NREL
Transforming ENERGY

Energy in the Balance: PV Reliability to Power the Energy Transition

Heather Mirletz, Silvana Ovaitt, Macarena Méndez Ribó, Seetharaman Sridhar, Teresa M. Barnes

PVRW 2023

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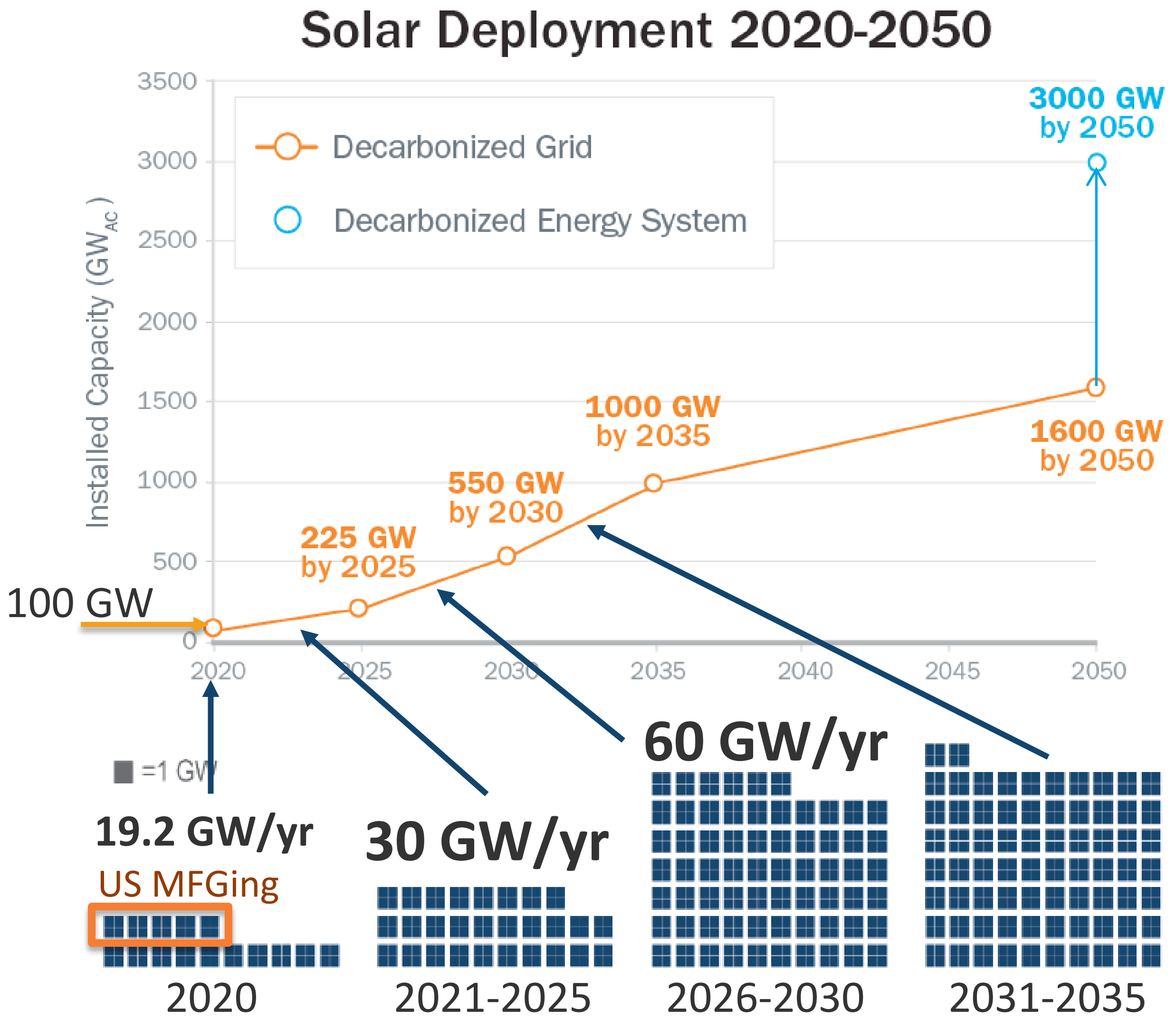
Decarbonization Goals

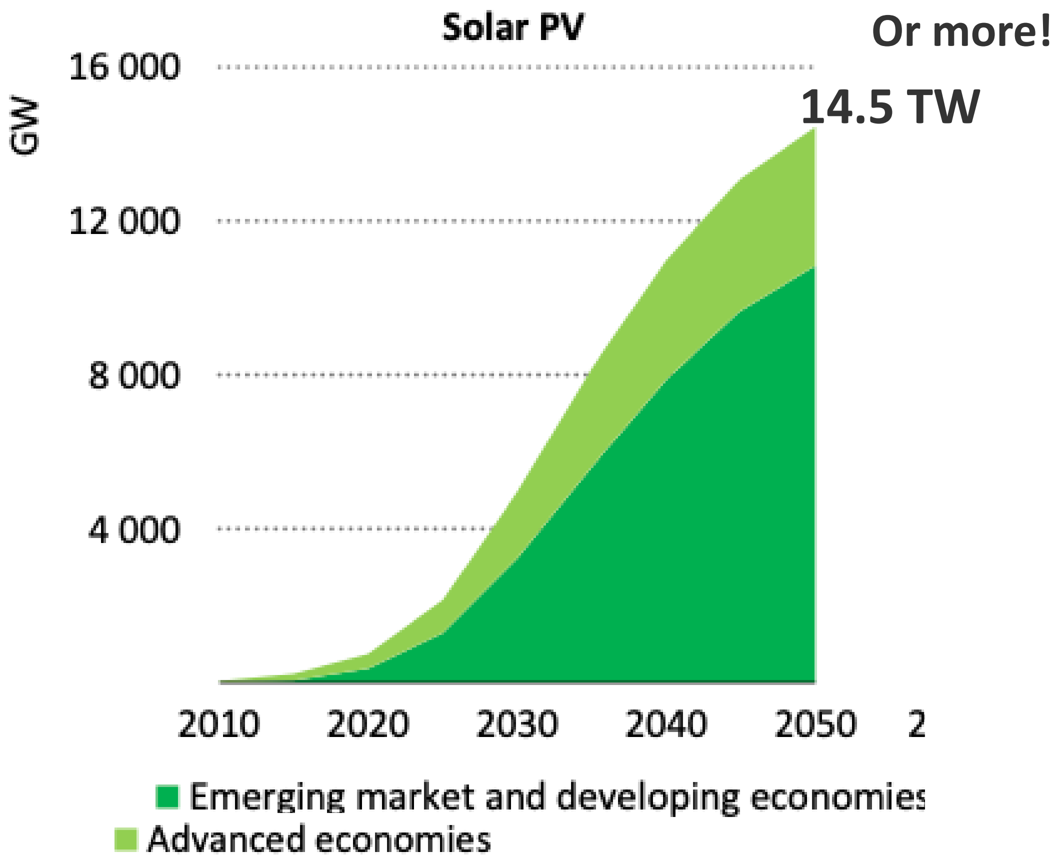
US electrical grid Decarb + some electrification

Solar Futures, Sept. 2021



Average Annual Deployment

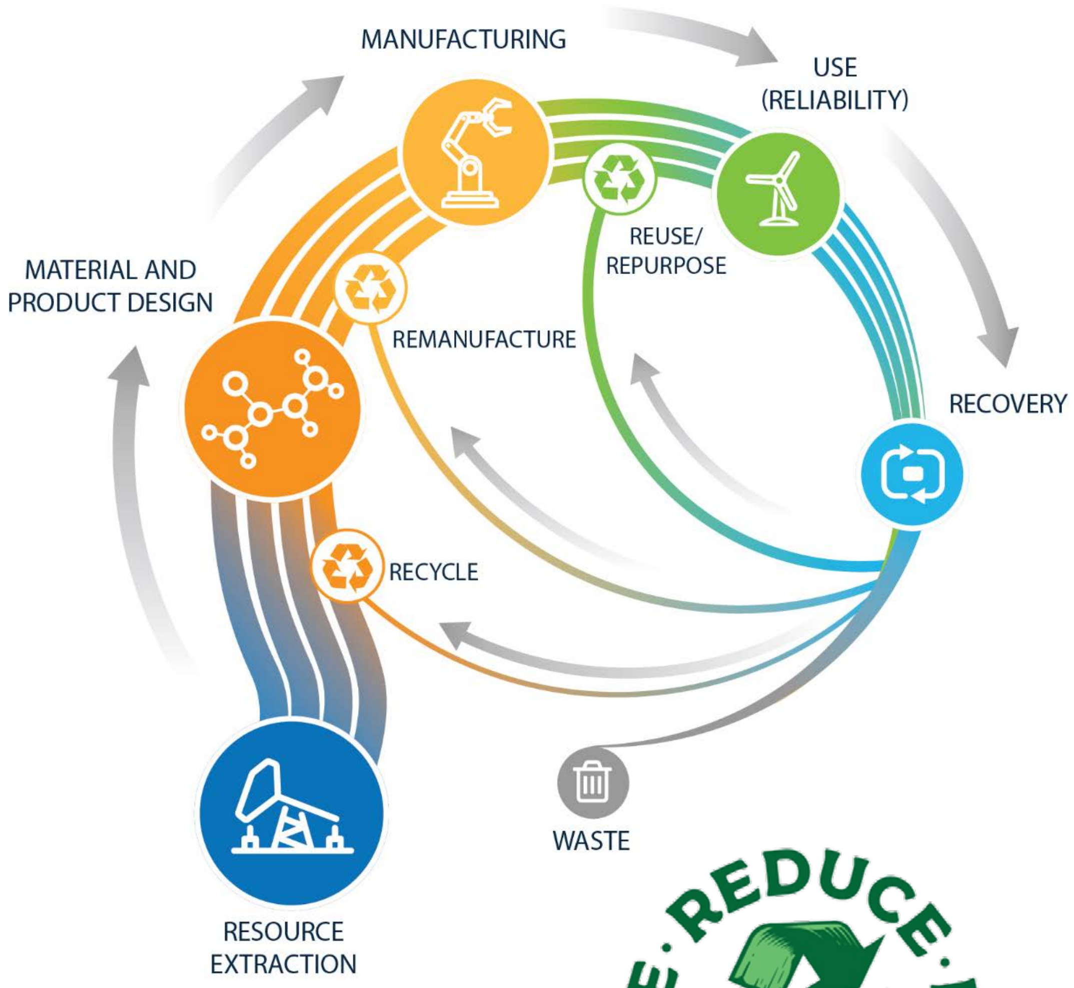
Global Capacity, IEA Net Zero



630 GW/Year by 2030
(currently ~130 GW/yr)

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?

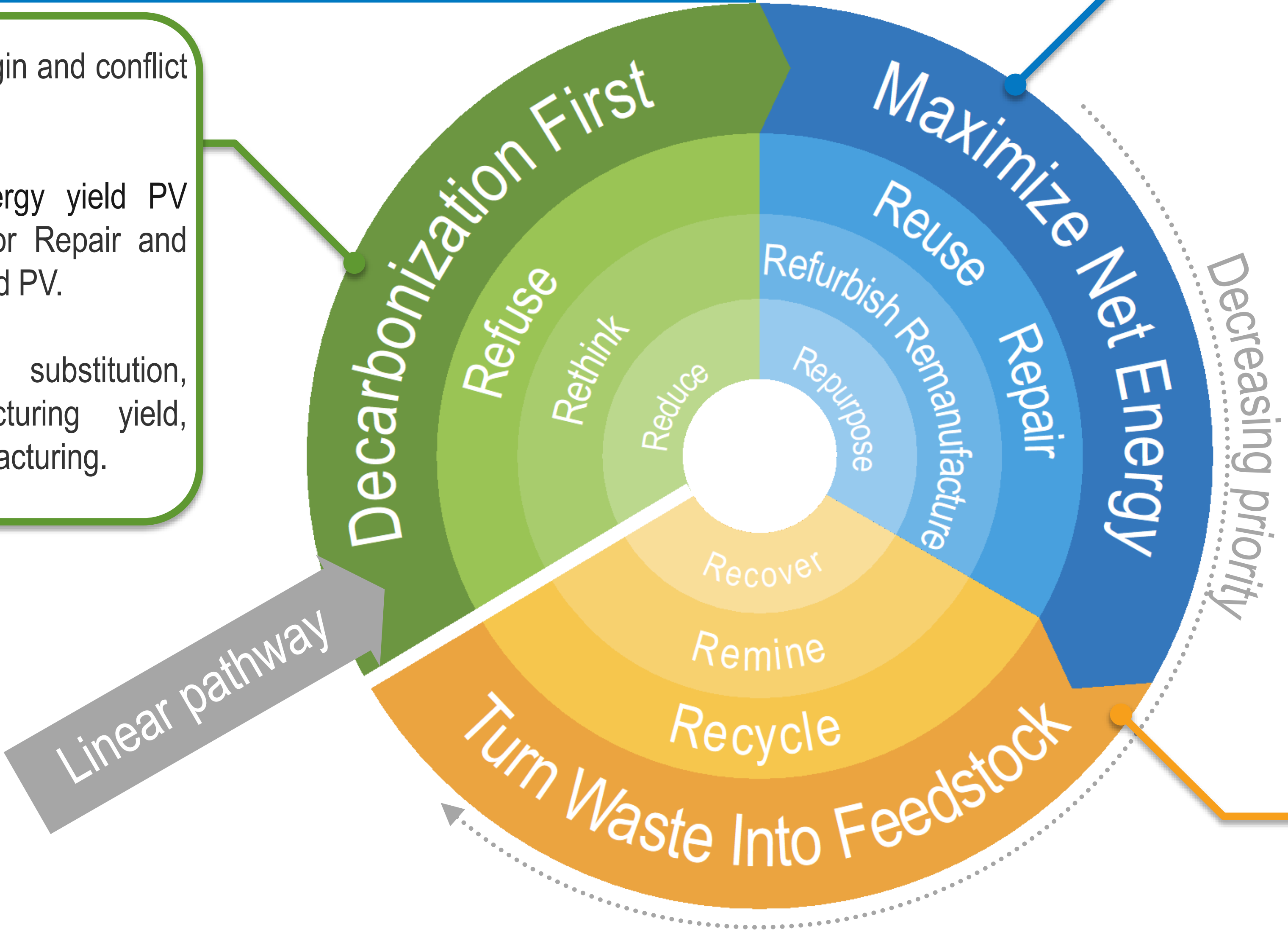


Circular R-strategies for PV in the Energy Transition

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
Thanks to M Mendez Ribo for graphic design

Metrics of Success

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

Installed Capacity
Maintain PV Capacity to meet Energy Transition

Virgin Material
Reduce Extraction of Virgin Materials

Waste
Reduce Wastes throughout PV lifecycle

Energy In
Minimize Energy demands of processes and materials

Energy Out
Maximize PV Yield for Energy Transition

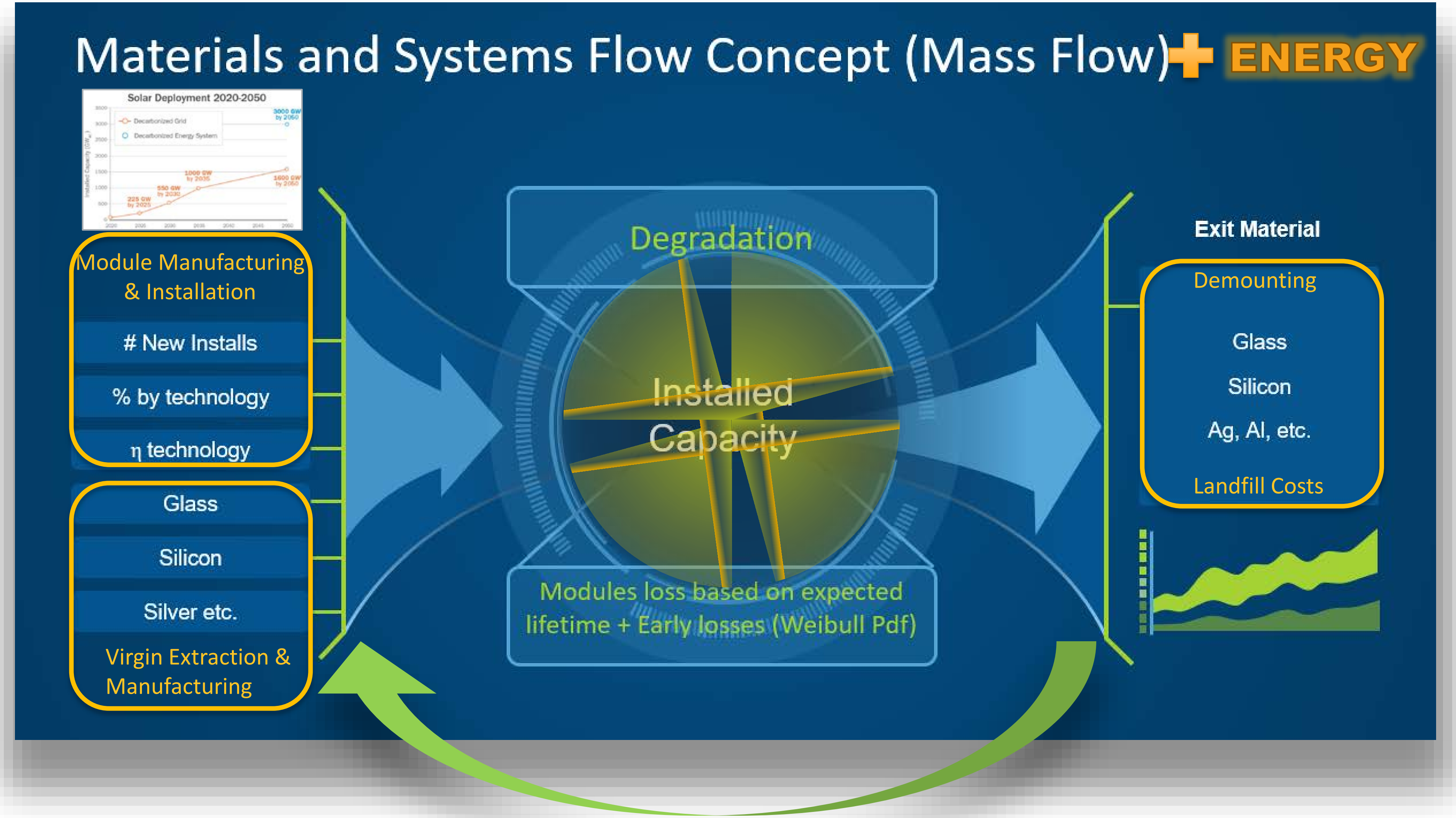
Energy Balance
Maximize EROI, EPBT, Net Energy

CO_2

More metrics to come

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

Energy Metrics Overview

Energy In

Energy Out

Energy Balances

Energy Balance

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

Capacity

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	$\frac{E_{out}}{E_{in}}$	Installs + replacements − degradation − failures − 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.

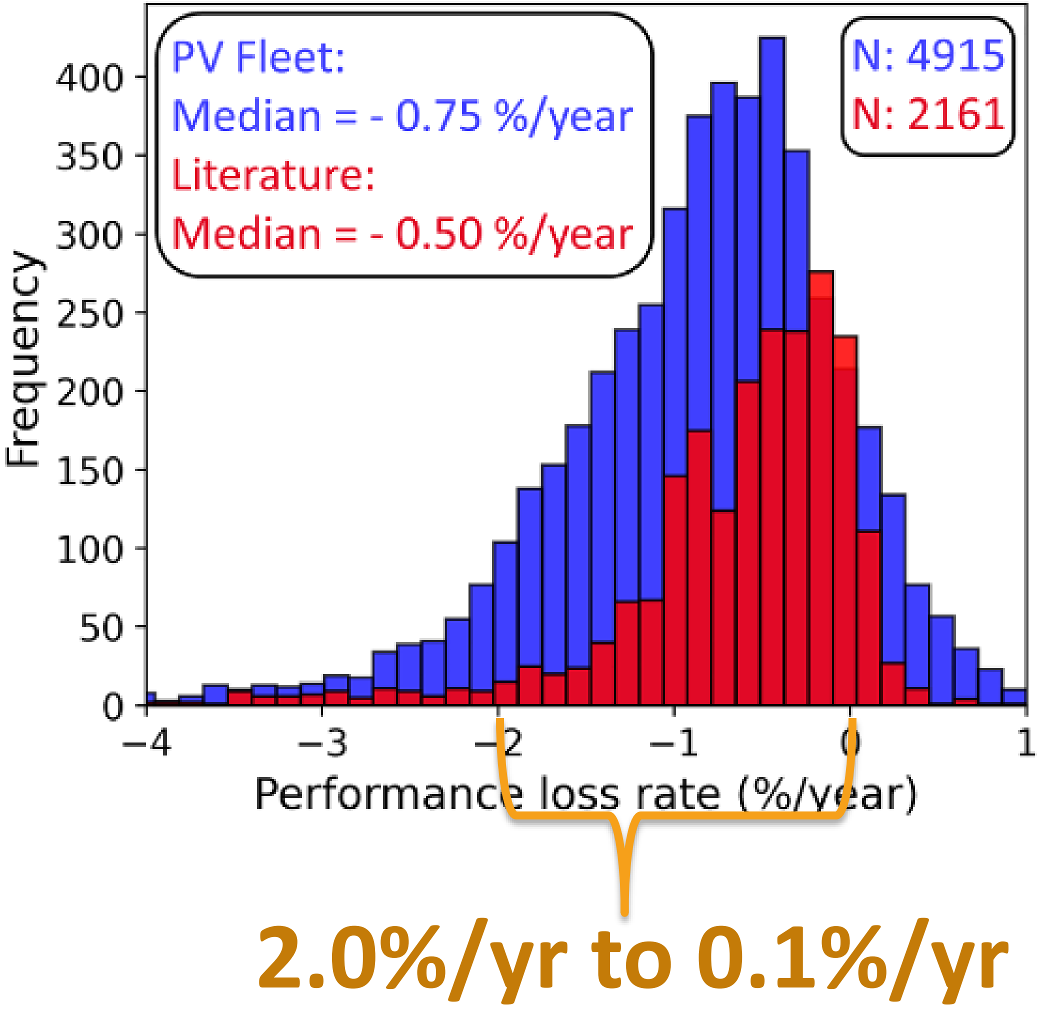
Note: Metrics are for internal comparison only

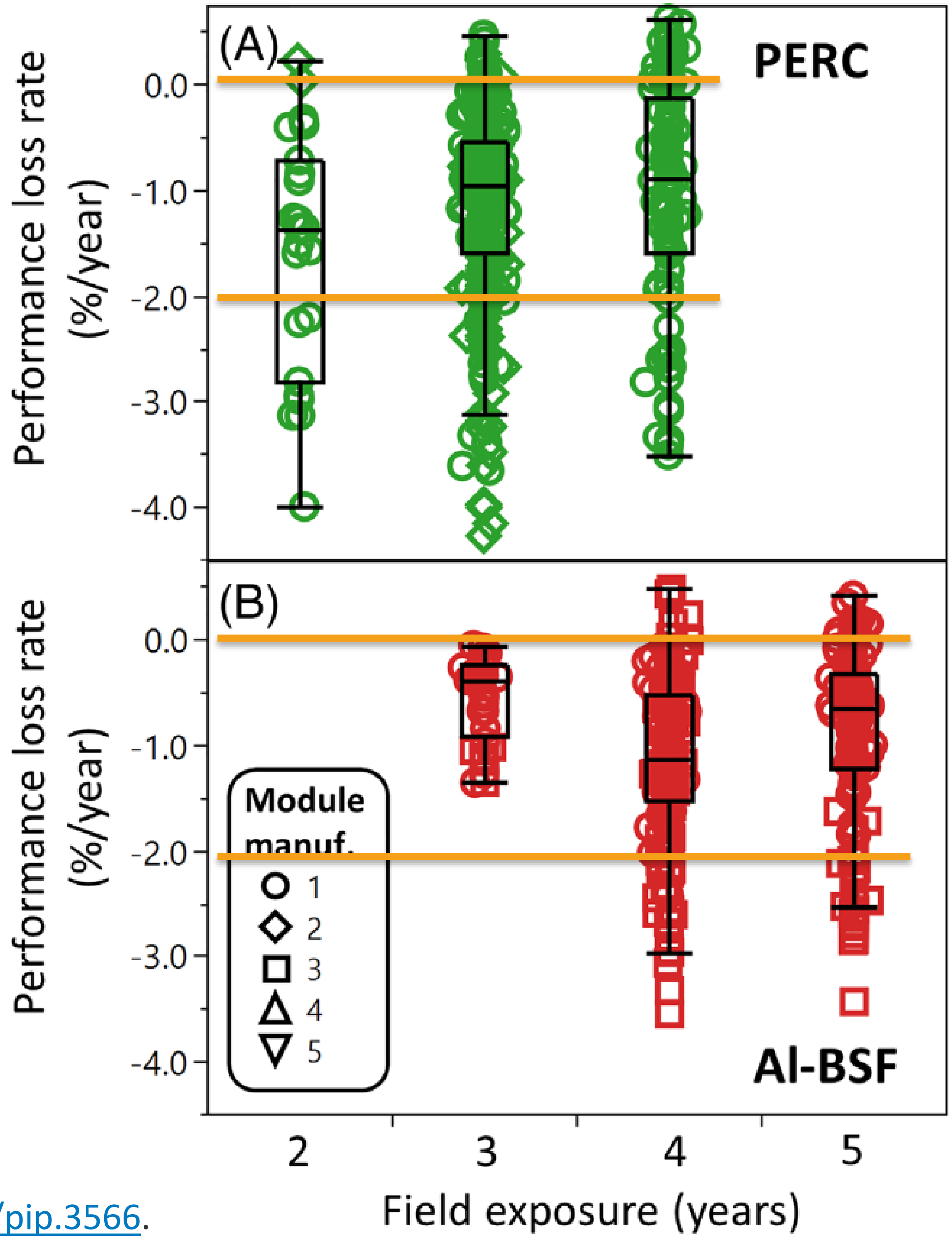
How do Modules reach EoL?

PV ICE EoL Functions

	Degradation	Failure	Project Lifetime
Definition	Predicted Annual Power loss	Unpredicted, sudden loss of power	Economic contract or module warranty
Model	Linear Rate with threshold	Weibull Function	Time value
Example Value	0.7%/year remove at 80% nameplate	T50 & T90 alpha & beta	30 years

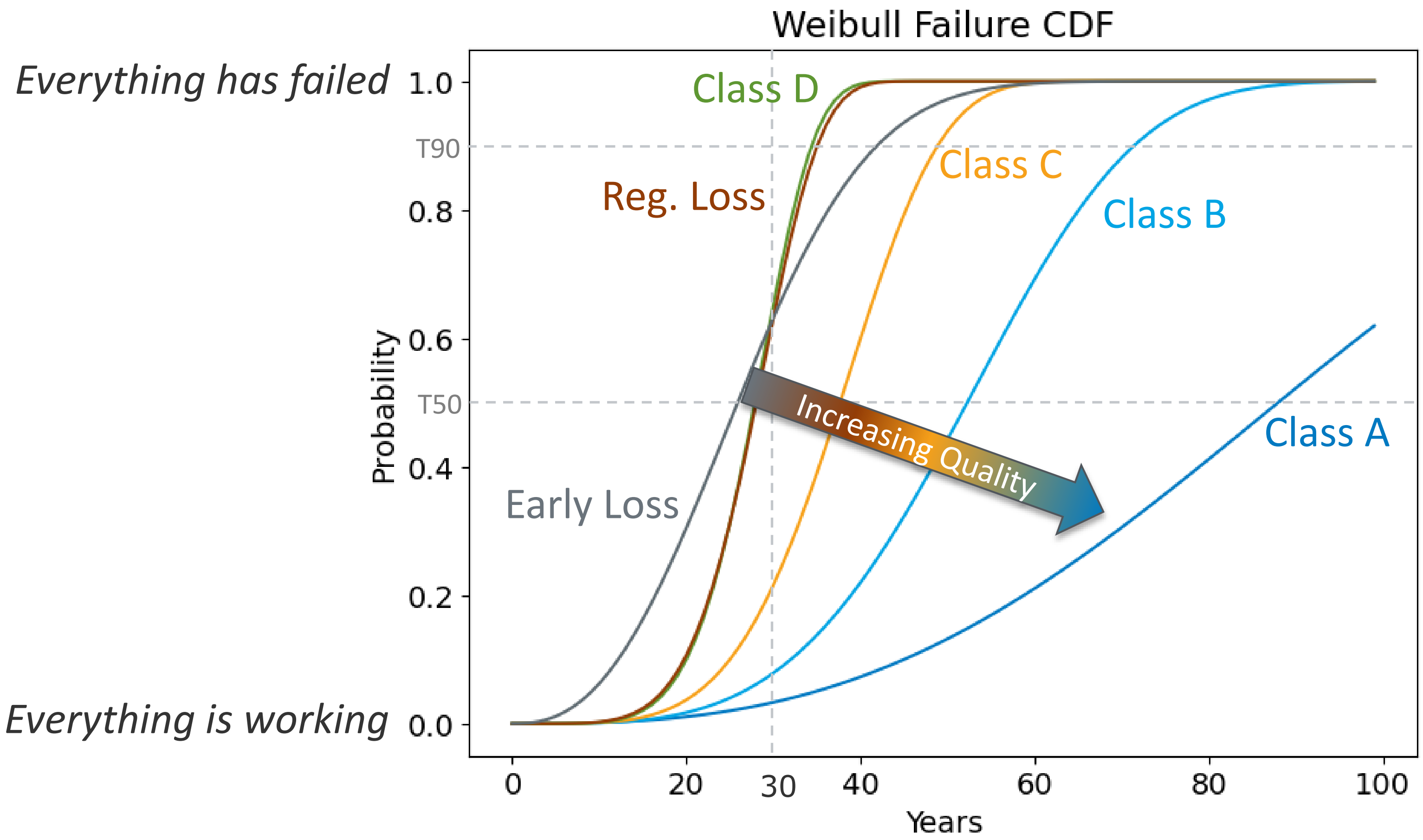
Literature Ranges: Degradation





Jordan et al. 2022. “Photovoltaic Fleet Degradation Insights.” *Progress in Photovoltaics: Research and Applications* https://doi.org/10.1002/pip.3566.

Literature Ranges: Failures



	Class A	Class B	Class C	Class D	Regular Loss	Early Loss
Alpha	2.810	3.841	4.602	5.692	5.3759	2.4928
Beta	100.238	57.491	40.767	29.697	30	30

Hieslmair 2021, PVRW . "Assessing the 'useful Life' of PV Modules: Reaching for 40 and 50 Year Module Useful Life."

Weckend et al. IRENA 2016. "End of Life Management: Solar Photovoltaic Panels."

Kuitche PVRW 2010. "Statistical Lifetime Prediction for Photovoltaic Modules."

Literature Ranges: Project Lifetime

Stated goal of SETO to reach 50 year module lifetime.
"SETO FY21 - Photovoltaics." energy.gov. https://www.energy.gov/eere/solar/seto-fy21-photovoltaics.

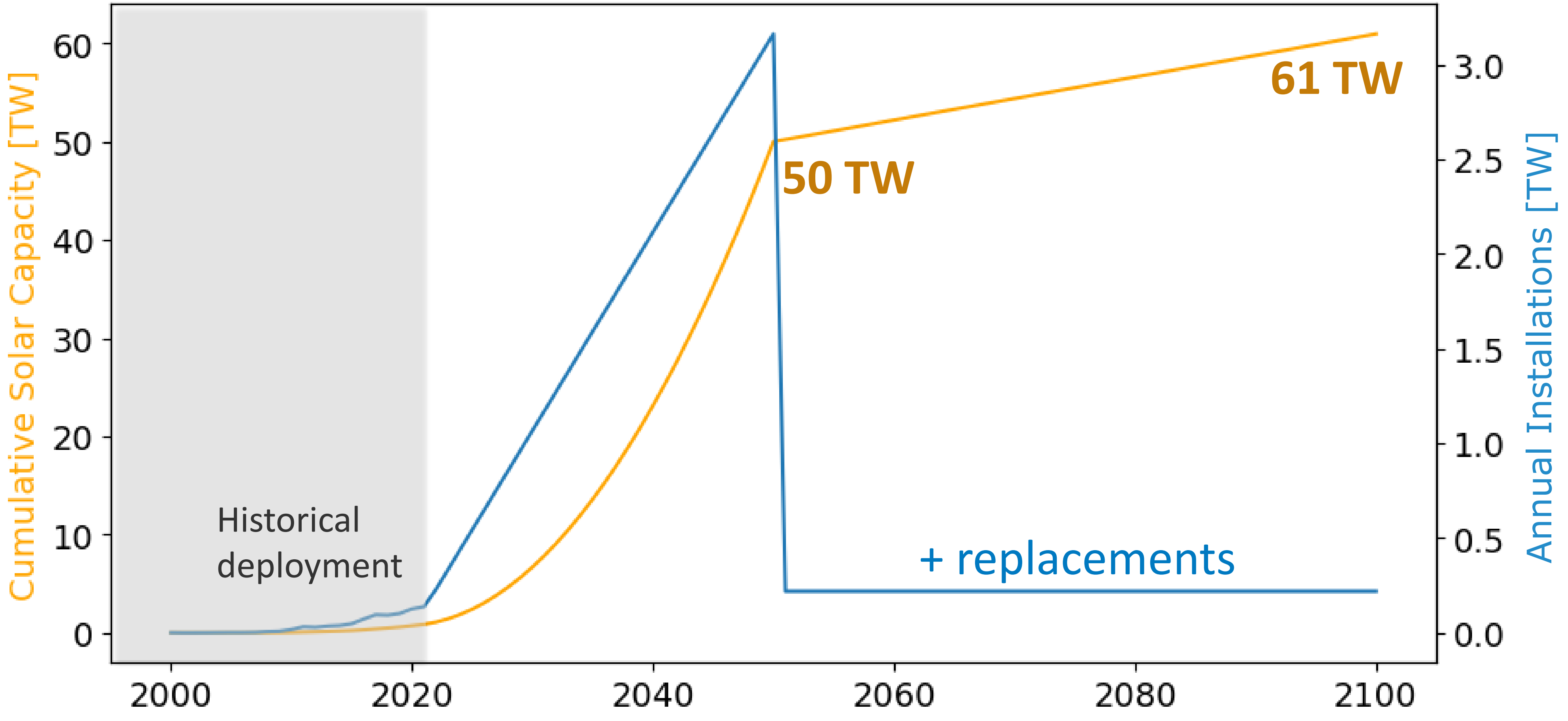
Establishes historical and current lifetime ranges.
Bolinger et al. LBNL 2022. "Utility-Scale Solar, 2022 Edition" https://doi.org/10.2172/1888246.

Argues for less than 10-year repowering.
Jean et al, 2019. "Accelerating Photovoltaic Market Entry with Module Replacement." *Joule*. https://doi.org/10.1016/j.joule.2019.08.012.

50 years
45 years
40 years
35 years
30 years
25 years
20 years
18 years
15 years
12 years
10 years
8 years

Global Deployment Targets

Literature: 14.5 TW to 70 TW by 2050
Created custom global deployment

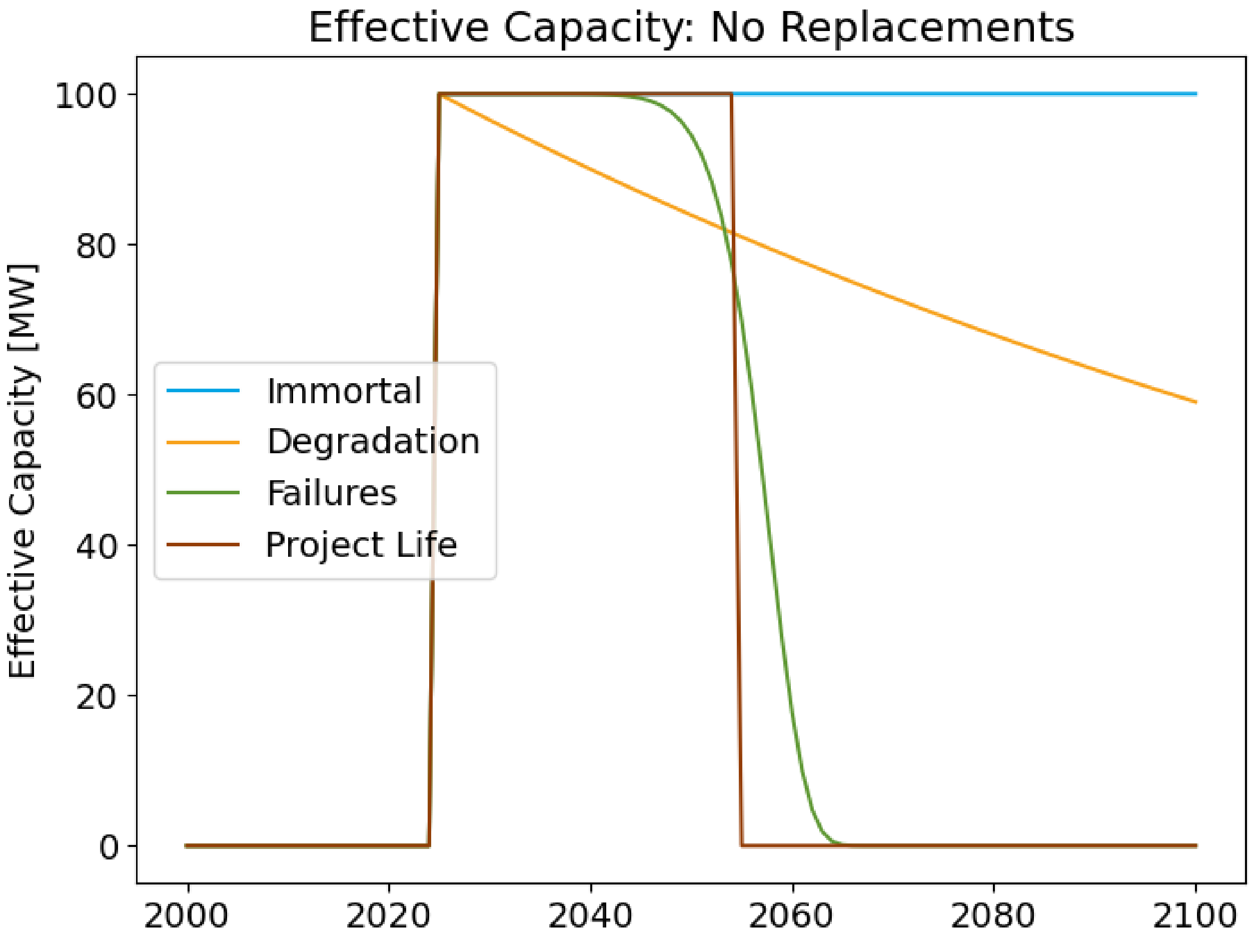


Results: Effects of Reliability

An Energy Analysis

Modes of EoL in 100 MW System

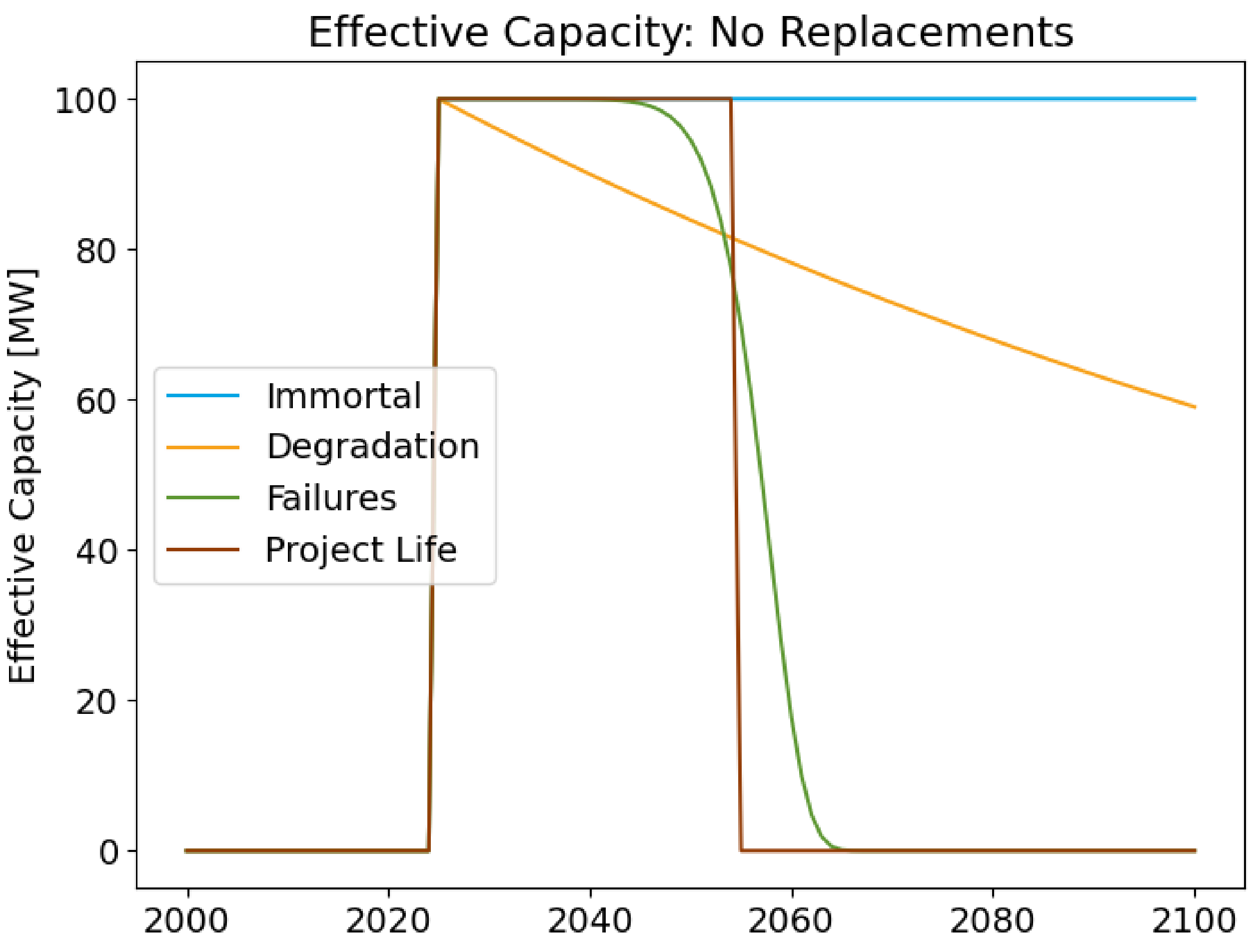
Isolated variable



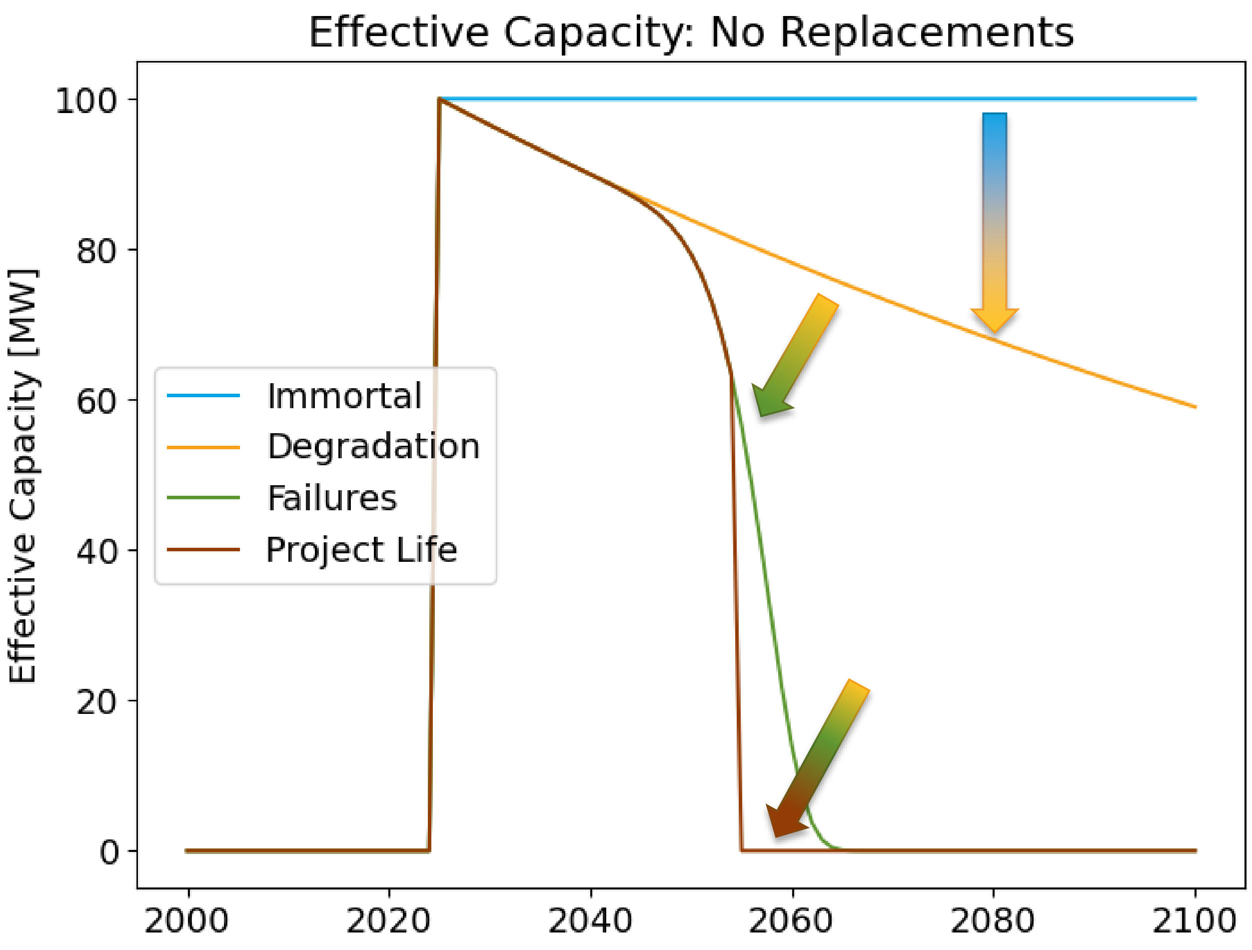
Additive effects

Modes of EoL in 100 MW System

Isolated variable

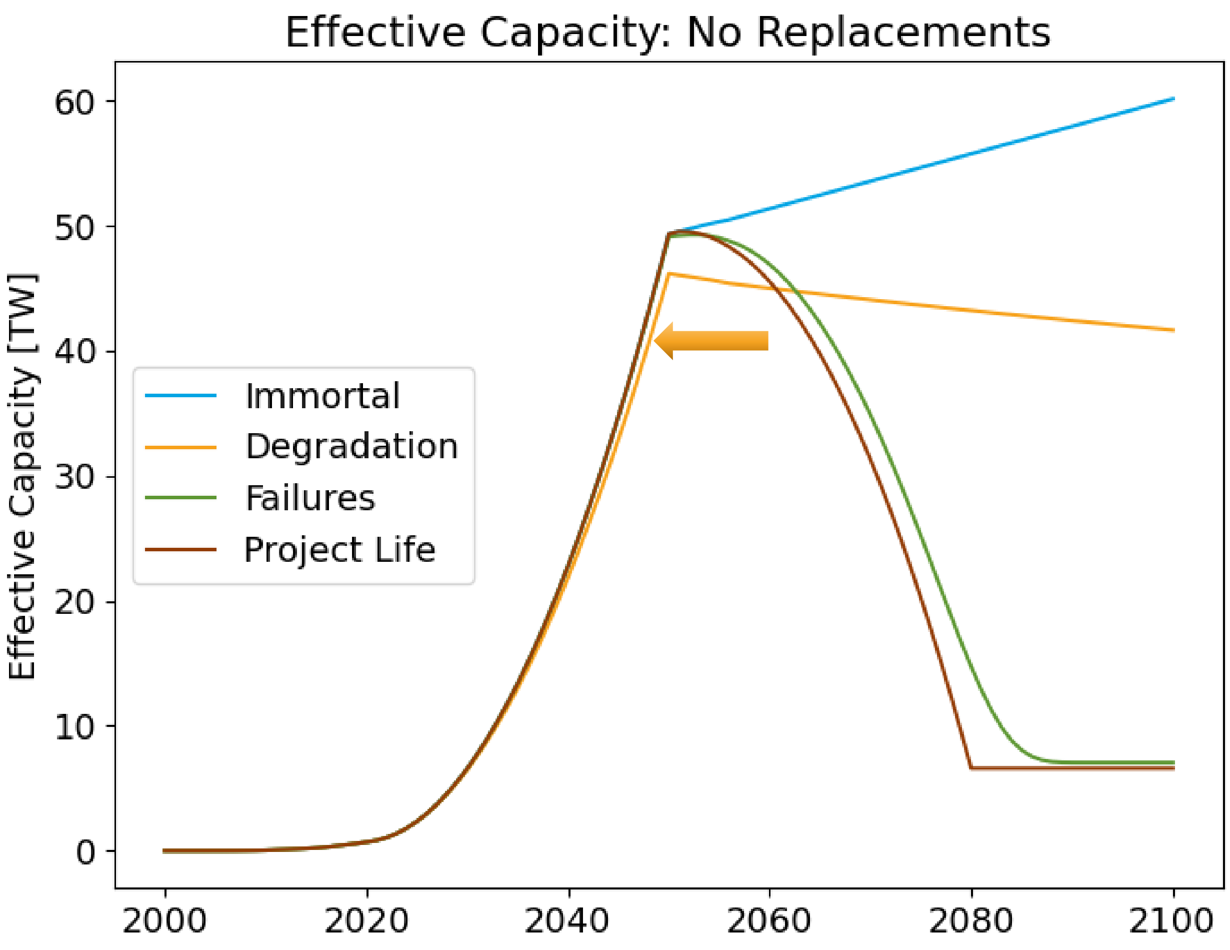


Additive effects

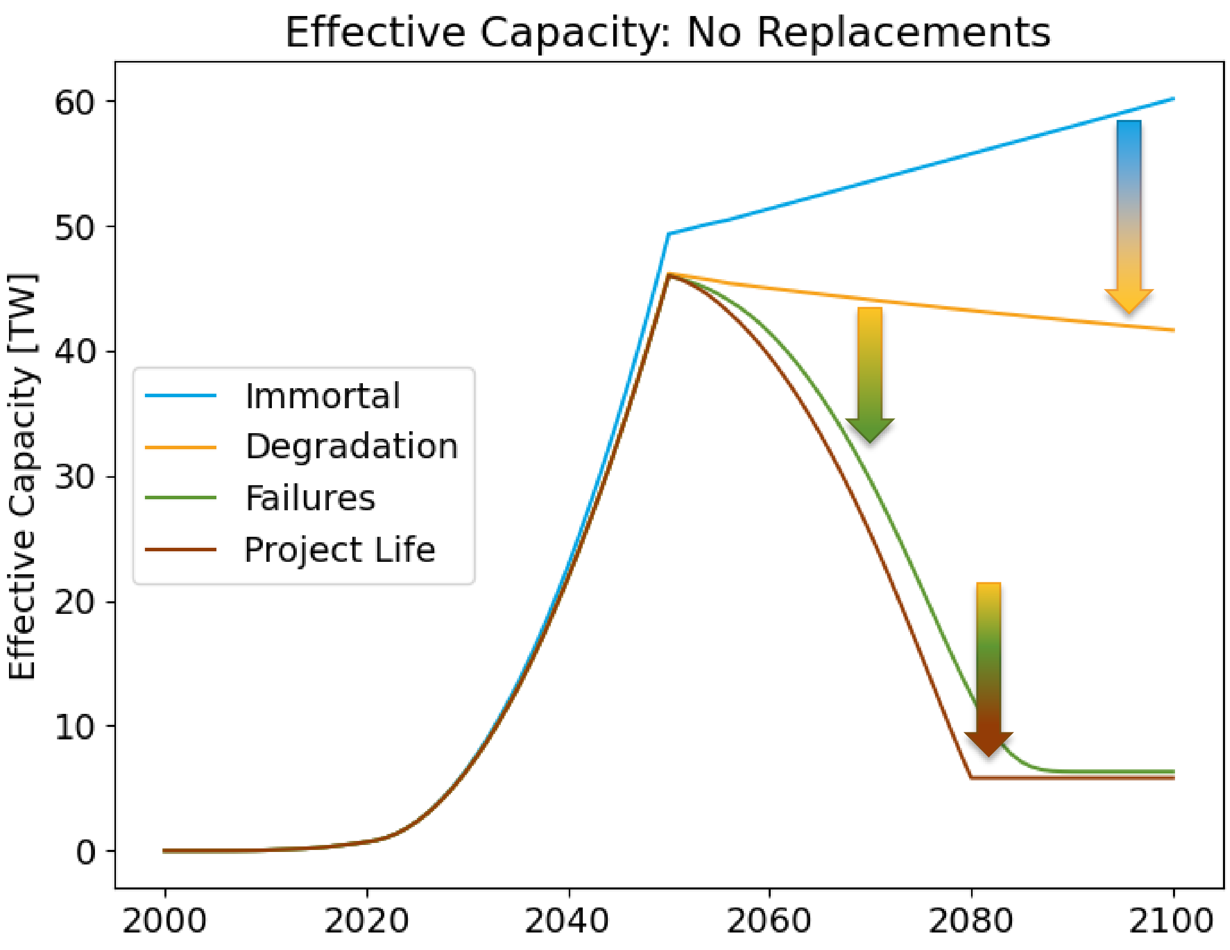


Modes of EoL in Global Scale Deployment

Isolated variable

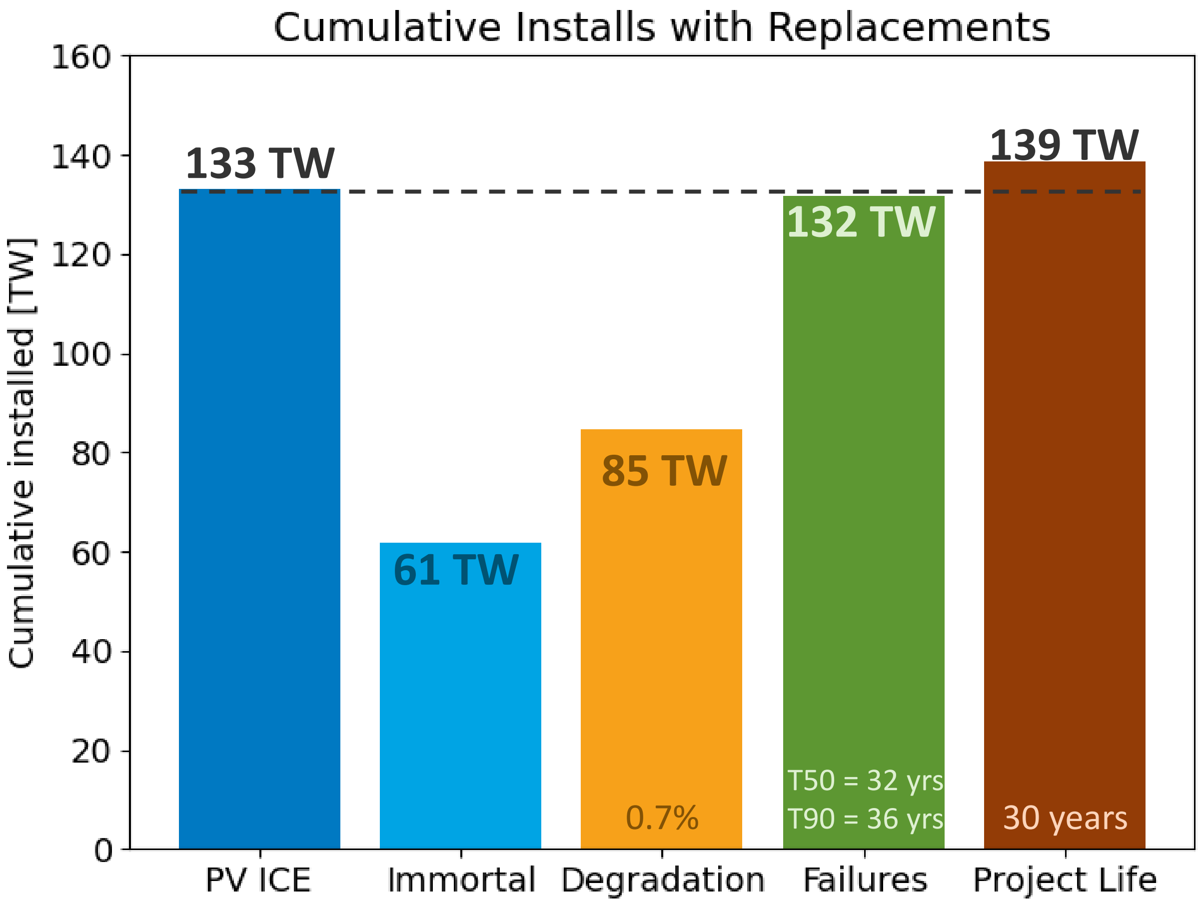


Additive effects

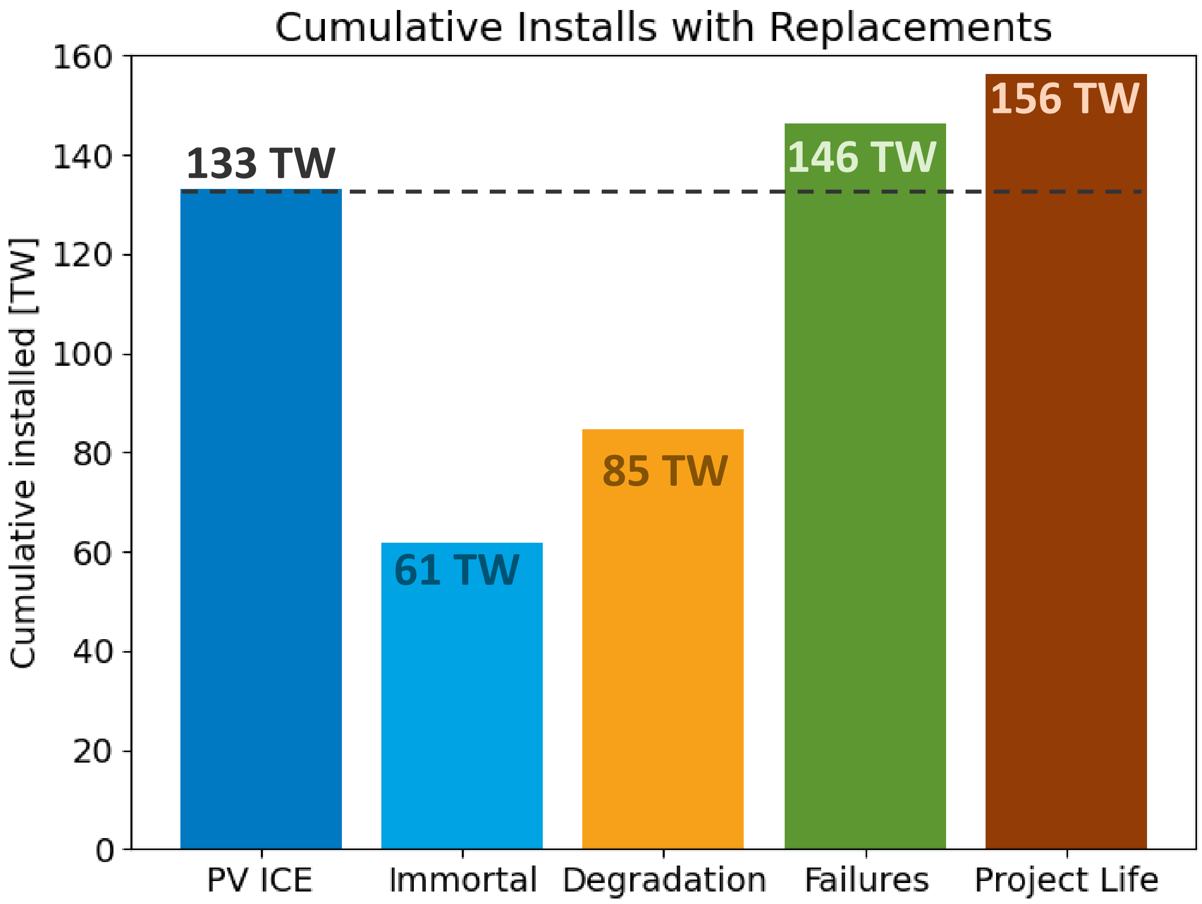


Required Replacements

Isolated variable



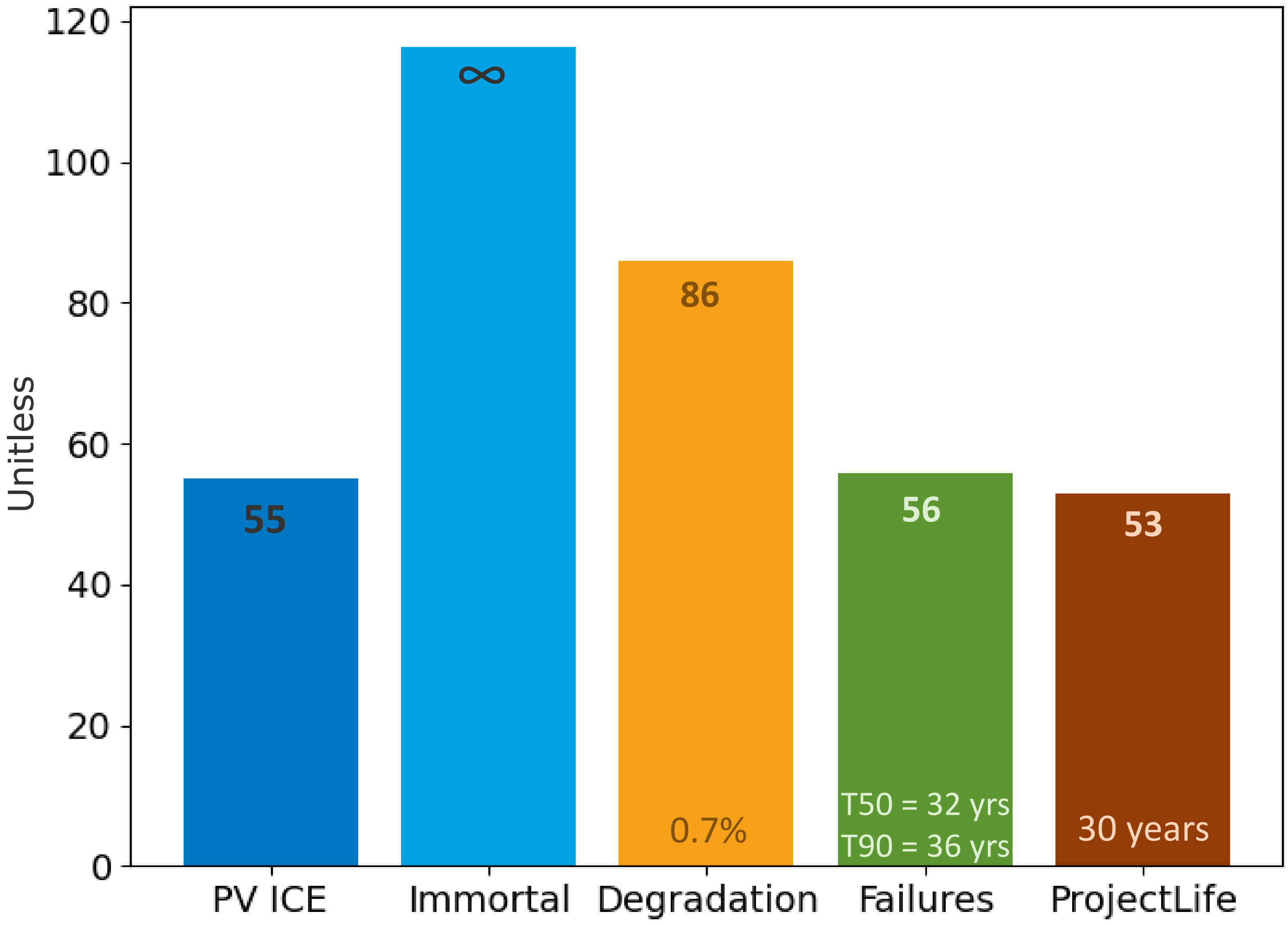
Additive effects



Note: PV ICE is our conservative projection of future average module properties.

Energy Balance

Isolated variable, includes replacements

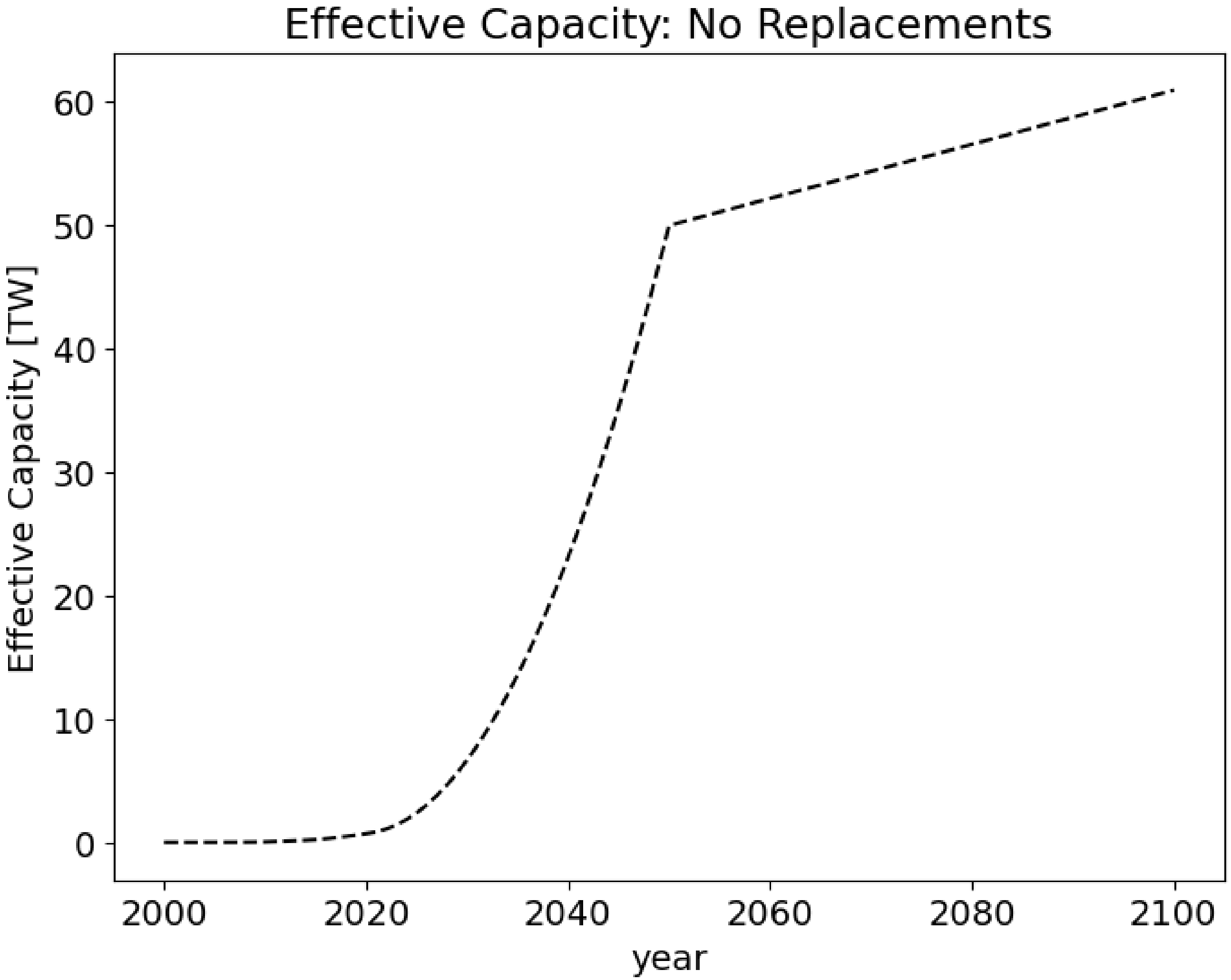


$$\frac{\sum_{2000,\,2100}^{All\ Systems} \boldsymbol{E_{out}}}{\sum_{2000,\,2100}^{All\ Systems} \boldsymbol{E_{in}}}$$

Project lifetime reduces Energy Balance most

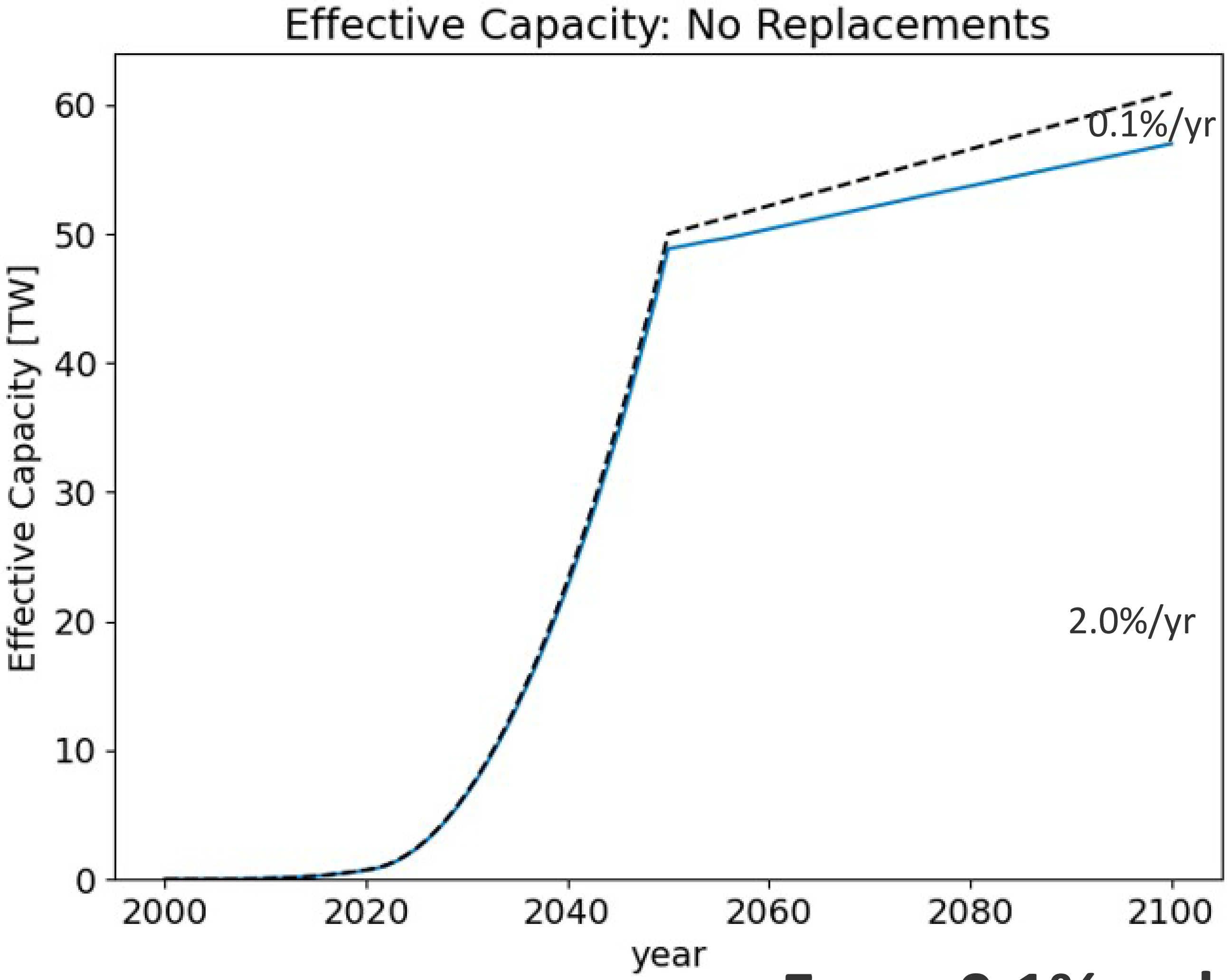
Note: Metrics are for internal comparison only

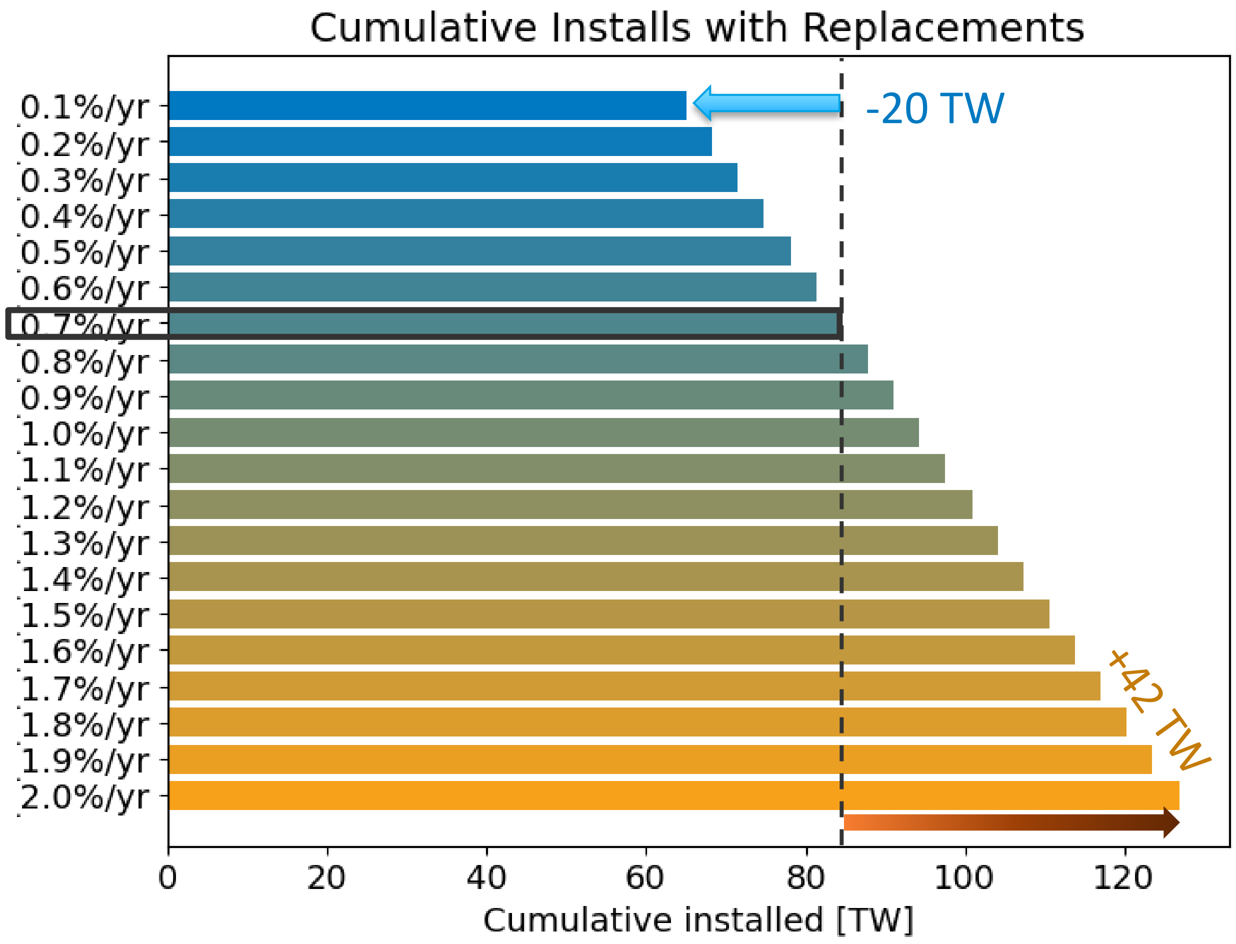
Explore Degradation



Threshold: remove at 80% of nameplate

Explore Degradation

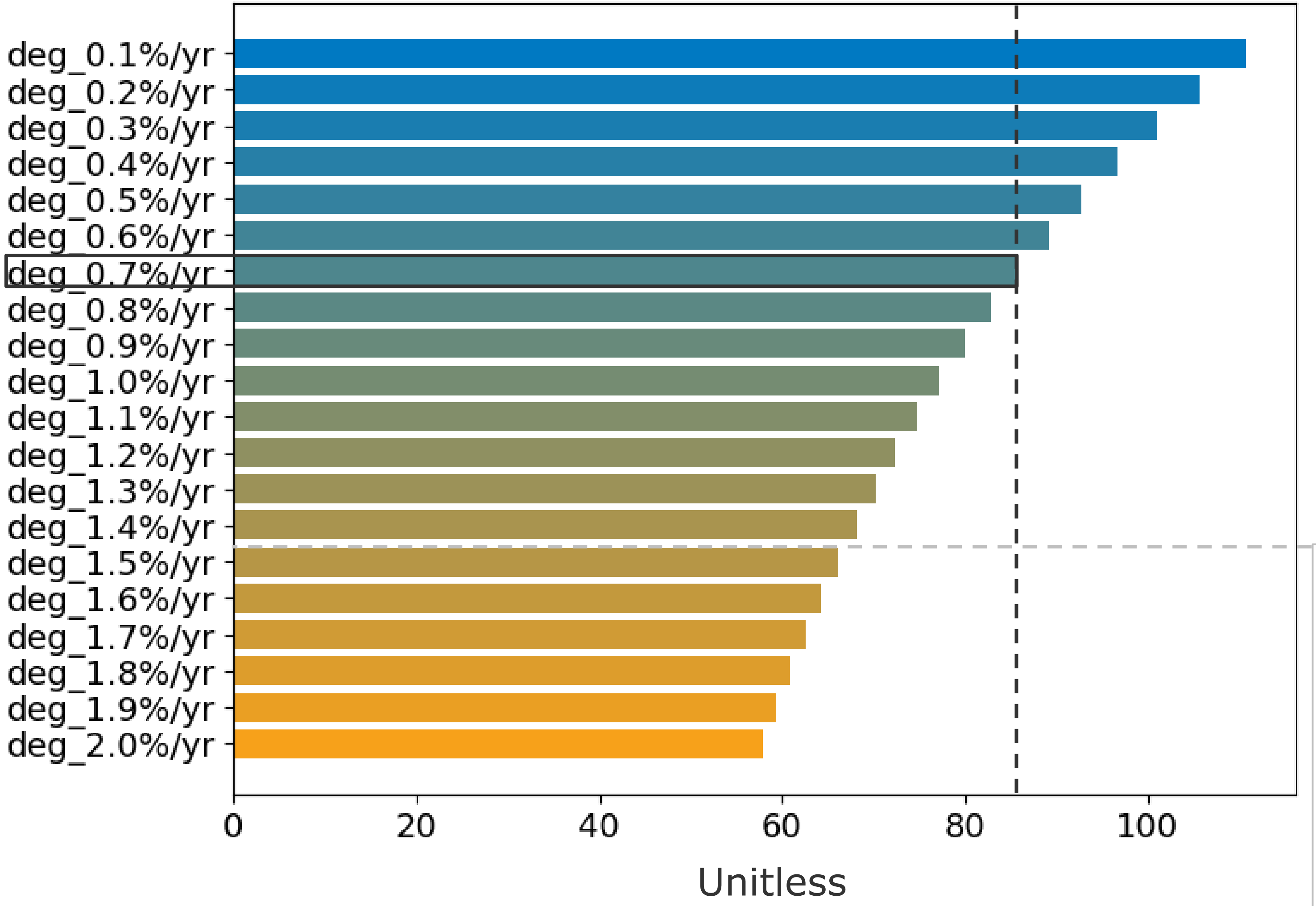




Every 0.1% reduction in degradation saves ~3 TW of replacements

Threshold: remove at 80% of nameplate

Energy Balance of Degradation



$$\frac{E_{out}}{E_{in}}$$

Also, Woodhouse et al (this morning) showed degradation rates ≥1.5%/yr limit economic value from ITC and PTC in U.S.

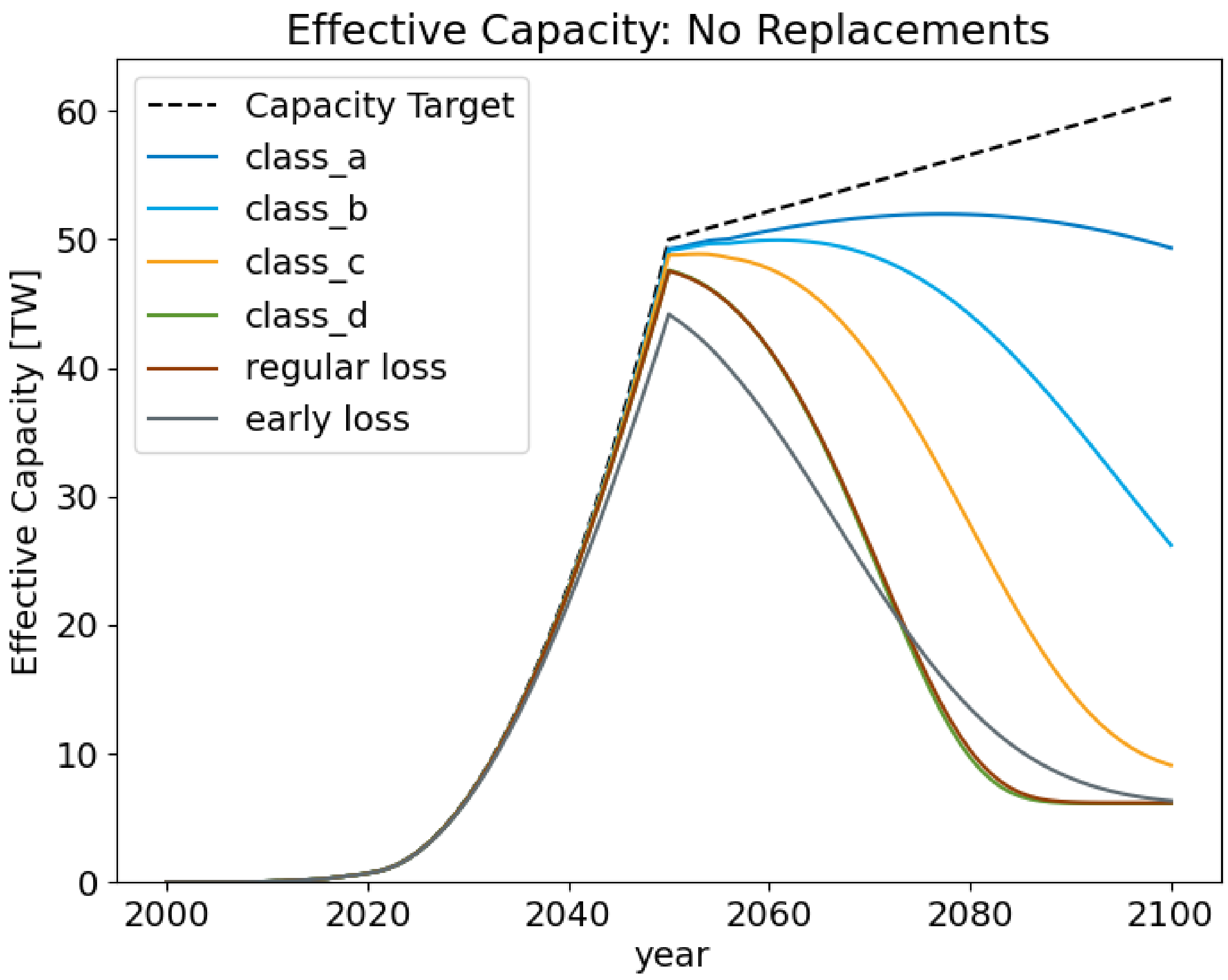
Non-linear Energy Balance as a function of degradation

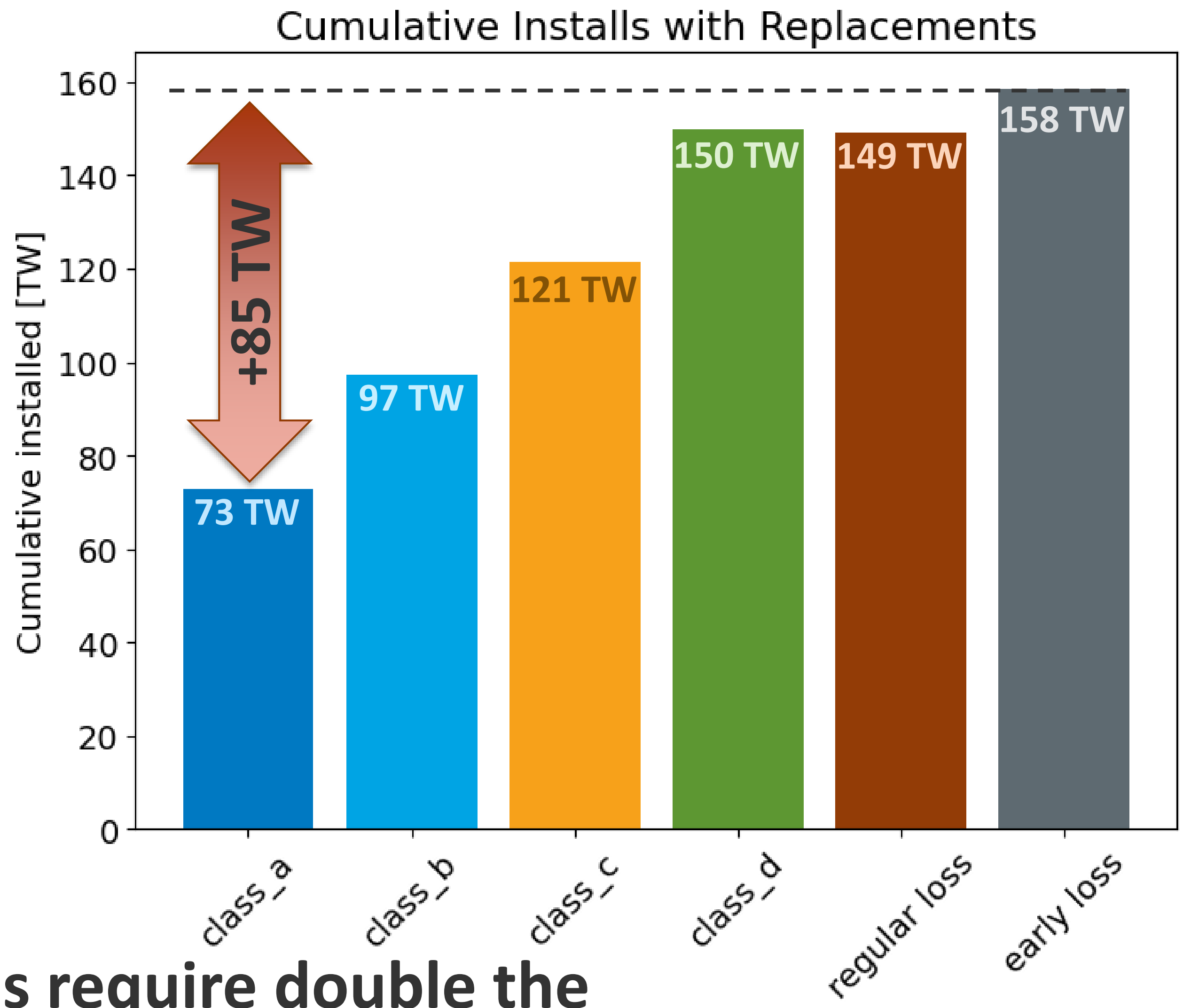
Note: Metrics are for internal comparison only

	Class A	Class B	Class C	Class D	Reg. Loss	Early Loss
Alpha	2.810	3.841	4.602	5.692	5.3759	2.4928
Beta	100.238	57.491	40.767	29.697	30	30

Hieslmair PVRW 2021, IRENA 2016, Kuitche PVRW 2010

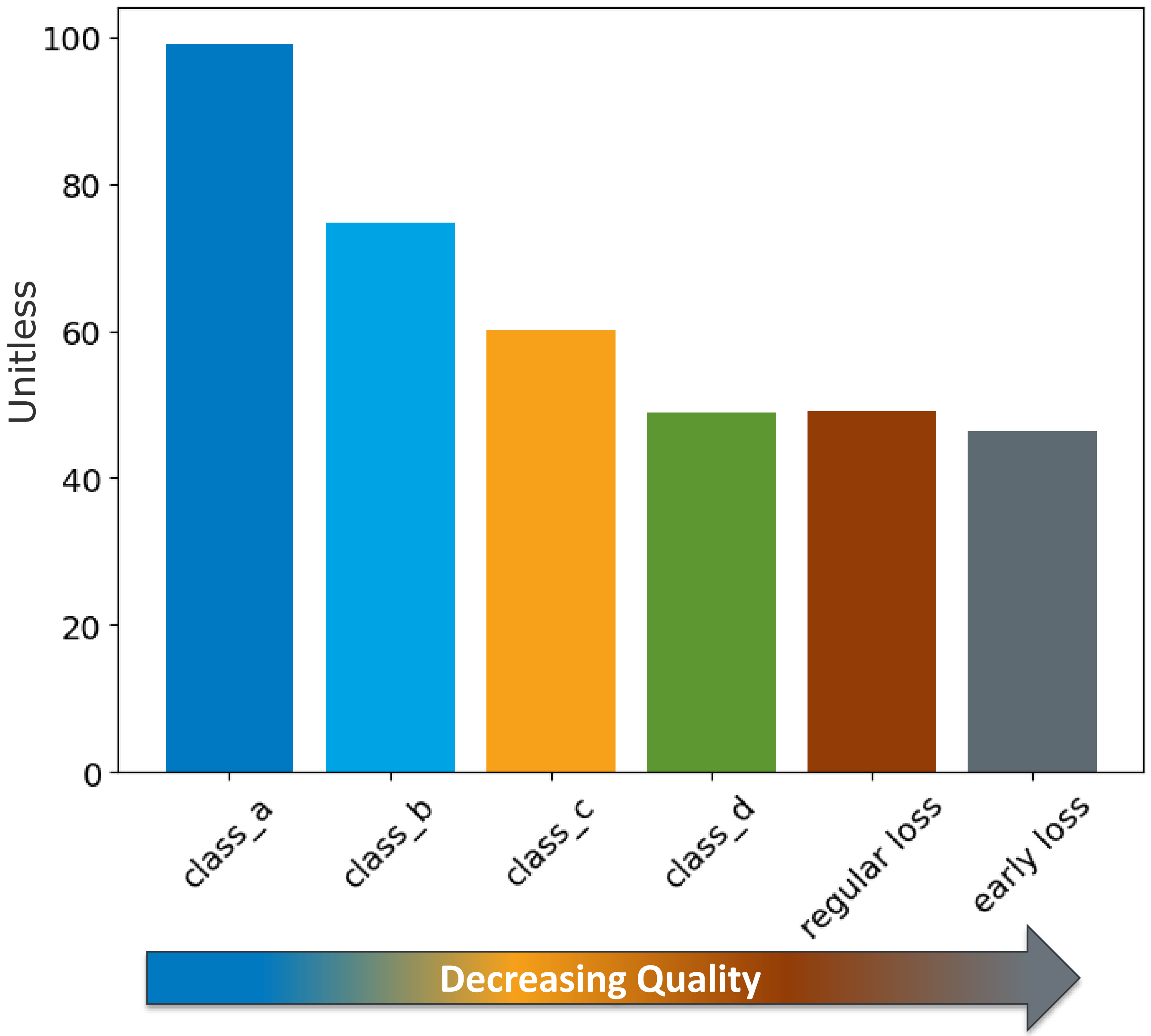
Explore Failures





Early Loss modules require double the installs of Class A modules

Energy Balance of Failures



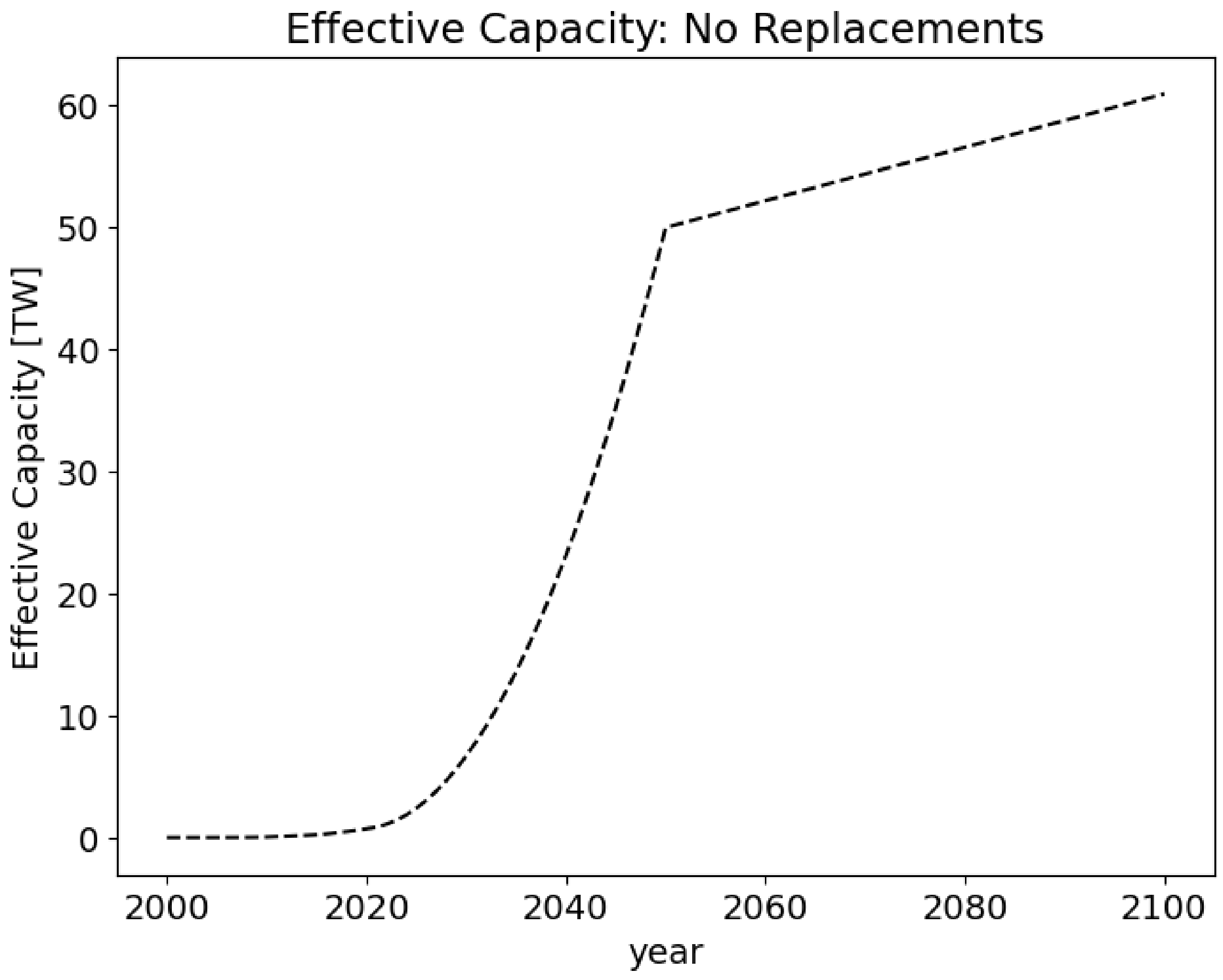
$$\frac{E_{out}}{E_{in}}$$

Improving Reliability increases Energy Balance

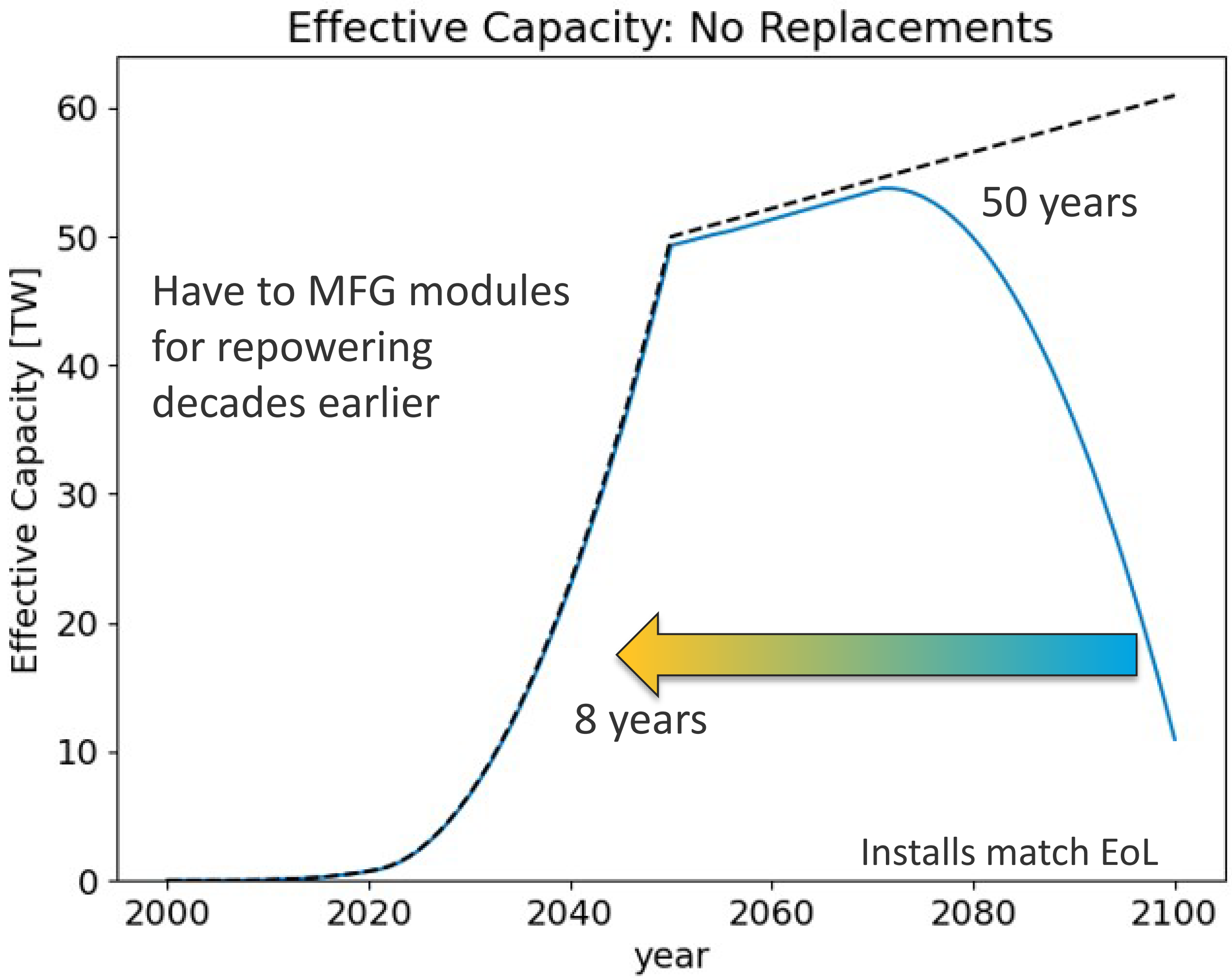
Class A modules scenario is **double** the Energy Balance of early loss scenario

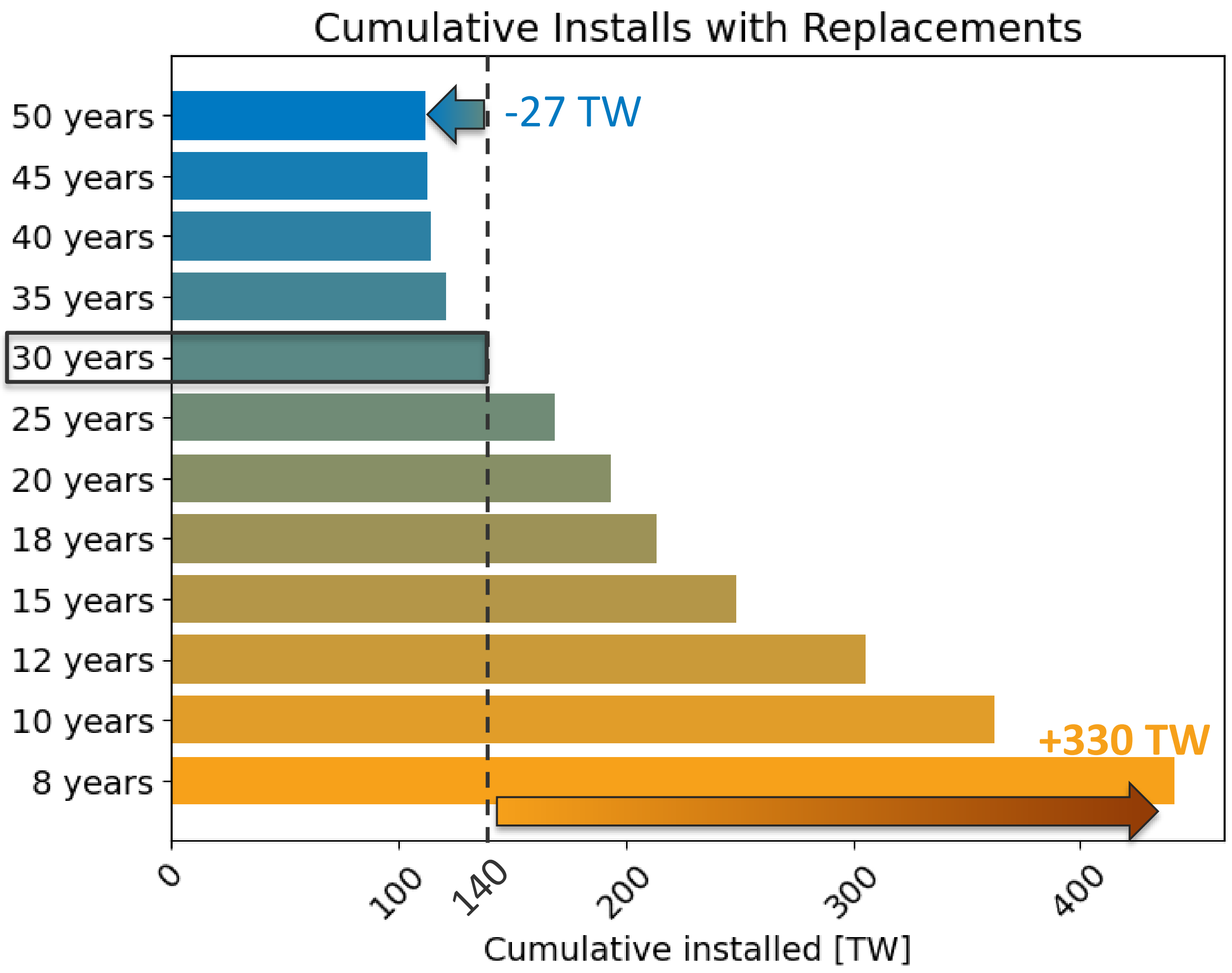
Note: Metrics are for internal comparison only

Explore Project Lifetime



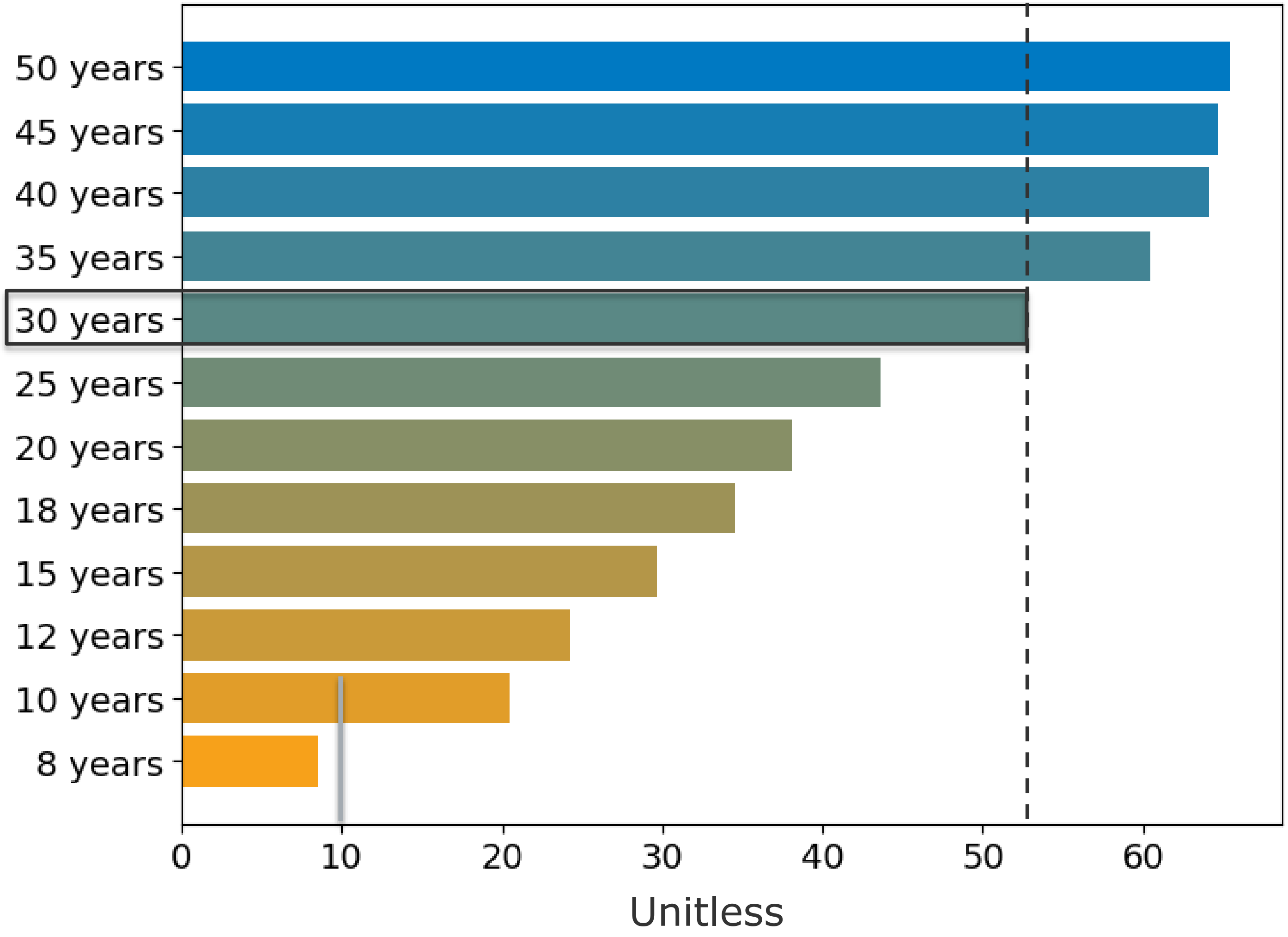
Explore Project Lifetime





Short project lifetimes require more replacements, sooner

Energy Balance of Project Lifetime



$$\frac{E_{out}}{E_{in}}$$

Energy Balance of long-lived modules likely artificially lowered by time period considered (2000-2100)

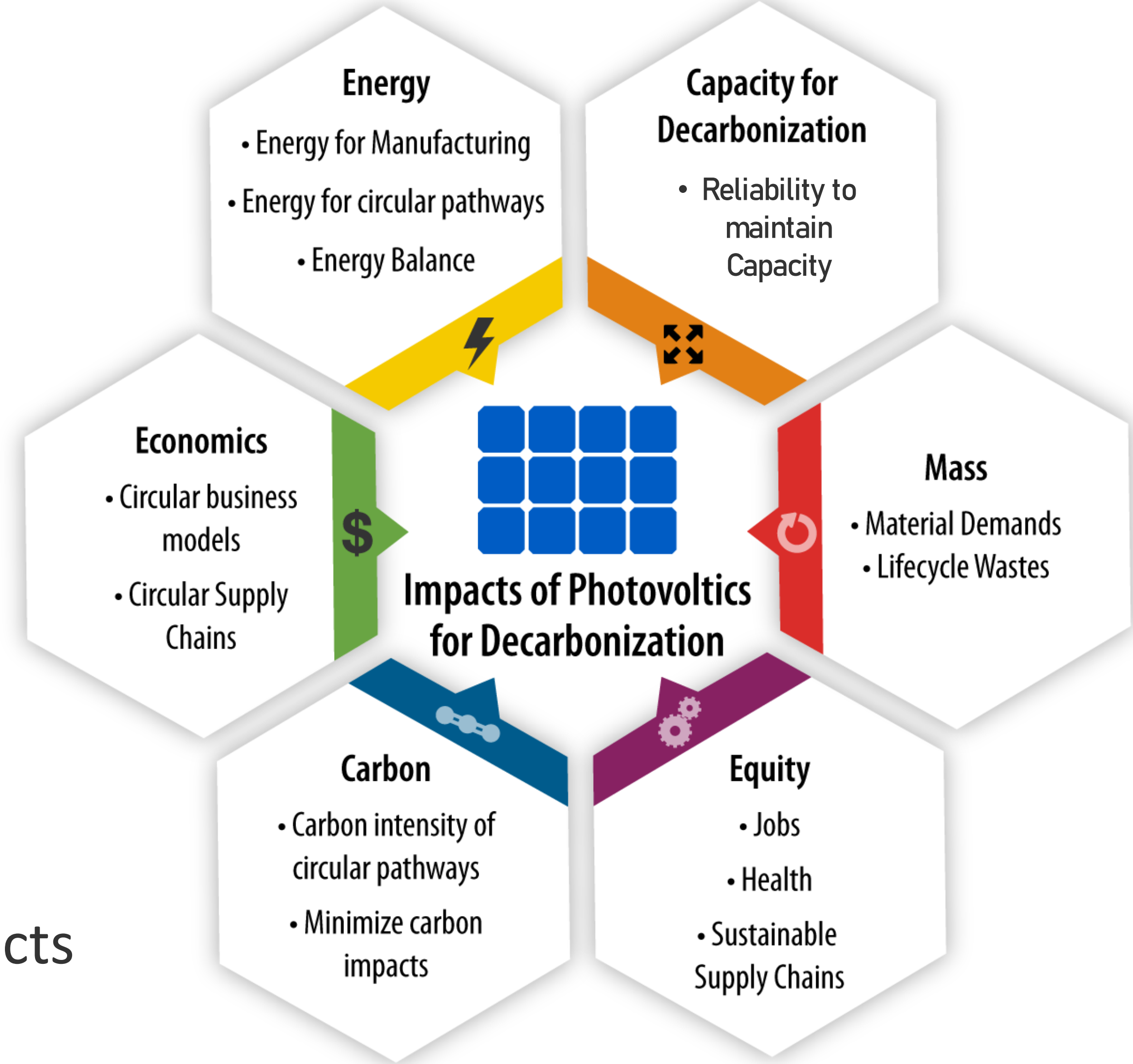
EROI of 10 is considered a minimum threshold
(Murphy et al. Sustainability 2022)
**this data would require harmonization*

Note: Metrics are for internal comparison only

Conclusions

For Energy Transition:

1. **Short project lifetimes require the most replacements, soonest**
   - 8 years means +330 TW of replacements
   - E.g.: Repowering decision
2. **Early loss modules require twice as many installs as Class A modules**
   - Class A = 73 TW
   - Early Loss = +85 TW of replacements
3. **Reducing degradation rate by 0.1% (rel.) can save 3 TW of replacements**
   - 2%/yr degradation needs +42 TW of replacements



Replacements = Manufacturing Demand and Impacts

Maximize Energy Balance

Analysis available at: https://github.com/NREL/PV_ICE/blob/development/docs/tutorials/18 - PVRW 2023.ipynb

Thank you!

Heather.Mirletz@nrel.gov or heathermirletz@mines.edu

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Proposed R's of PV

	R-Strategies	Generalized Description	Proposed PV Specific
Decarbonize First	**R0: Refuse**	Refuse fossil fuels and carbon intensive materials	**Decarbonize First** **Refuse Virgin and Conflict Materials**
	R1: Rethink	System design and integration for net energy yield over time	High energy yield PV systems Future proofing/backward compatible Design for Repair and Reliability Integrated PV
	R2: Reduce	Reduce energy, material, and carbon input	**Reduce Material usage/W_p** Material substitution Increase manufacturing yield Decarbonize manufacturing
Maximize Net Energy	R3: Reuse	Re-use if good condition	Merchant Tail, Resell in secondary market
	R4: Repair	Repair and maintenance for extended life	Onsite repair of modules and components
	R5: Refurbish	Restore older to updated functionality	Demount and transport modules for repairs Replace storm damaged modules on site
	R6: Remanufacture	Use parts in new product for same function	Disassemble, replace cells, relaminate
	R7: Repurpose	Use parts in new product with different function	Repower system with new components
Turn waste into feedstock	R8: Recycle	Process materials, high or low quality	Separate modules and components, reclaim materials
	R9: Remine	Landfill mining	Mine input materials from landfills, refine
	R10: Recover	Energy recovery through incineration	Burn component materials for energy generation

Mirletz, Ovaitt, Barnes, 2022 "Quantifying Energy flows in PV Circular Processes"
PVSC Proceedings

Lit EROI

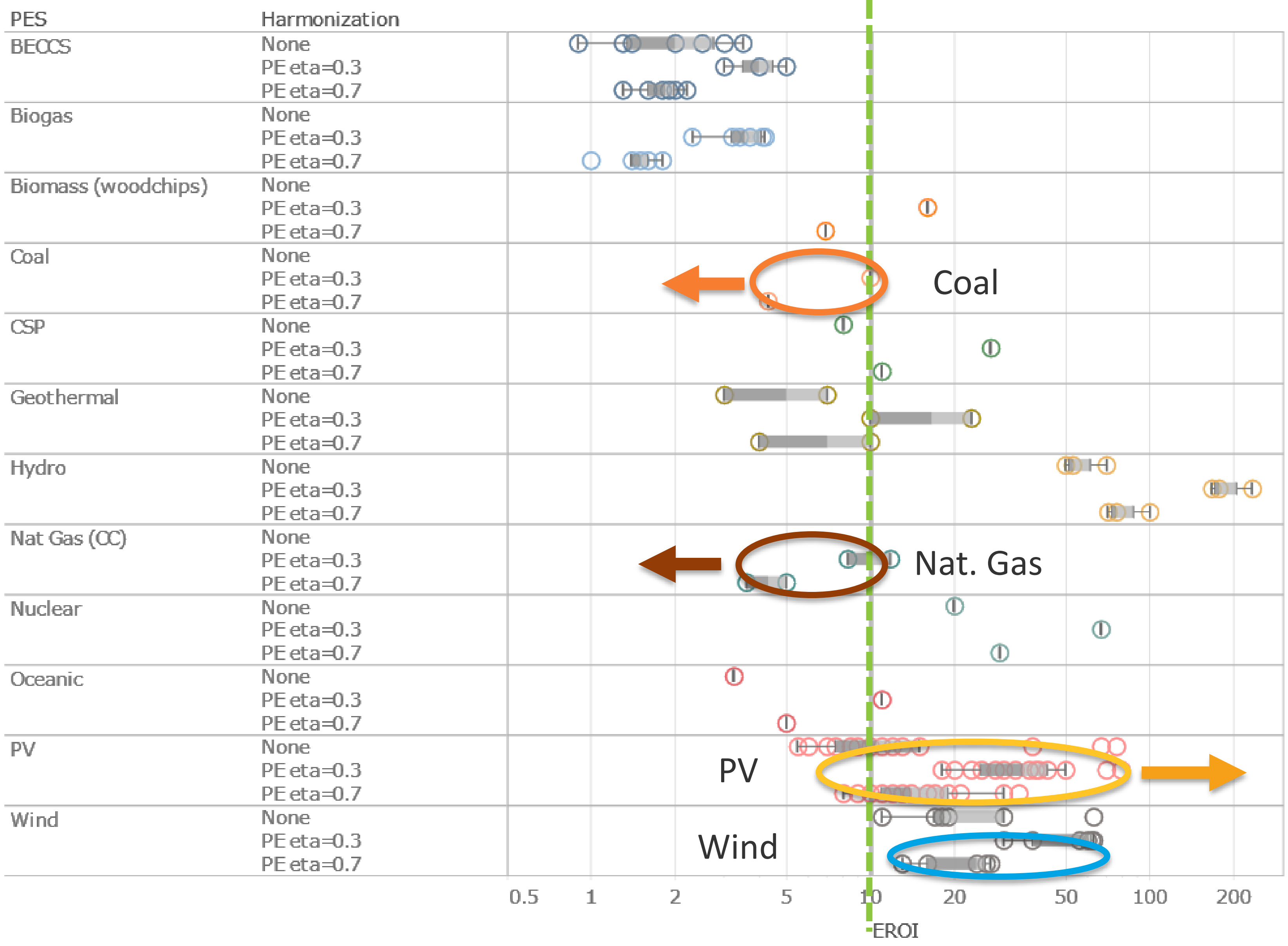


Figure 7. EROI values for electricity, respectively, as originally published (Harmonization = "None"), and post-harmonization in terms of equivalent primary energy output, respectively assuming deployment in a thermal-dominated electricity grid mix (Harmonization = "PE eta = 0.3"), and deployment in a de-carbonized electricity grid mix (Harmonization = "PE eta = 0.7"). BECCS = bioenergy with

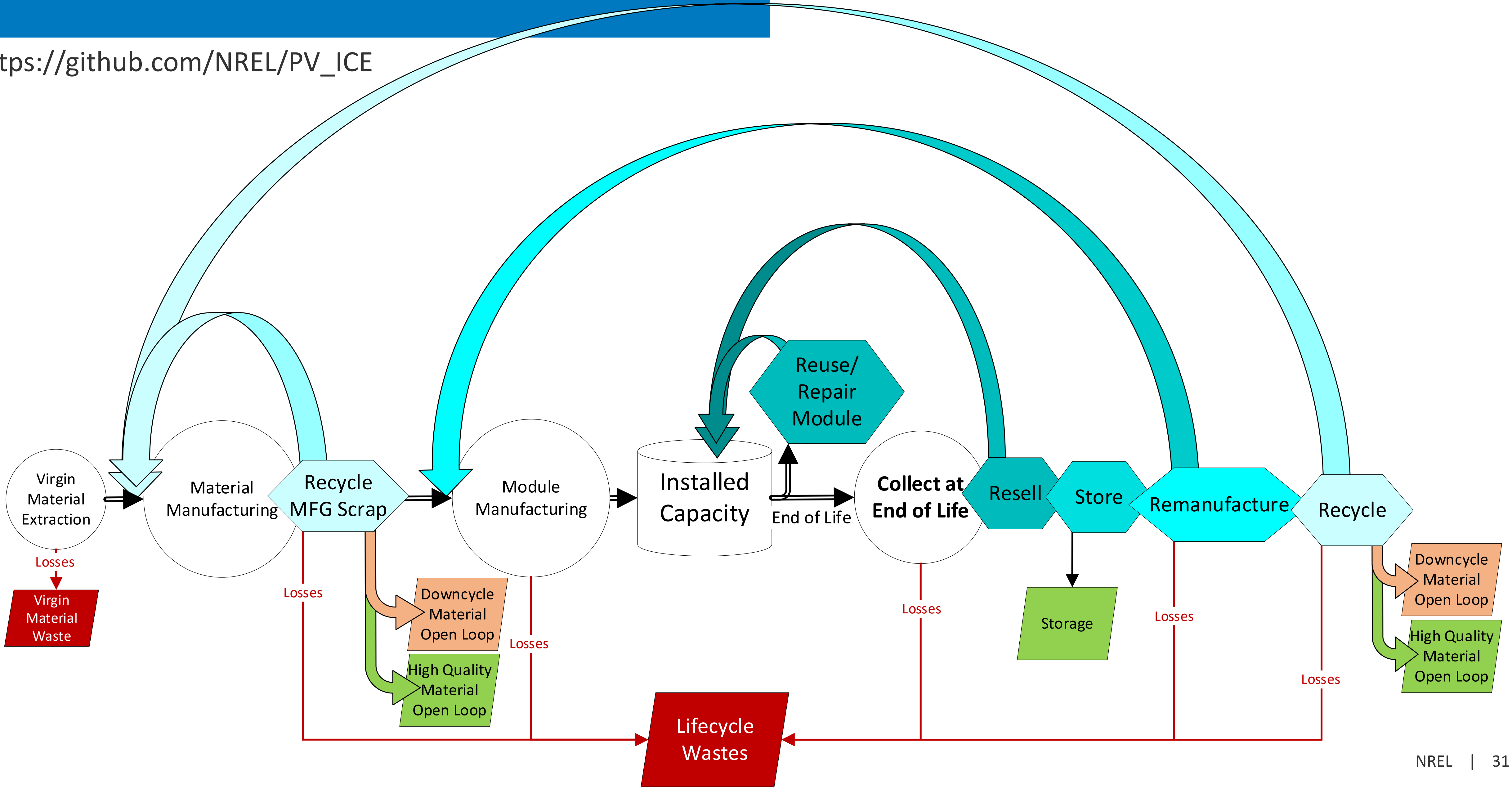
EROI of fossil fuels will decrease with time because you have to put more energy in to extract.

On the other hand, EROI of PV will increase with time because we get better efficiencies. Even if the extraction energy of the materials increases with time, so does the energy yield/generation.

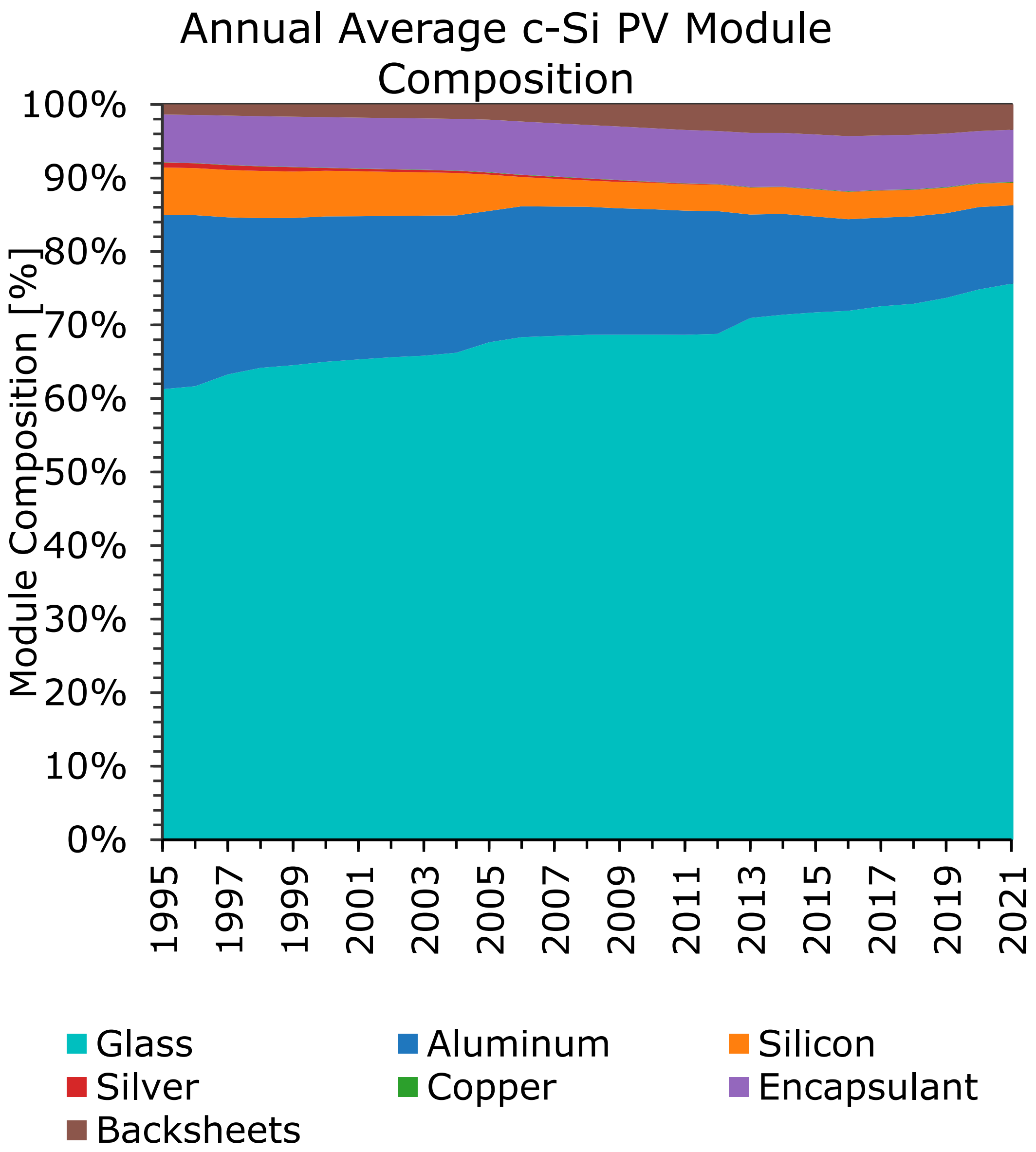
One way to mitigate the increasing extraction energy would be to use circular economy pathways for materials.

PV ICE Flows

https://github.com/NREL/PV_ICE



Material Composition of Avg PV module over time



Ovaitt & Mirletz (2021). PV in the circular economy, a dynamic framework analyzing technology evolution and reliability impacts.

https://doi.org/10.1016/j.isci.2021.103488