Solar Photovoltaic Panel End-of-Life Estimates for the U.S

Methodology & Model Demo

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Center for Environmental Solution and Emergency Response

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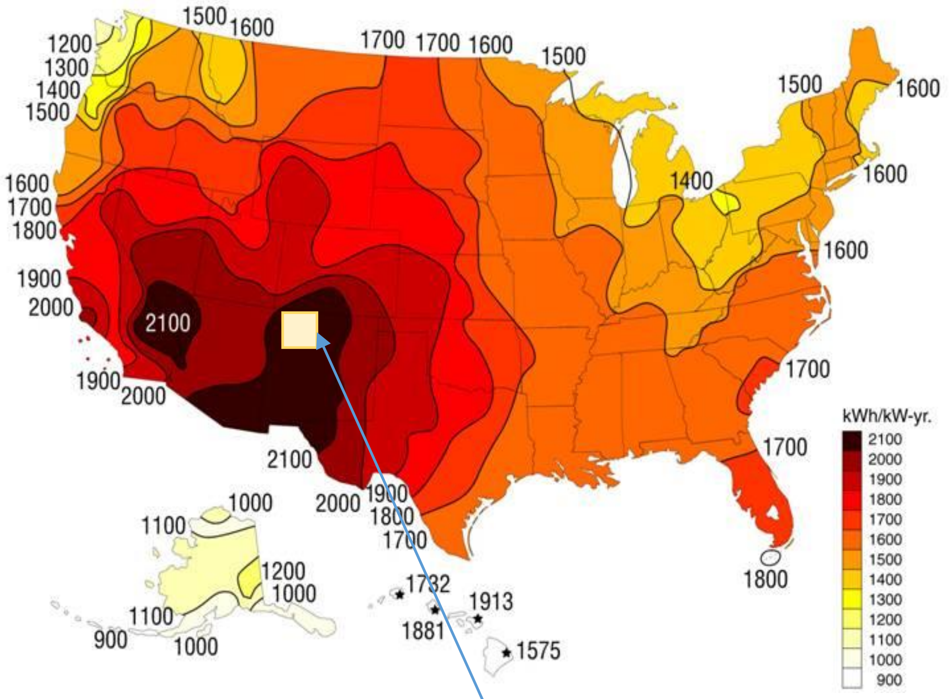
Potential of Solar Energy



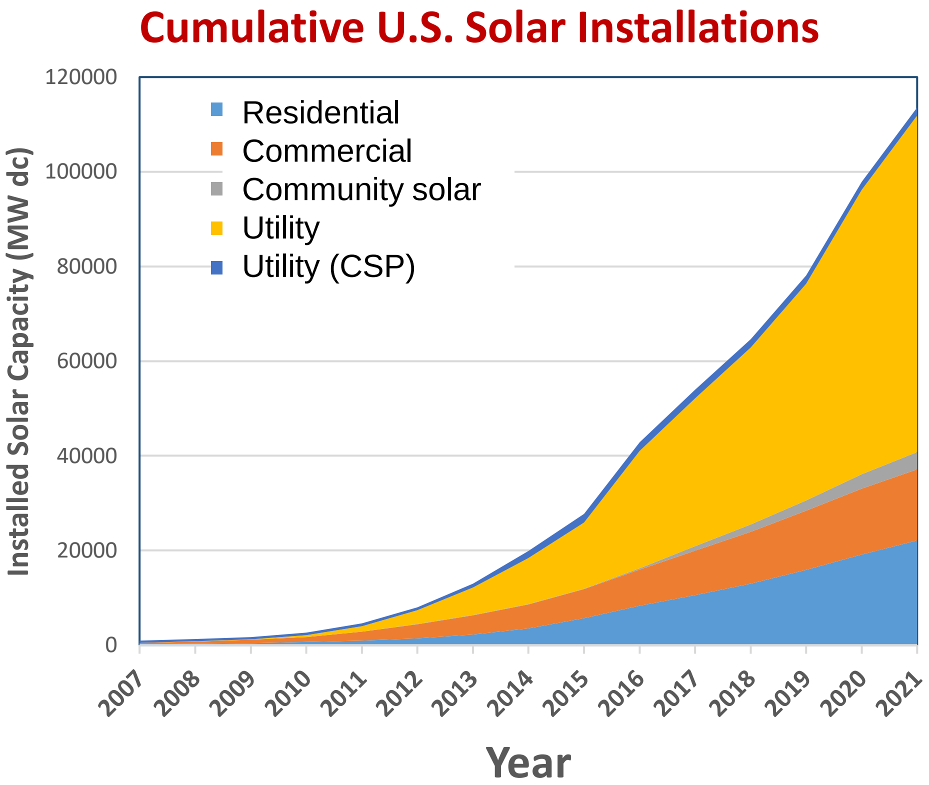
To Meet the US power needs:
Solar panel area = 100x100 miles^2

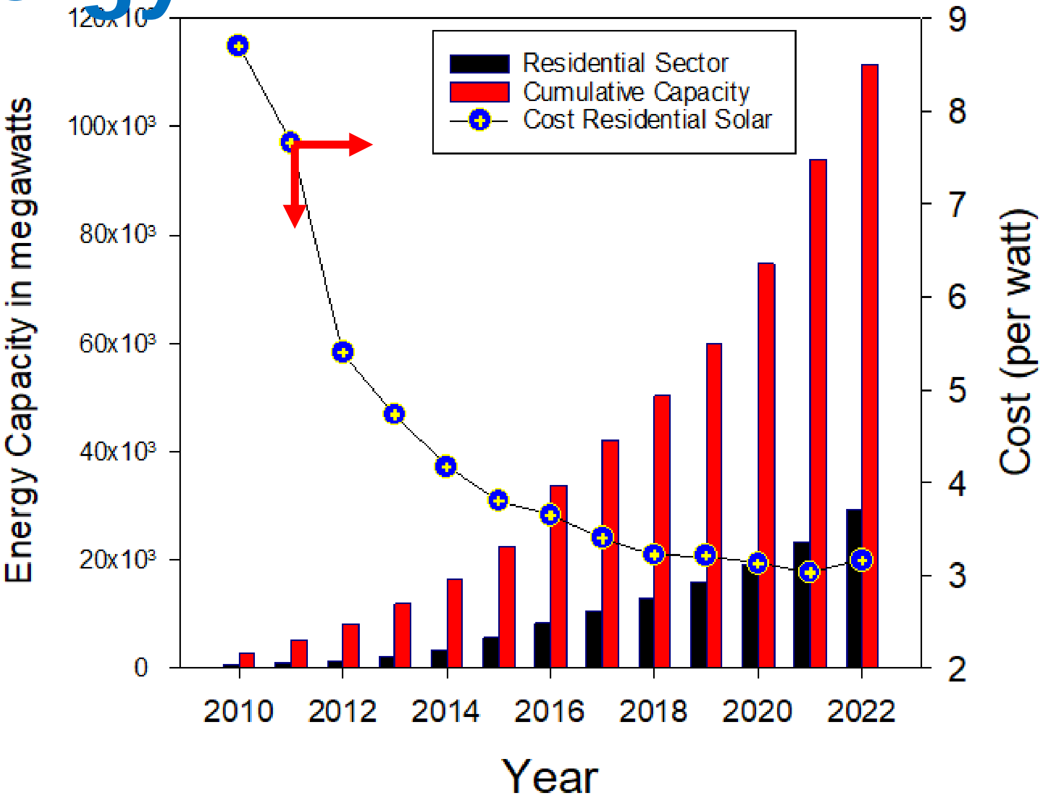
- 2023 US solar energy 2.38 x 10^5 MWh., but it is still 0.01% of solar energy
- Solar power the cheapest source of clean electricity around globally (*IEA 2022*)
- Utility-scale solar projects are cheaper to build than operating existing coal plants (*Lazard 2021*)
- If PV panels are 20% more efficient = 10^4 mi^2 → size of Lake Erie power US

Venditti, 2021, Electrification

Lazard. 2021. Lazard's Levelized Cost of Energy Analysis - Version 15.0. Lazard. https://www.lazard.com/media/sptlfats/ lazards-levelized-cost-of-energy-version-150-vf.pdf.

Increasing Adoption and Growth of Solar Energy





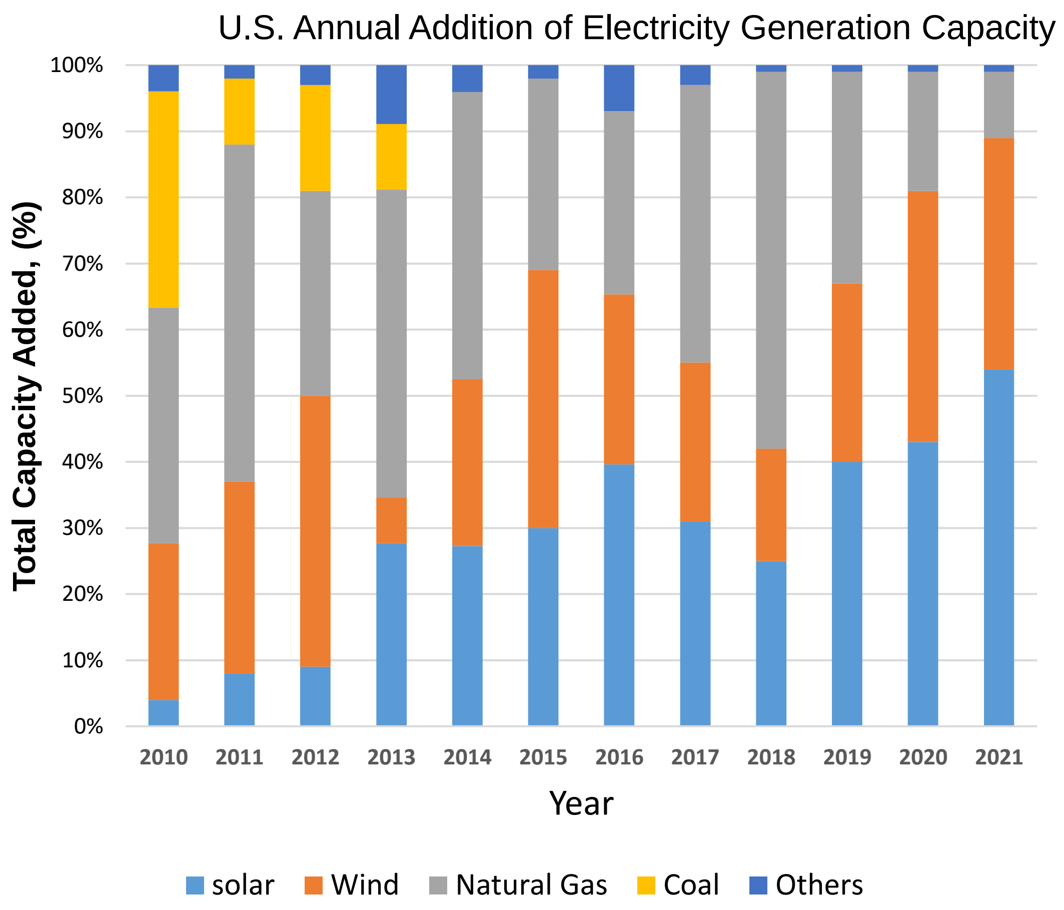
- **Last decade growth = 42%, where the 2022 growth large than 100 GW = 3%**
- **Use of solar energy will continue to grow rapidly**
- **Solar is the fastest growing energy source in the U.S.**

- **Drivers**: Lower price 50% down in 10 yr.,
- Utility-scale price =$16 –35/MWh
- Government incentives
- Recognition of environmental benefits

Source: Solar Energy Industries Association, SEIA

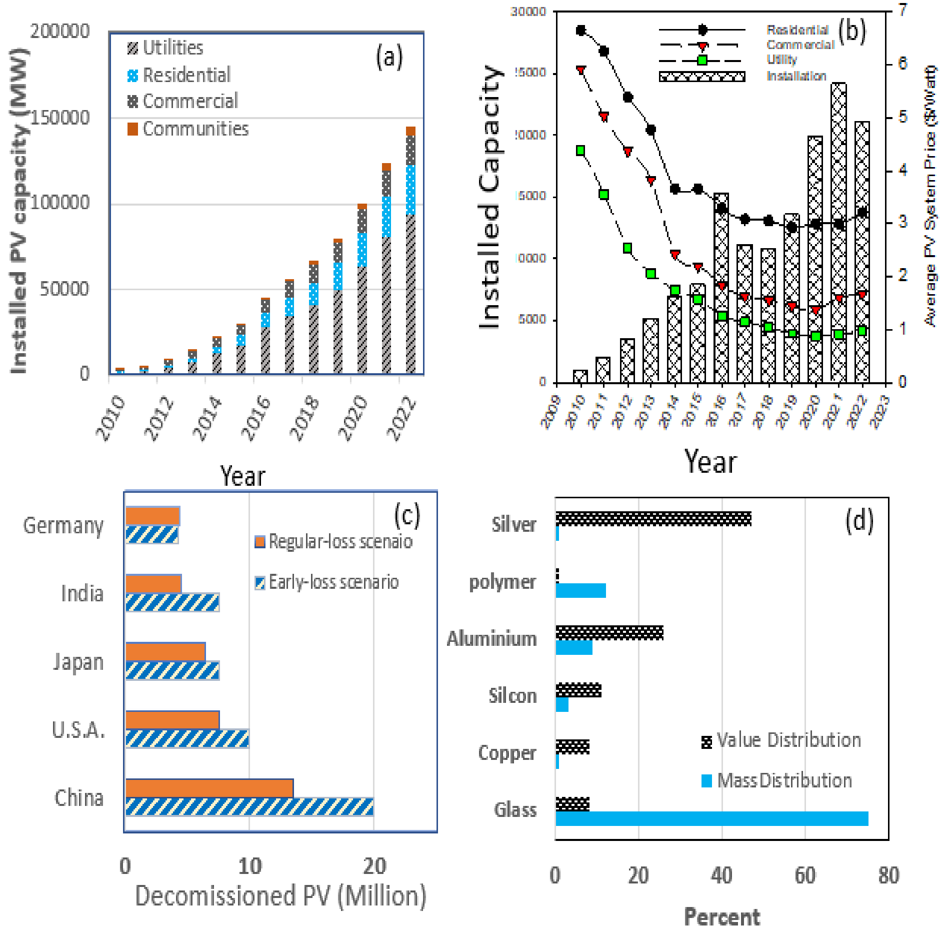
National Solar Trends and Projections

- U.S. electric generation capacity from solar
  - 2010 → 4%/yr, and 2020 → 43% /yr of solar contribution to electricity capacity added to the grid, Solar share: 2010 (0.1%), 2021 (4%), 2023 (7.21%)
- Huge surge in solar panel disposal is anticipated in the and 2030s, and beyond
- Increasing volume of decommissioned PV panels *growing exponentially*, coupled with resource management regulations could boost effective solar panel recycling market.
- PV scrap presents a *huge untapped potential* for the recycling 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

End of Life PV Panels



U.S. – Expected Second Largest PV Waste Volume

Because of the large-scale solar capacity of past and expected deployment, it is imperative to focus on the management of scrap generated from existing and upcoming installations

Solar panels - an eco-disaster waiting to happen?

1 day ago

Climate change

By Daniel Gordon

The Climate Question podcast, BBC Sounds

BBC 2022

Source: IRENA

Project Objectives

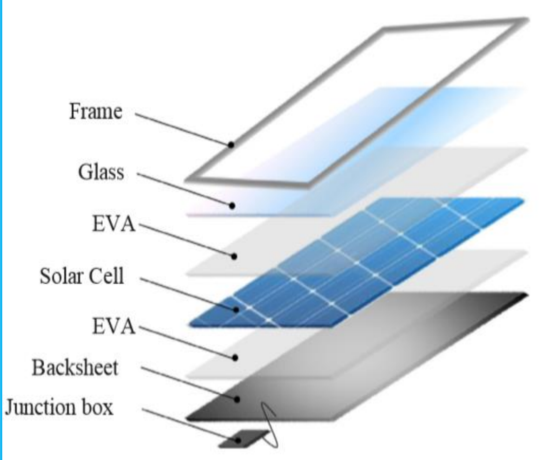
To help EPA , and state solid waste managers estimate the end-of-life (EoL) management of photovoltaic (PV) panels and determine if existing recycling technologies and reuse pathways are sufficient to meet the projected panel scrap generation in the next 20-30 years.

1. Project quantities of EoL PV panel scrap 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.

PV Modules Types and Material Used

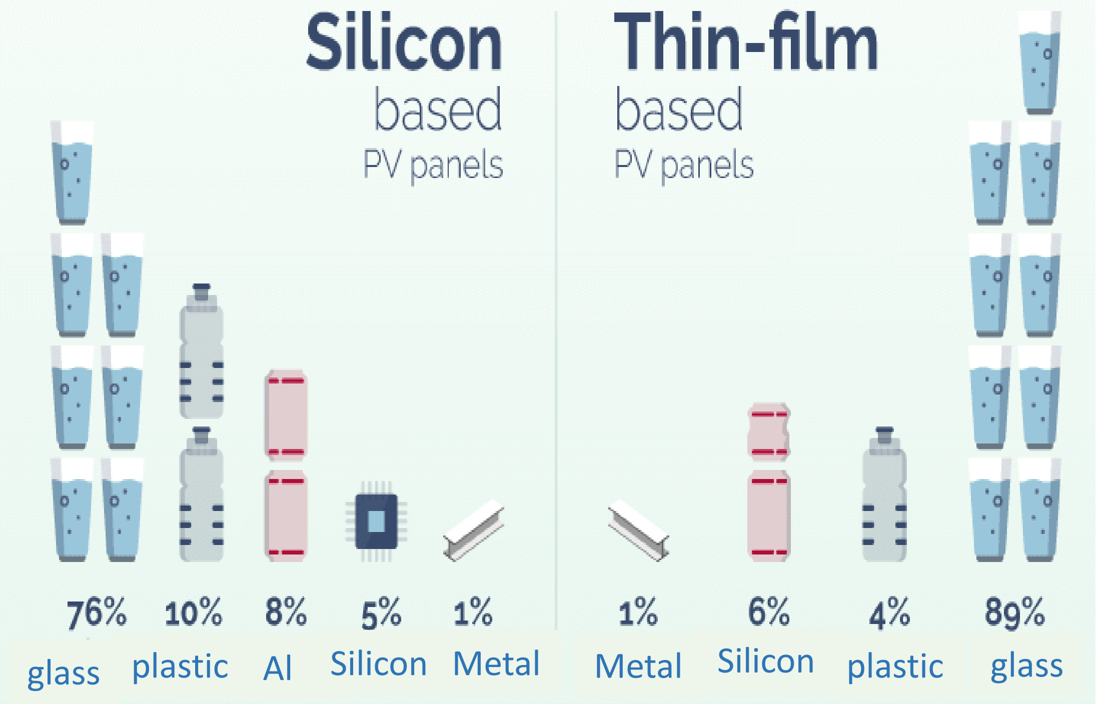
Evolving Technology

- **First generation**: poly and mono crystalline silicon (c-Si)
- **Second generation**: thin-film technologies like cadmium telluride (CdTe), amorphous and copper-indium-gallium-selenide (CIGS)
- **Third generation**: includes technologies that are not available on a large scale (e.g. concentrated photovoltaic or organic solar cells, organic solar panels, CPV panels.)



General structure of PV panel

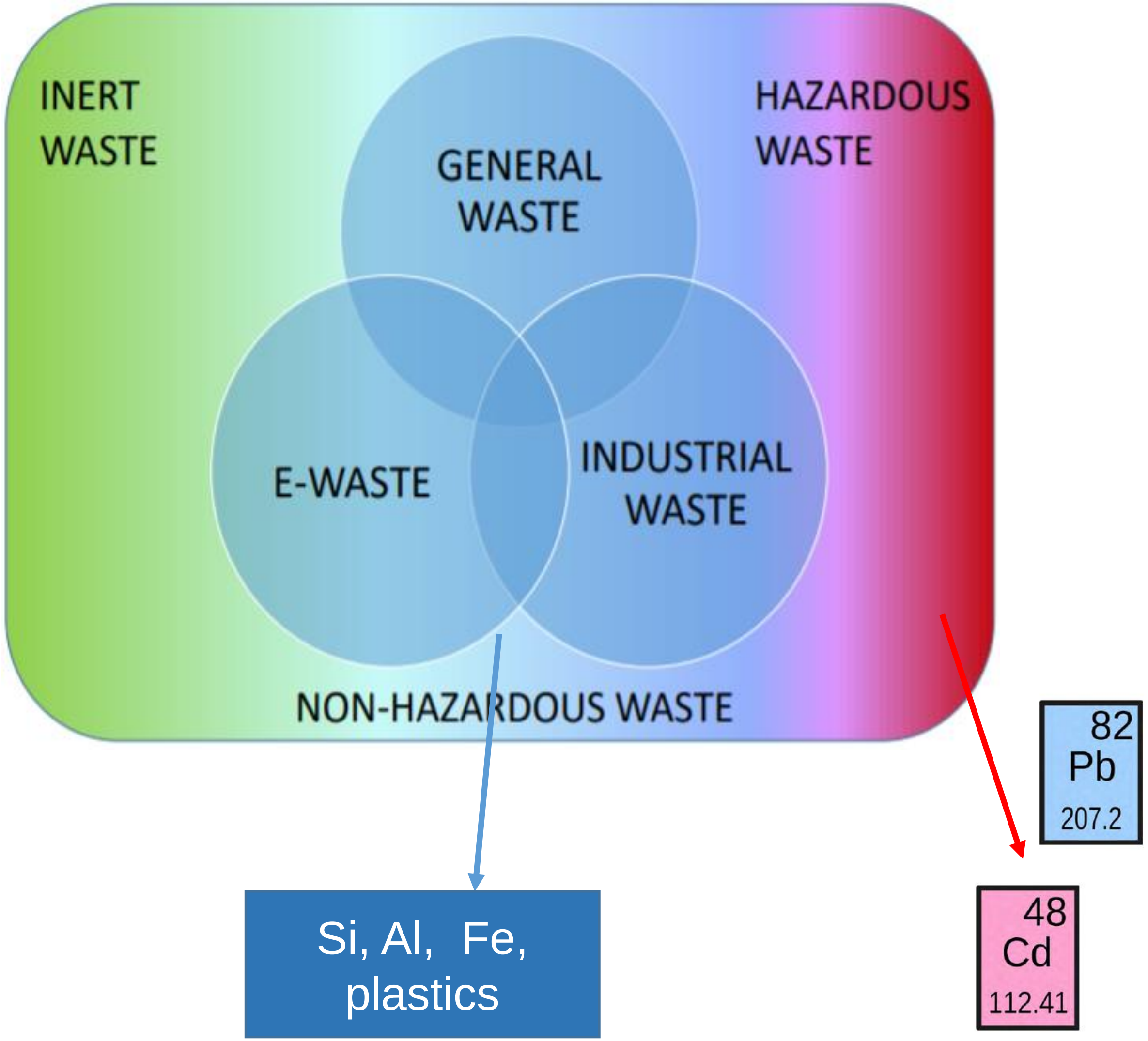
EVA - ethyl vinyl acetate



Source: GREENMATCH

The weight of the various resources from a typical solar panel after disassembly and extraction,

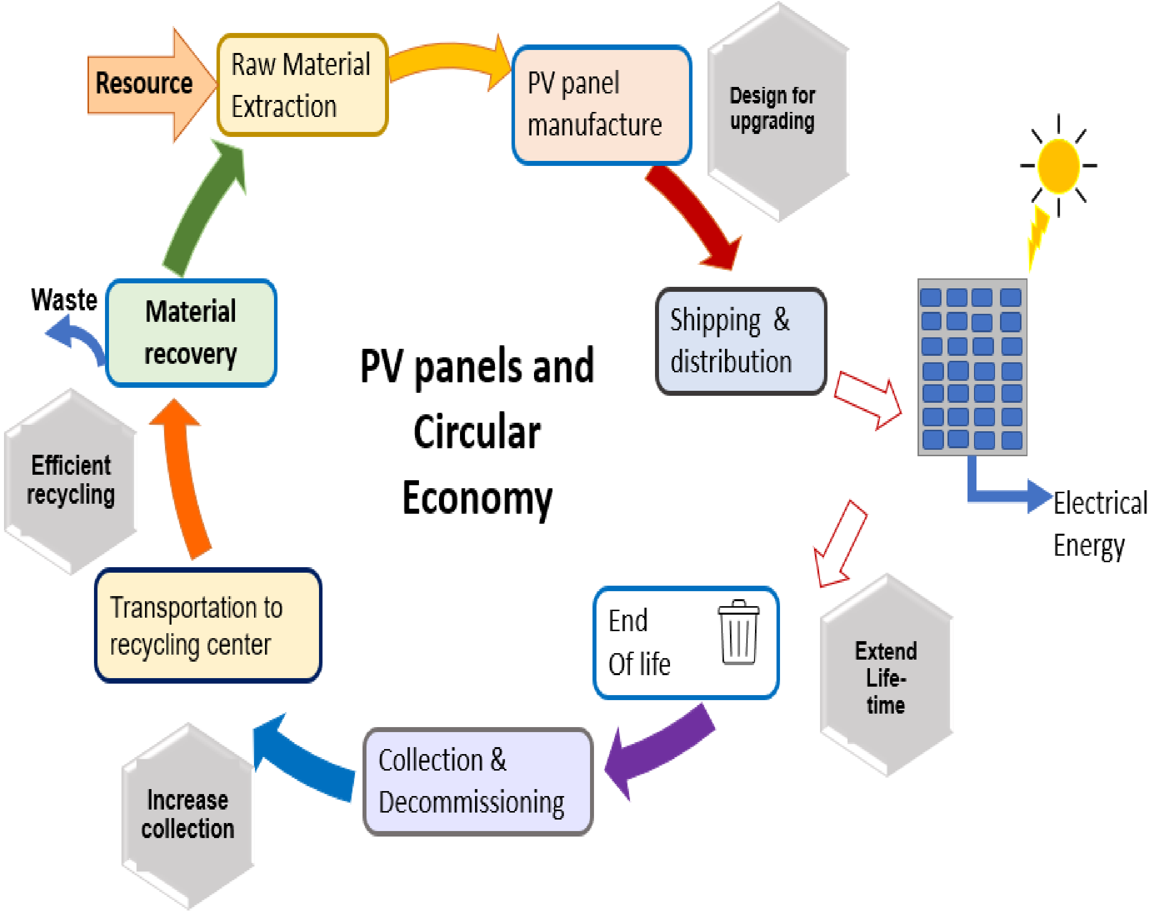
Waste Classification



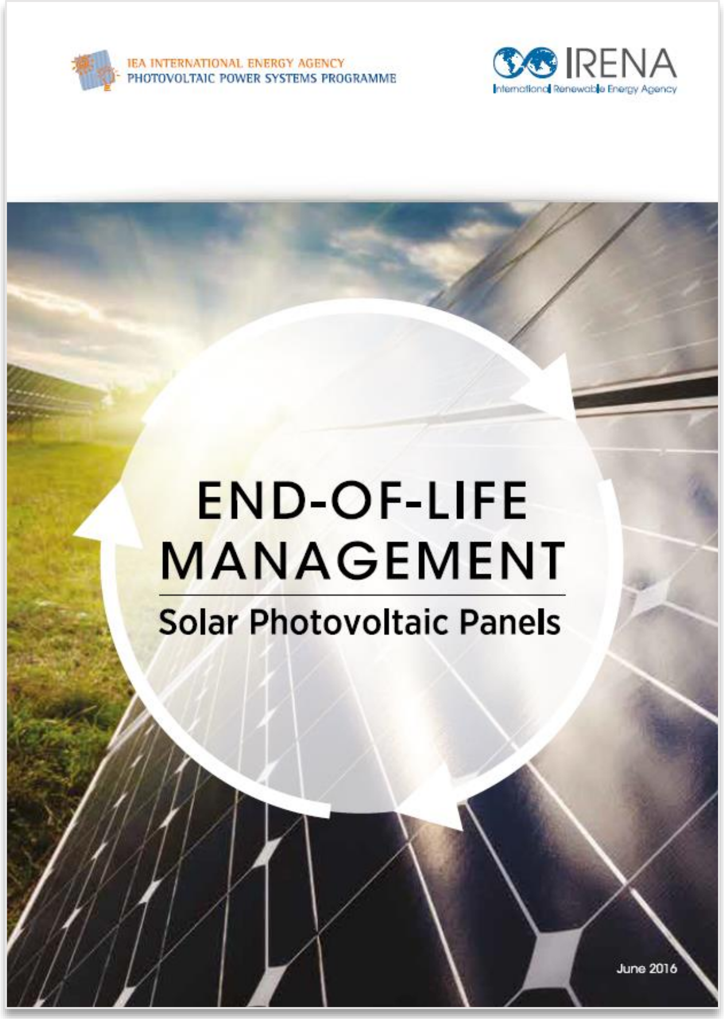
- Solar panels differ in metals, most contain small quantities of lead and cadmium, are harmful to human & environment at high levels.
- Typically, standard leaching tests and material concentration limits determine the classification and minimum requirements for treatment and disposal
- Most of the structure of PV-panel such as Al-frame is not hazardous waste, and can be demanufactured and recycled,
- Both technical and economic difficult to recover small quantities of valuable metals, such as silver.

Circular Economy Approach for Solar Panels

- Solar panel generate electricity with minimal maintenance and produce no green house gas emissions
- Responsible PV panel scrap management also lays the foundation for a circular economy.
- Collect and dismantle end-of-life panels to recover valuable materials (silicon, glass, metals).
- Use recovered materials to produce new panels, reducing reliance on virgin resources and environmental impact.
- Waste management leads to new employment opportunities



Guiding Methodology for Estimating EoL PV Panels



- International Renewable Energy Agency (IRENA) IEA-PVPS methodology (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

United States Environmental Protection Agency

Methodology Overview by IRENA and IEA-PVPS

Determined PV capacity out to 2050 by country

- 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

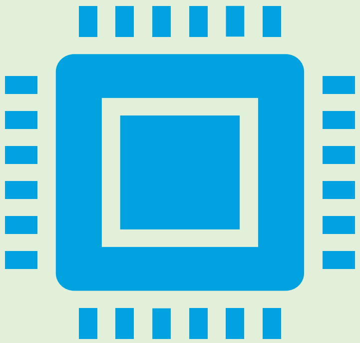
Estimated the probability of PV panel losses

- 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

PV Panel Scope and Expected Lifetimes



PV Market

2 market segments: residential and commercial

Commercially-available panels, no deviation in individual manufacturer performance

Not considering off-grid

PV Panel Lifetime

25 to 30 years

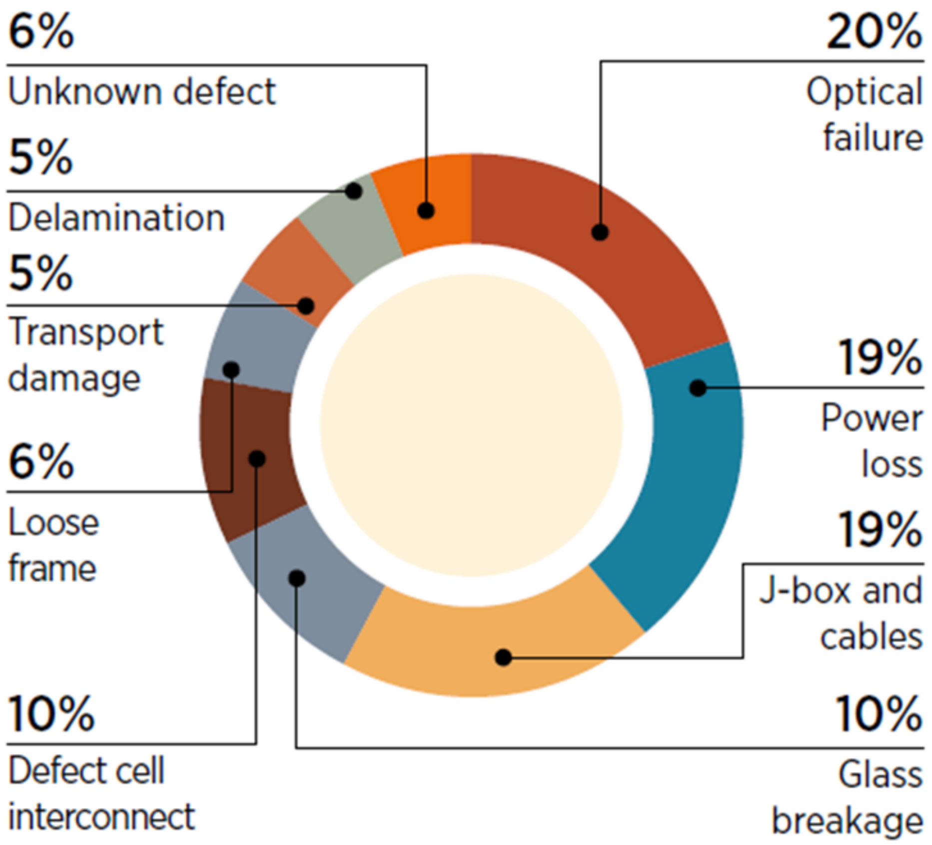
Point at which panels may drop to 80% efficiency and tend to be upgraded or replaced

No comprehensive tracking of when PV panels enter the EoL stage

Reasons for EoL decommissioning

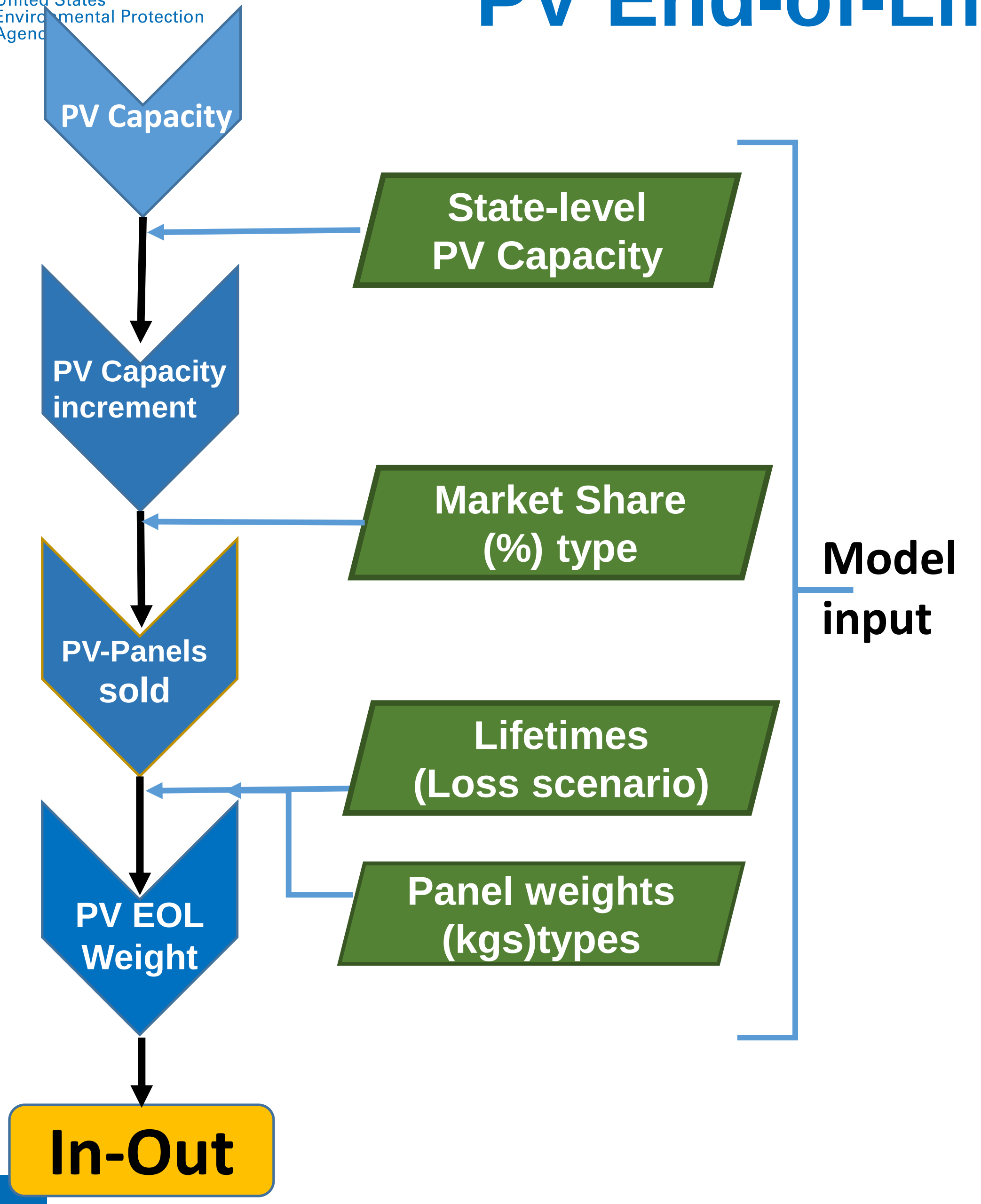
- **Regular Loss**
  - Design end of life of the module is about 25 year.
  - Decommissioning (the end of the period or performance for a solar project)
- **Early Loss**
  - Early failure due transportation, module handling, and project operations
  - Project operations: human errors, cell cracks and snail cracks, back contacts (Kontges et al, 2014)
  - 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 losses**
  - 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)

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
- **Weight of panels-** index by consumer type

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Model Assumptions

Model	Data input and references
EoL PV projections by state are based on the state's actual and projected electricity generation capacity. **Regular-loss scenario input assumptions** ○ 30-year average panel lifetime was taken from literature **(Frischknecht et al., 2016).** ○ 99.99% loss after 40 years ○ The 40-year technical lifetime assumption is based on depreciation times and durability data from the construction industry (Greenspec, 2016). ○ Life-time probability model parameters were obtained from literature data **Early-loss scenario input assumptions** ○ 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, and ▪ 2% of modules are broken in production per year. ▪ A 99.99% probability of loss was assumed using the Weibull function. ▪ The early-loss input assumptions were derived from different literature sources **(IEA-PVPS, 2014a; Padlewski, 2014; Vodermeyer, 2013; DeGraaff, 2011).**

Weibull Function Used to Estimate PV Failure

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

- *F(T)* Probability of PV panels reaching service time of t
- t = time
- β = scale parameter, average panel lifetime
- α = shape parameter, determined from PV reliability studies, differs by scenario

A continuous probability distribution used to analyze life data, model failure times, and product reliability.

Presented as either a 2 or 3 parameter function.

Parameter values are based on PV reliability studies.

Weibull Probability Loss Function for PV Panels

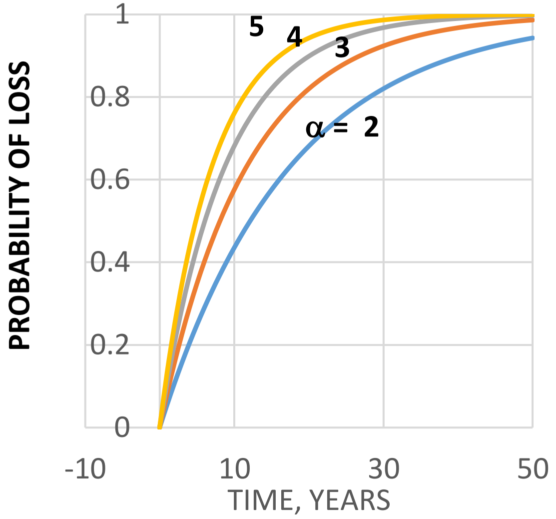
- **Average panel lifetime = 30-year**
- **Both early-loss and regular-loss scenarios were modelled using the Weibull function based**

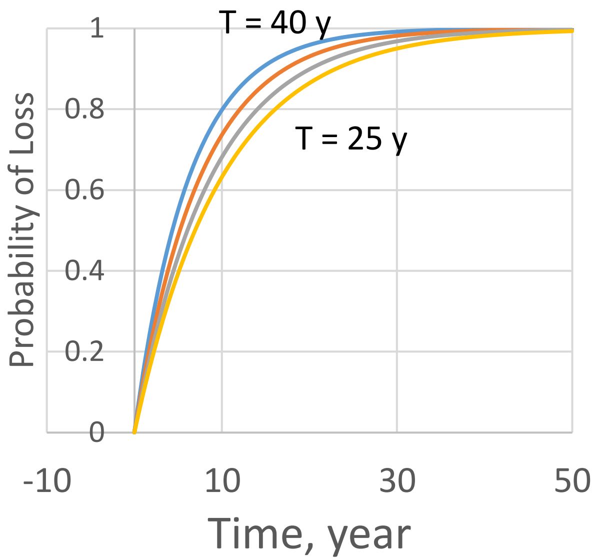
$$F(t) = 1 - e^{-\left(\frac{t}{T}\right)^{a}}$$

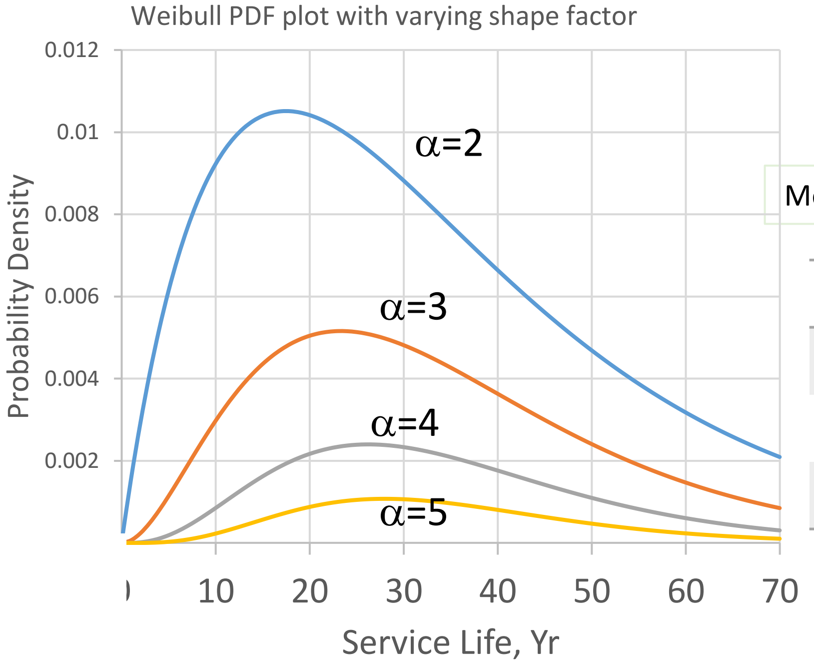
t = time in year
T = average life-time
α = shape factor

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

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





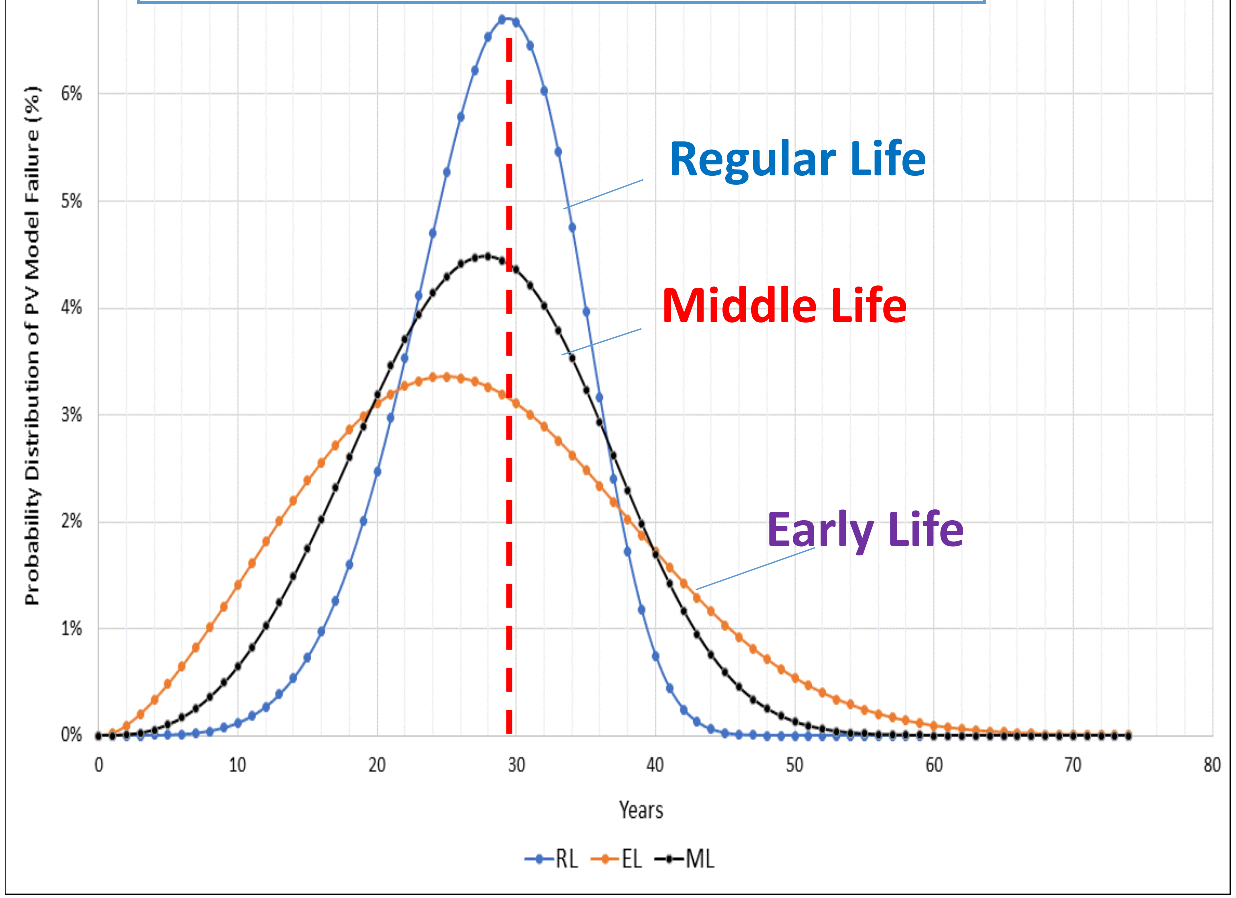


Median=T(ln2) $^{1/\alpha}$

α	T
2	**29**
3	31
4	32
5	32.5

Weibull Probability Distributions

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



- Assumed PV panel lifetime of 30 years for commercial and residential
- Modeled 3 scenarios

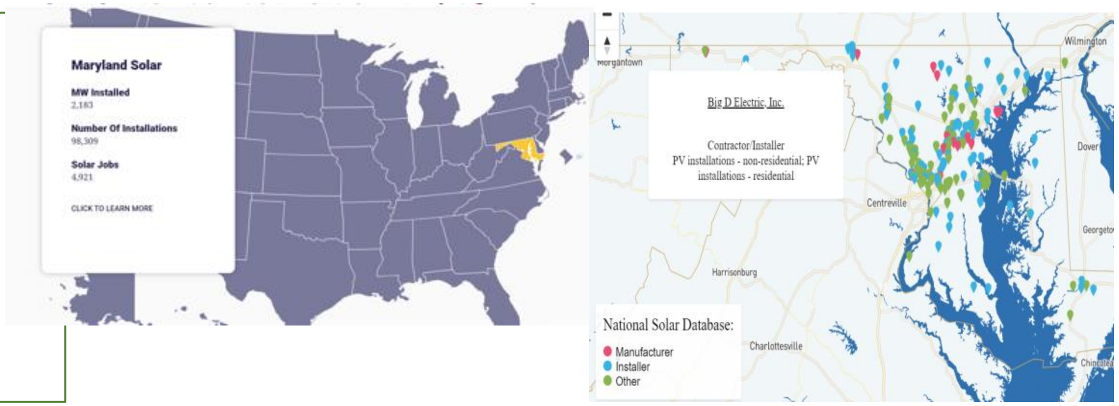
Scenarios	Weibull Parameters	
	α (shape)	t (scale)
Regular Loss	5.3759	30
Early Loss	2.4928	30
Mid Loss	3.5	30

Larger α - the steeper the curve & higher probability of loss at 30 yr or more

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

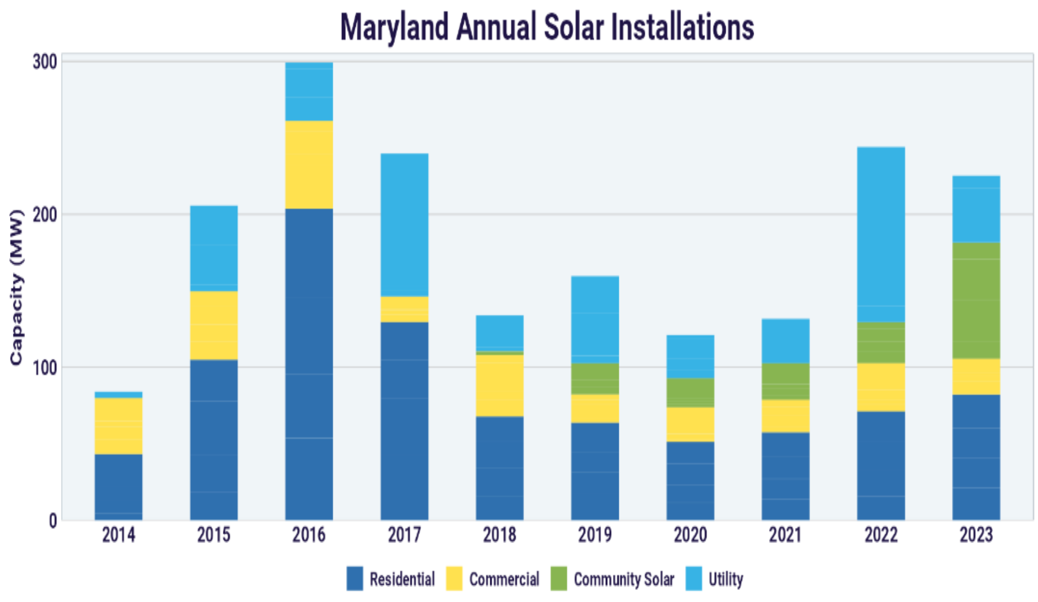
Installed State PV Capacity (MW)

- Solar Energy Industries Association (SEIA)
- EIA 2023 Annual Energy Outlook (AEO)
  - Projections of solar PV capacity growth between 2025 and 2050



Maryland Solar

- National Ranking: **20th (30th in 2023)** .
- State Homes Powered by Solar: **266,917 homes**.
- Percentage of State's Electricity from Solar: **6.53%**.
- Solar Companies in State: **208 (19 Manufacturers, 105 Installers/Developers, 84 Others)**.
- Total Solar Investment in State: **$5.2 billion**.
- Prices have fallen **43% over the last 10 years**.
- Growth Projection: **2,314 MW over the next 5 years (ranks 27th)**.



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

Market Share

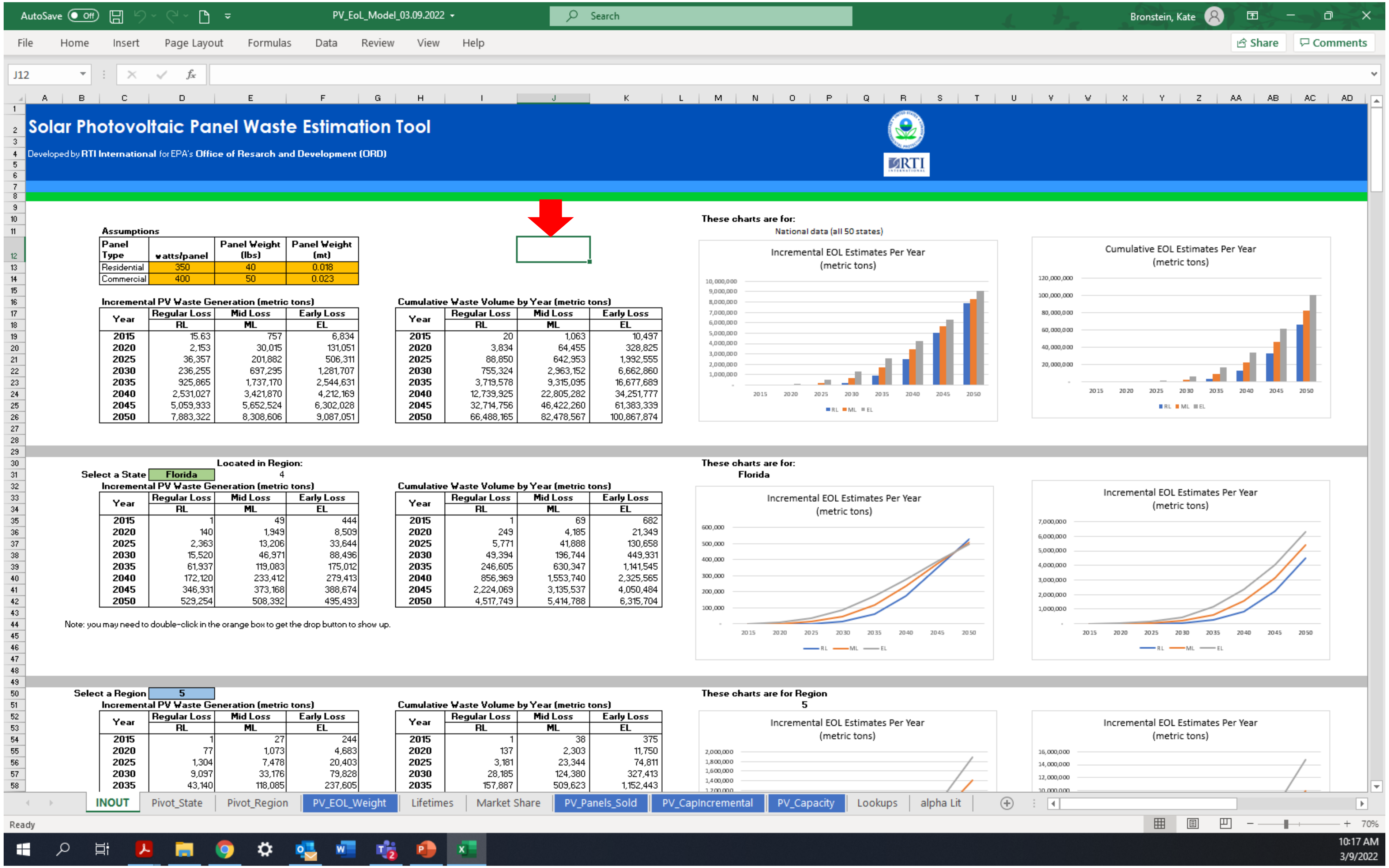
- The data obtained from U.S. Energy Information Administration contain the monthly cumulative installation count and capacity of generators that are net metered, by technology, state, and sector.
- Done to separately estimate EoL mass from *commercial* vs. *residential* panels
- Percentage of total installed solar PV capacity from 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

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 (lbs)
Residential	65” x 39” 33 to 50 lbs	350	40
Commercial	78” x 39” 50+ lbs	400	50

INOUT Worksheet – Main User Interface



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

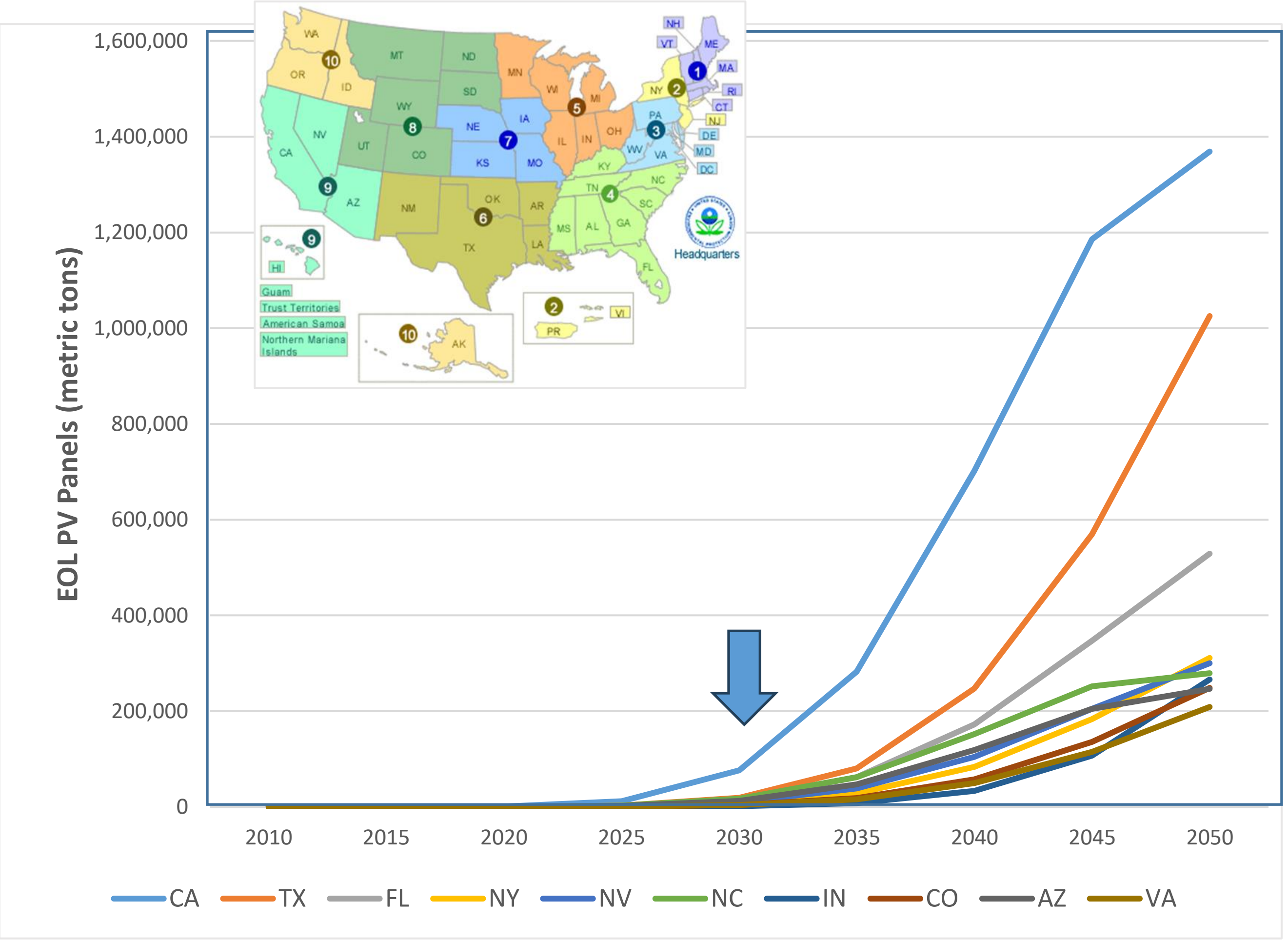
EoL PV Panel Loss (metric tons)

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

United States Environmental Protection Agency

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

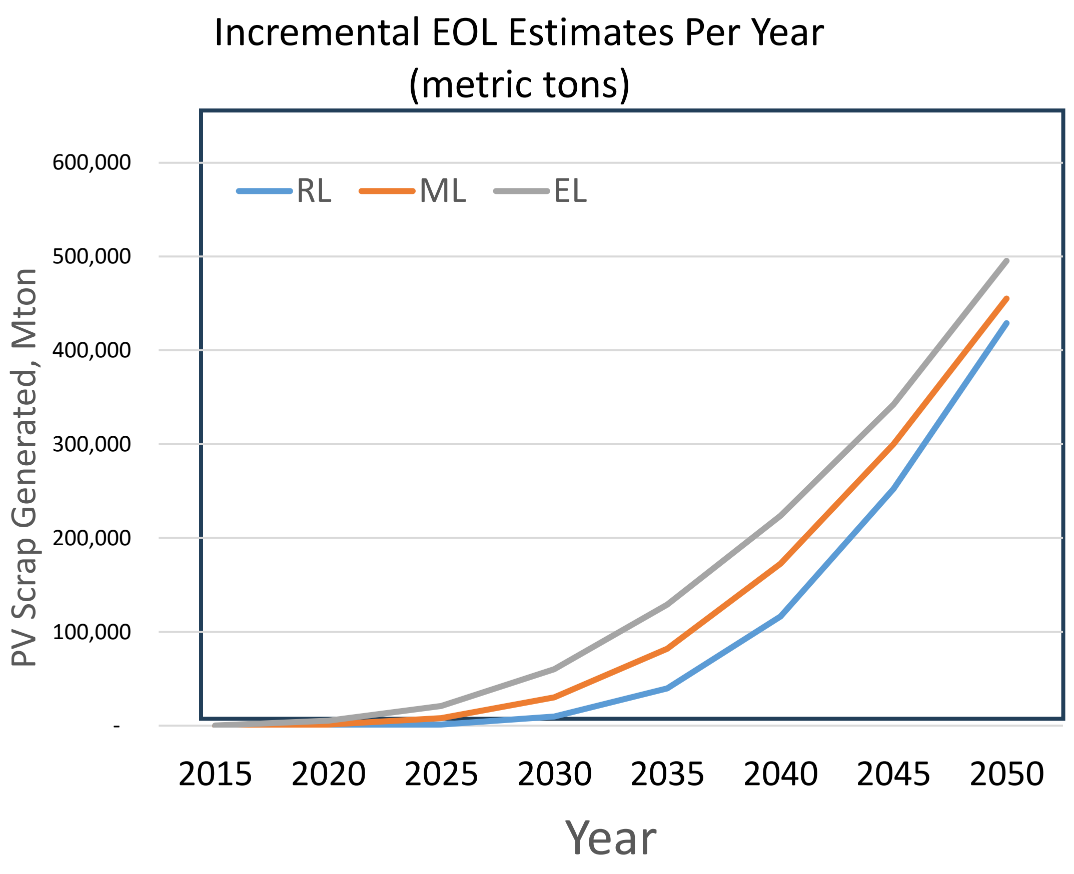


Estimates for Maryland PV Scrap generation

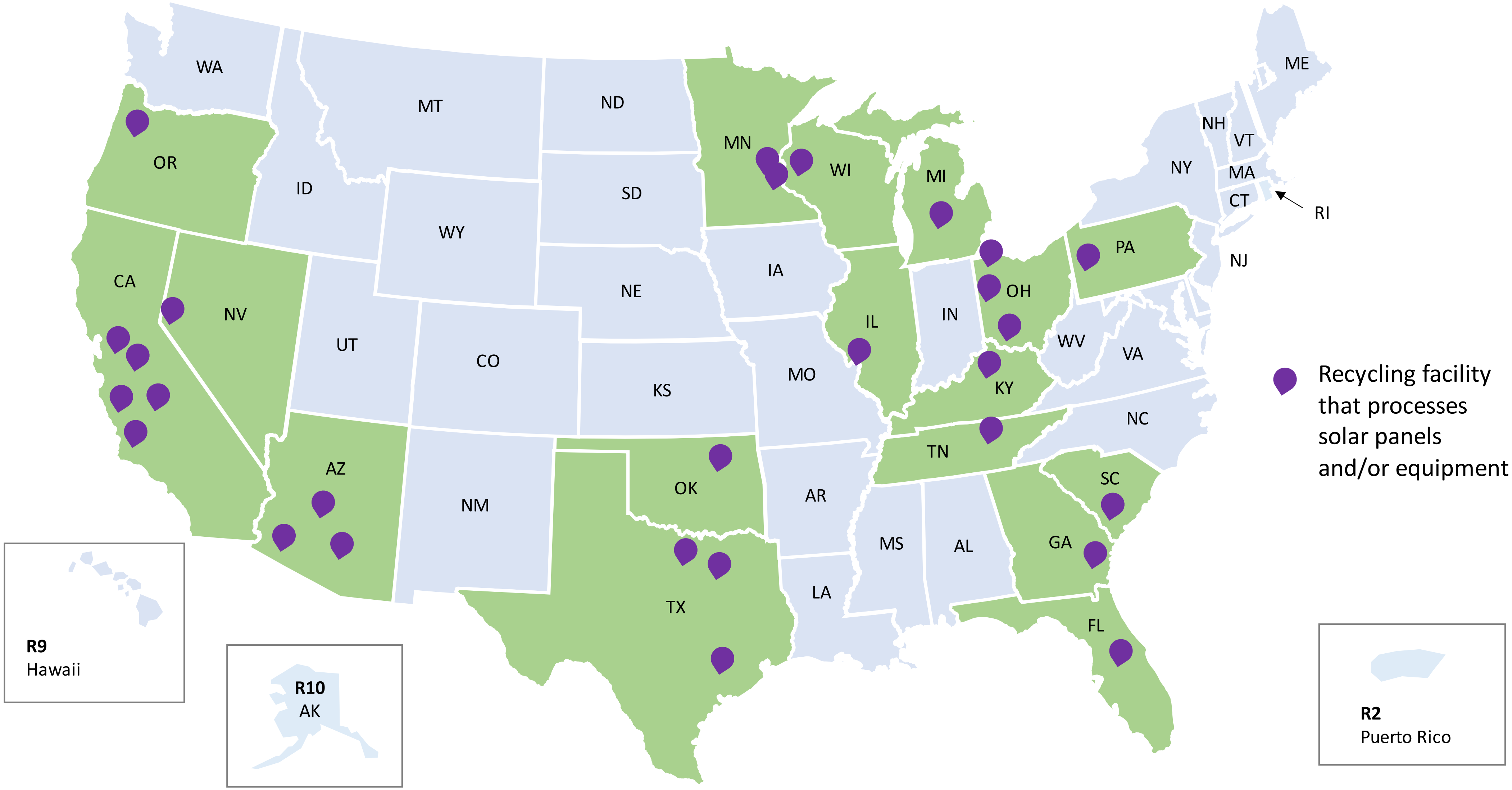
Incremental PV Scrap Generation (metric Ton)

Year	Regular Loss	Mid Loss	Early loss
	RL	ML	EL
2015	0	4	42
2020	15	256	1304
2025	352	2529	7709
2030	2,940	11,015	23,264
2035	13,836	31,540	51,226
2040	44,133	69,240	92,950
2045	102,352	125,313	147,889
2050	180,689	196,196	215,033

Region 3



PV Panel and Equipment Recycling Facilities (as of 2020)



Data survey by ITRC - 2022

United States Environmental Protection Agency

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 (needs implantation)
  - CA, HI designation of solar PV panels as universal waste

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

Challenges for PV panel managment

Technical Feasibility of Recycling: Designing PV panels for Longer service time and for Recycling: Extending module life reduces additional material to make new panels. Easy dismantle and recycling of end-of-life (EOL) panels are should be considered in the design of PV panels.

Infrastructure Challenges: Need for dedicated solar-panel recycling plants. There are limited PV panel processing and recycling facilities around the world, and end-of-life solar PV panel management is a newly emerging field that needs further research and development.

Policy Issues: Multiple state and federal programs for recycling and EoL managment

Economic Issues: Demonstrate the economic benefits of PV panels recycling . EOL solar-panel recycling can effectively save natural resources and reduce the cost of production.

Policy and Regulation on PV Panels

- **Policy Importance**

  Critical for ensuring safe handling, storage, transport, reuse, recycling, and disposal of PV equipment. Current regulatory standards and recycling facilities vary by region.

- **State and Local Regulations**

  Many regions have established guidelines for proper disposal and recycling of PV panels. State legislation, policies, and programs can drive or hinder sustainable PV panel end-of-life (EoL) management.

- **Universal Waste Rule (UWR)**
  - EPA is currently developing a new universal waste category to help management of PV panels at end of life, simplifying collection, storage, and transport for recycling.
  - UWR under RCRA streamlines hazardous waste management, encourages recycling, and makes it easier for generators to manage PV panel scrap.
  - Managing solar panels as universal waste will allow handlers to accumulate end-of-life solar panels for up to one year and will promote recycling by providing an alternative set of management standards under RCRA Subtitle C.

- **Extended Producer Responsibility (EPR)** *(Washington State, and Niagara county NY)*
  - Increasingly being adopted by the industry and states, this policy requires manufacturers to manage their products at EoL. Includes establishing recycling or take-back programs.

- **Infrastructure Needs**

  Essential to build comprehensive EoL infrastructure to promote clean energy, and materials recovery of decommissioned PV panels.

Conclusion

- Growing PV panel scrap presents a new environmental challenge and unprecedented opportunities to create value and pursue new economic avenues.

- No federal regulations exist in the US specifically for collecting and recycling end-of-life PV panels. However, the EPA is also working on regulations for end-of-life management of PV panels through the development of a *Universal Waste Rule* for solar panels. California, Washington, Hawaii and Minnesota are also developing regulations for end-of-life management of PV panels.

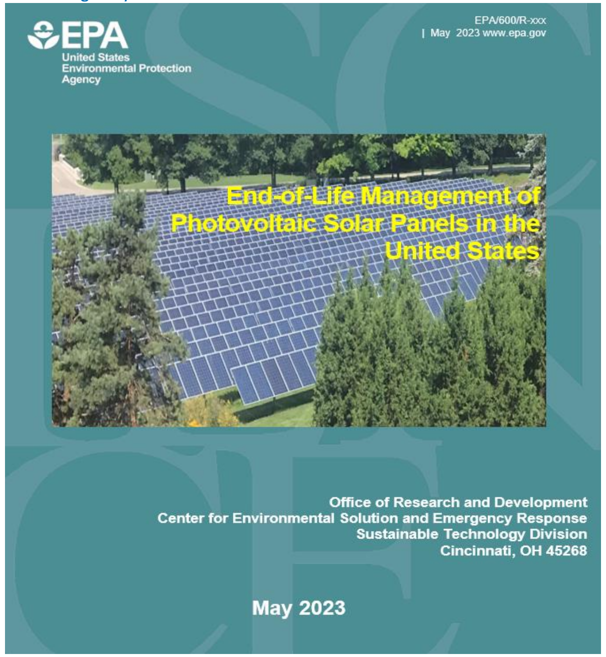
- A system-level approach to PV EoL management can enhance the *integration of stakeholders*: PV suppliers, consumers, recyclers, and solid waste managers but would likely require new federal legislation.

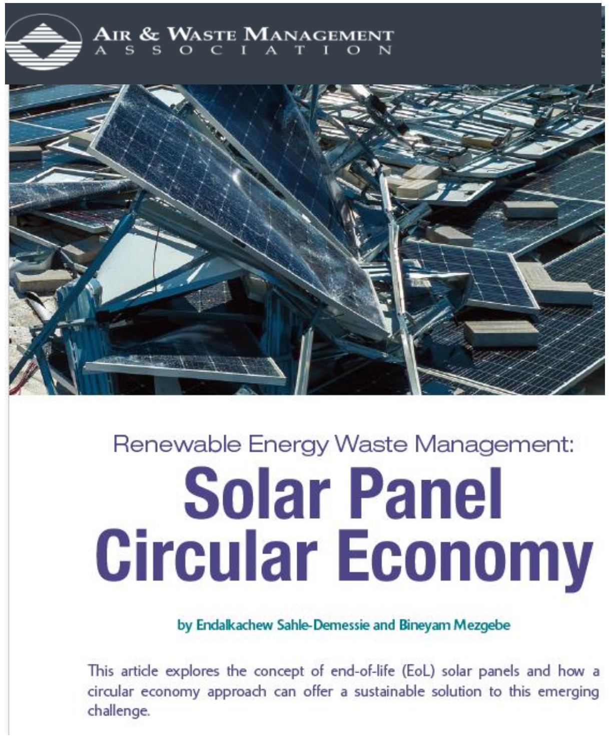
- *R&D, education and training*, and supporting data and analyses are all needed to support PV end-of-life management.

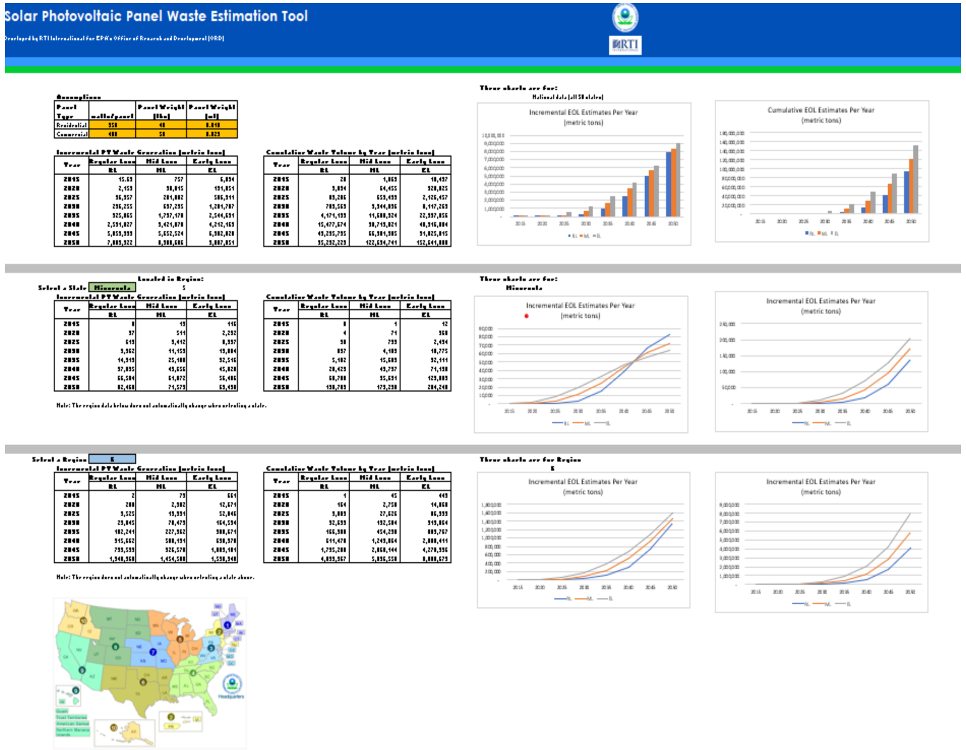
- Stimulating *investment and innovative financing schemes* for PV end-of-life management is necessary to overcome financing barriers and ensure the support of all stakeholders

EPA United States Environmental Protection Agency

ORD Report and Tool on Solar Panels







URLs/Downloads:

End-of-Life Management of Photovoltaic Solar Panels in the United States (PDF, 68 pp, 3116 KB, about PDF)

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Module Lifetime and Recycling Rate New Materials

Factors: **Material flow,** energy demand, carbon intensity of manufacturing, equity, and economics

15 yr service

- High close-loop recycling reaching 95%,
- Require high recollection, recycling & remanufacturing
- Large volume of materials in short term
- Unlikely

30 yr service

- Current technology
- Low recycling rate
- Base-line scenario

50 yr Service

- **Not available**
- **Easier to achieve de carbonization goals**
- **reduce demand for new material, and excessive replacement goal**
- **Provide longer grace period for recycling infrastructure development**

Presentation Outline

- Future of Solar Energy – Trend analysis
- Circular economy and solar panel management
- End-of-life management of Solar Panels
    - International Renewable Energy Agency (IRENA) and IEA Photovoltaic Power System Program (PVPS) End of Life (EoL) Management report
    - Model assumption and selected parameters
    - Weibull distribution function
- Photovoltaic (PV) Waste Estimation Tool → Demo
- State and Federal regulation for end-of-life managment
- Summary