# A Circularity Assessment for Silicon Solar Panels Based on Dynamic Material Flow Analysis

48th IEEE Photovoltaics Specialists Conference (PVSC 48)
June 21, 2021

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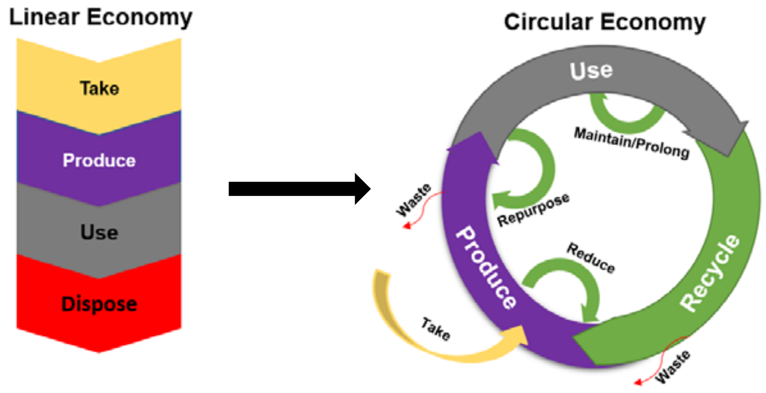


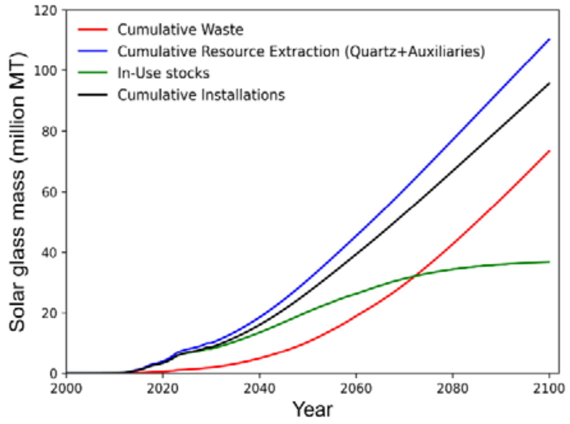


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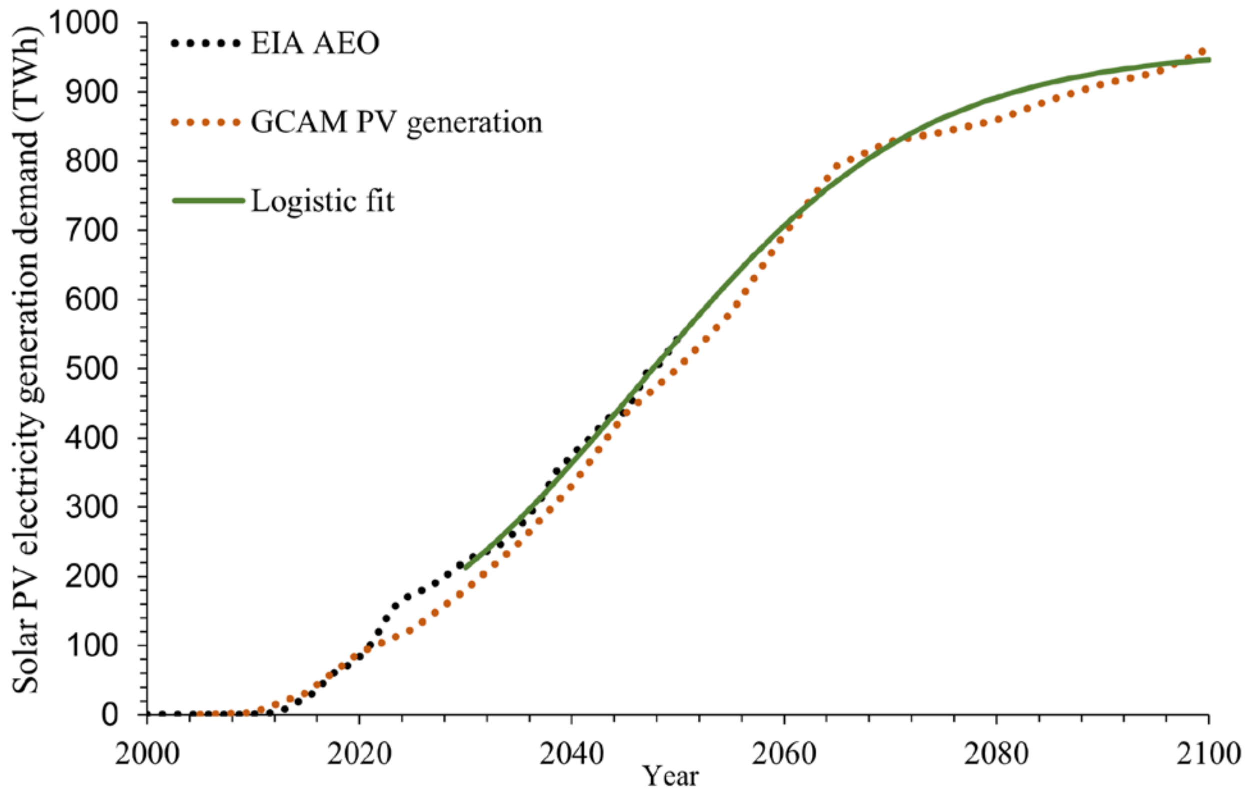
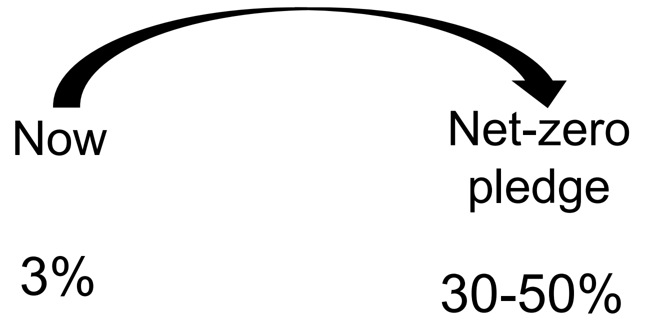
# Rapid Deployment of Solar PV is a Key to Faster Decarbonization of Electricity Sector

**U.S. has pledged net-zero carbon emissions by 2050 and 95% decarbonization of electricity sector by 2035**




Solar PV share in U.S. electricity generation



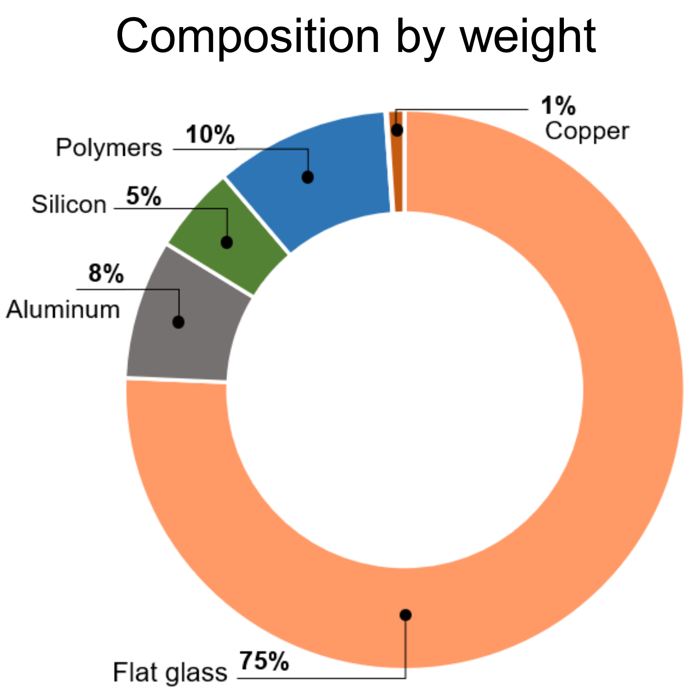

**How much material is needed? What are the impacts on existing material supply chains due to this rapid growth?**

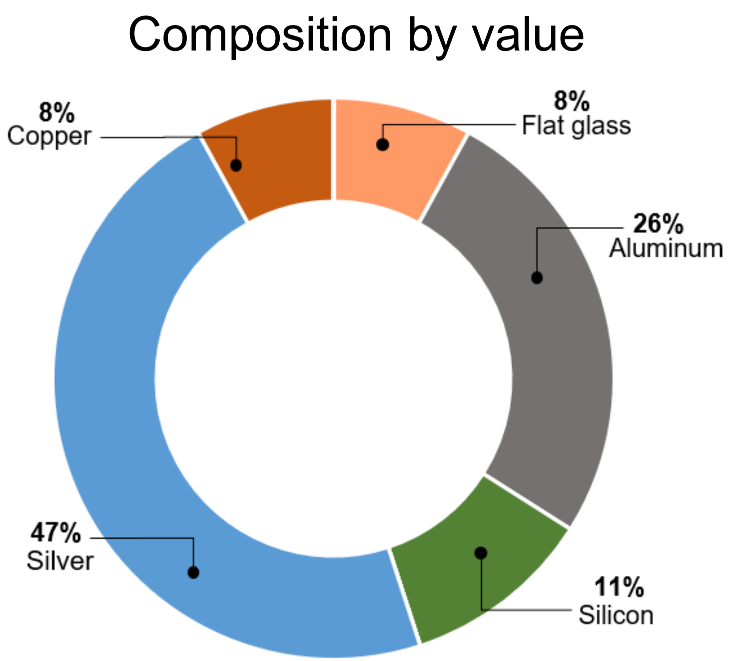
Source: U.S. SETO 2021

# Fast Growth Now, More Waste Later: A Transition to a Circular Economy is Needed

**Initial estimates of End-of-Life (EOL) PV module waste by 2050:**

Worldwide ~78 million metric tons (MT) → ~10% of electronic waste
U.S. ~13 million MT




**Material flows also carry:**

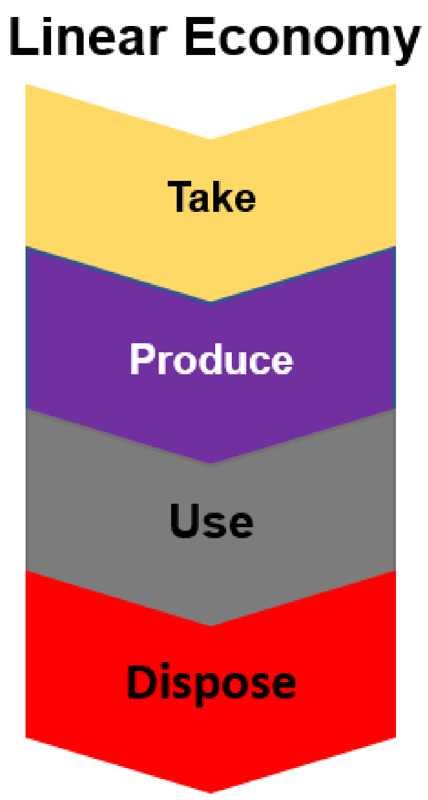
- Energy investments
- Emissions (air, water and soil)
- Environmental impacts
- Economic value ($)

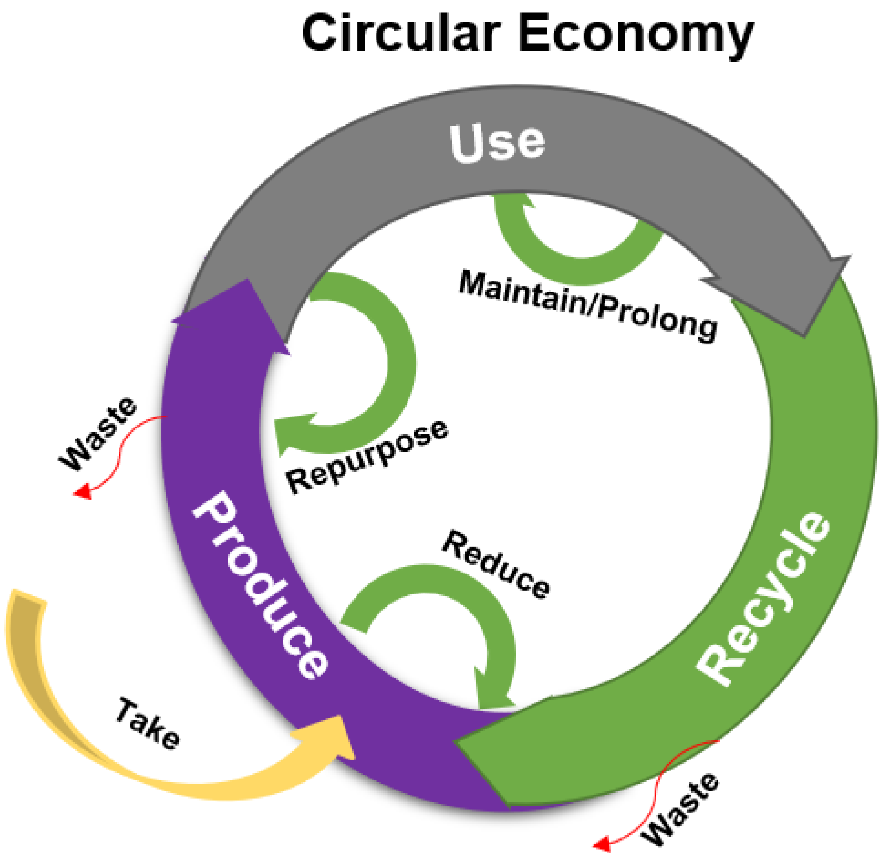
**PV glass and aluminum frames are studied here**

## Landfilling is wasteful and not sustainable

Source: IRENA/IEA PVPS 2016, CSA group 2020

# Circular Economy Practices Eliminate Waste and Conserve Raw Materials, Thus Promoting Environmental Sustainability

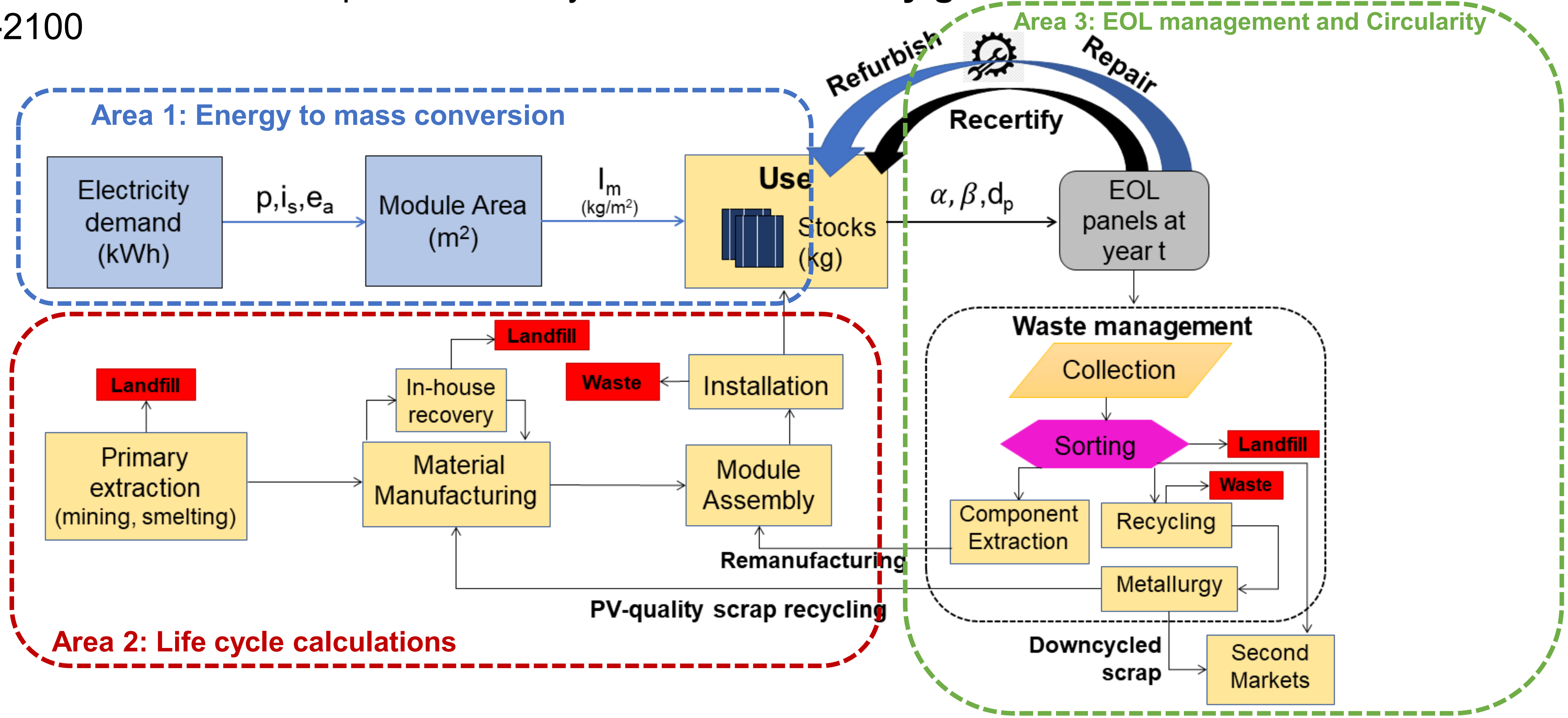



**Need to consider material life cycles to quantify impacts of circularity practices**

# Photovoltaic Dynamic Material Flow Analysis (PV DMFA) Model

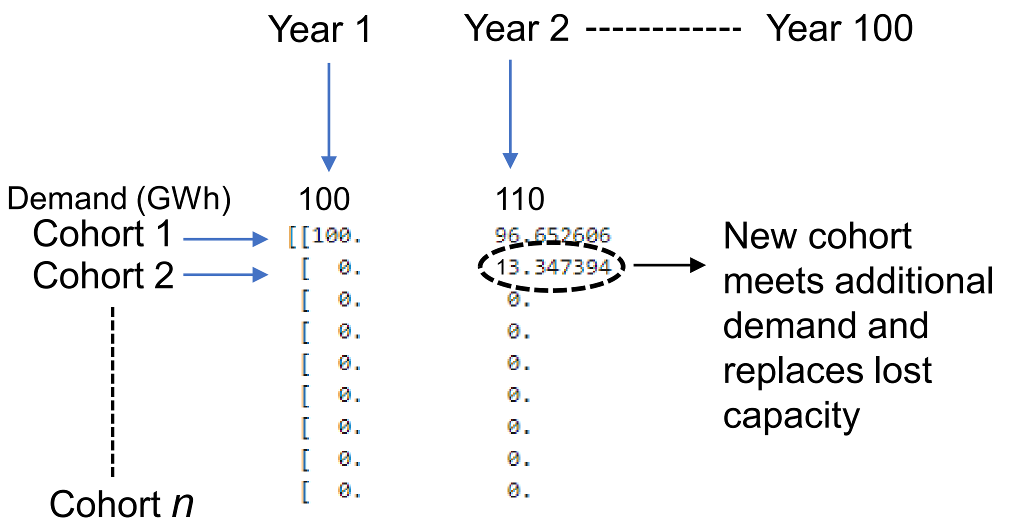
Open-source, process-based sustainability framework to **quantify stocks and flows** in the **life cycle** of PV materials based on historical and predicted utility-scale **PV electricity generation** in the United States in the period 2000-2100



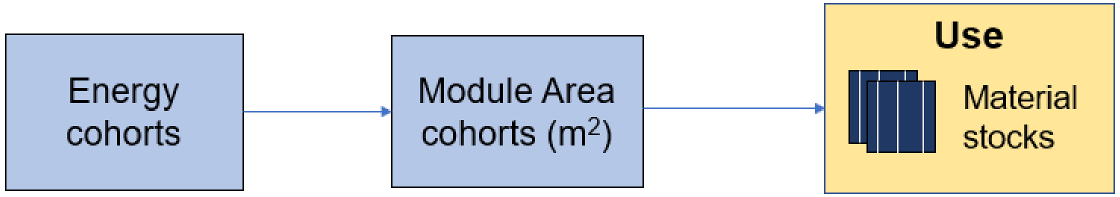

Cradle-to-Cradle System Boundary

# Energy, Area and Mass Cohorts Capture Evolution of Model Parameters with Time

A cohort is the group of PV panels installed in a given year with a unique set of parameters



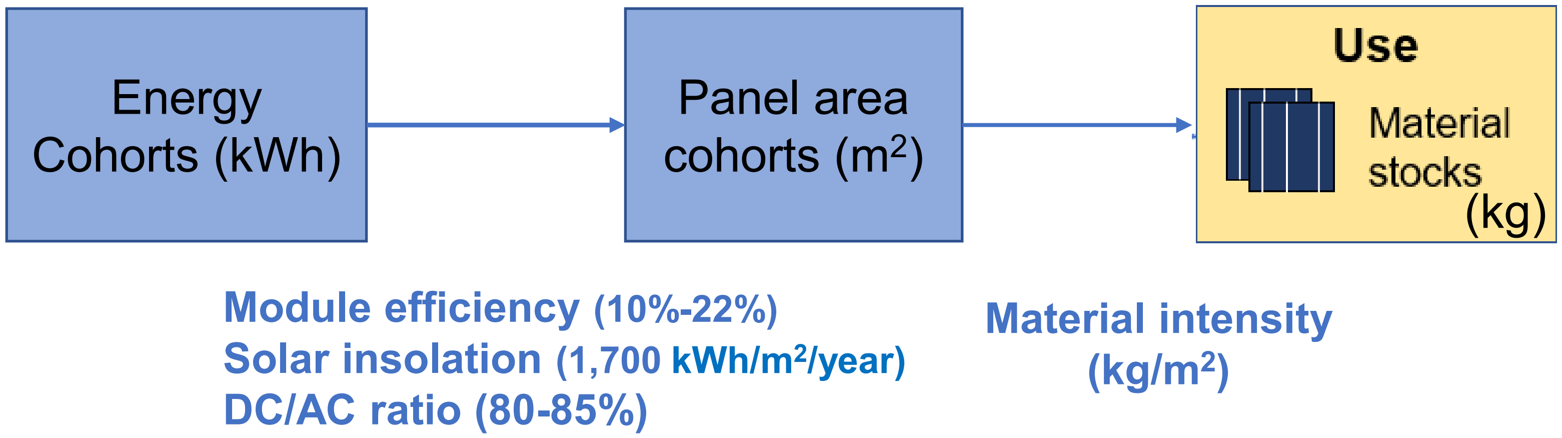

*Hypothetical example of energy cohort calculation*




- U.S. utility-scale PV demand predictions are sourced from EIA and GCAM
- Cohort electricity generation capacity decreases due to panel efficiency degradation **AND** random losses throughout system lifetime modelled by 2-parameter Weibull lifetime probability distribution
- A cohort reaches EOL if cumulative Weibull is 98% **OR** if efficiency degradation is 80% of installation efficiency (~20% degradation)

**Energy cohorts are used to estimate module area cohorts that are converted into material installations, in-use stocks and retirements**

# Energy, Area and Mass Cohorts Capture Evolution of Model Parameters with Time




Roadmap reports (e.g., ITRPV, Wood Mackenzie, SEIA) are used to estimate weighted average parameter values with time for each cohort

**Model allows for regional and sectoral analysis**

# Research questions

**Solar glass and aluminum frames are presented as case studies (~85% by wt. ; ~35% by value)**

**Baseline Scenario**

What is the size of PV material flows over time in a baseline scenario?

**Parametric Study**

What are the most influential PV related parameters in PV module waste generation?

**PV DMFA**

**Impacts of Circularity Practices**

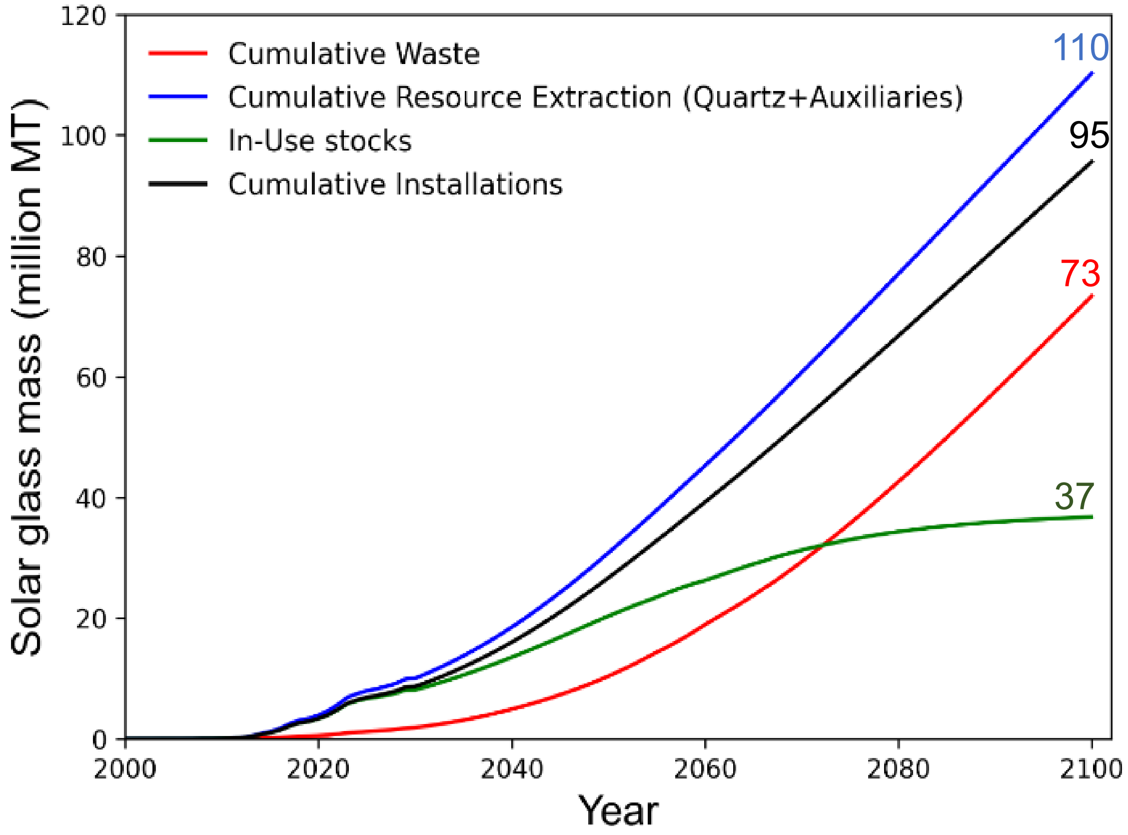
What are the impacts of module reuse, refurbishment, remanufacturing and recycling on waste generation?

**PV module design trends**

What are the impacts of module design shifts (i.e., bifacials, high-power large modules) on glass+aluminum?

In a baseline scenario, no panel EOL waste management is assumed

# Soaring Demand for PV Flat Glass

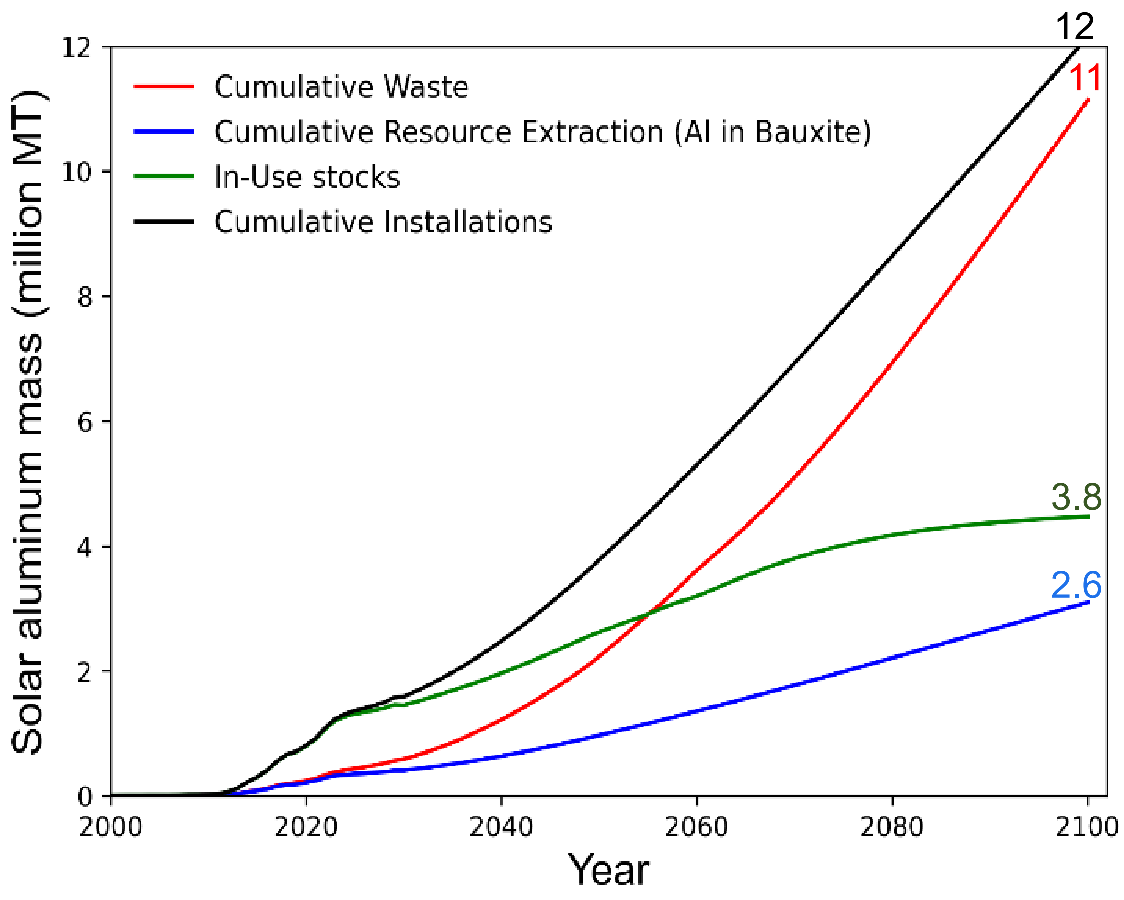



- Over 80% of life cycle waste arises from use phase → EOL circular pathways could reduce this waste stream
- Average worldwide cumulative flat glass manufacturing capacity is ~88 million MT;  U.S. share is 12 million MT
- In 2020, flat glass manufacturing deficit doubled glass prices and resulted in interrupted module deliveries

**Source: IRENA; ITRPV reports; USGS**

# Growth in PV Aluminum Demand

PV frames are made of aluminum 6063 alloy (U.S. ISRI code *ToTo*)
Aluminum 6063 alloys allow for multiple recycling without loss in functionality




**Roadmap reports predict lighter and thinner frames and growing shares of frameless modules**

# Research questions

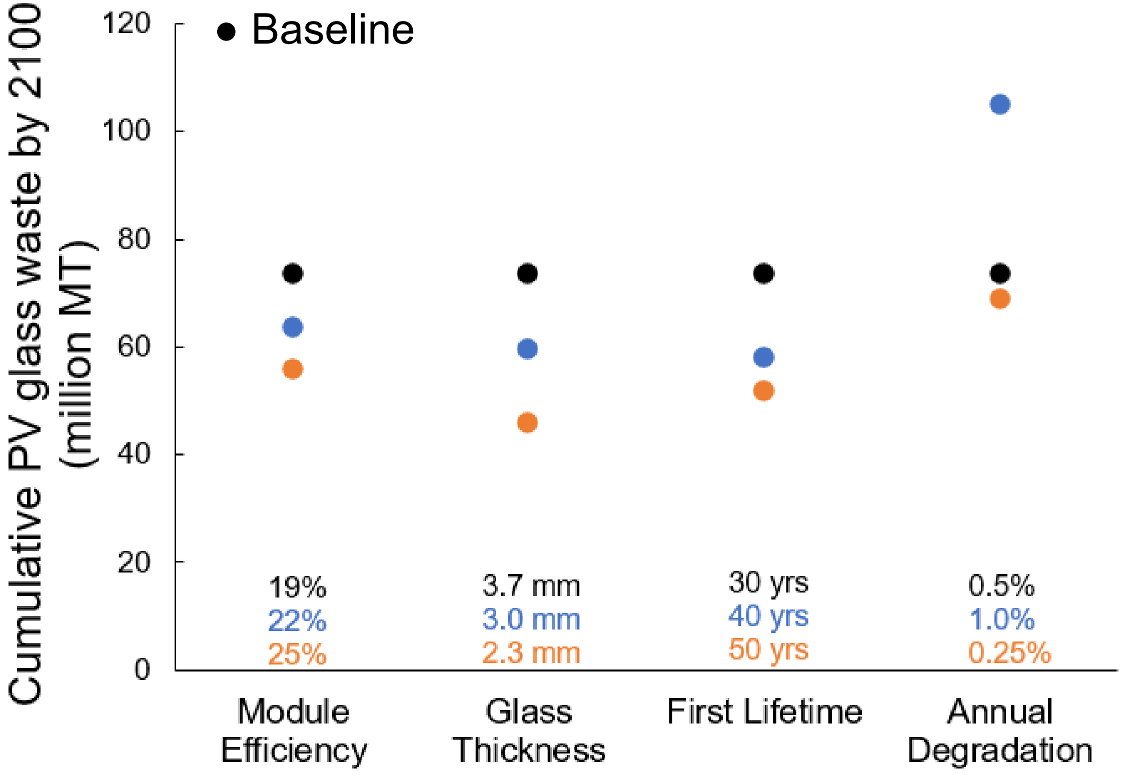
**Parametric Study**

What are the most influential PV related parameters in PV module waste generation?

**PV DMFA**

**Only PV glass is considered for parametric study**

# Initial Deployment Parameters Have a Significant Impact on Waste Reduction




**Only PV glass is considered**

PV glass savings by 2100:

- Extending module lifetime by 10 years → ~15 million MT
- Every 1% gain in module efficiency → ~3 million MT
- Reducing annual degradation to 0.25% → ~ 6 million MT
- Thinning a glass sheet by ~0.7 mm → ~20 million MT

**Module designs tailored for reliability improve lifecycle resource efficiency**

# Research questions

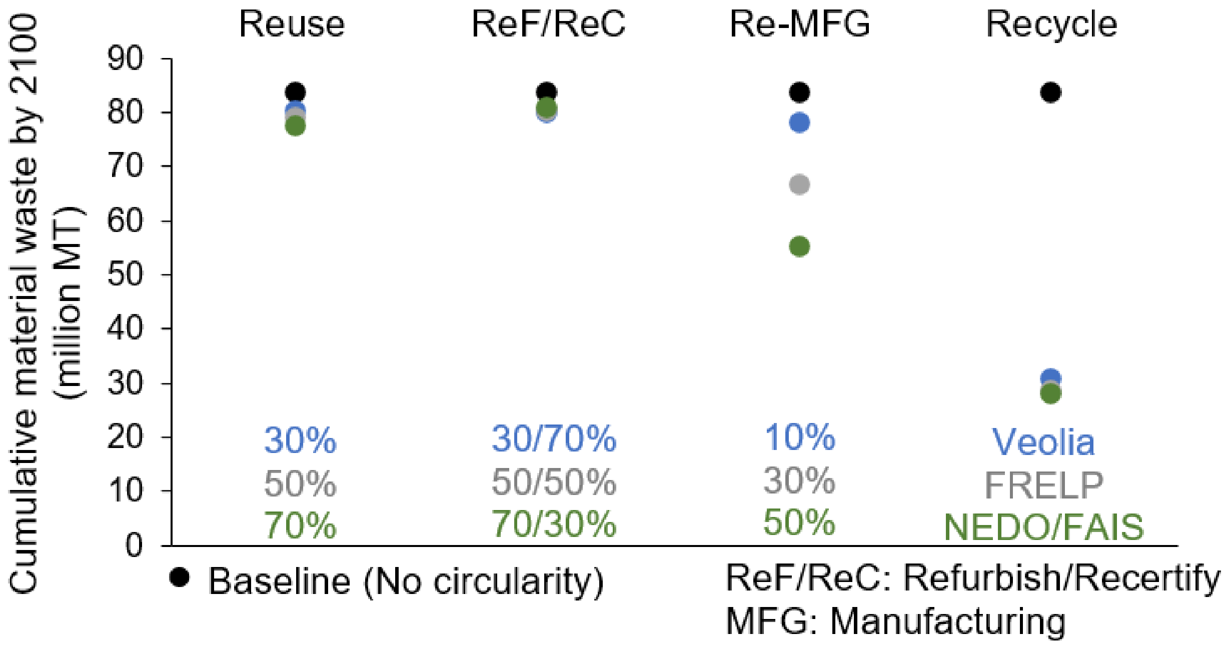
**Solar glass and aluminum frames are presented as case studies (~85% wt. ; ~35% value)**

**PV DMFA**

**Impacts of Circularity Practices**

What are the impacts of module reuse, refurbishment, remanufacturing and recycling on waste generation?

# Dedicated PV Recycling and Component Remanufacturing are Potentially Important Circular Practices




PV glass savings by 2100:

- Component extraction for 10% of modules → 7 million MT
- PV recycling → 55 million MT

Reusing modules, whether refurbished or not, has small effect on waste → Fast growth and considerable efficiency degradation in first life

NEDO/FAIS → Thermal → Unbroken glass
Veolia and FRELP → Mechanical → Broken cullet

- Shredding → scrap contamination → cannot be accepted by flat glass manufacturers

**High purity, high value scrap recovery in PV recycling should be emphasized**

# Research questions

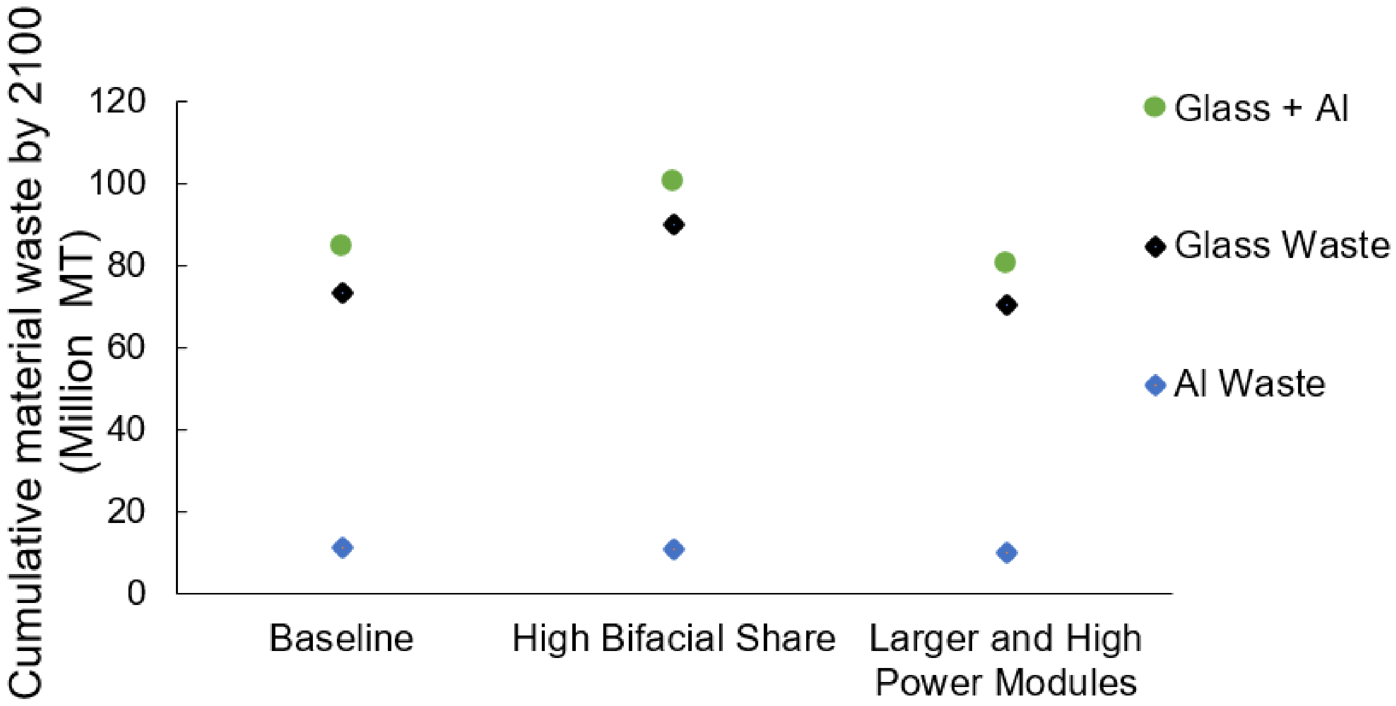
**Solar glass and aluminum frames are presented as case studies (~85% wt. ; ~35% value)**

**PV DMFA**

**PV module design trends**

What are the impacts of module design shifts (i.e., bifacials, high-power large modules) on glass+aluminum?

# New Module Design Trends Require Advanced Planning for Resources




Bifacials may grow from 10% in 2020 to 60% in 2030

- Dual glass
- ~3-10% gain in power from backside
- Require additional ~20 million MT compared to glass-backsheet modules

Large-size, high-power (>500 W) modules

- Dual and lighter glass sheets/ lighter frames to comply with module weight specifications
- Could save 3 million MT of PV glass and 10 million MT of aluminum frames

**Source: ITRPV ; Wood Mackenzie**

# Conclusions

- PV DMFA model estimates PV material flows in their cradle-to-cradle life cycle → Can be used as a data support tool for technoeconomic and life cycle analysis sustainability assessments
- High purity, high value dedicated PV recycling and component remanufacturing are potentially important EOL circular practices in the PV circular economy
- Improved system performance and reliability parameters is a key enabler for improved material circularity in PV value chain

**PV DMFA model will be released soon as an open-source software tool for users to evaluate materials and scenarios of interest**

Acknowledgment:
This conference presentation was developed based upon funding from the Alliance for Sustainable Energy, LLC, Managing and Operating Contractor for the National Renewable Energy Laboratory (NREL) for the U.S. Department of Energy under PRIME CONTRACT NO. DE-AC36-08GO28308 and SUB-2020-10029. 

NREL/PR-6A20-80276

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