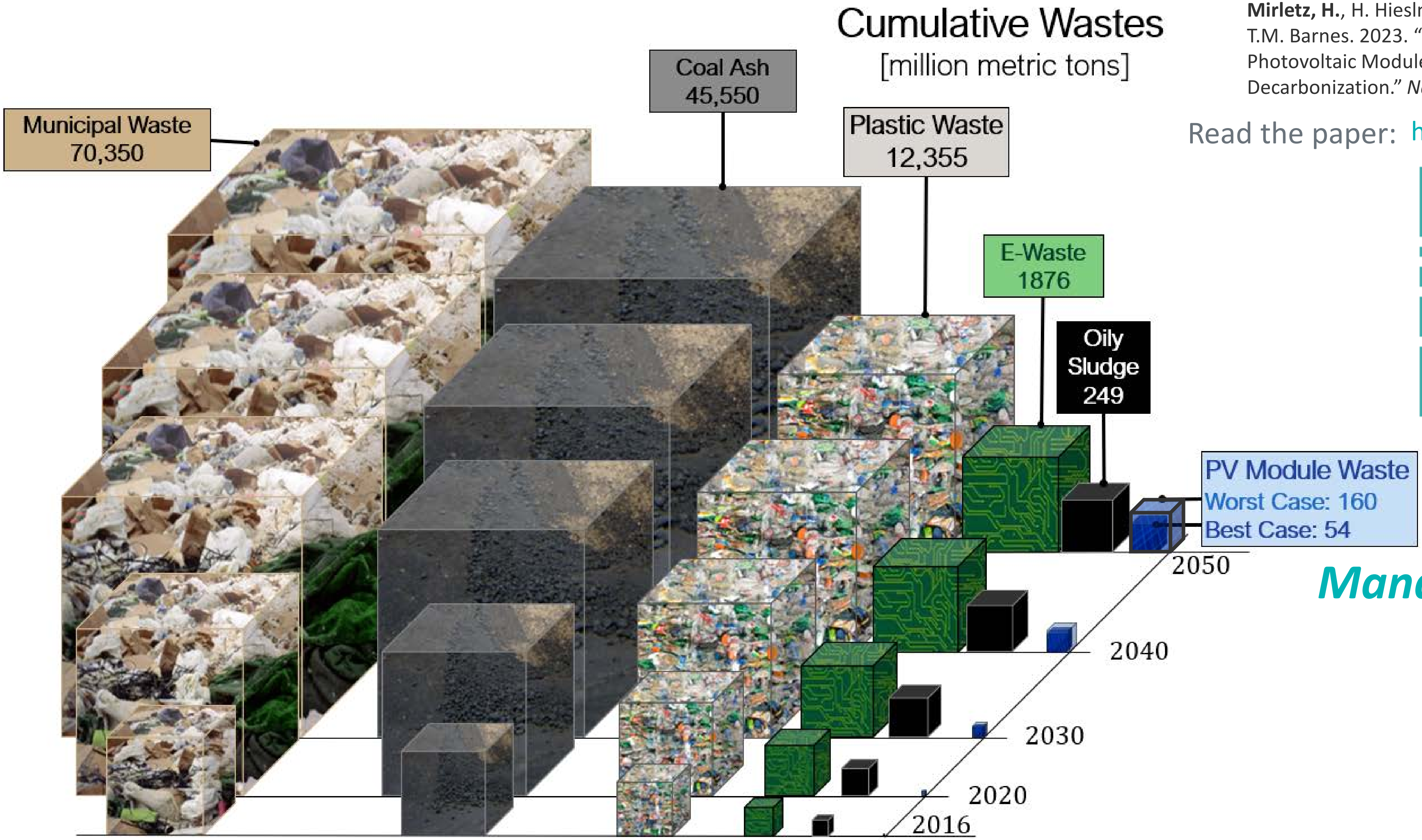


Mirletz 2023 PVRW



Million metric tonnes of PV end-of-life modules Cumulatively in 2050

Cumulative PV "Waste" by 2050 in Perspective

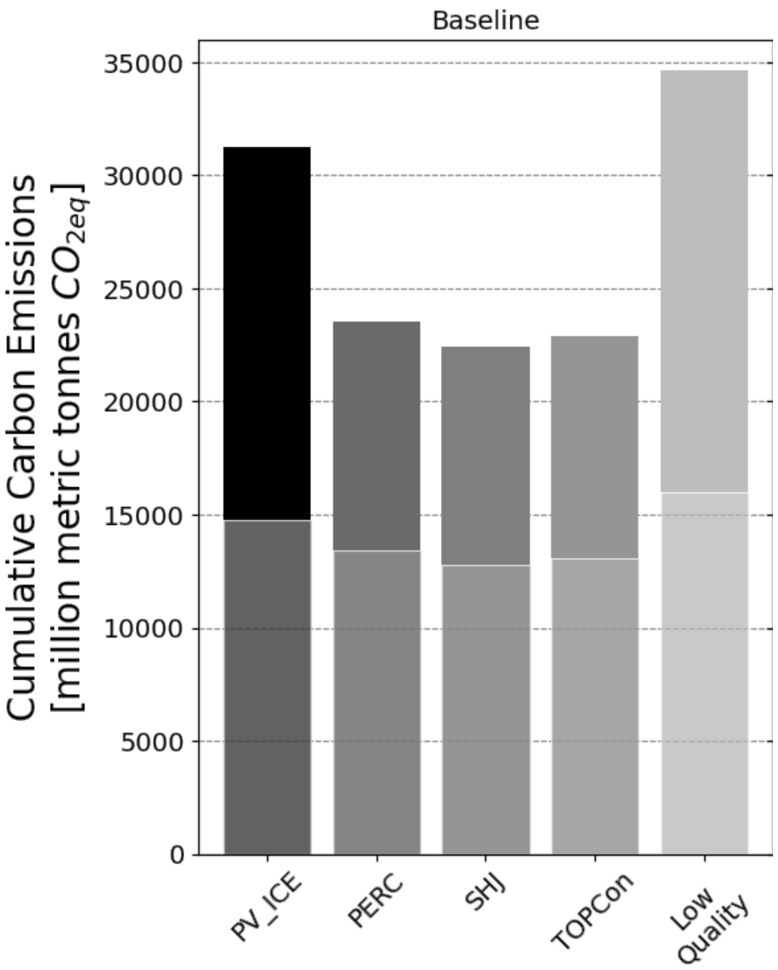


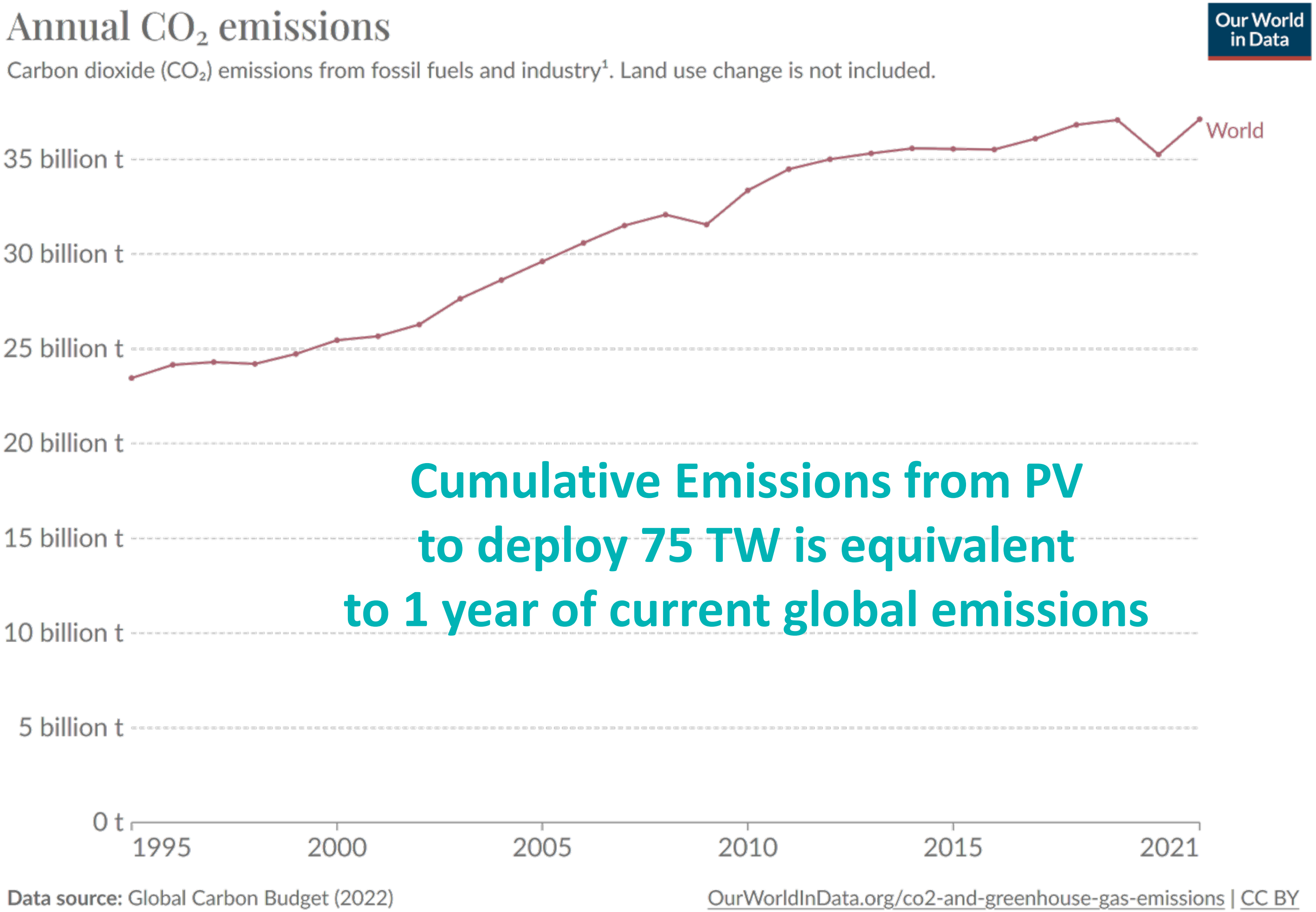
Mirletz, H., H. Hieslmair, S. Ovaitt, T. L. Curtis, and T.M. Barnes. 2023. "Unfounded Concerns about Photovoltaic Module Toxicity and Waste Are Slowing Decarbonization." *Nature Physics*

Read the paper: https://rdcu.be/dnOZR

Manageable

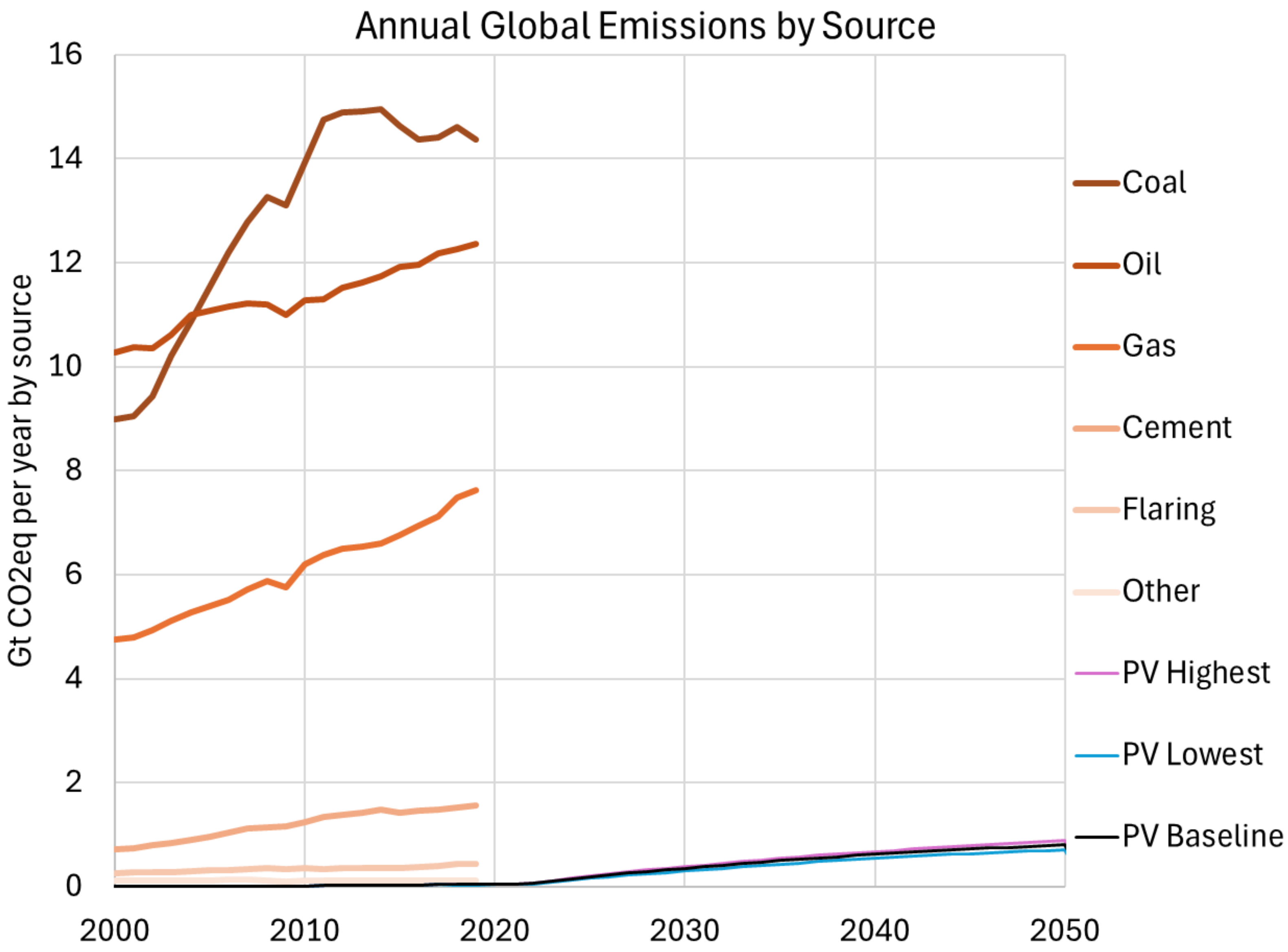
Carbon in Context: Cumulative through 2100





Cumulative Emissions from PV to deploy 75 TW is equivalent to 1 year of current global emissions

Masson-Delmotte et al. IPCC 2021
Wikoff et al. Joule 2022



Jackson et al. "Persistent Fossil Fuel Growth Threatens the Paris Agreement and Planetary Health." *Environmental Research Letters.* Dec 2019.

Annual emissions from fuel sources eclipse PV emissions

Takeaway Messages

Circular Economy R-Action	PV module Design Aspect
Reduce	Efficiency
Reduce & Reuse	**Lifetime**
Remanufacture & Recycle	Material Circularity

Even if we made no improvements, PV "waste" and carbon intensity are *manageable* and miniscule compared to doing nothing.

Efficiency & Bifaciality

- improvements can reduce peak material demands (30%) and increase energy yield (9%)

Material Circularity

- Alone cannot reduce impacts of deploying low quality module
- Great for reducing waste (76%)
- Can reduce virgin material demands (up to 29%)
- Pre-2050 material sourcing: adjacent industries, responsible mining practices…

Lifetime improvements ease the path to energy transition

- delay the need for replacements
- reduce the number of replacements
- increase energy yield
- provide a grace period to ramp up material circularity

Circular Economy ≠ Recycling

Don't forget to make it last

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

Analyses coming soon to an EPJ PV near you!

Thank you!

Questions?


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Special Issue on 'EU PVSEC 2023: State of the Art and Developments in Photovoltaics', edited by Robert Kenny and João Serra

ORIGINAL ARTICLE OPEN ACCESS

Prioritizing circular economy strategies for sustainable PV deployment at the TW scale

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