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EPA Tools & Resources Webinar

Renewable Energy Management: Solar Panel Recycling

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US EPA Office of Research and Development

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United States Environmental Protection Agency

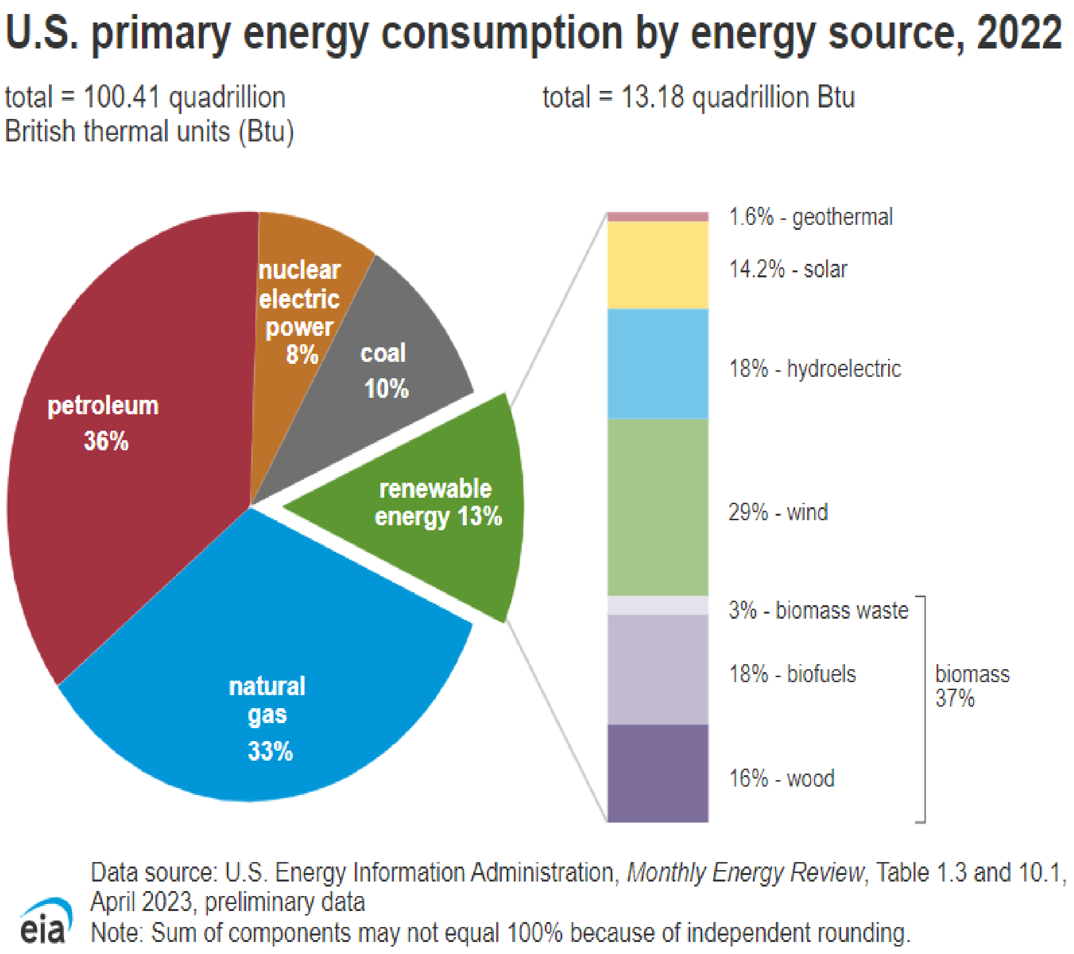
Project Objectives

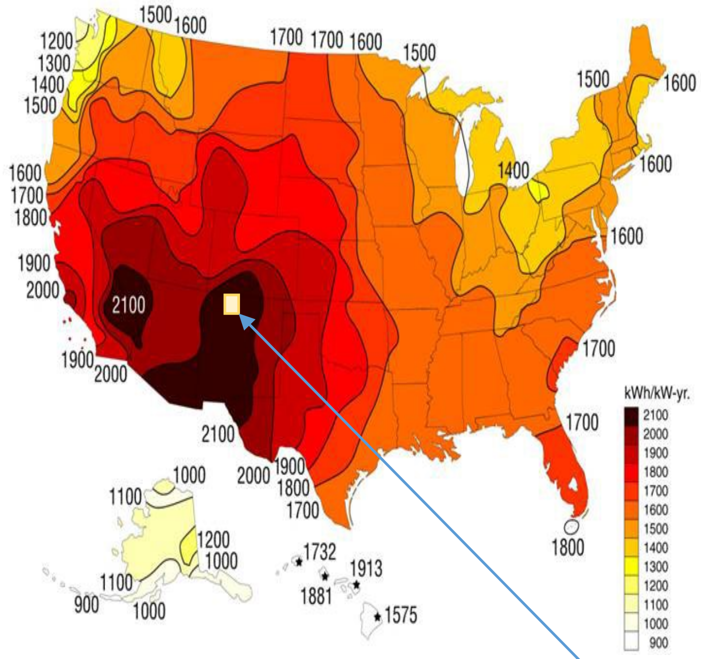
To help EPA and state solid waste managers estimate the end-of-life management (EoL) practices of photovoltaic (PV) panels and determine if existing recycling technologies and reuse pathways are sufficient to meet the projected panel waste generation in the next 20-30 years.

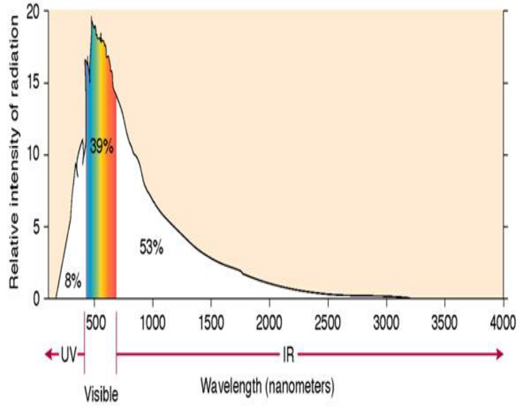
1. Project quantities of panel waste that may be generated in specific states or regions in the next 20-30 years (out to 2050).
2. Summarize the life cycle analysis of a PV panel, focusing on EoL management practices and waste by-products generated from the recycling process.
3. Document existing EoL management options currently available and promising technologies.
4. Identify viable panel reuse opportunities.

Background and National Trends

Solar Potential has a High Potential





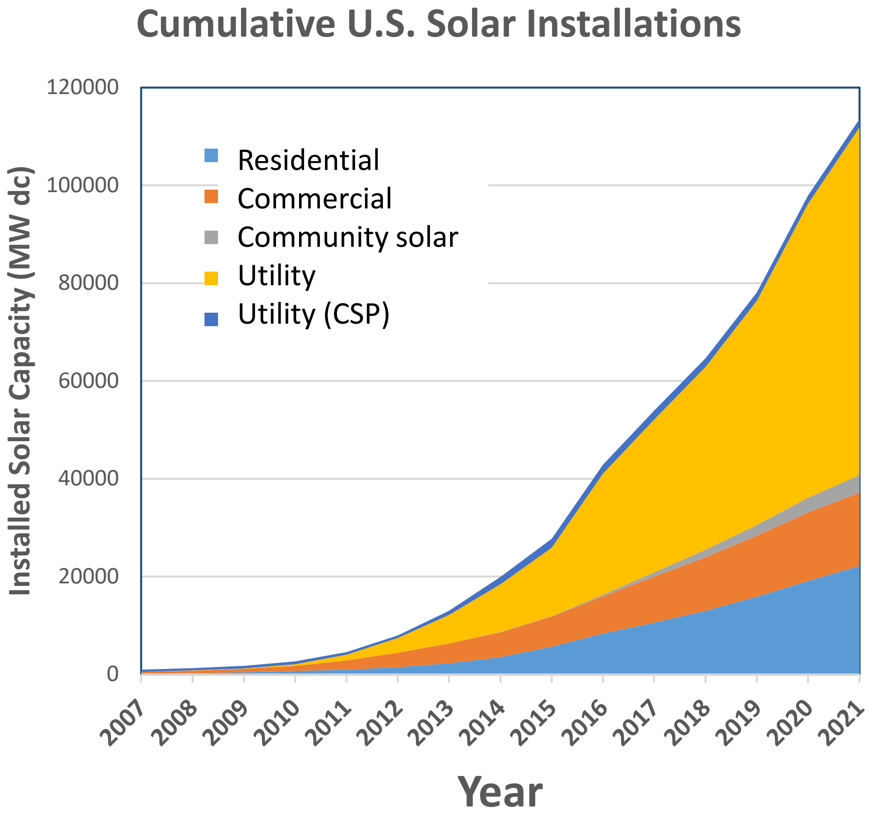


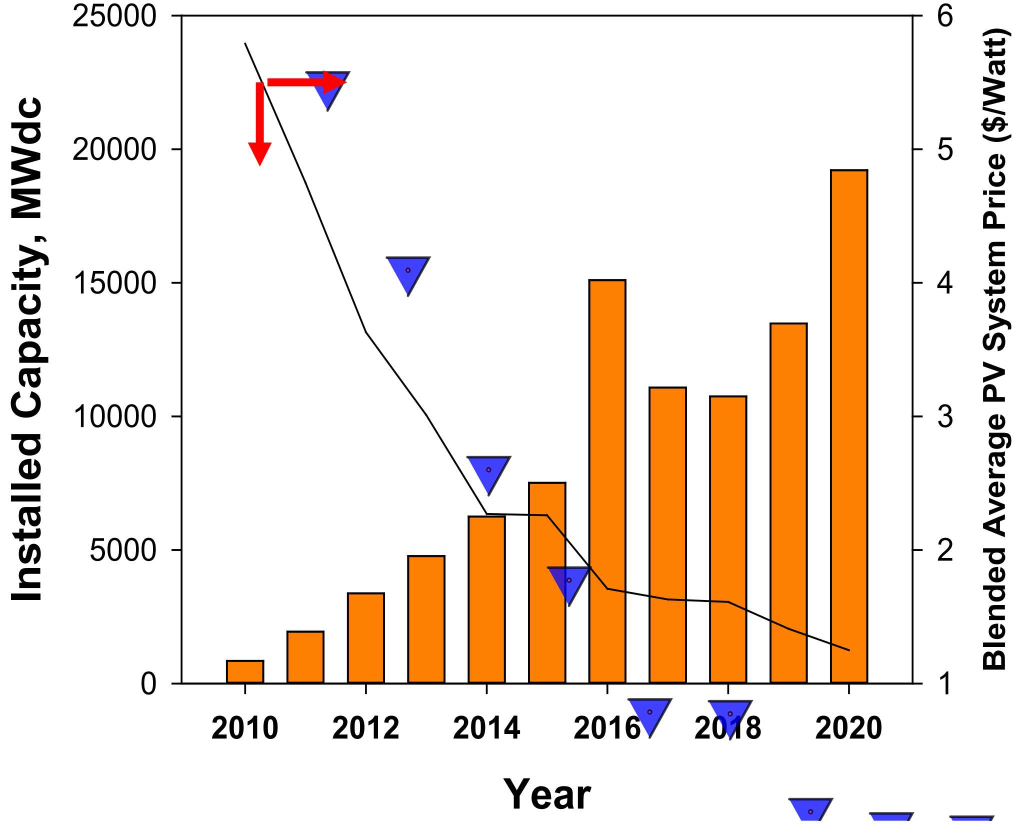
To meet the US power needs: Solar Area = 100 x 100 miles^2

- Solar energy used in the US = 400 EJ/yr
- Solar energy from sun= 10,800 EJ/day
- Usage percentage = 0.01% of solar energy

Source: U.S. Energy Information Administration;
Feldman and Margolis. 2019. "Q4 2018/Q1 2019 Solar Industry Update", NREL/PR-6A20-73992.

Solar Energy is Growing & Panel Prices Falling





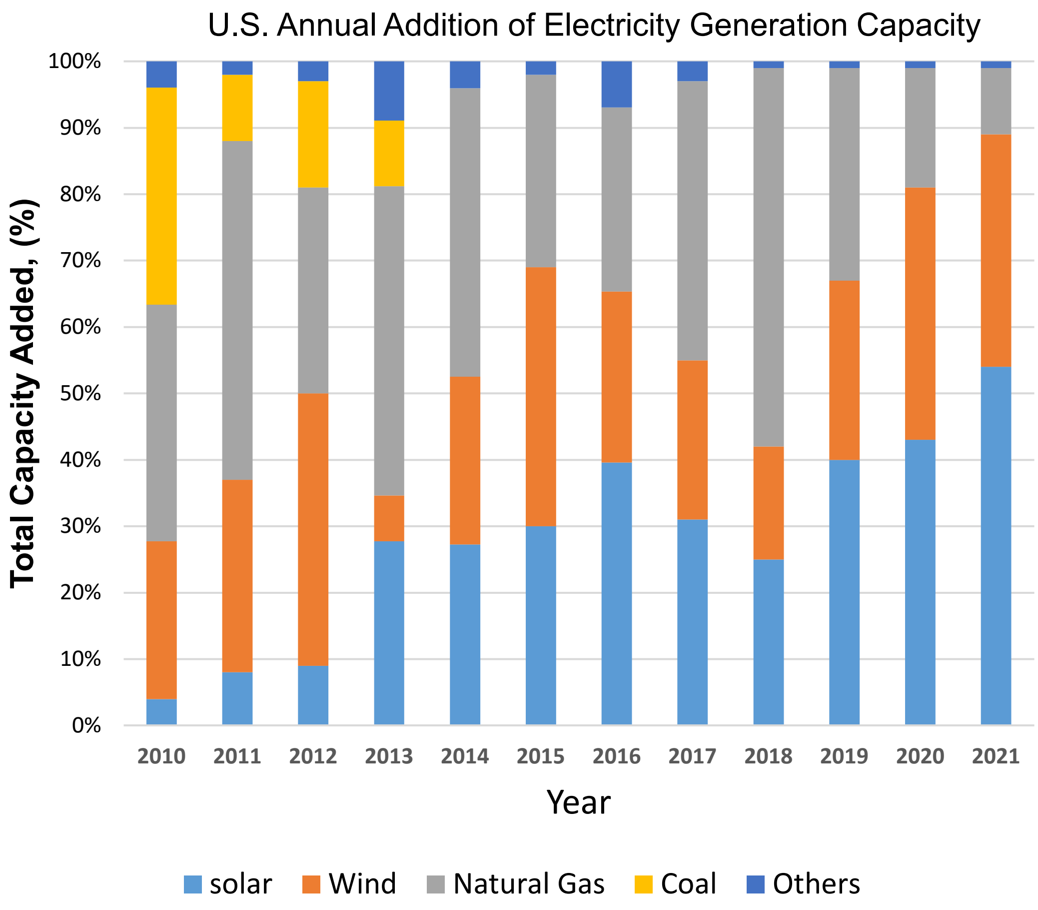
- 42% growth over the last decade
- 2022 growth > than 100,000 MW = 3%
- Most growth coms from utility-scale sector
- PV installed in 2022 is close to the same amount installed cumulatively at the end of 2018

- Installation price per household is down 50% over the last 10 years
- Utility-scale price = $16 – 35 /MWh

Source: Feldman and Margolis. 2019, NREL/PR-6A20-73992, Solar Energy Industries Association, SEIA

National Solar Trends and Projections

- Solar power is the fastest growing energy source in the U.S.- Q1 2021 the U.S. installed 5000 MW, 46% increas
- US **new** electric generation capacity from solar
  - 2010 → **4%**, and 2020 → **43%** of solar contribution to electricity capacity added to the grid, *Solar share*: 2010 (0.1%), 2021 (4%)
- Huge surge in solar panel disposal is anticipated during the 2030s and beyond
- Increasing volume of decommissioned PV panels (*growing exponentially)*, coupled with resource management regulations, could boost effective solar panel recycling market
- PV waste presents a *huge*, *untapped potential* for the recycling management market



Feldman, D. and R. Margolis, 2021. H2 2020 Solar Industry Update. NREL. April 6, 2021.
SEIA/Wood Mackenzie, 2021. Solar Market Insight Report Q2 2021

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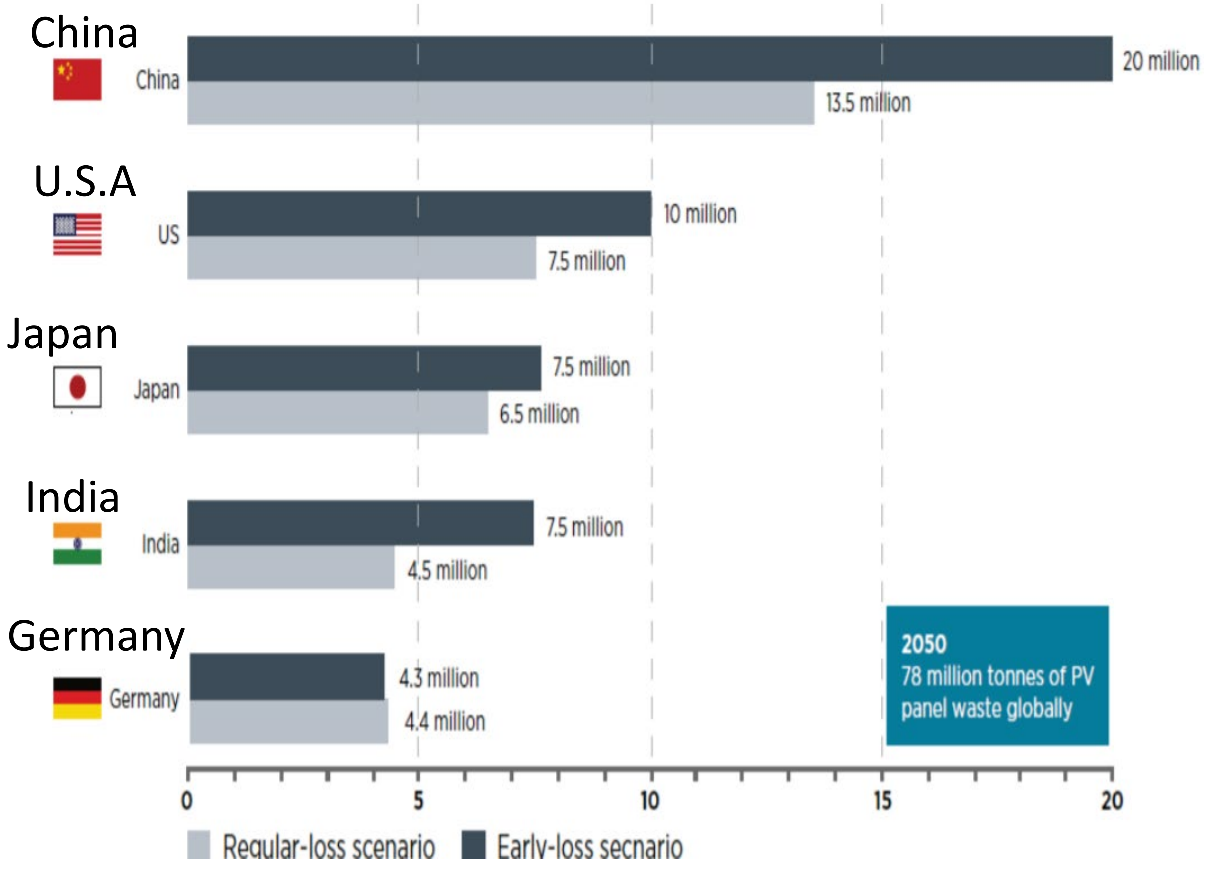
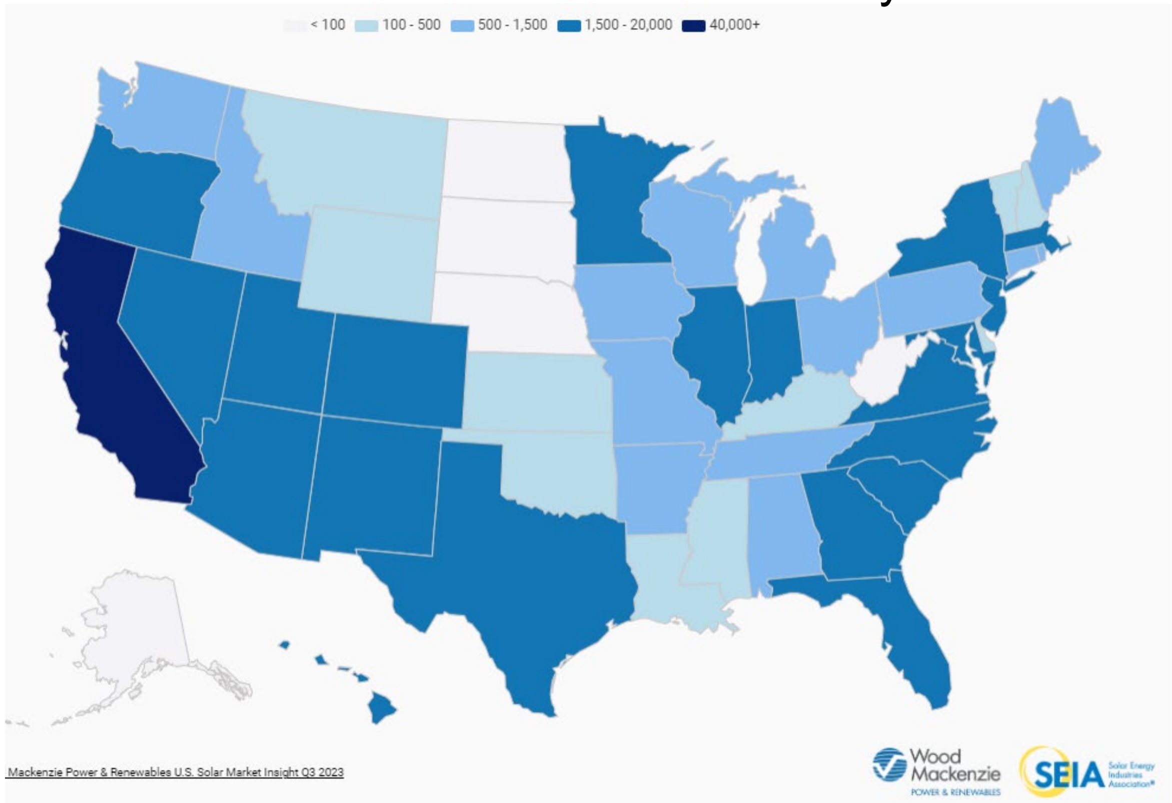
End of Life PV Panels will be a Significant Challenge in Future



U.S.: Expected Second Largest PV Waste Volume

Cumulative U.S. Solar Installation by State

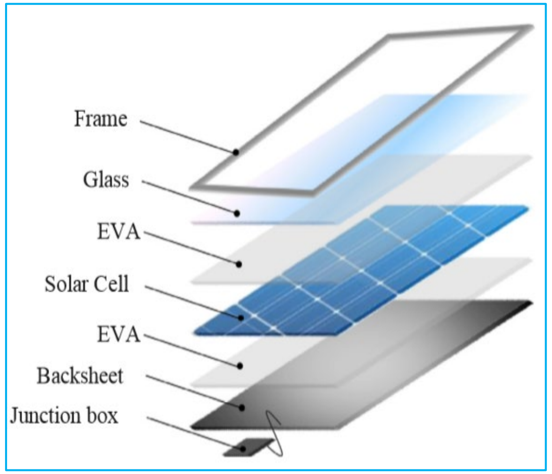


- Global e-waste = 41.8 million metric tons (record set in 2014).
  -Annual PV waste was 1000x less
- By 2050, PV panel waste could exceed 20% of the record global e-waste.
- We don't want to repeat mistakes of e-waste – Risking for PV as clean technology

Source: IRENA, 2016, Solar Energy Industries Association (SEIA)

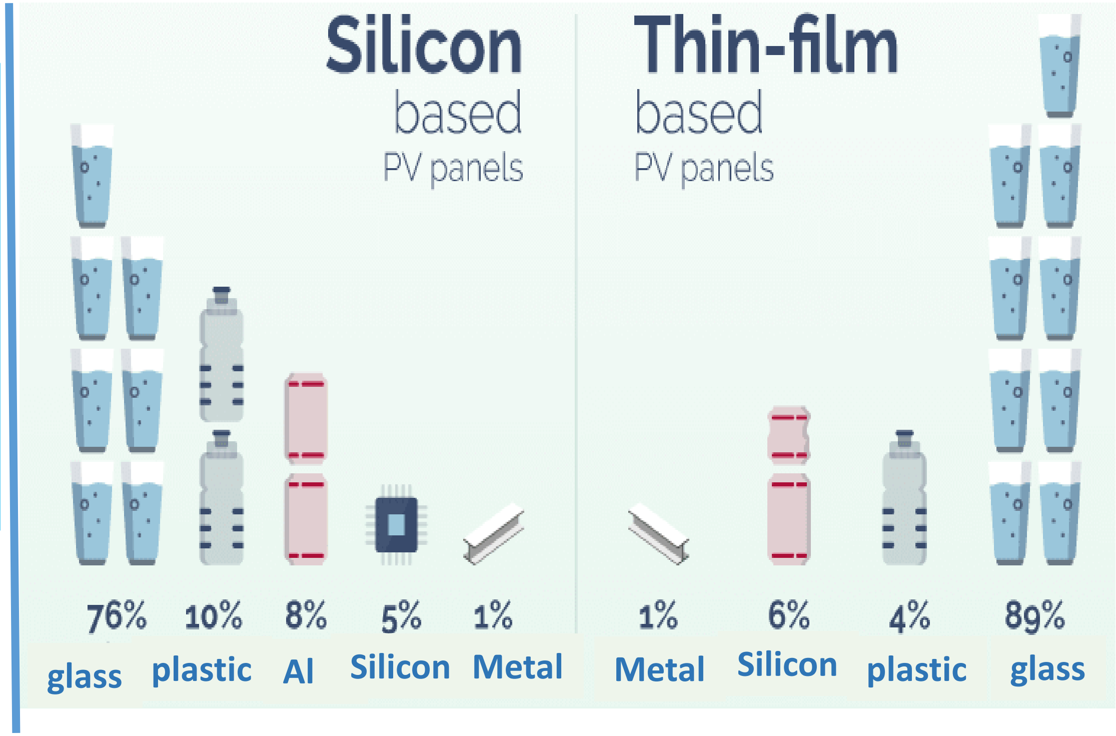
Types of Photovoltaic (PV) Modules and Material Used

- Distinction between first, second, and third generation PV modules
- **First generation**: poly and mono crystalline silicon (c-Si) (> 90% market share)
- **Second generation**: thin-film technologies like cadmium telluride (CdTe), amorphous and copper-indium-selenide (CIS)
- **Third generation**: includes technologies that are not available on a large scale (e.g. concentrator photovoltaic or organic solar cells)



General structure of PV panel

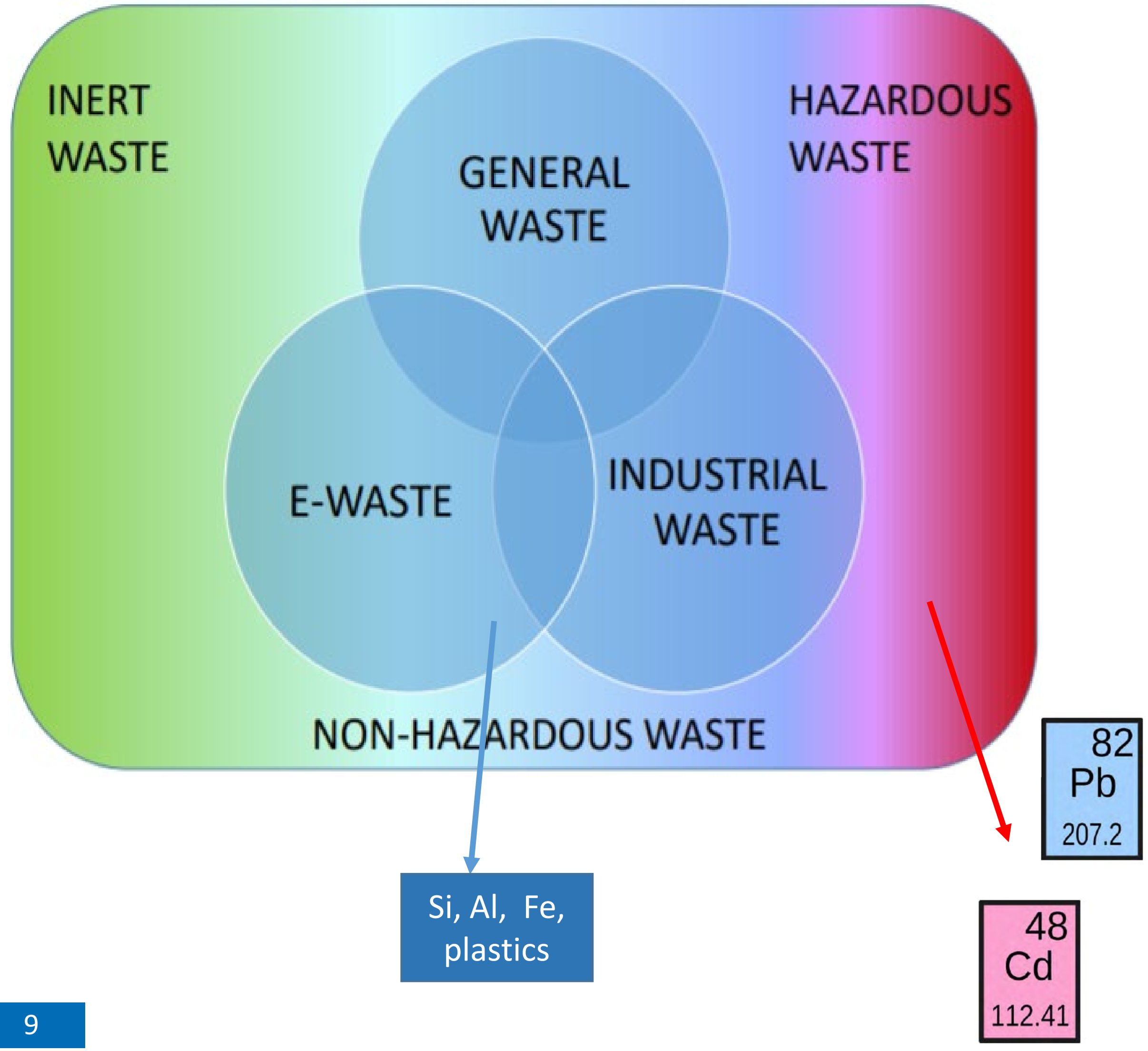
EVA - ethyl vinyl acetate



- Glass is the bulk material > 76%
- Minor constituents of valuable and hazardous materials
- Critical materials: Tellurium, antimoney, Ga, Indium

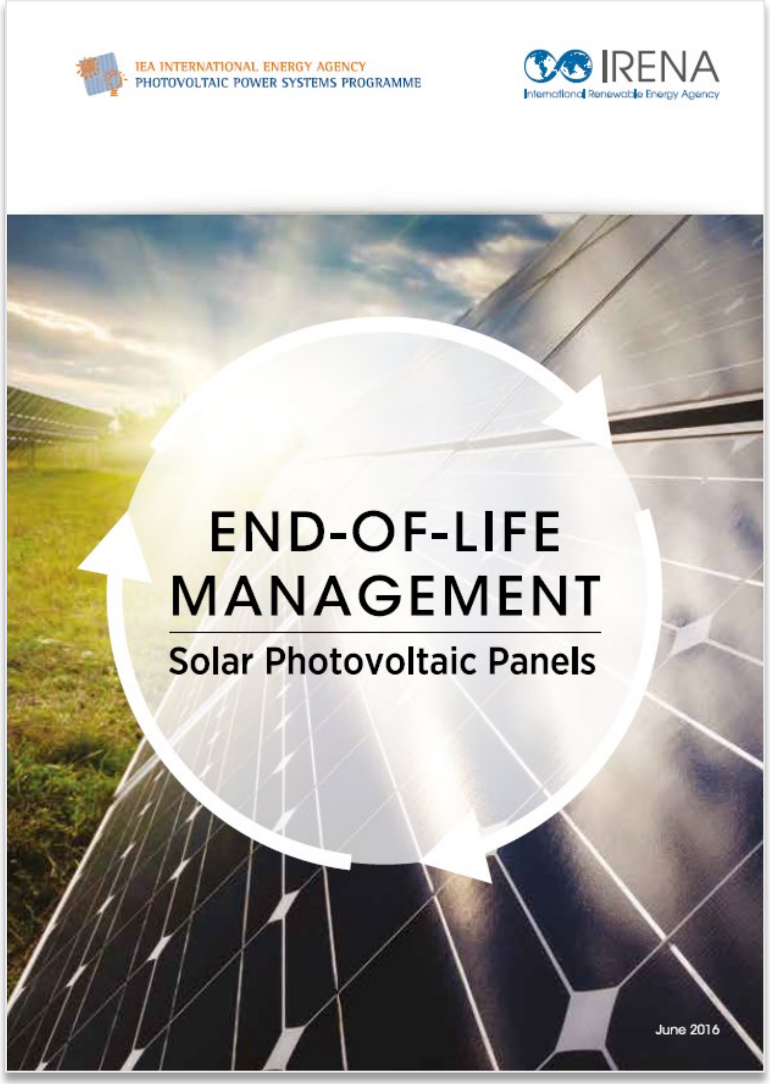
Source: GREENMATCH

Waste Classification



- PV panel technologies contain trace amounts of hazardous materials metals (such as Zn, Cd, Se, In, Ga, Pb, and others) in semiconductor and solder
- Different *waste characterization tests* and *sampling methods* can lead to a different classification of PV panel waste,
- Standard leaching tests and material concentration limits determine the classification and minimum requirements for treatment and disposal
- Most of the structure of a PV panel (such as Al-frame) is not hazardous waste and can be de-manufactured and recycled

Guiding Methodology for Estimating EoL PV Panels



- *International Renewable Energy Agency* (IRENA) and *International Energy Agency, Photovoltaic Power System* (IEA-PVPS (2016, 2021)
- Global estimates for developed countries out to 2050
- Modeled using the Weibull distribution function and defined parameters from the literature and stakeholders
- Early loss and regular loss scenarios

download the report

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PV Panel Scope and Expected Lifetimes

PV Market

Two market segments: residential and commercial

Commercially-available panels, no deviation in individual manufacturer performance

Not considering off-grid panels

PV Panel Lifetime

25 to 30 years

Point at which panels may drop to 80% efficiency and tend to be upgraded or replaced

No comprehensive tracking of when PV panels enter the end-of-life stage

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Methodology Overview by IRENA and IEA-PVPS

Determined PV capacity out to 2050 by State

- Existing IRENA report data for 2016 and 2030
- Interpolation between 2016 and 2030 using average growth in 5-year blocks
- Applied a conservative 2.5% escalation between 2030 and 2050

Converted PV capacity to mass

- Calculated an average ratio of mass of PV per unit capacity (metric tons/MW) by averaging available data from leading manufacturers on panel weight and nominal power

Estimated the probability of PV panel losses

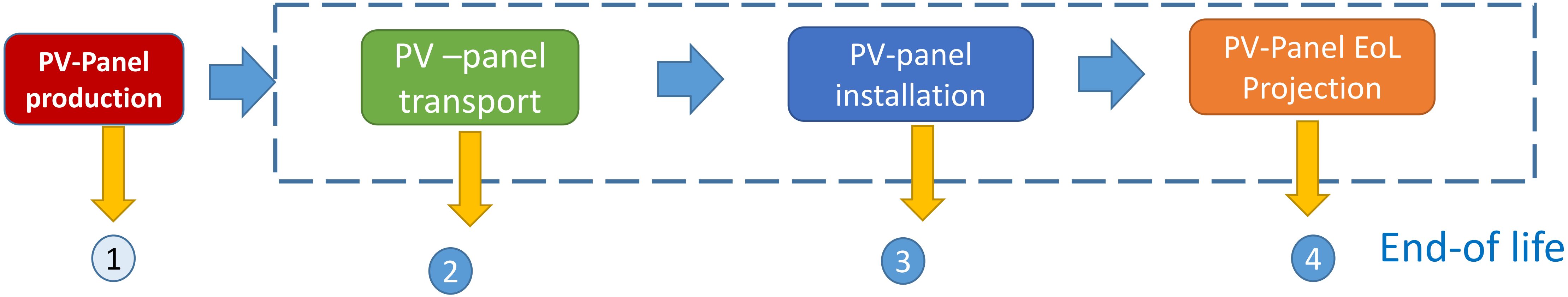
- **Probability** of failure for regular-loss and early-loss scenarios using the Weibull distribution function

Multiplied the PV panel loss by assumed panel weight

- Results in annual tonnage of PV EoL panels

Solar PV Panel Waste Projection

- At present PV market is young
- 2030: PV panel waste streams ~ 4-14% of production
- 2050: PV panel waste ~ 80% of installation

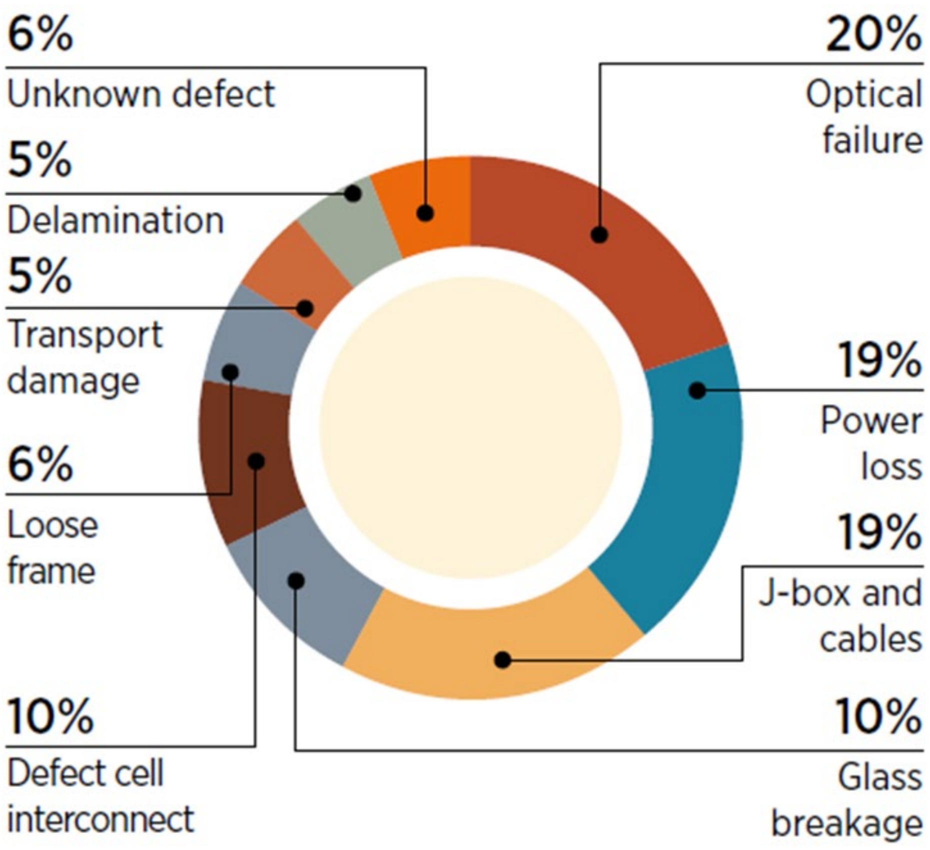


- Most waste is generated during four primary life cycle phases of PV panel
  1) Panel production
  2) Panel transportation
  3) Panel installation and use
  4) End-of-life disposal of the panel
- *The following waste forecast model covers all life cycle stages except production*

Reasons for Early Stage PV-Panel Failures

- **Regular**
  - End of expected panel life failure (i.e., 25 to 30 years)
  - Decommissioning (the end of the period or performance for a solar project)
- **Early**
  - Early failure
  - Identified safety issues
  - Weather damage (e.g., hail, extreme winds) and natural disasters (e.g., hurricanes, flooding, fires)
- **Mid-Life** (sometime between early and regular)
  - Homeowners who choose to uninstall an existing solar installation
  - Part replacement (e.g., inverters), panel refurbishment
  - Economic viability
- **Other**
  - Waste generated from solar panel manufacturing
  - A generator who decides to discard unused solar panels
  - Panels that were found (illegally dumped or abandoned)

PV-Panel Failure rate



Based on IEA-PVPS (2014a)

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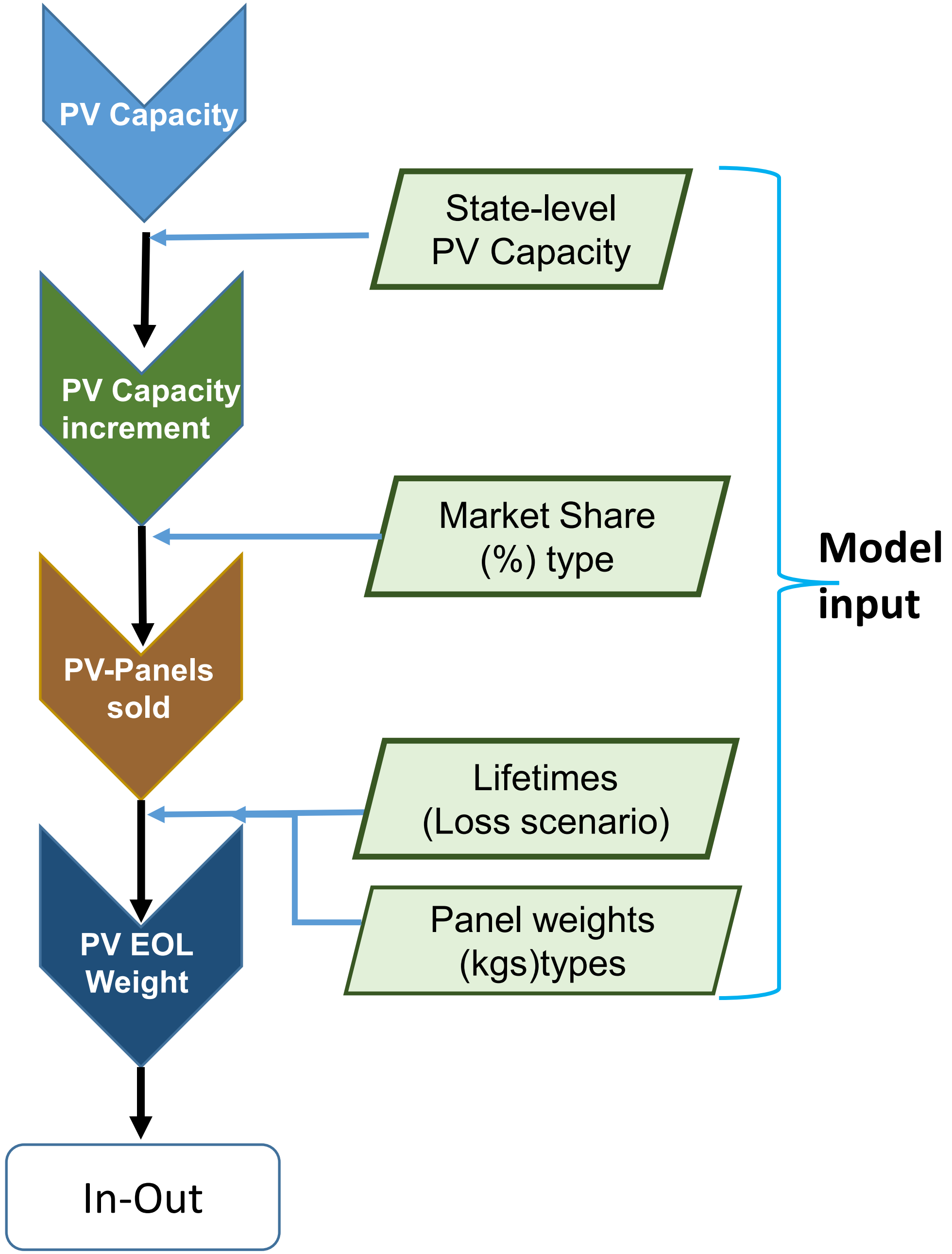
APPROACH

End-of-Life Projection Methodology

PV End-of-Life Model Process Flow Map



PV Panel Waste Stream Flow Model

- **Installed Solar** *PV capacity* (MW)
  - Predict future growth projection (source: Solar Energy Industries Associates (SEIA))
- **Market Share**: *residential, commercial, industrial*
  - Customer segment: residential versus commercial
  - Source: International Energy Agency
  - EIA-860 Non-Net Metering Distributed Capacity (MW), and Net Metering Capacity (MW)
  - EIA-860, Existing nameplate Capacity Energy Source, Producer Type and State
- **Quantifies** when and how much PV panels come to EoL
  - What is the increase in capacity
  - The conversion & probability of loss during the PV panel life cycle

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Model Assumptions

Model	Data Input and References
Regular-loss scenario input assumptions ○ 30-year average panel lifetime ○ 99.99% loss after 40 years ○ Extraction of Weibull model parameters from literature data **Early-loss scenario input assumptions** ○ 30-year average panel lifetime ○ 99.99% probability of loss after 40 years ○ Inclusion of supporting points for calculating nonlinear regression **Installation/transport damages**: ○ 0.05% of installed modules fail annually ○ 0.05% of modules fail before leaving manufacturer per year ○ 2% of modules are broken in production per year	• The 30-year average panel lifetime assumption was taken from literature (Frischknecht et al., 2016). • A 99.99% probability of loss was assumed using the Weibull function. The 40-year technical lifetime assumption is based on depreciation times and durability data from the construction industry (Greenspec, 2016). • The early-loss input assumptions were derived from different literature sources (IEA-PVPS, 2014a; Padlewski, 2014; Vodermeyer, 2013; DeGraaff, 2011).

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Modeling PV-Panel Failure

$$F(t) = 1 - \exp\left[-\left(\frac{t}{T}\right)^{\alpha}\right]$$

- F – fraction of PV panels that failed after time t,
- T = scale parameter, average panel lifetime
- α = shape parameter, determined from PV reliability studies, differs by scenario

A continuous probability distribution function (**Weibull Function) is** used to model failure times, and product reliability

Presented as either a 2 or 3 parameter function

Parameter values are based on PV reliability studies

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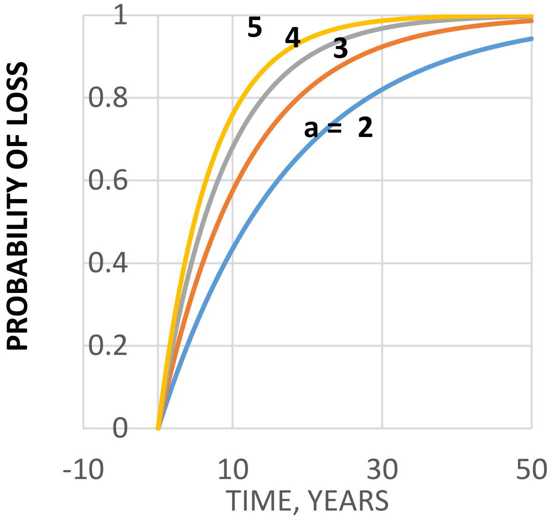
Weibull Probability Loss Function for PV Panels

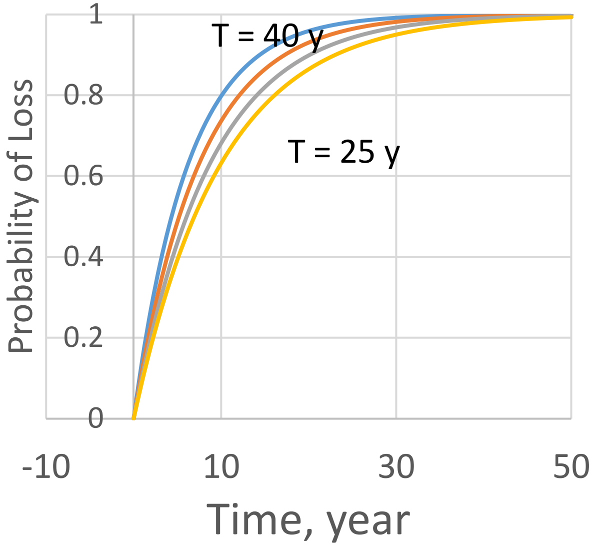
- Average panel lifetime = 30-year
- Both early-loss and regular-loss scenarios were modelled using the Weibull function based

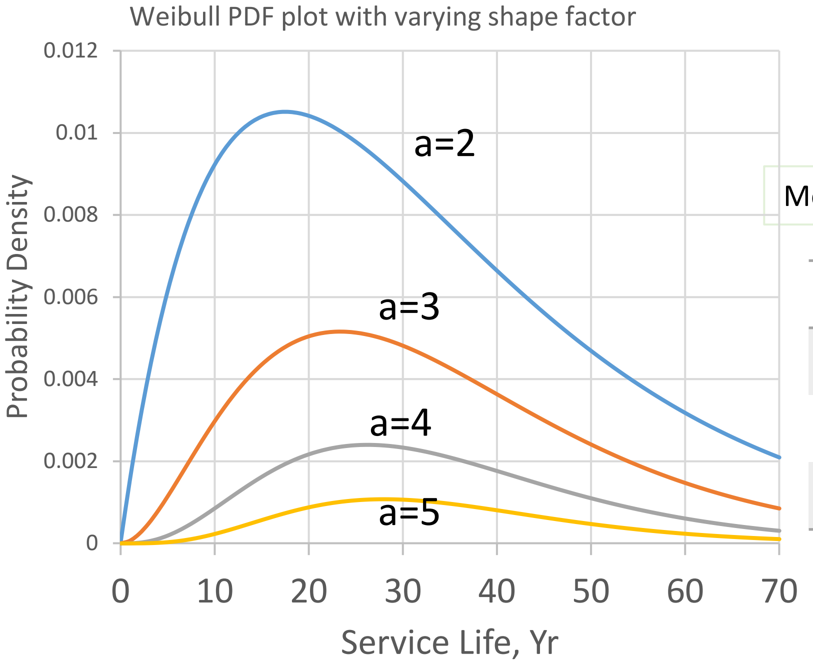
$$F(t) = 1 - e^{-\left(\frac{t}{T}\right)^{a}}$$

t = time in year
T = average life-time
α = shape factor

Scenarios	Weibull Parameters	
	α (shape)	T (scale)
Regular Loss	5.3759	30
Early Loss	2.4928	30
Mid Loss	3.6	30





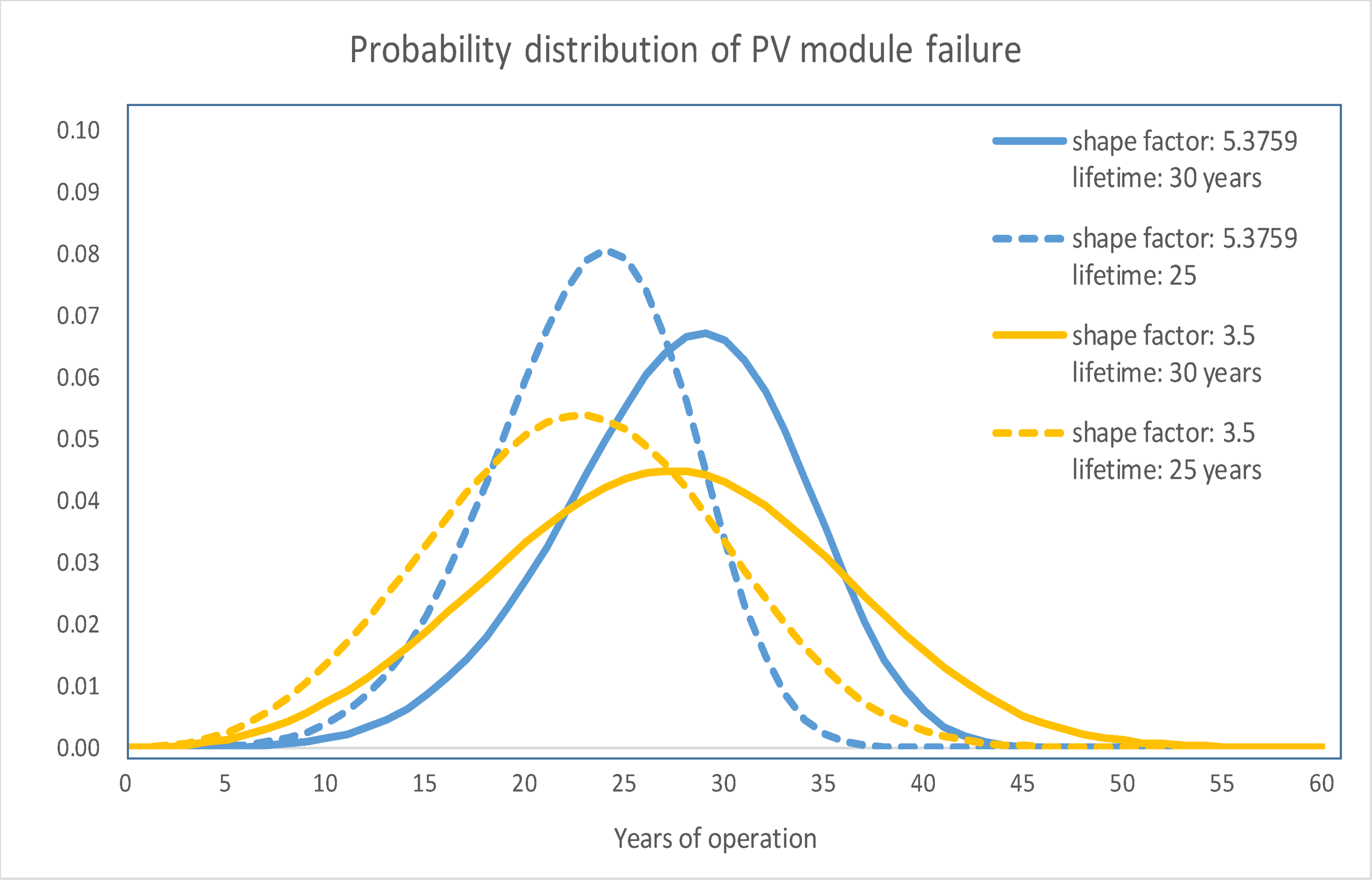


Median=T(ln2) $^{1/a}$

a	T
2	**29**
3	31
4	32
5	32.5

(Frischknecht, et al., 2016) and 5.3759 (Kuitsche, 2010; Zimmerman, 2013)

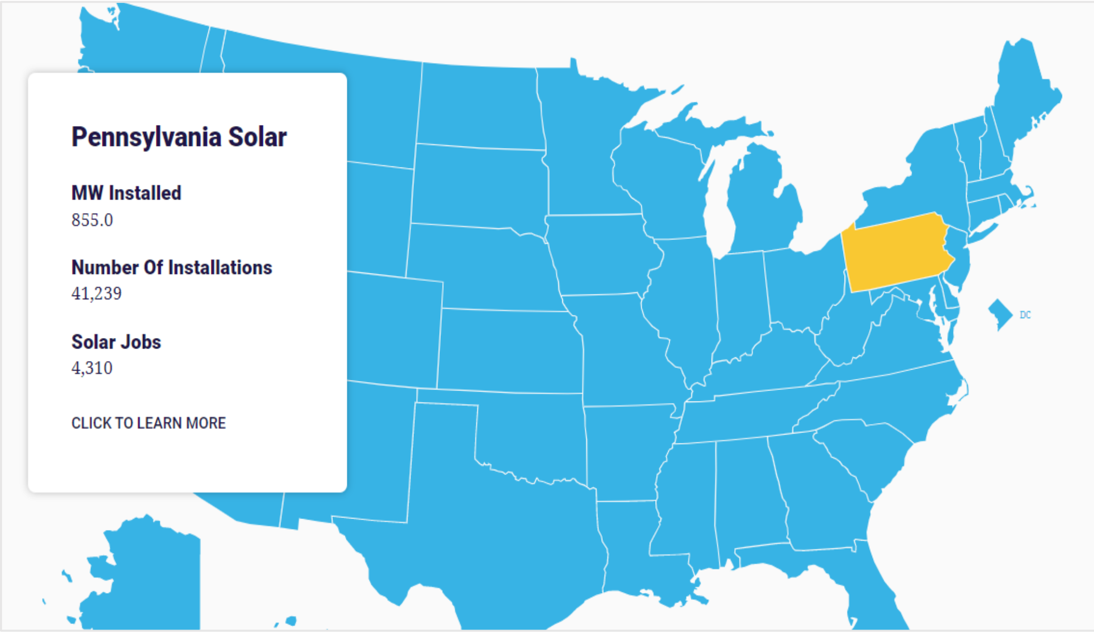
Example Weibull Distributions of PV Module Failure



- For Shape factor 3 – 4, Weibull distribution is bell-shaped Normal distribution
- Most PV modules have shape > 5 This form of distribution models are left-skewed → rapid wear-out failures during the final period of product life, when most failures happen.
- Utilities should be prepared increased failure rate and waste generation over time

Installed State PV Capacity (MW)

- Solar Energy Industries Association (SEIA)
  - Installed capacity by state to Q4 2020
  - Projections by state between 2021-2024
- EIA 2020 Annual Energy Outlook (AEO)
  - Projections of solar PV capacity growth between 2025 and 2050
- The U.S. Energy Information Administration (EIA)



SEIA Solar State by State, https://www.seia.org/states-map

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Market Share Data Source

- Done to separately estimate EoL mass from **commercial vs. residential** panels
- **Percentage of total installed** solar PV capacity in 2019 for residential and commercial segments
  - EIA-861, Non-Net Metering Distributed Capacity (MW)
  - EIA-861, Net Metering Capacity (MW)
  - EIA-860, Existing Nameplate Capacity Energy Source, Producer Type, and State

- **Market share calculations**
  - Summed residential capacity from both EIA-861 datasets
  - Assumed the commercial segment data included all non-residential installed PV capacity (commercial, industrial, and electric utilities)
  - Calculated the percentage of total installed solar PV capacity by state

Lifetimes and Scenario Runs for EoL Modeling

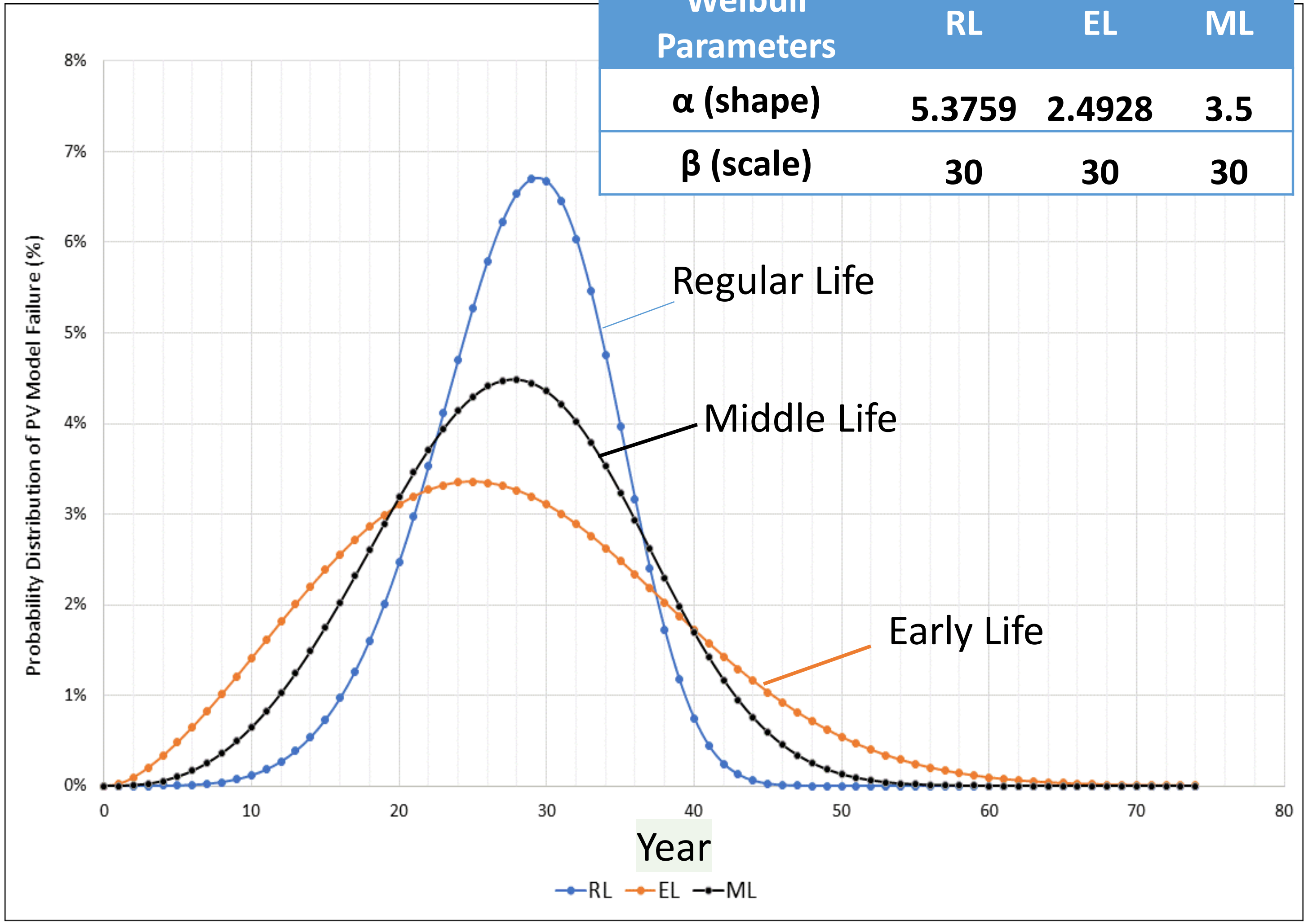
- Assumed PV panel lifetime of 30 years for commercial and residential
- Modeled three scenarios

Scenarios	Weibull Parameters	
	α (shape)	T (scale)
Regular Loss	5.3759	30
Early Loss	2.4928	30
Mid Loss	3.5	30

- Larger shape factor α results in a steeper curve
- Higher probability of loss at 30 yr or more

α parameter sources: Kuitsche, 2010; Zimmermann, 2013; Frischknecht, 2016

Weibull Probability Distributions for Different Scenarios



Weibull Parameters	RL	EL	ML
α (shape)	5.3759	2.4928	3.5
β (scale)	30	30	30

- The shape parameter allows us to model the characteristics of many different life distributions
- High number of initial failures, decreases over time as the defective panels are eliminated.
- Failure rates may be influenced by external factors that not related to design & manufacturing – degradation & loss of efficiency, newer modules.

Panel Generation Capacity and Weight

- Used to convert annual incremental installments of PV capacity (MW) to the number of PV panels installed each year
- Multiplied by average panel weight to estimate the total installed weight

Panel Type	Range of Size and Weight	Modeled Capacity (watts/panel)	Modeled Panel Weight (lb.)
Residential	65” x 39” 33 to 50 lbs	350	40
Commercial	78” x 39” 50+ lbs	400	50

RESULTS

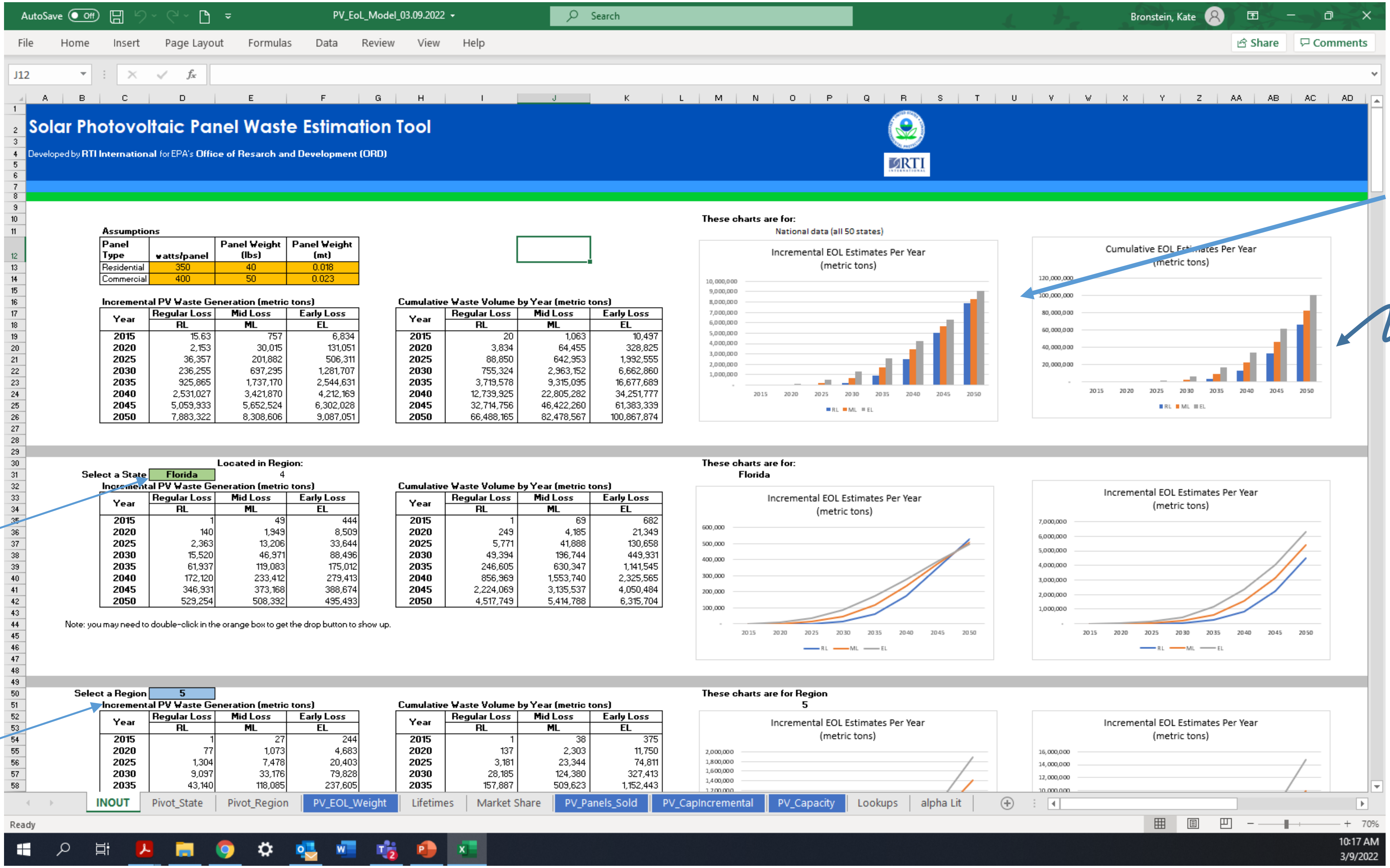
Solar PV Panel Waste Estimation Tool Demo

EoL PV Panel Assumptions & Limitations

- Assumed to cover all types of crystalline silicon (C-Si) and thin-film cadmium telluride (CdTe) panels
- Standard panel weight for commercial and residential
- One average lifetime parameter
- Transboundary or international exports of EoL PV panels are not incorporated
- State projections, in general, do not specifically factor in any new state legislation
  - Washington manufacturer takeback program
  - CA designation of solar PV panels as universal waste

- Quantity of panels circulating in the secondary market in the US and those exported are not considered
- Does not include any data for US territories
- Need to further investigate off-grid installed capacity and projections, which may be larger for residential versus commercial situations

INOUT Worksheet: User Interface for PV-panel Waste Estimation



Assumptions

Panel Type	watts/panel	Panel Weight (lbs)	Panel Weight (mt)
Residential	350	40	0.018
Commercial	400	50	0.023

Incremental PV Waste Generation (metric tons)

Year	Regular Loss RL	Mid Loss ML	Early Loss EL
2015	15.63	757	6,834
2020	2,153	30,015	131,051
2025	36,357	201,882	506,311
2030	236,255	697,295	1,281,707
2035	925,865	1,737,170	2,544,631
2040	2,531,027	3,421,870	4,212,169
2045	5,059,933	5,652,524	6,302,028
2050	7,883,322	8,308,606	9,087,051

Cumulative Waste Volume by Year (metric tons)

Year	Regular Loss RL	Mid Loss ML	Early Loss EL
2015	20	1,063	10,497
2020	3,834	64,455	328,825
2025	88,850	642,953	1,992,555
2030	755,324	2,963,152	6,662,860
2035	3,719,578	9,315,095	16,677,689
2040	12,739,925	22,805,282	34,251,777
2045	32,714,756	46,422,260	61,383,339
2050	66,488,165	82,478,567	100,867,874

Select a State: Florida — Located in Region: 4

Incremental PV Waste Generation (metric tons)

Year	Regular Loss RL	Mid Loss ML	Early Loss EL
2015	1	49	444
2020	140	1,949	8,509
2025	2,363	13,206	33,644
2030	15,520	46,971	88,496
2035	61,937	119,083	175,012
2040	172,120	233,412	279,413
2045	346,931	373,168	388,674
2050	529,254	508,392	495,493

Cumulative Waste Volume by Year (metric tons)

Year	Regular Loss RL	Mid Loss ML	Early Loss EL
2015	1	69	682
2020	249	4,185	21,349
2025	5,771	41,888	130,658
2030	49,394	196,744	449,931
2035	246,605	630,347	1,141,545
2040	856,969	1,553,740	2,325,565
2045	2,224,069	3,135,537	4,050,484
2050	4,517,749	5,414,788	6,315,704

Note: you may need to double-click in the orange box to get the drop button to show up.

Select a Region: 5

Incremental PV Waste Generation (metric tons)

Year	Regular Loss RL	Mid Loss ML	Early Loss EL
2015	1	27	244
2020	77	1,073	4,683
2025	1,304	7,478	20,403
2030	9,097	33,176	79,828
2035	43,140	118,085	237,605

Cumulative Waste Volume by Year (metric tons)

Year	Regular Loss RL	Mid Loss ML	Early Loss EL
2015	1	38	375
2020	137	2,303	11,750
2025	3,181	23,344	74,811
2030	28,185	124,380	327,413
2035	157,887	509,623	1,152,443

Yearly incremental

cumulative

Select a state

Select a Region

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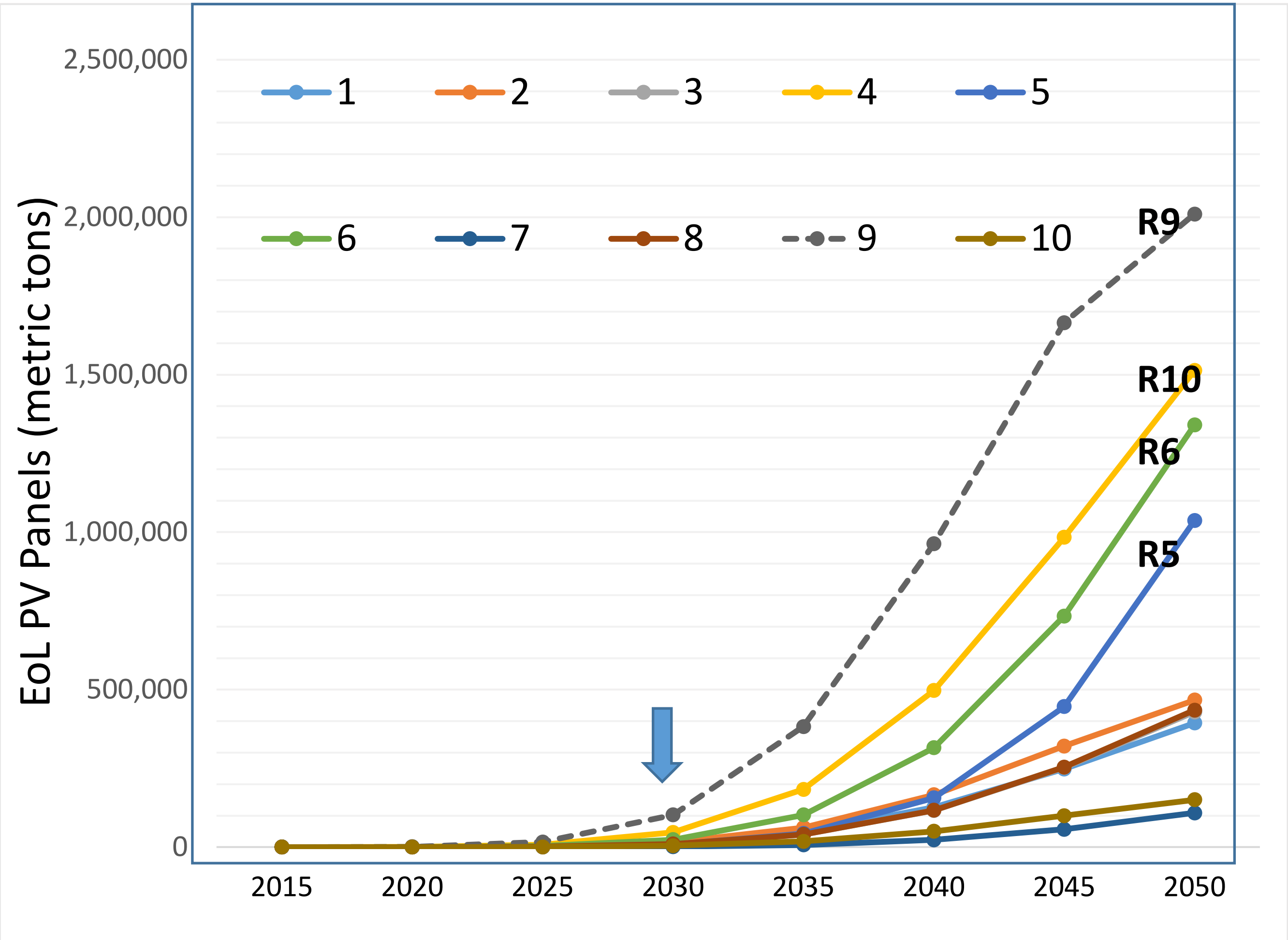
EoL PV Panel Loss (metric tons)

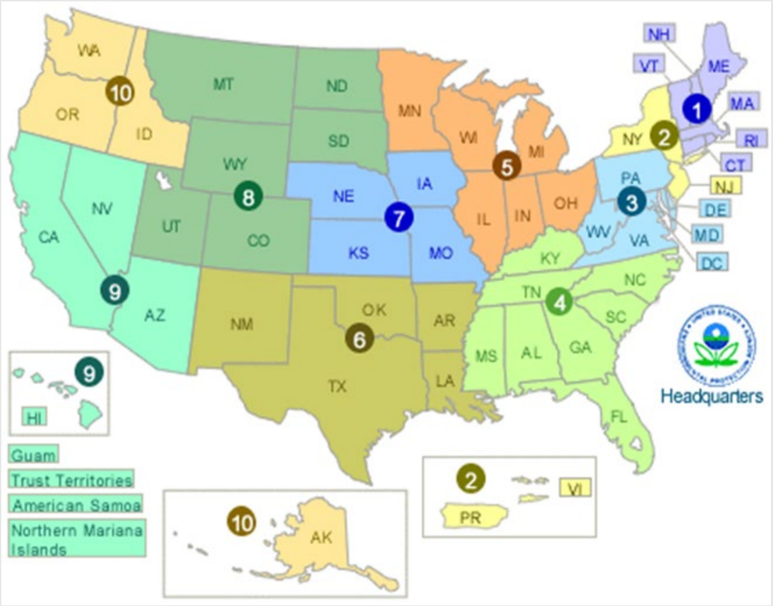
Year	Regular	Mid	Early
2015	16	757	6,834
2020	2,153	30,015	131,051
2025	36,357	201,882	506,311
2030	236,255	697,295	1,281,707
2035	925,865	1,737,170	2,544,631
2040	2,531,027	3,421,870	4,212,169
2045	5,059,933	5,652,524	6,302,028
2050	7,883,322	8,308,606	9,087,051
2050 IRENA	7.5 million	--	10 million

Current model prediction

Total PV panel loss could reach 4 – 9 wt % current municipal solid waste

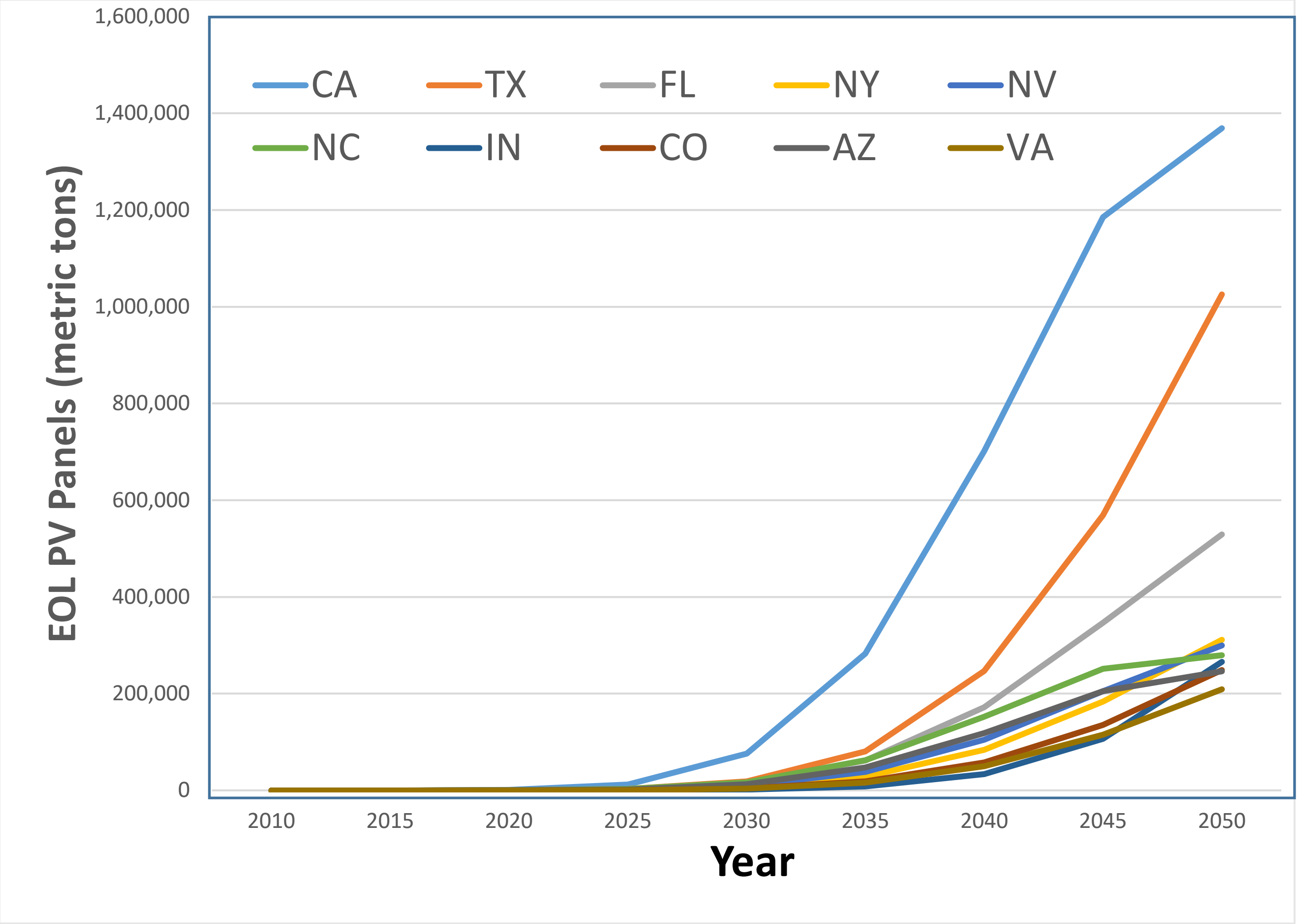
EoL PV Panel Projects by Region (RL, mt)



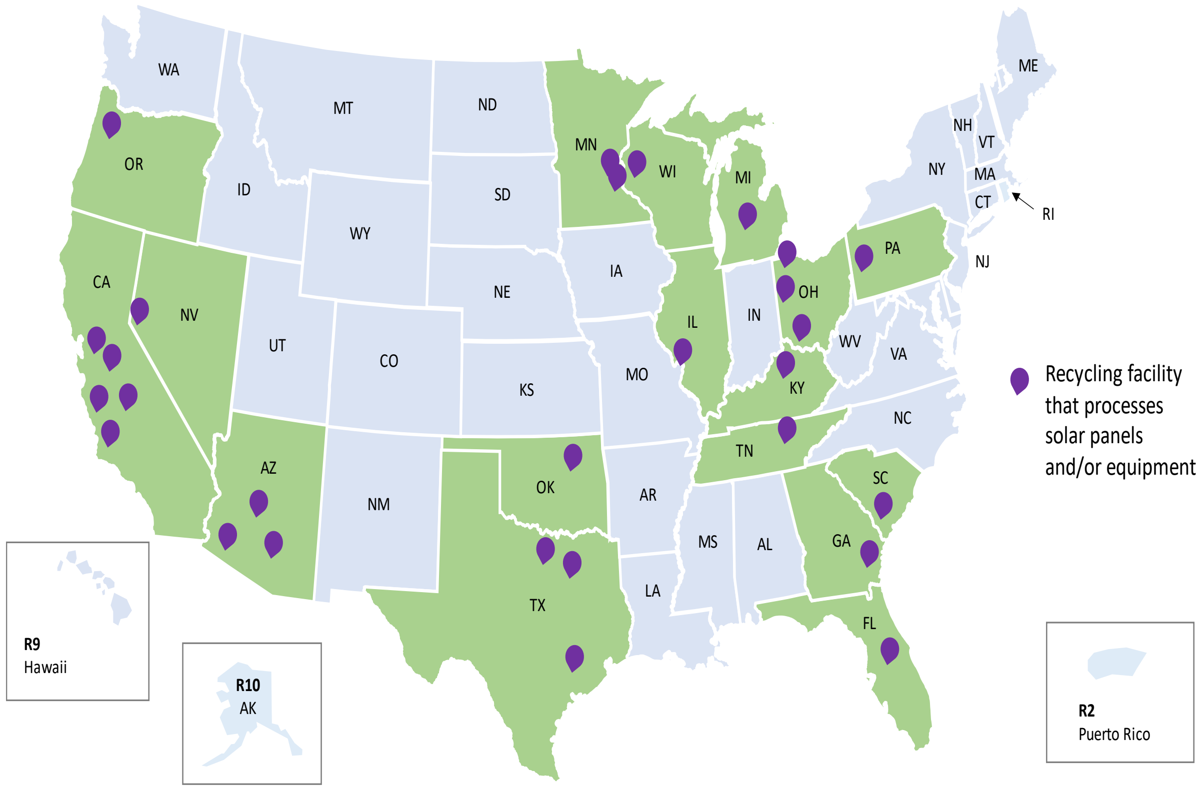


Top 10 States Under the Regular Loss Scenario by 2050

Highest Installed Capacity (2020)	Largest EoL Generators, RL (2050)
CA	CA
TX	TX
NC	FL
FL	NY
AZ	NV
NV	NC
NJ	IN
MA	CO
GA	AZ
NY	VA



PV Panel & Equipment Recycling Facilities and Benefits



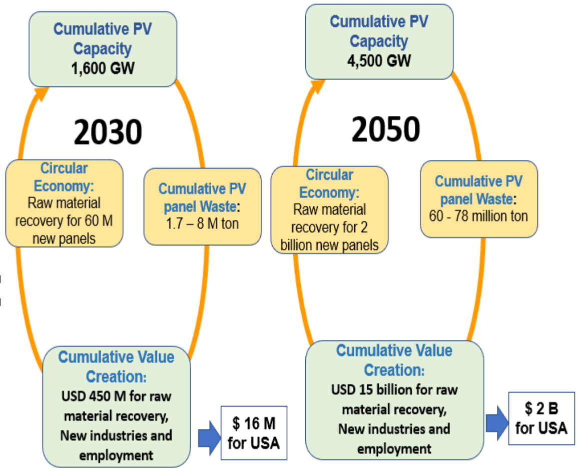
Data from 2020)

- Most recycling facilities are in Southwest, and Midwest U.S.
- Recovery of glass, metals, and semiconductor have lower environmental impacts
- While extraction, refinement and supply of the respective materials from primary resources energy intensive.
- Specialized PV-panel separation technologies are sought to achieve high purity products
- The highest impact of PV panel recycling is climate change from transport, electricity supply and waste disposal.
- Lengthen PV-panel module use life – weather resilient → extend life to 50 yr

Citation: P. Stolz, R. Frischknecht, K. Wambach, P. Sinha, G. Heath, 2018, Life Cycle Assessment of Current Photovoltaic Module Recycling, IEA PVPS Task 12, International Energy Agency Power Systems Programme, Report IEA-PVPS T12-13:2018.

Drivers, Barriers and Enablers to a Circular Economy

- 95% of the materials in a solar panel can be recycled using current technology, (Demonstrated by Veolia Environmental –Pilot-scale test)
- Glass and aluminium are easier to recycle, but the challenge is extracting silver and lead, and refining silicon.
- Barriers outweigh the drivers and enablers because cost to recycle EoL solar panels tends to be cost-prohibitive largely because there is not enough volume to achieve economies of scale currently.
- This will likely change in the next 10 to 20 years given EoL PV panel projection estimates
- European Union requires 85% collection rate and 80% recycling
- Current U.S. laws are set by individual states
- One uncertainty in the future recycling market is changing technc materials



Source: IEA/IRENA, 2016

United States Environmental Protection Agency

Ongoing and Planned EoL PV Panel Model Refinements

- Improving the *static assumptions* used in the calculations for market share over time
- Considering alternative loss scenarios that modulate the average panel lifetime and alpha parameter in Weibull function
- Investigating solar installation and EoL projections in Puerto Rico and US territories
- Making user improvements, such as automating the regional selection when selecting a state in the INOUT worksheet, adding a filterable results tab with sort by state, etc.
- Incorporating life cycle analysis results to estimate waste generated from landfill disposal and recycling
- Uncertainty assessments nationally, region, or state

United States Environmental Protection Agency

Key Takeaways

- Solar-energy boom will trigger a landslide waste in the coming decades and a new environmental challenge. Increased volume open unprecedented opportunities to create value and pursue new economic avenues

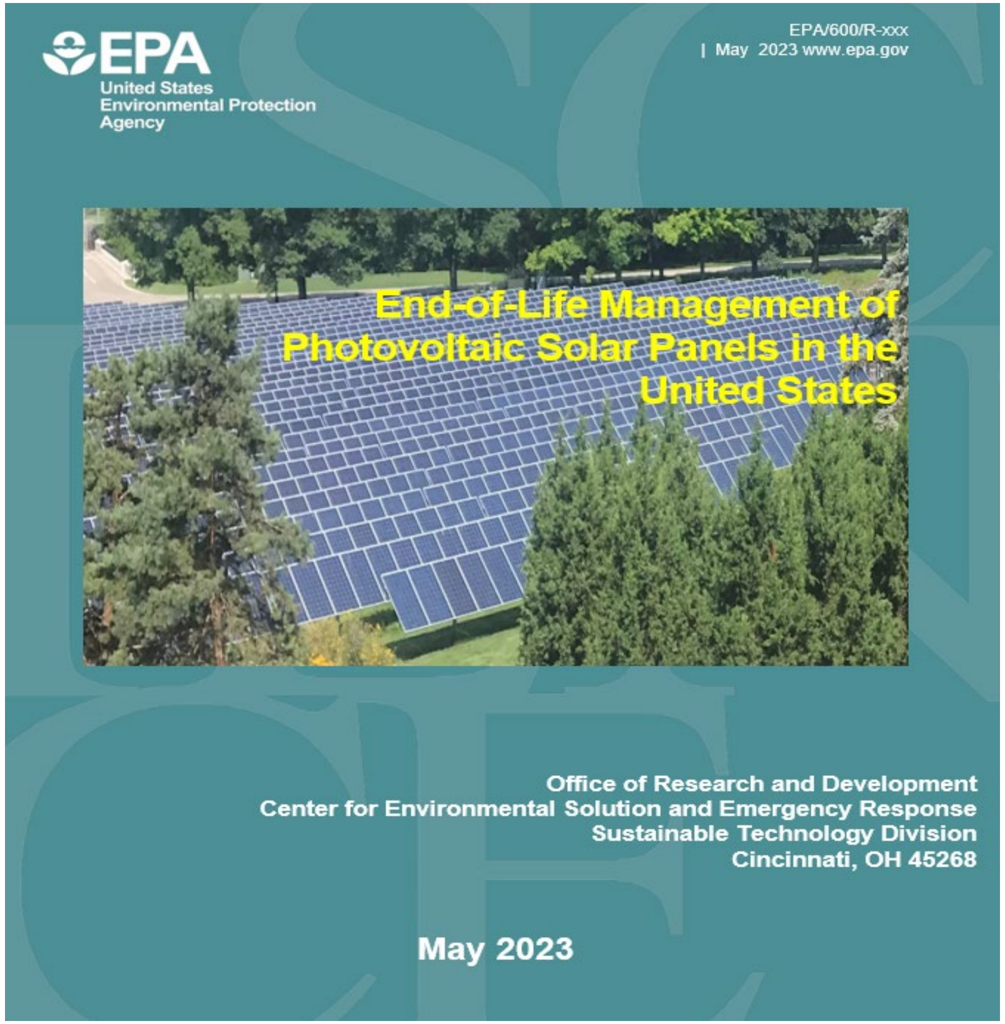
- No federal solar panel specific regulations currently exist in the US for collecting and recycling end-of-life PV panels. California and Minnesota are developing regulations for end of life (EoL) management of PV panels

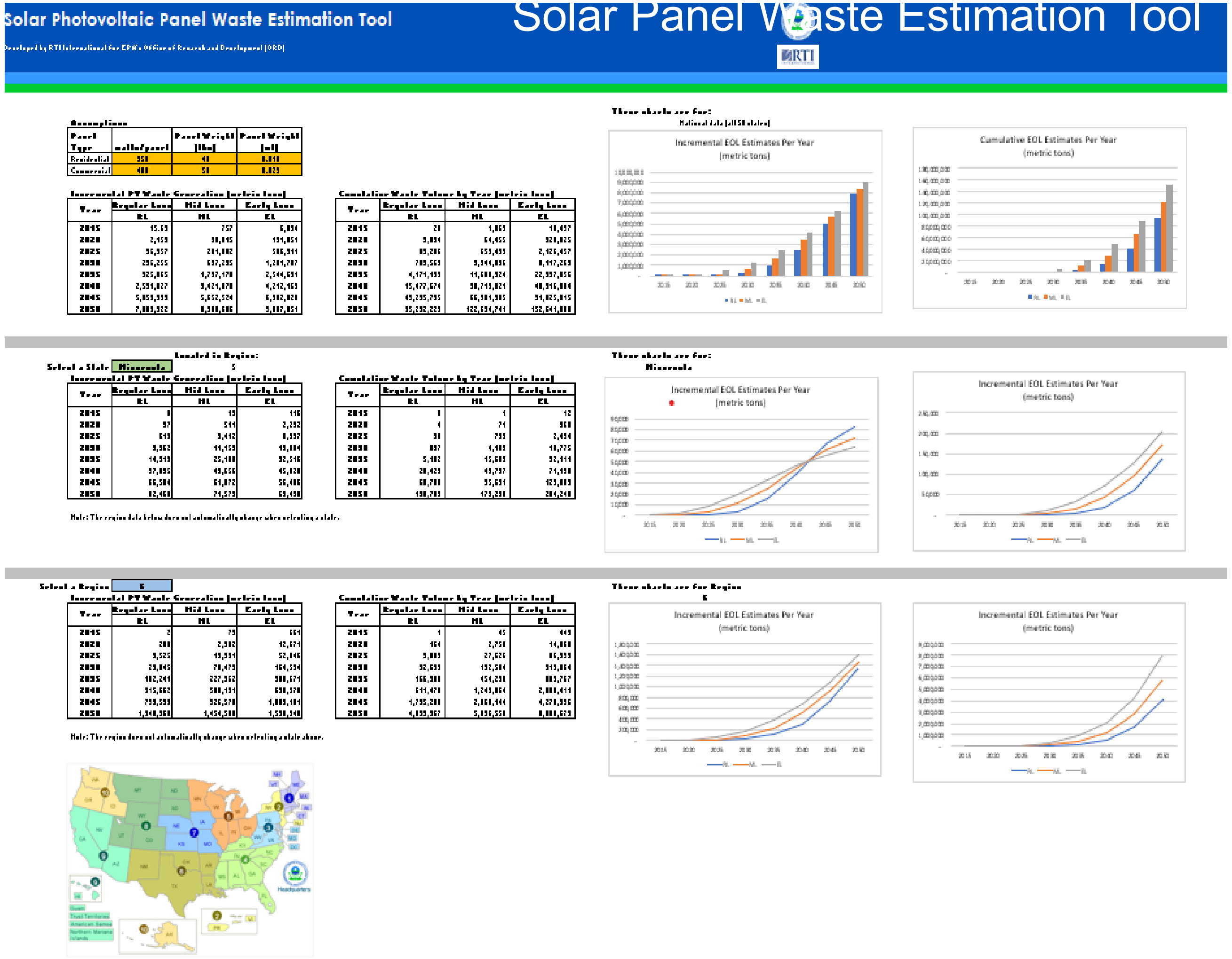
- A system-level approach to PV EoL management can enhance the integration of stakeholders: PV suppliers, consumers, recyclers, and solid waste managers

- Research & development, education and training, and regulatory mandate are needed to support economically feasible PV EoL management

- Stimulating investment and innovative financing schemes for PV EoL management are necessary to overcome financing barriers and to ensure the support of all stakeholders

ORD Report and Tool on Solar Panels





This ORD report and tool will be available soon for public download from EPA web site.

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