

THE LIFE OF A SOLAR PANEL

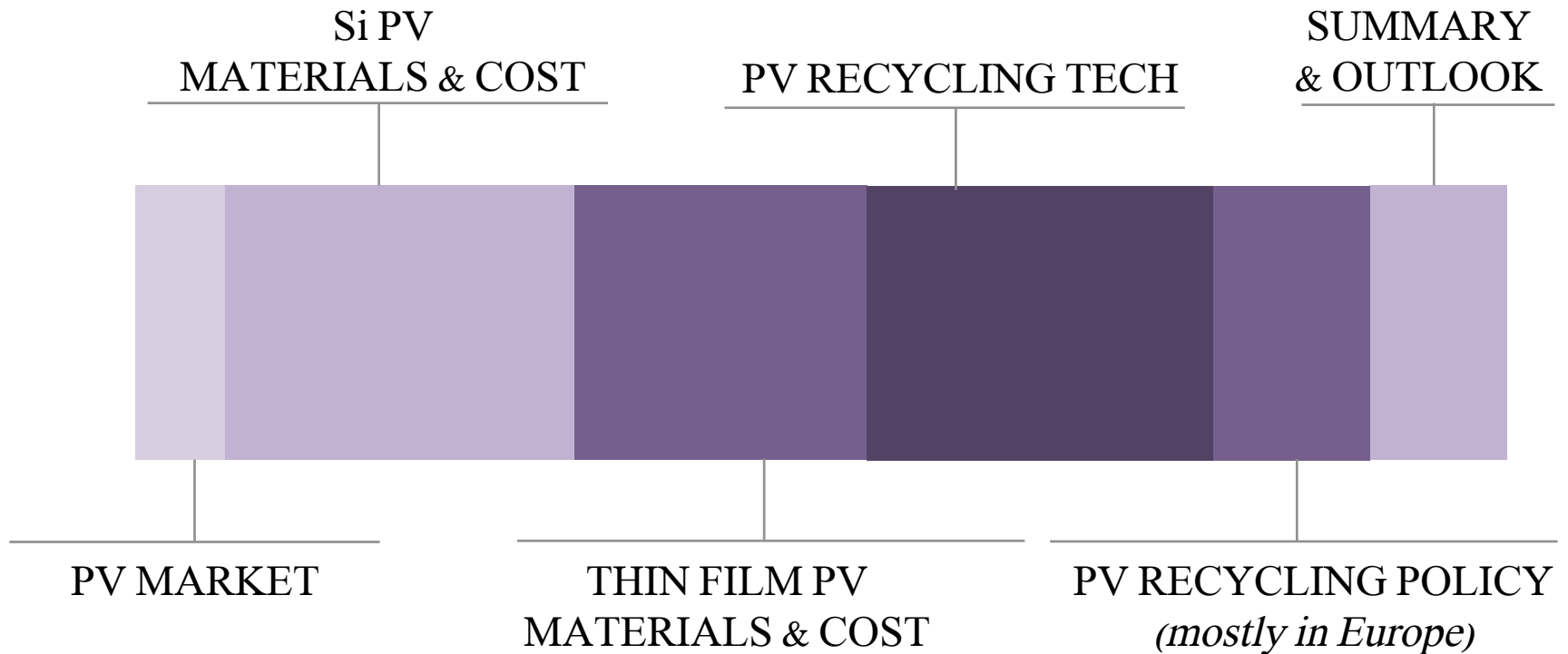
FROM RAW MATERIALS
TO RECYCLING



Image from Sint Smeding © Creative Commons 2008

HEJC
9/22/2017
CHRISTINA CHANG

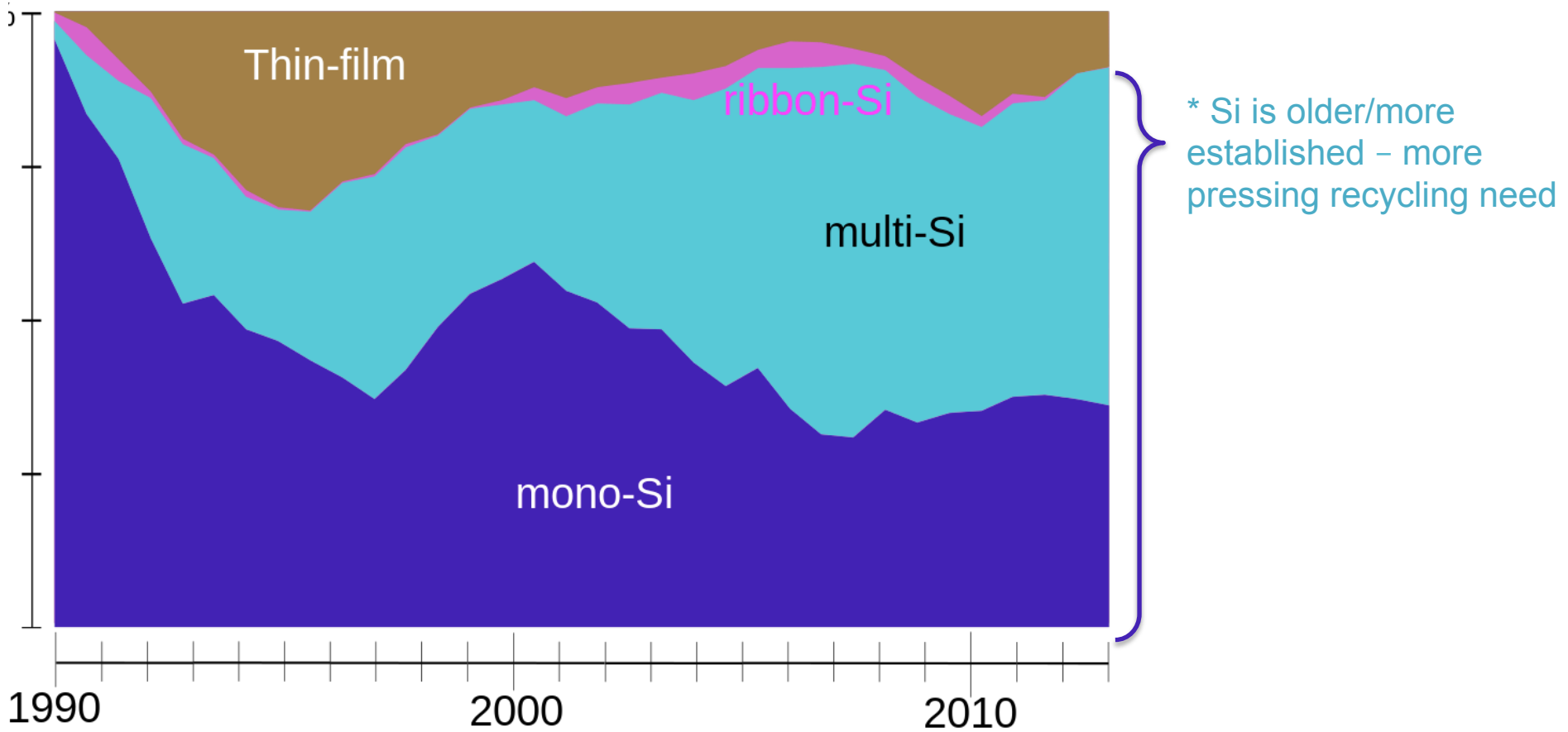
PRESENTATION STRUCTURE



1. PV Market



Global PV Market Share is ~90% Si, ~10% thin film



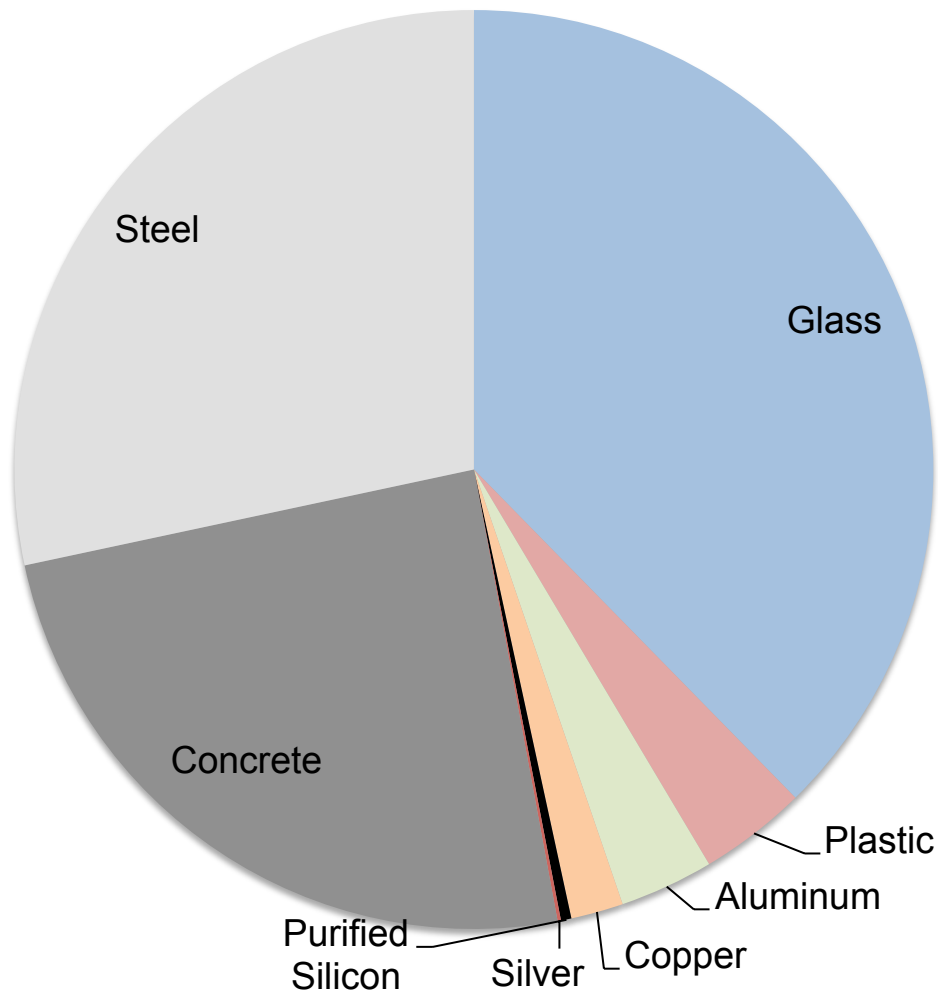
* Si is older/more established – more pressing recycling need

What materials are used in Si PV installations?

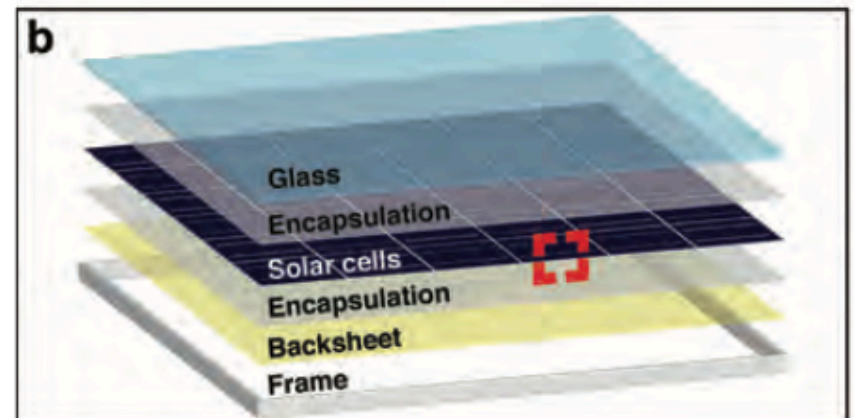
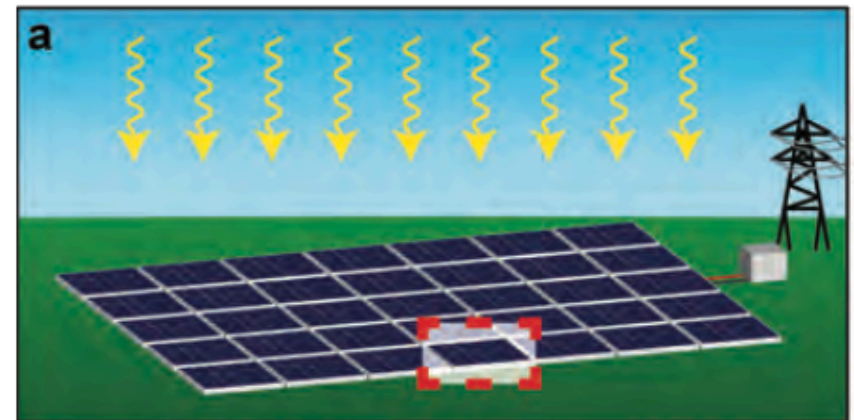
Silicon
Glass
Plastic
Concrete
Steel
Aluminum
Copper
Silver



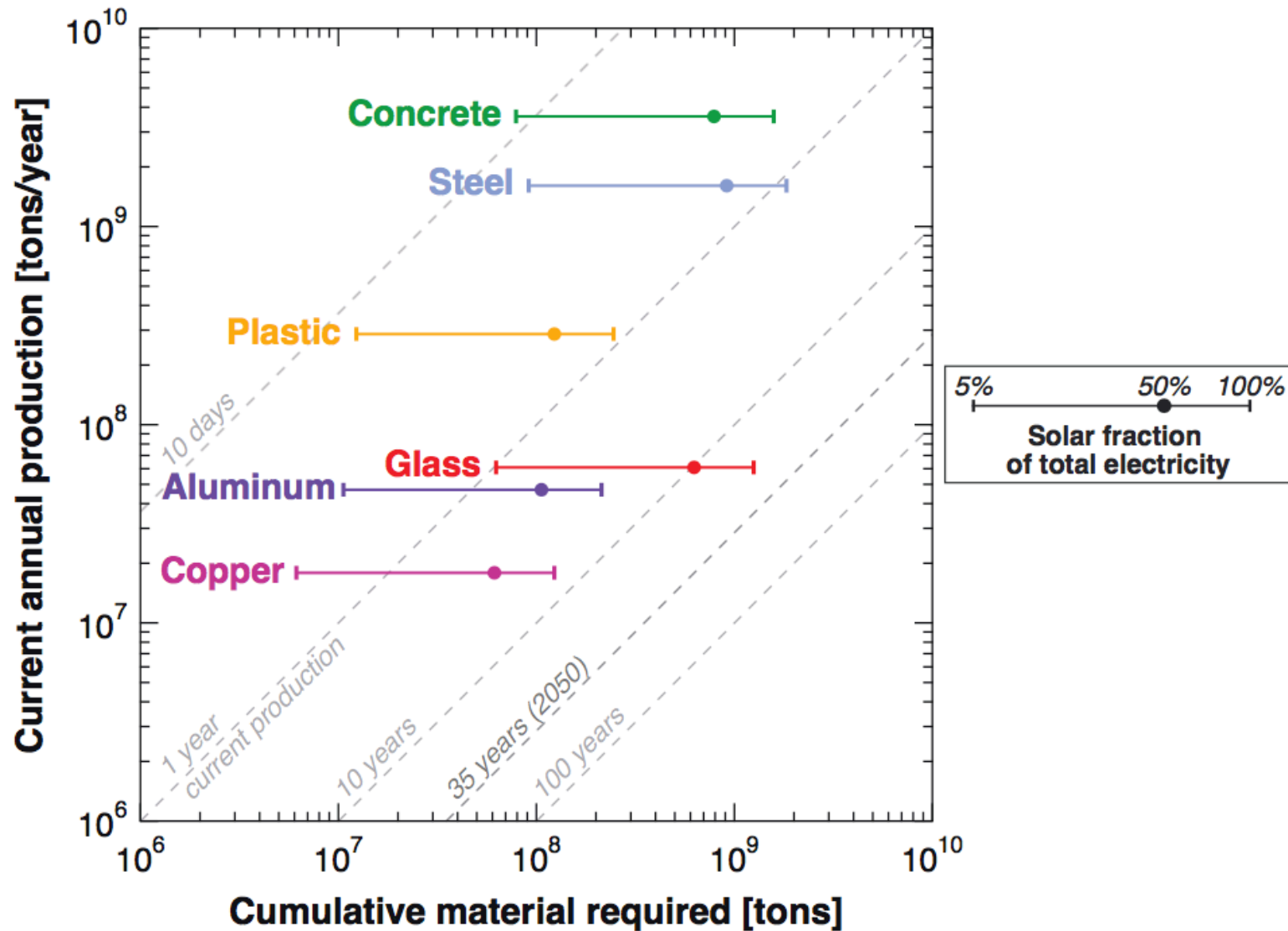
What materials are used in Si PV installations?



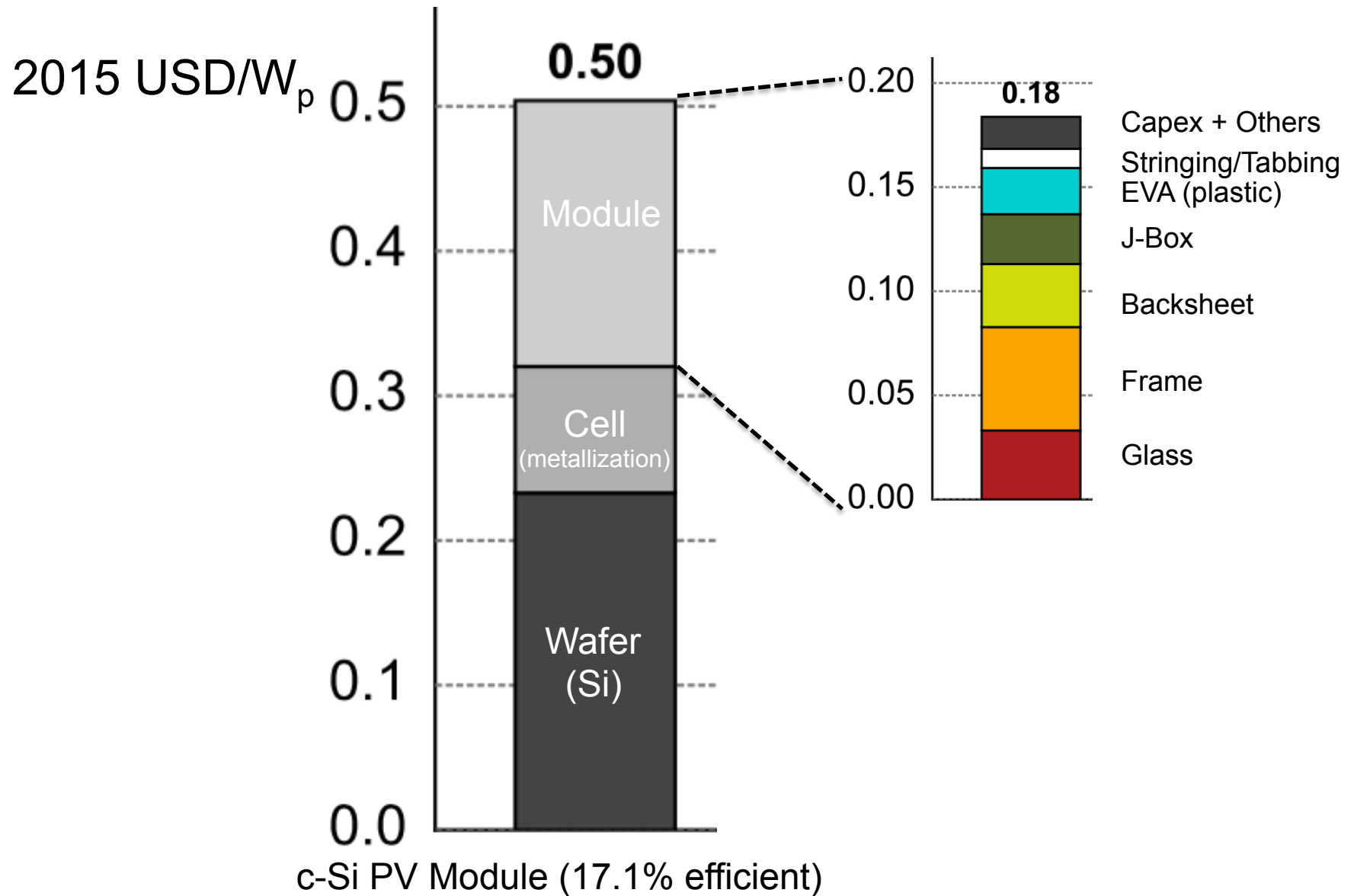
	Use in PV Module	wt %
Glass	Module	80%
Plastic	Module, wire connectors	~8%
Aluminum	Frame, wire	~7%
Copper	Wire	~4%
Purified Silicon	Solar absorber material	~0.8%
Silver	Grids / cell pads	~0.3%



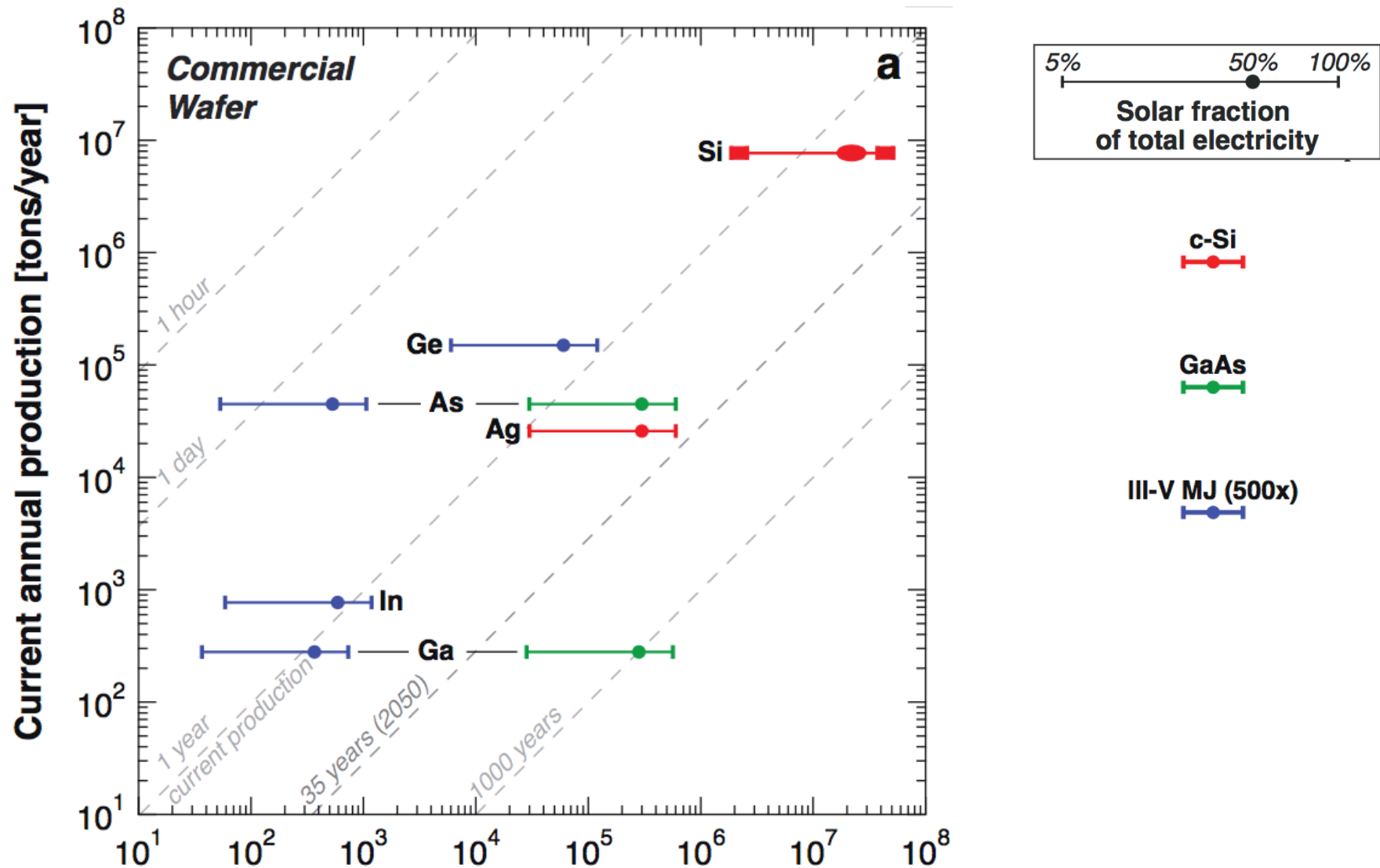
Commodity Materials Requirements for Large-scale Deployment of Silicon PV



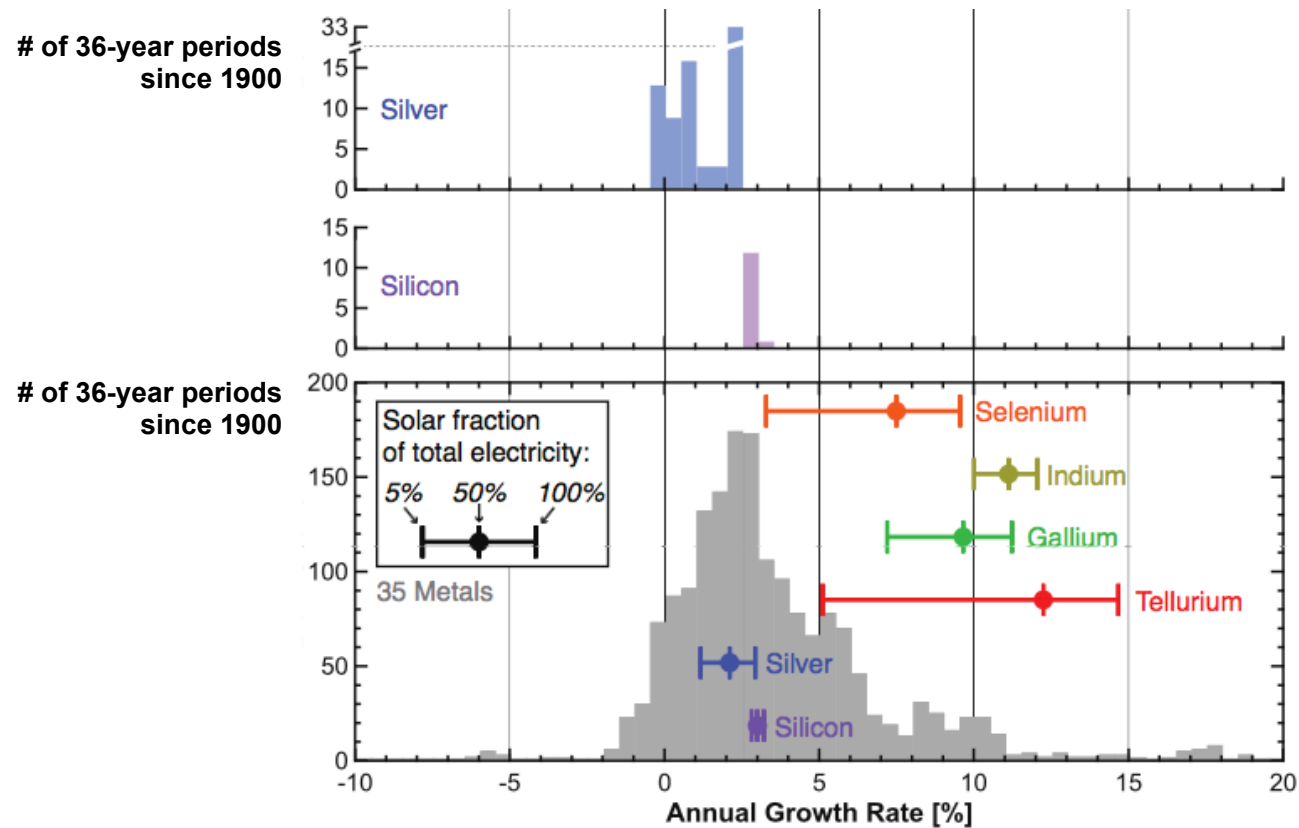
Si is 40% of module cost; Ag is ~15%



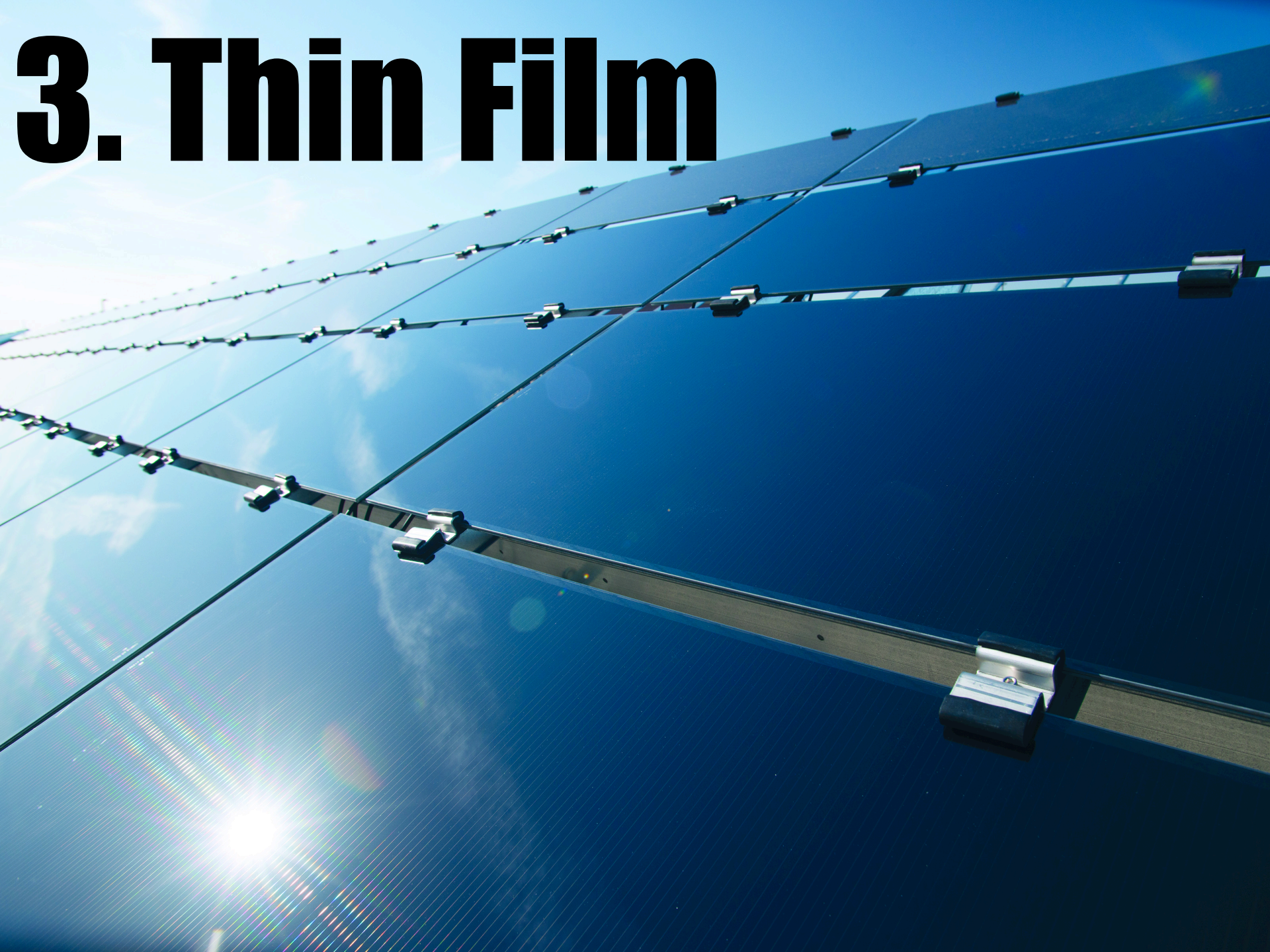
Critical Element Requirements for Large-Scale Deployment of Commercial Wafer Technologies



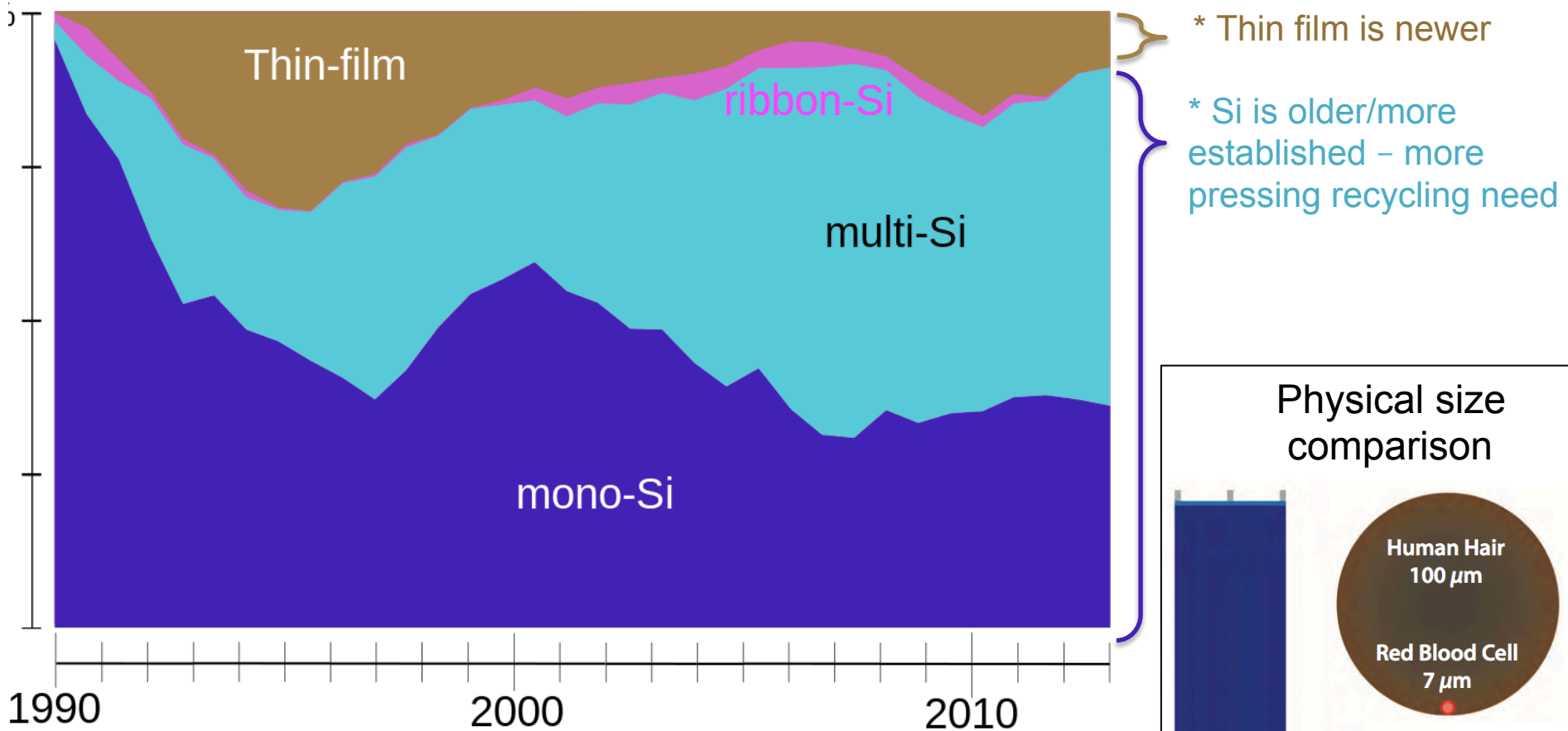
Required growth rates for production of critical elements Si and Ag are within historical growth rates



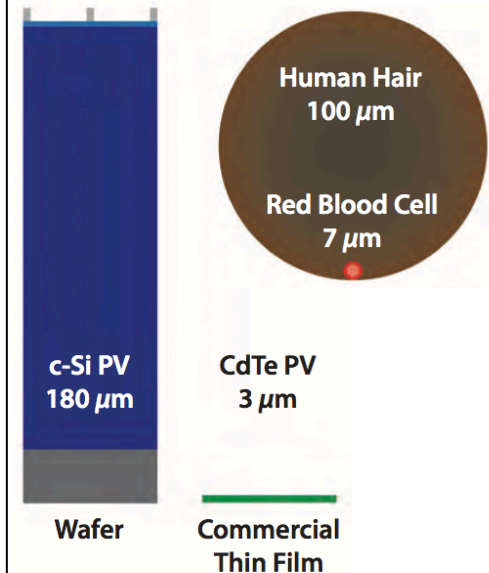
3. Thin Film



Global PV Market Share is ~92% Si, 8% thin film



Physical size comparison



Thin film cells were 8% of the solar PV market in 2014

Technology		2014	2020	2030
Silicon-based (c-Si)	Monocrystalline	92%	73.3%	44.8%
	Poly- or multicrystalline			
	Ribbon			
	a-Si (amorph/micromorph)			
Thin-film based	Copper indium gallium (di)selenide (CIGS)	2%	5.2%	6.4%
	Cadmium telluride (CdTe)	5%	5.2%	4.7%
Other	Concentrating solar PV (CPV)	1%	1.2%	0.6%
	Organic PV/dye-sensitised cells (OPV)		5.8%	8.7%
	Crystalline silicon (advanced c-Si)		8.7%	25.6%
	CIGS alternatives, heavy metals (e.g. perovskite), advanced III-V		0.6%	9.3%

To achieve 100% solar penetration by thin film technologies, production of rare elements (Te, Ga, In Se) would have to increase up to 100-fold compared to cumulative production

Used in CdTe

Used in CIGS



	Silicon ^{xi}	Silver	Tellurium	Gallium	Indium	Selenium
Abundance [fraction] ^{xii}	0.28	7.5×10^{-8}	1.0×10^{-9}	1.9×10^{-5}	2.5×10^{-7}	5.0×10^{-8}
Cumulative production (1900–2012) [10^6 tons] ³⁹	160	1.1	0.010	0.0026	0.010	0.091
Cumulative amount in PV by 2050 for 100% PV penetration [10^6 tons]	51	0.60	0.79	0.11	0.19	0.51
Ratio of 2050 PV cumulative production to cumulative 1900–2012 production	0.32	0.53	76	43	18	5.6

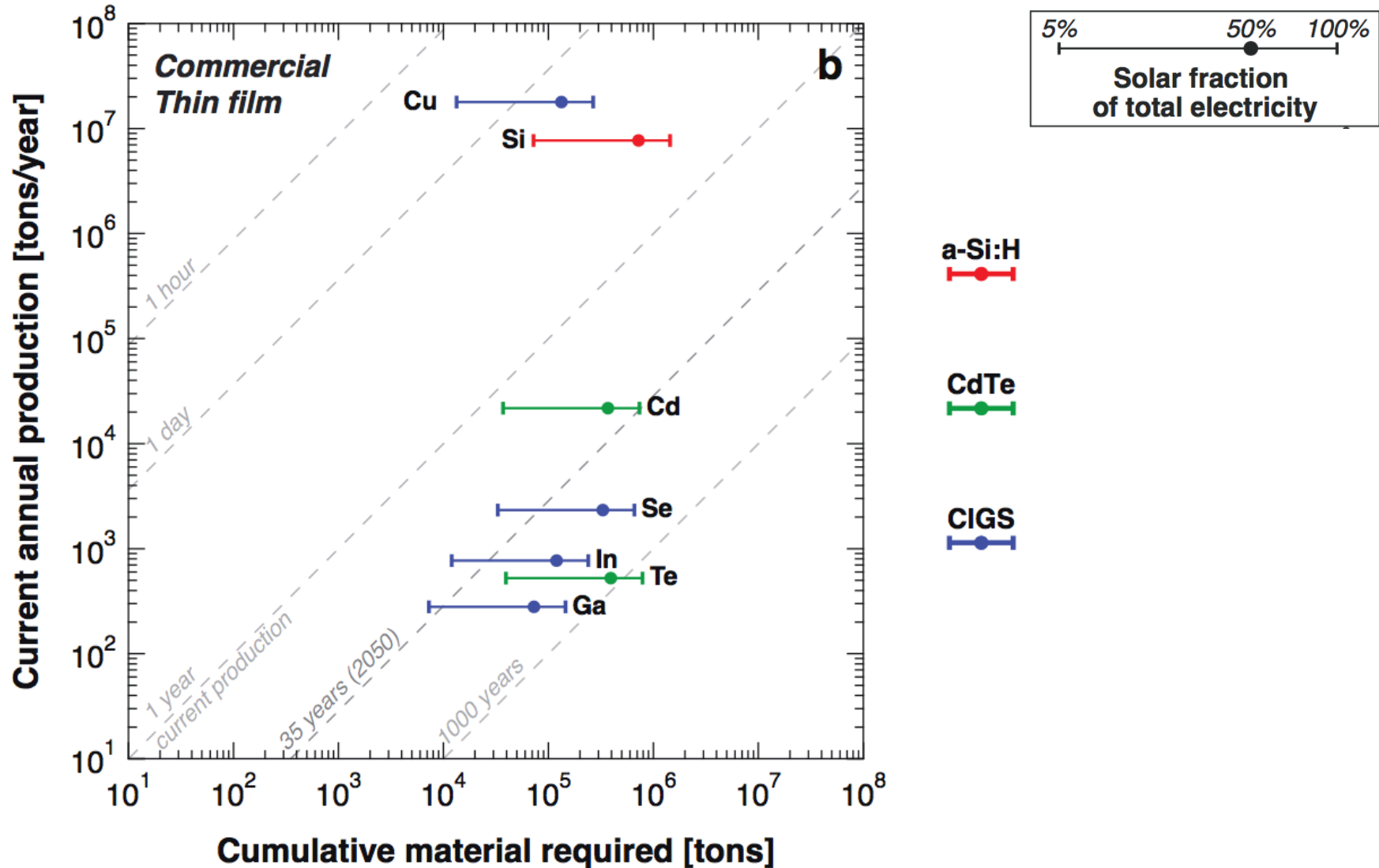
The picture is even more complicated:

- Absolute amt required << amt in Earth's crust
 - E.g. only 1/10,000,000 amt of known Te required for 100% CdTe PV for US electricity production
- Only economical to mine any element if found in high abundance in deposits
- Te, Ga, In, Se are typically found as byproducts of more common elements

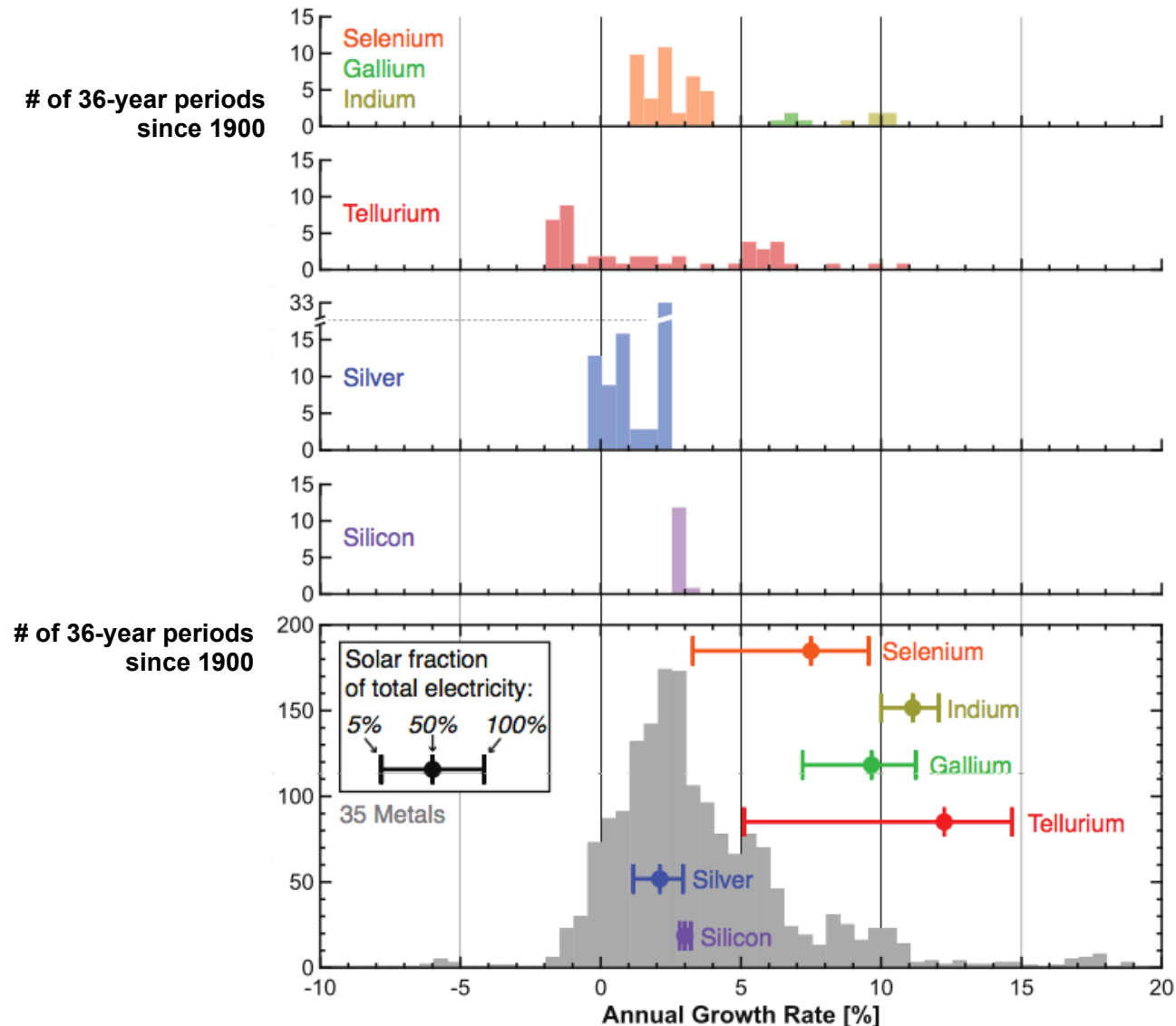
Production Volume and Monetary Value of PV-Critical Elements Produced as Byproducts, Relative to Parent Products

	Tellurium	Gallium	Indium	Selenium	Silver
Parent source	Copper	Aluminum	Zinc	Copper	Copper, lead, primary silver
Global production of parent in 2012 (10 ³ tons)	17,000	46,000	14,000	17,000	17,000 (copper)
Global production of byproduct in 2012 (10 ³ tons)	0.53	0.38	0.78	2.2	26 (silver)
Value of 2012 parent production (billion 2012\$)	140	100	28	140	140 (copper)
Value of 2012 byproduct production (billion 2012\$)	0.08	0.20	0.51	0.27	26 (from all sources)

Critical Element Requirements for Large-Scale Deployment of Commercial Thin-Film Technologies



Historic data on production growth for different metals compared to required growth rates for PV-critical elements



Do we need PV panel recycling?

Conventional silicon PV:

- Availability
 - optimistic for Si, moderate for Ag
 - If use of Ag for electrical contacts can be reduced or eliminated, no fundamental materials supply constraints (re: ability to meet a large fraction of global electricity demand in 2050)
- Cost
 - Si is 40% of module cost, Ag ~15% of module cost; could recycling help bring this down? (depends on technique + purity)

Thin Film PV:

- Availability:
 - not optimistic, little historical precedent for huge increase needed
- Cost:
 - If can recycle economically, may help reduce cost
- Environmental
 - Toxicity concerns for Cd, Te, Ga, Se waste!

4. PV Recycling Technology



Recycling Technologies

Silicon

see video (link below)

up to 95% mat'ls recycled

1. Dismantle Al frames and junction boxes
2. Crush module
3. Separate components: hand inspection, vibration-based size exclusion, laser-selection
4. Refine
5. Anything leftover, send for waste-to-energy recovery

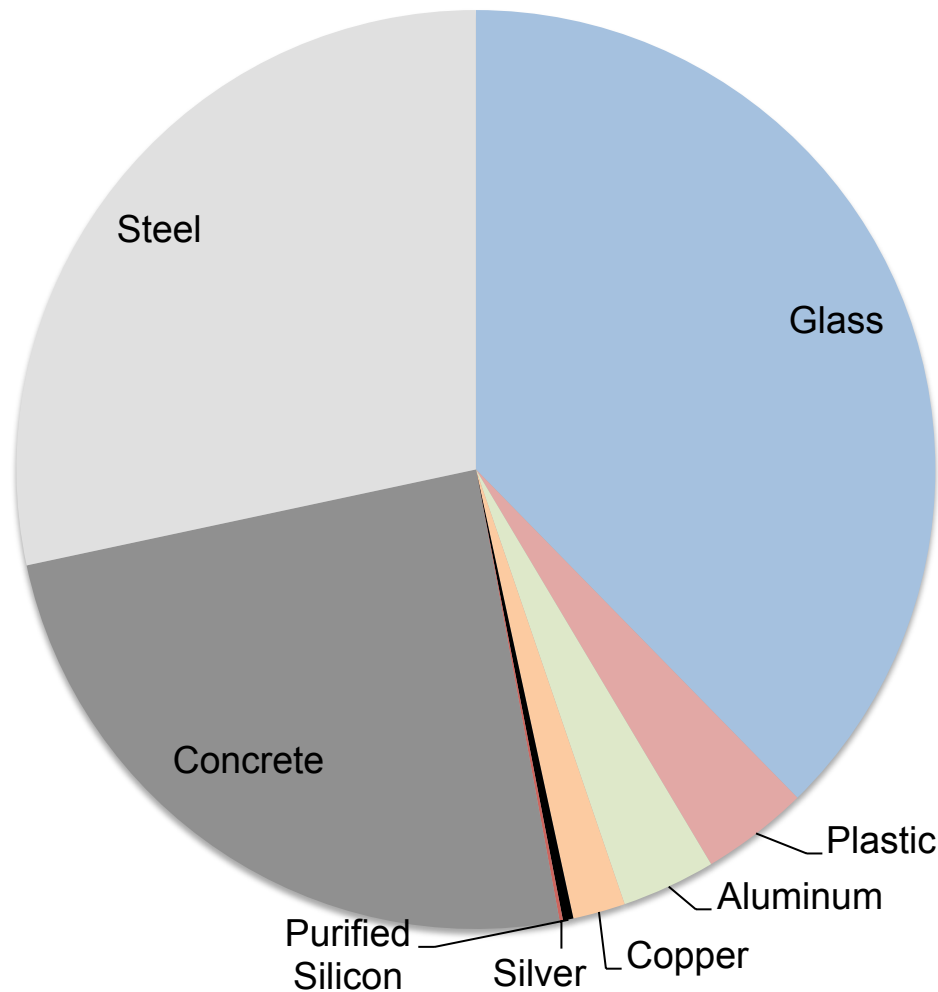
Thin Film

CdTe, CIS, CIGS

up to 95% mat'ls recycled

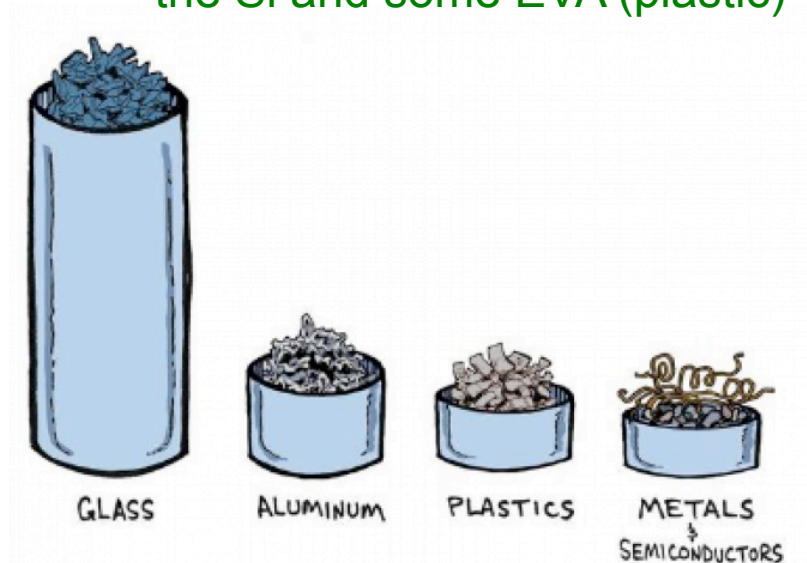
1. Dismantle Al frames and junction boxes
2. Crush module
3. Chemical bath treatment to separate the various elements
4. Refine
5. Anything leftover, send for waste-to-energy recovery

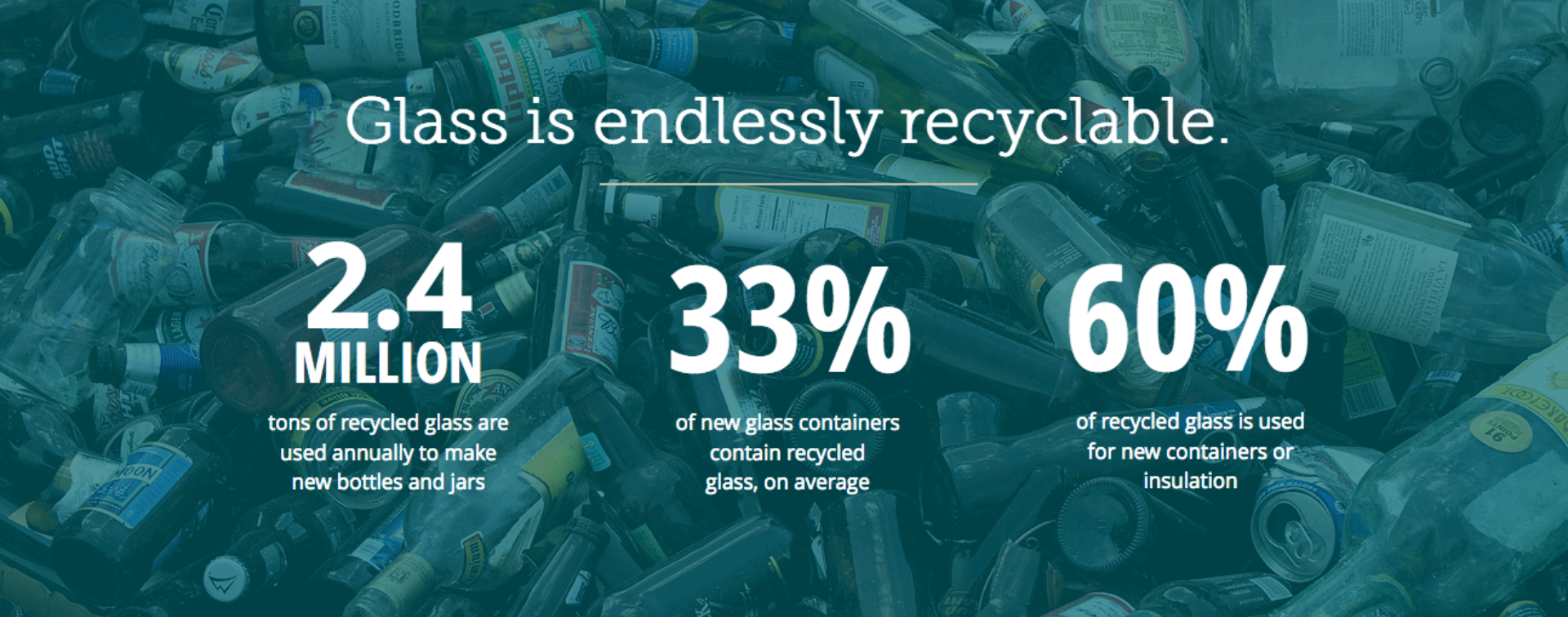
What materials can be recycled in Si PV installations?



	Use in PV Module	wt %
Glass	Module	80%
Plastic	Module, wire connectors	~8%
Aluminum	Frame, wire	~7%
Copper	Wire	~4%
Purified Silicon	Solar absorber material	~0.8%
Silver	Grids / cell pads	~0.3%

- Up to ~95% of a Si module can be recycled
- This is everything except for the Si and some EVA (plastic)





Glass is endlessly recyclable.

2.4 MILLION

tons of recycled glass are
used annually to make
new bottles and jars

33%

of new glass containers
contain recycled
glass, on average

60%

of recycled glass is used
for new containers or
insulation

Glass recycling process:

1. Sort by color
2. Crush
3. Melt
4. Mold into new products (e.g. bottles, jars)

Recycling saves about 95% of the energy required to make Al from virgin materials:
massive Al recycling market



Si recycling to high enough purity is still experimental

Table 1

Summary of experimental work conducted on PV recycling.

Authors	Process	Materials Recovered
Frisson et al. (2000)	• Pyrolysis in a conveyer belt furnace and pyrolysis in a fluidized bed reactor • Etching using a sequence of 15% HF, 4–1 H₂SO₄·H₂O solution, 40% HNO₃ • Emitter etch in 20% NaOH	• Silicon
Radziemska and Ostrowski (2010)	• Removal of the aluminum coating by etching, using 30% KOH to remove Al metal coatings • Etching using a mixture of 250 ml HNO₃ (65%), 150 ml HF (40%), and 150 ml CH₃COOH (99.5%) 3 ml Br₂ for removing Ag coatings, AR coatings and n-p junctions	• Silicon
Kang et al. (2012)	• Recovery of glass using organic solvents • Thermal decomposition to remove the adhesive layer and recover the semiconductor • Obtainment of 99.99% pure silicon by immersion of the recovered cell in an etching solution combined with surfactant	• Glass • Silicon
Wang et al. (2012)	• Two-step heating process for PV module thermal delamination • Acid etching to remove tin-lead coating from copper and metal impurities from the silicon wafer	• Glass • Silicon • Copper

Thin-film PV recycling (CdTe, CIGS)



Modules

Recycling

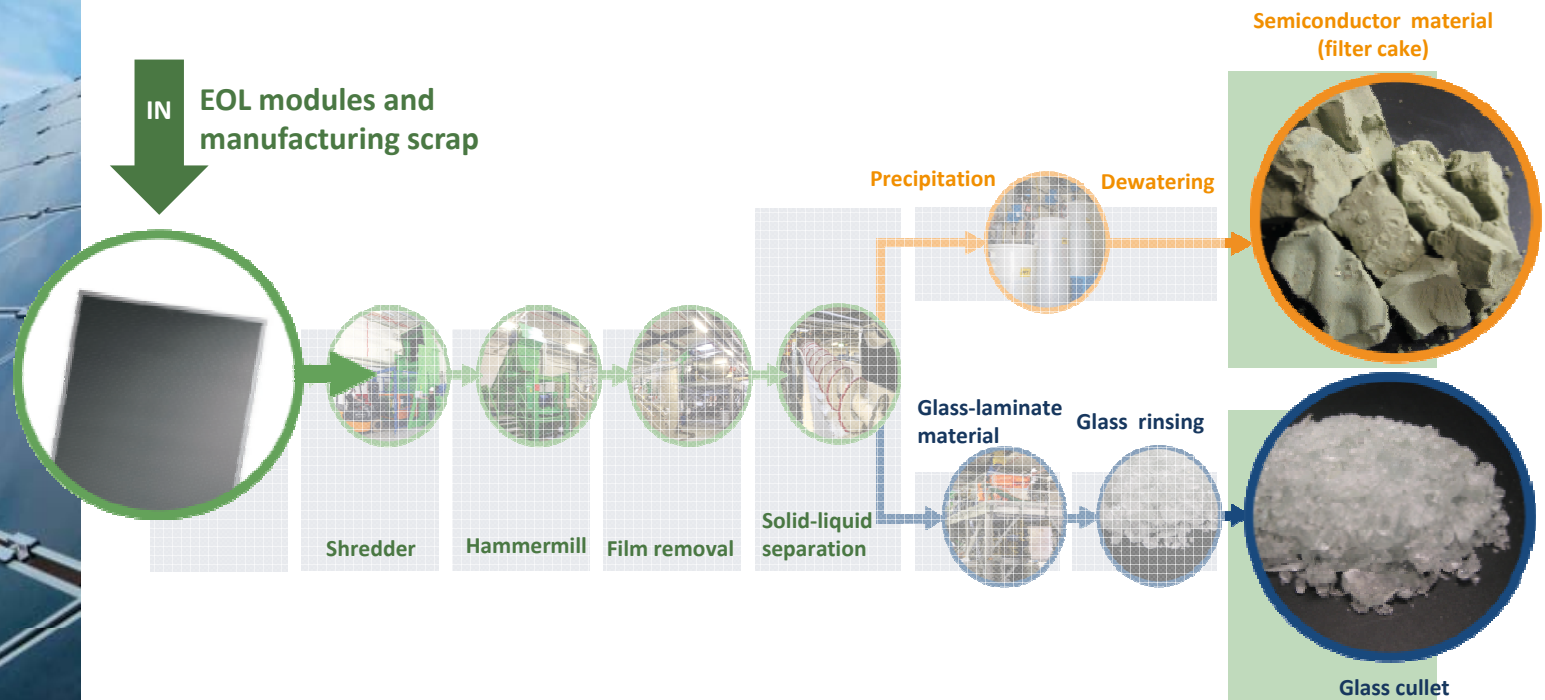
First Solar recycling recovers up to 90% of materials

First Solar's state-of-the-art recycling facilities are operational in the U.S., Germany and Malaysia, with a scalable capacity to accommodate high volume recycling as more modules reach the end of their 25+ year life. Our proven recycling process achieves high recovery rates. Up to 90 percent of the semiconductor material can be reused in new modules and 90 percent of the glass can be reused in new glass products.

*Cadmium and tellurium separation and refining are conducted by a third-party.

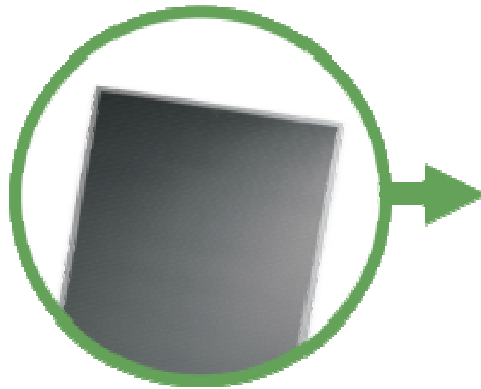
* First Solar pre-funds 100% of estimated collection and recycling costs at the time of module sale.

First Solar Recycling Process

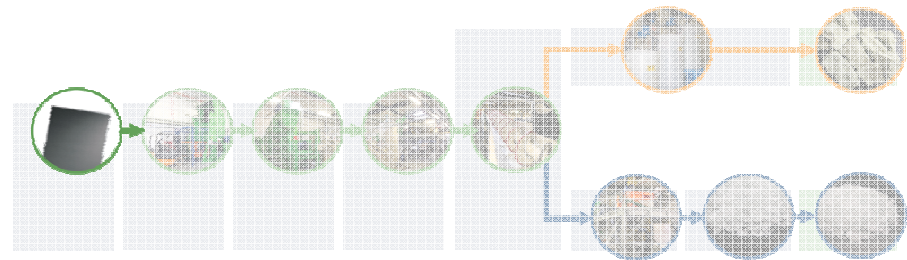


● Module Recycling Process

Collection



- First Solar provides packing materials and collects waste modules upon customer request.
- Once at First Solar's recycling plant, the modules are collected in hoppers and loaded by forklift into a shredder.



First Solar Confidential & Proprietary

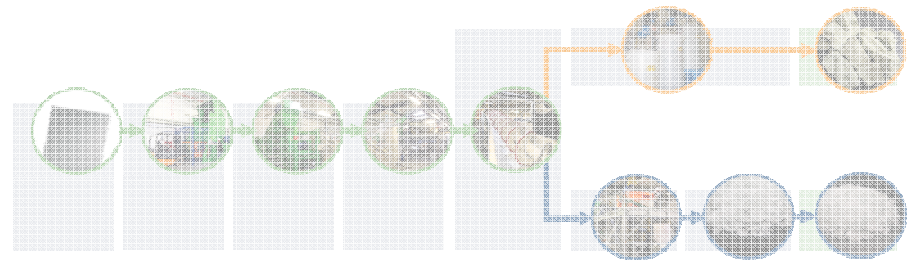
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● Module Recycling Process

Aspiration System



- Used for dust control in all dry parts of the recycling process
- Equipped with pre-filters and high efficiency particulate air filters (HEPA) which are 99.95% efficient.
- Collected dust and filters are disposed of in an environmentally safe manner.

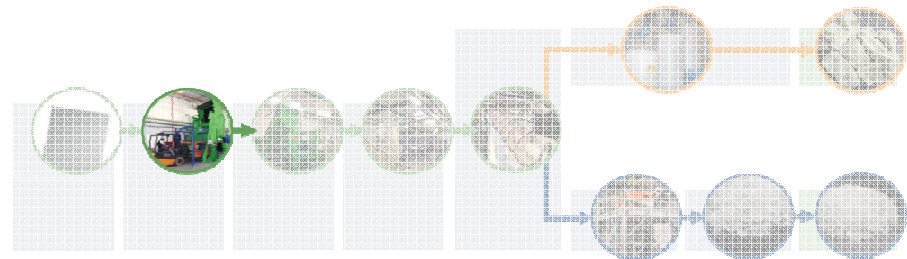


● Module Recycling Process

Shredder

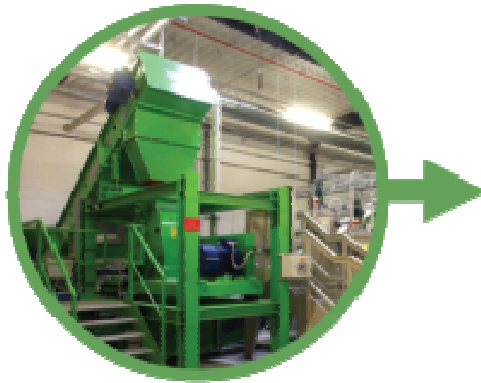


- The modules are reduced in size in a two step process.
- Step one uses a shredder to break the modules into large pieces.

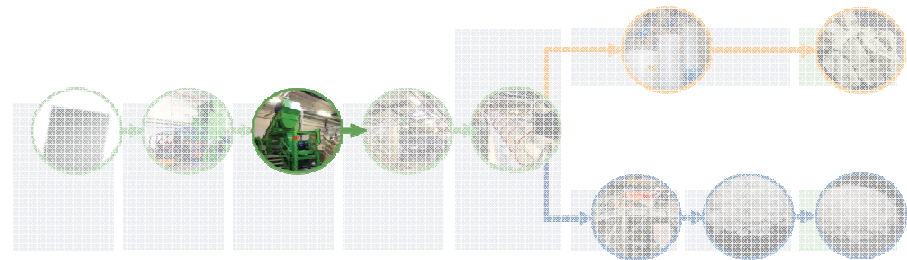


● Module Recycling Process

Hammermill

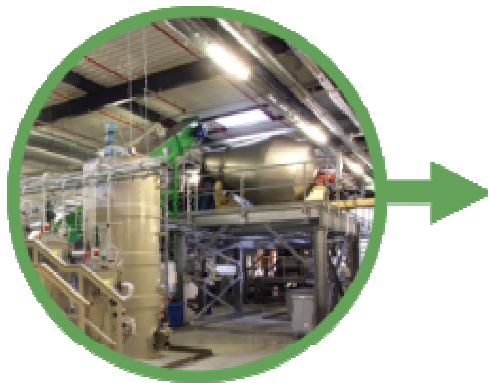


In step two, the hammermill crushes the glass further into approximately 4-5mm pieces, small enough to ensure the lamination bond is broken.

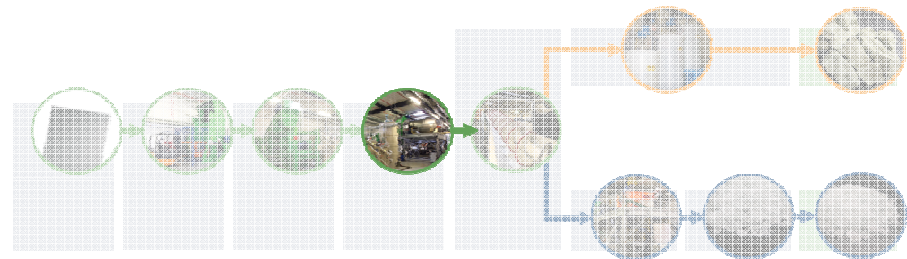


● Module Recycling Process

Film Removal



The semiconductor films are removed by the addition of acid and peroxide in a slowly rotating, stainless steel drum.

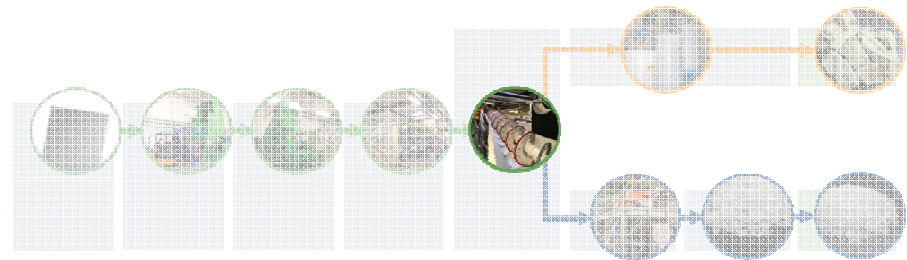


● Module Recycling Process

Solid-Liquid Separation



- The drum is slowly emptied into a classifier where glass materials are separated from liquids.
- A rotating screw conveys the glass up an incline, leaving the liquids behind.

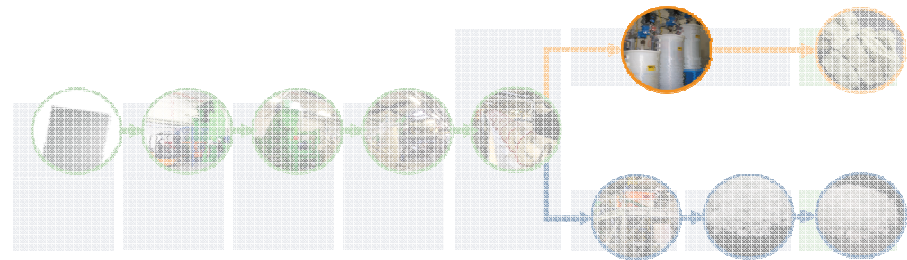


● Module Recycling Process

Precipitation



- The metal-rich liquids are pumped to the precipitation unit.
- The metal compounds are precipitated in three stages at increasing pH.

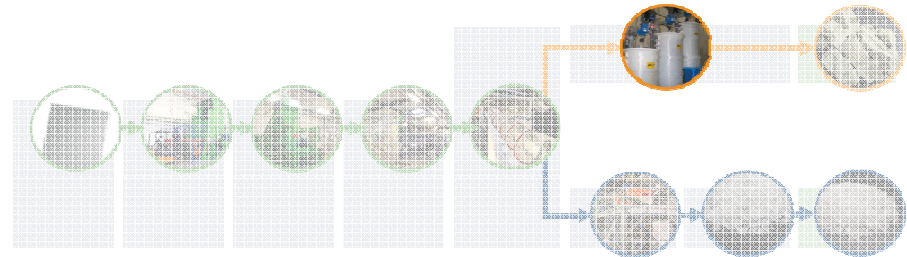


● Module Recycling Process

Dewater



- The precipitated materials are concentrated in a thickening tank.
- Resulting metal-rich filter cake is packaged for processing by a third party

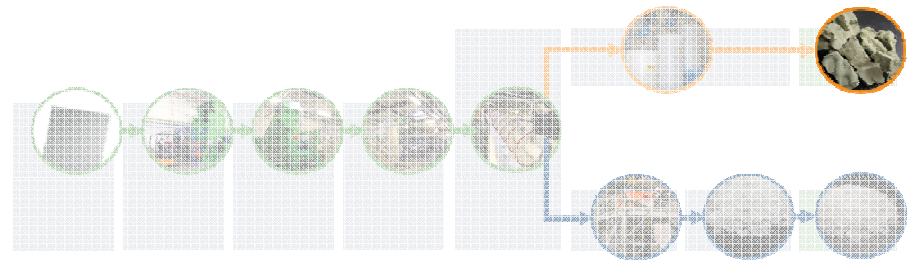


● Module Recycling Process

Metal-Rich Filter Cake



Results: ~95% recycling of semiconductor material for use in new modules.

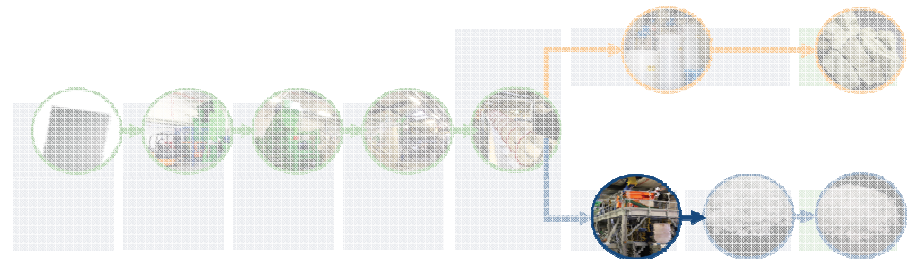


● Module Recycling Process

Glass-Laminate Material



A vibrating screen separates the glass from the larger pieces of laminate material



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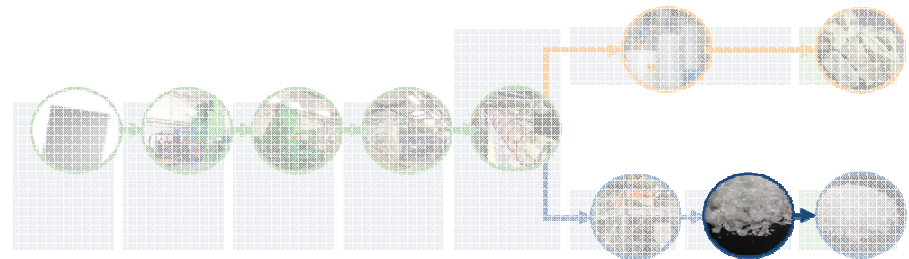


● Module Recycling Process

Glass Rinse



- Rinsed to remove any residual semiconductor films that physically remain on the glass.
- Cleaned glass is packaged for recycling.



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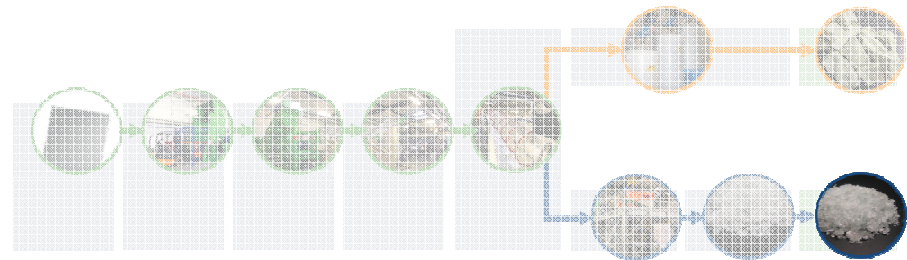
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● Module Recycling Process

Clean Glass



Results: ~90% recycling of glass for use in new glass products.



● Product Recovery and Quality



- Approximately 90% of the module weight is recovered; most of this is glass.
 - Glass will be reused in a new glass product



- Estimated recovery of Te and Cd is 95%
 - Te and Cd will be purified by a third party for reuse in First Solar modules.

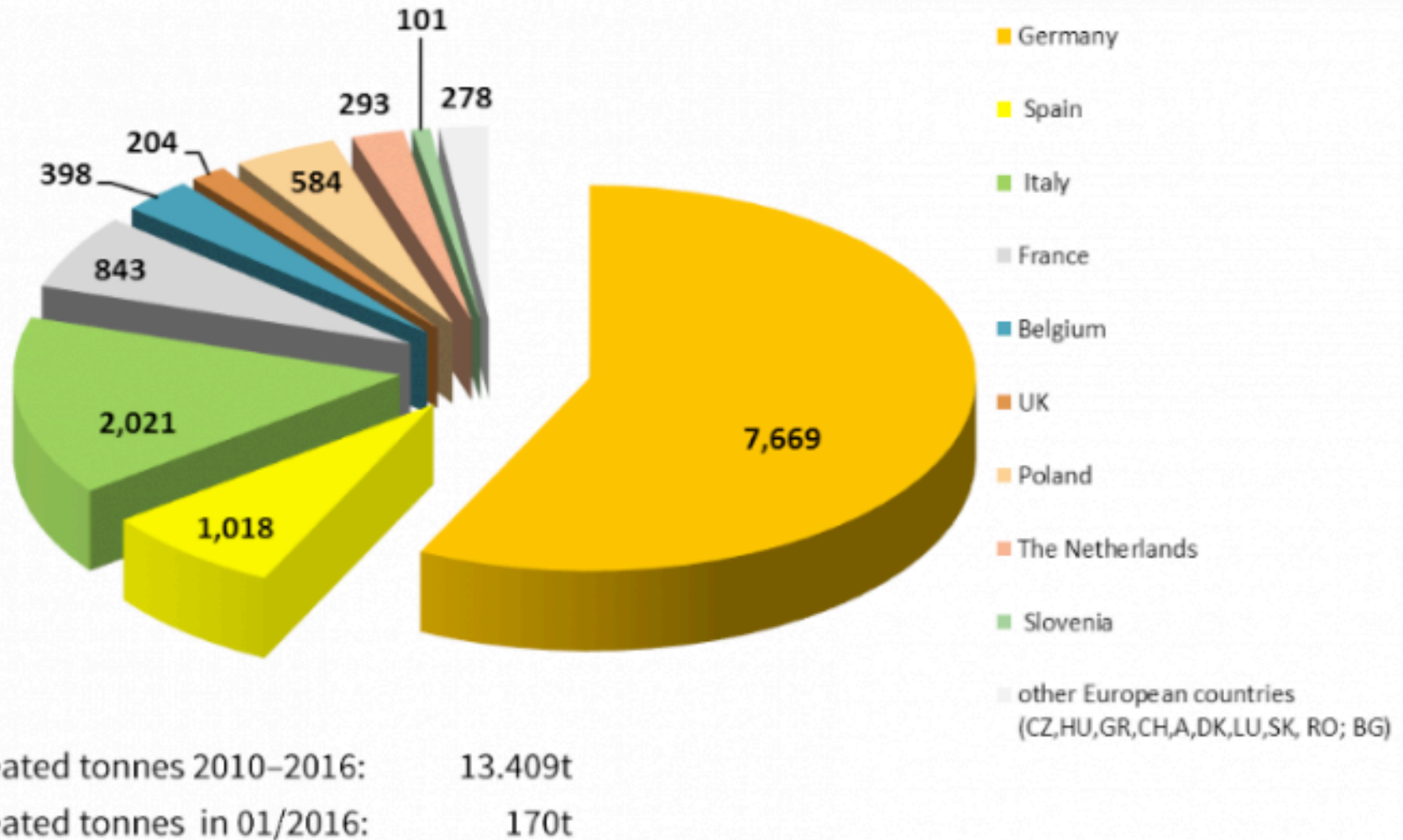
All First Solar manufacturing sites have commercial scale recycling facilities.

First Solar is continually looking at ways to optimize it's Module Collection and Recycling Program. (sic)

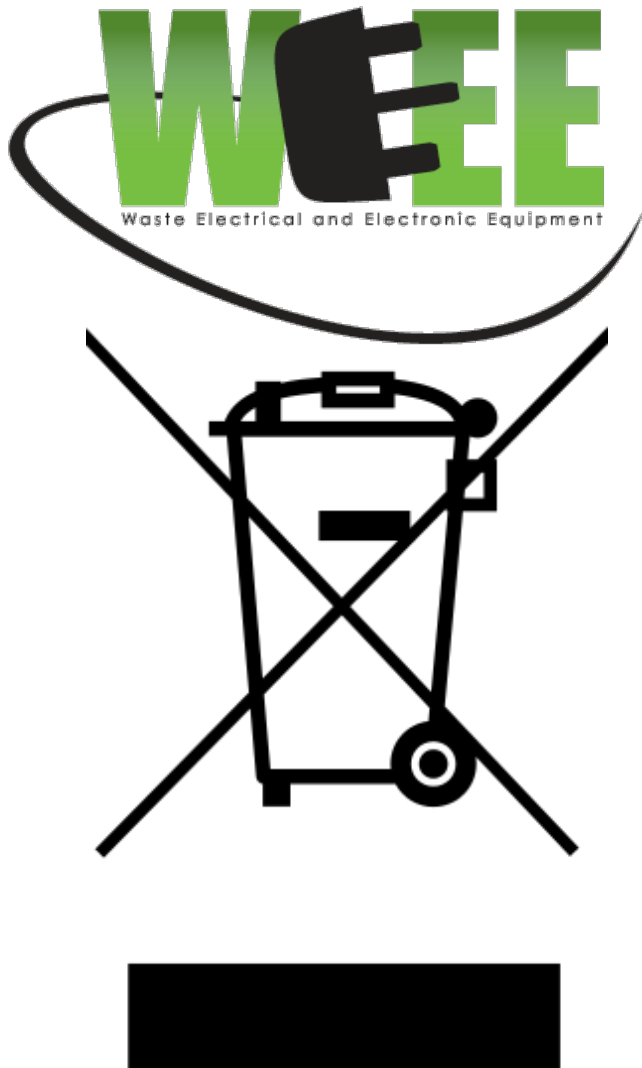
5. PV Recycling Policy



European PV recycling stats in metric tons



European PV recycling is due to the Waste Electrical and Electronic Equipment (WEEE) Directive



About 2 years ago, producers of photovoltaic panels became responsible for the disposal and recycling of the modules they sell in EU member states.

Goals:

1. Encourage the industry to develop products that are easier to recycle and use fewer raw materials.
2. Lead producers to factor in the cost of the collection and end-of-life treatment of their products into the cost paid by the consumers.

European PV Recycling Policy Context



Policy

- All producers have an obligation to recycle
- Member states can choose how to finance
- E.g. Belgium has a fixed price of €2 / panel which they pass on to customer, and guarantee to recycle it at end of life
 - E.g. France will implement next year a variable price based on panel size and absorber technology
- At end of life, customer just puts panel in container stations around Europe
- Many companies for electrical/electronic equipment recycling (PV Cycle is the only one that's PV-specific)

Technology

- Si PV is established
- CdTe / CIGS – no panels have yet been submitted for recycling; working with what panels they get to invent/improve processes

USA PV Recycling Policy Context



Regulations

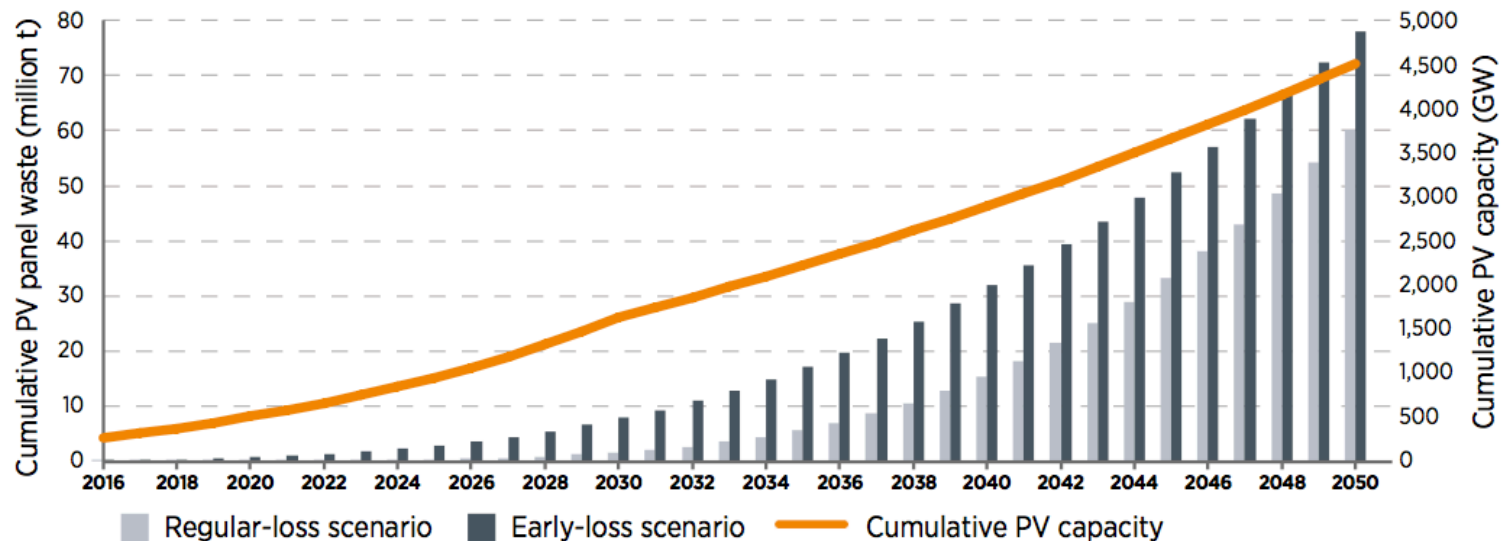
- No Federal rules except for general requirements such as RCRA:
 - Spent PV classified Hazardous Waste if they fail the EPA TCLP test (Ag, Cd, Cu, Pb)
- Several states have regulations that go beyond RCRA
 - California (CA) has additional threshold limits for hazardous materials classification
 - CA Senate Bill 489 classifies end-of-life PV panels as Universal Waste, (facilitating easy transport); pending EPA approval

Practices

- Sent to metal/electronics recyclers (Sun Power, Solar City, Sun Run, other?)
- Hazardous waste landfilling
- Regular land filling
- Refurbishing modules that are in good enough condition
- Stockpiling in warehouses
- In-house recycling (First Solar, Ohio)

Summary & Outlook

Estimated cumulative global waste volumes of end-of-life PV panels



Recycling Practices and Material Production

- Waste challenge is vast:
 - Recycling required for CdTe / CIGS to be a major player; still in early stages
 - Process to recycle Si could be very lucrative if invented (Si is 40% of module cost!)
 - Ag risk is borderline

Policy

- Pan-European WEEE framework successful so far
- USA: CA leading the way; no prospect for nationwide PV recycling; companies will only follow suit if required by policy (e.g. First Solar uses regulated Cd in their panels)

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FROM RAW MATERIALS
TO RECYCLING



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9/22/2017
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Critical Element Requirements for Large-Scale Deployment of Emerging Thin-Film Technologies

