# Future Challenges for PV Manufacturing at the Terawatt Level

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# The Context

# Geochronology

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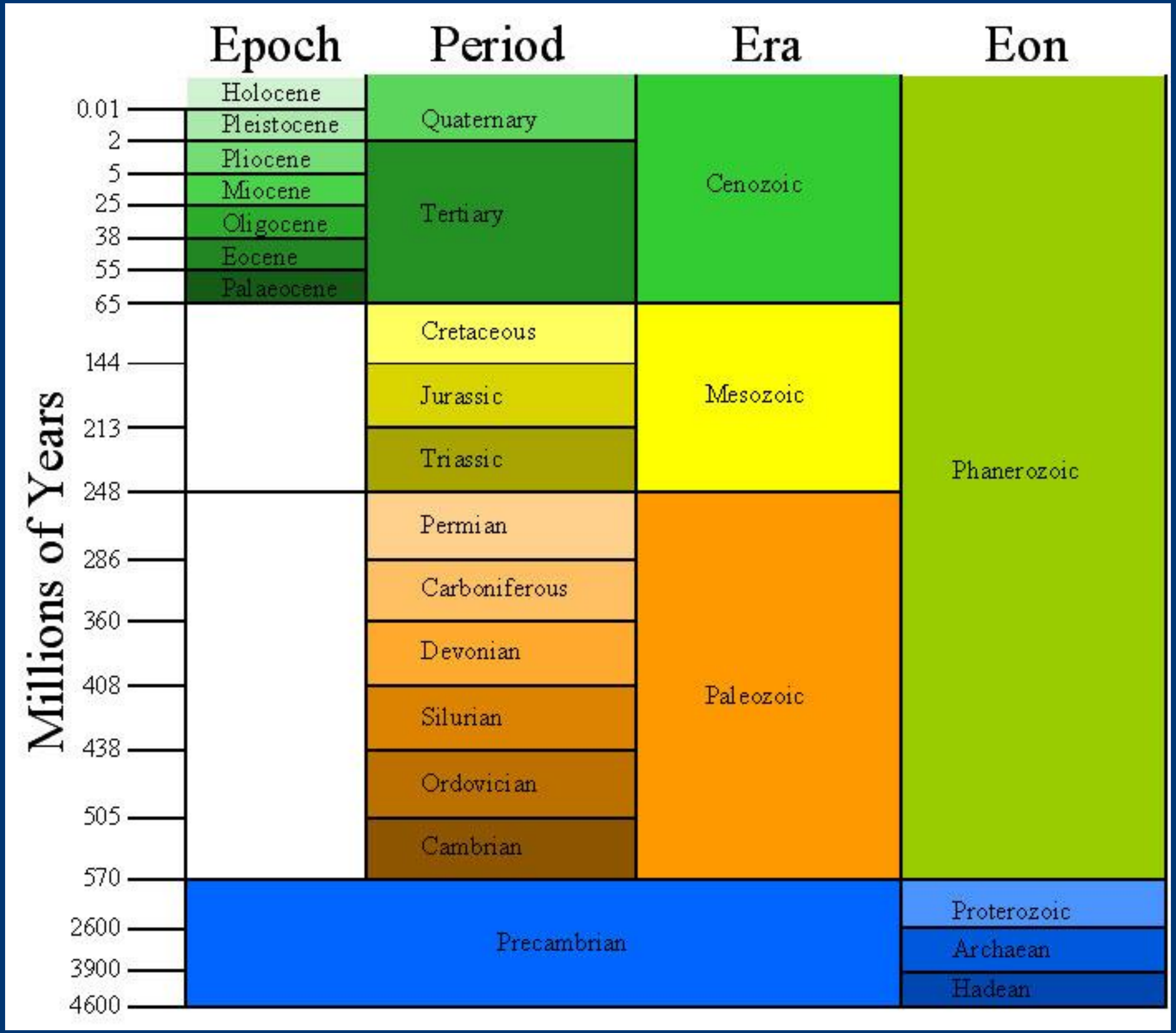
In Geology, the timescale is divided into:
Eon > Era > Period > Epoch > Age

Officially, we are currently in the Holocene Epoch of the Quaternary Period of the Cenozoic Era.

The Holocene* is the name given to the last 11,700 years of the Earth's history — the time since the end of the last major glacial epoch, or "ice age.“

* The word is formed from two Ancient Greek words. *Holos* (ὅλος) is the Greek word for "whole." "Cene" comes from the Greek word *kainos* (καινός), meaning "new." The concept is that this epoch is "entirely new."





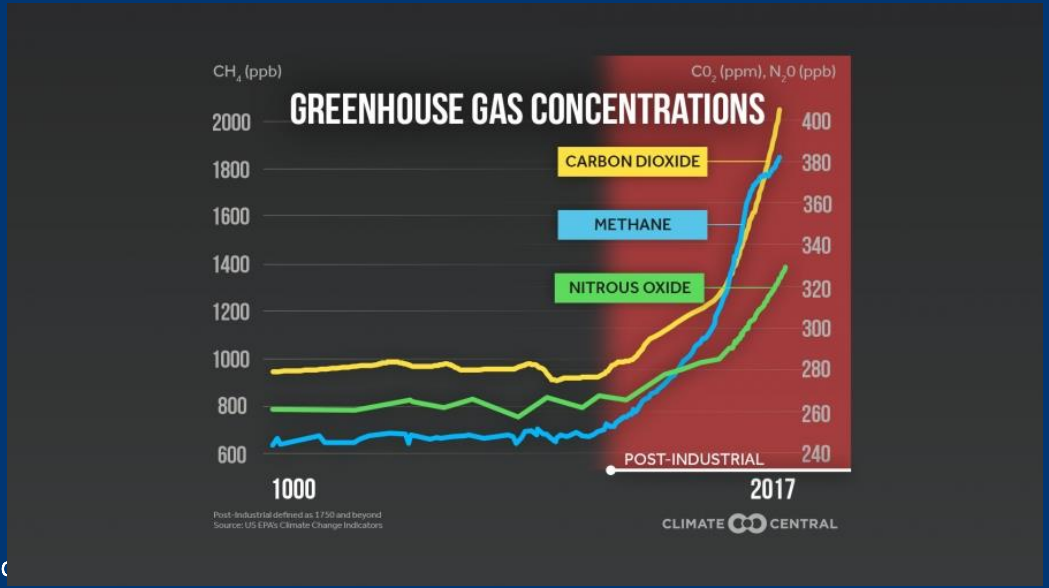
# Anthropocene*

/ˈanθrəpəˌsiːn/

*noun*

the current geological epoch, viewed as the period during which human activity has been the dominant influence on climate and the environment.

One proposal, based on atmospheric evidence, is to fix the start with the Industrial Revolution, ca. 1780, with the invention of the steam engine.





** Proposed since 2000, but not yet approved by the International Commission on Stratigraphy (ICS) nor the International Union of Geological Sciences (IUGS)*

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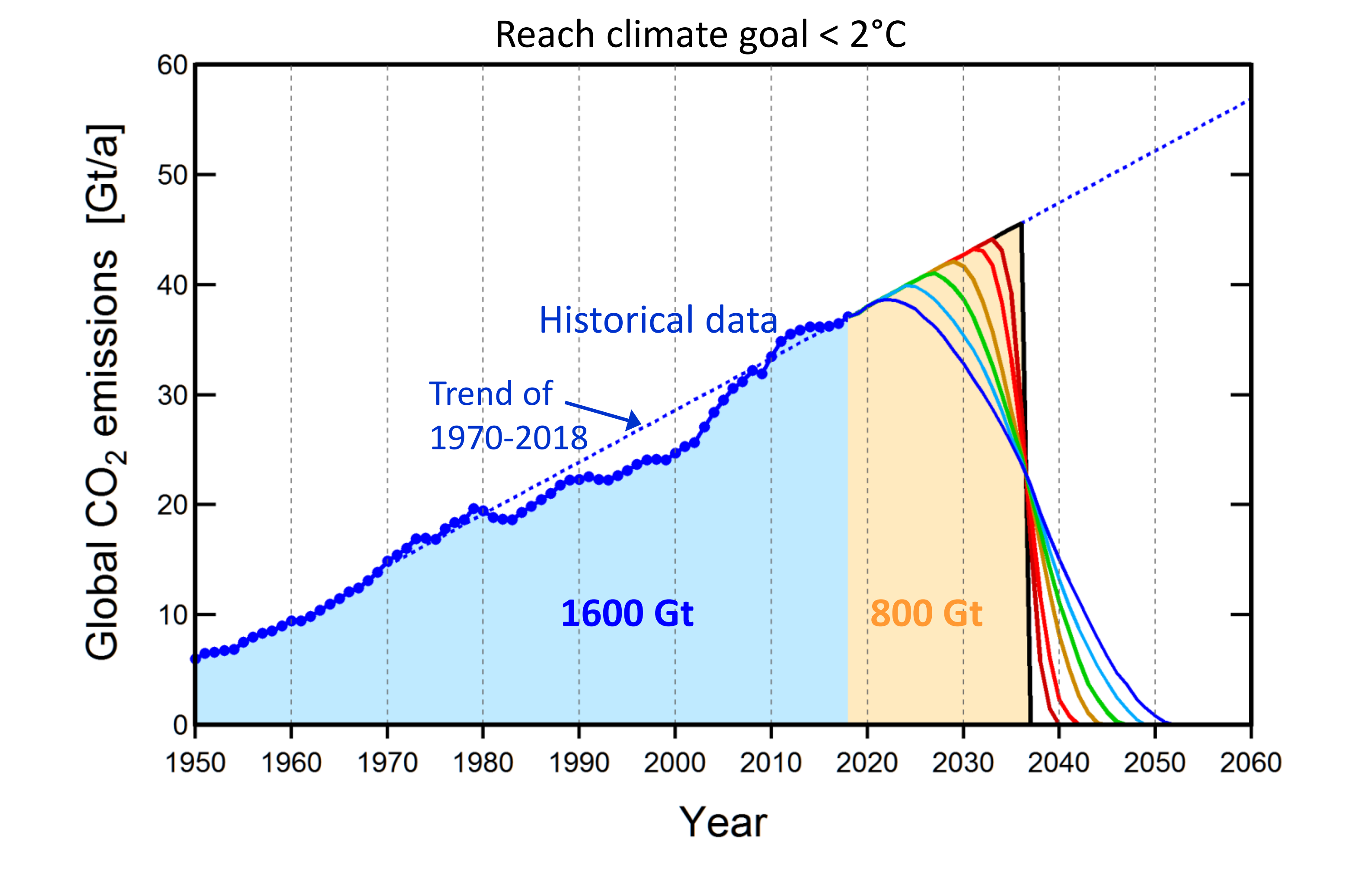
# To fulfill the Paris COP21 Agreement, we are allowed to generate only 800 GT* of $CO_2$, then zero. The next 10 years will be decisive.




While developing our new PV technologies, when making design, materials and process decisions, we cannot ignore anymore the context of Global Climate Change.

- **Can we develop quick enough?**
- **Is our technology sustainable?**
- **What is our embedded Energy, and $C0_2$?**

***Note: Only 400GT of $CO_2$ allowed if target is 1.5°C**

Historical data: U.S. Dep. of Energy (DOE)



[1] G. Luderer et al, Nature (climate change) 8, 262 (2018)

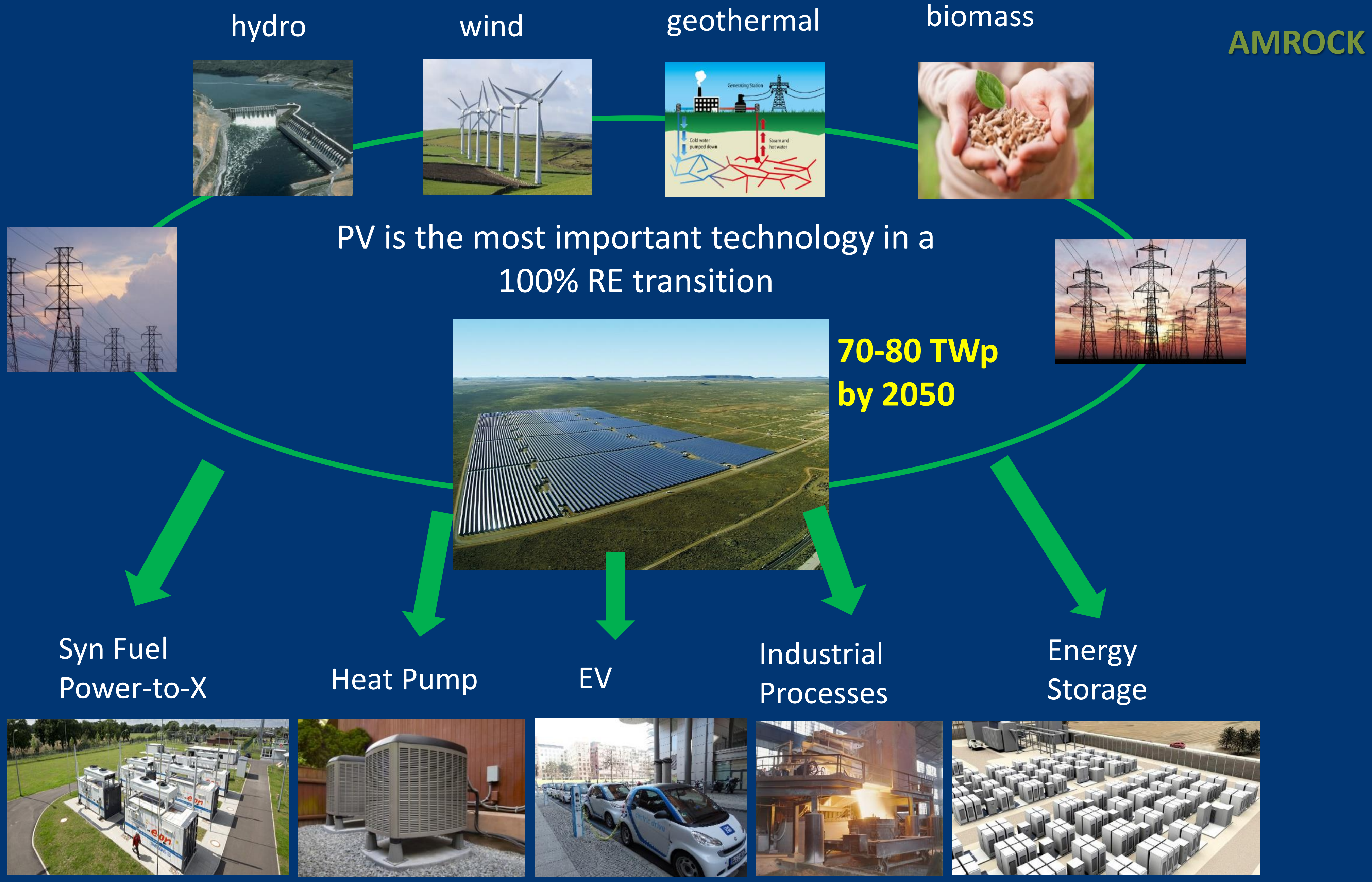
# If we don't, the consequences will be disastrous!

- The World is probably right now on a path of > +4°C by the end of the Century. We are approaching the point when it will be too late to act.
  - Increase of average Earth temperature
  - Destabilisation of Gulf Stream and Jet Stream
  - Extreme climate-related disasters (floods, wild fires, hurricanes, tornadoes)
  - Rise of sea water level
  - Ocean acidification
  - Desertification
- A +4°C World might only support 1 billion people, maybe half a billion !*

➢ The only goal is (almost) 100% Renewable Energy by 2050

➢ A complete transformation of the energy economy, just in one generation

*J. Rockström, director of the Potsdam Institute for Climate Impact Research


hydro
wind
geothermal
biomass
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PV is the most important technology in a 100% RE transition
70-80 TWp by 2050
Syn Fuel Power-to-X
Heat Pump
EV
Industrial Processes
Energy Storage

# The Silicon PV Roadmap

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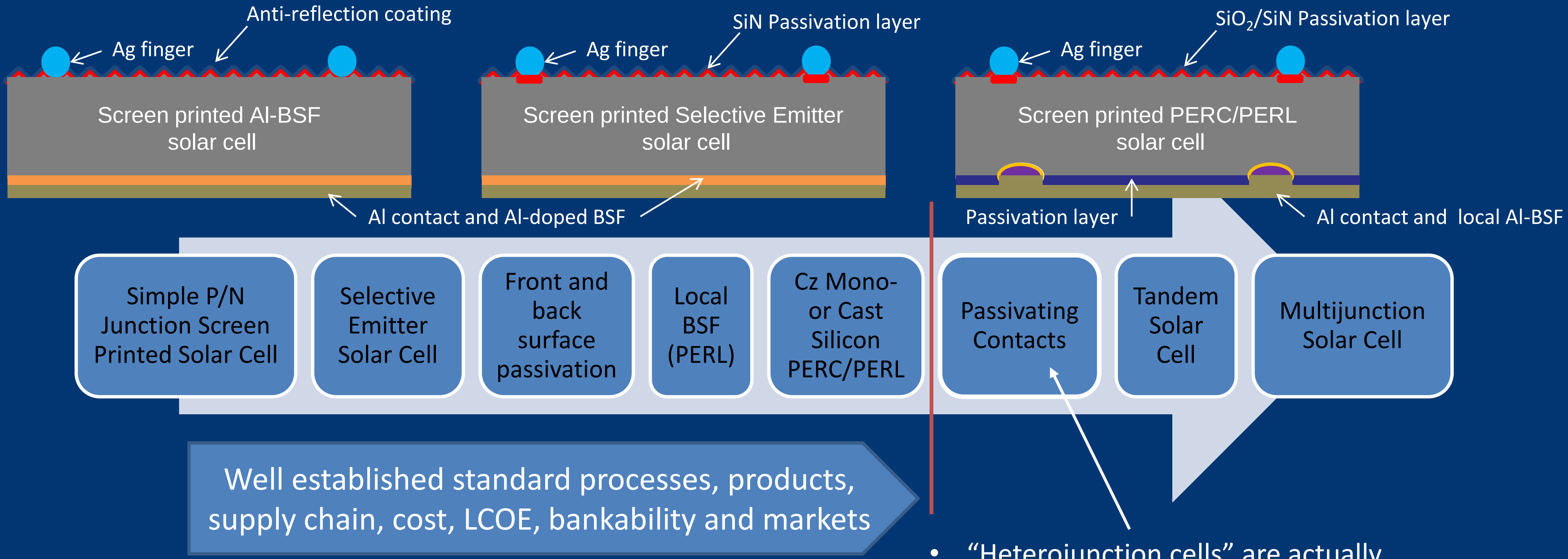
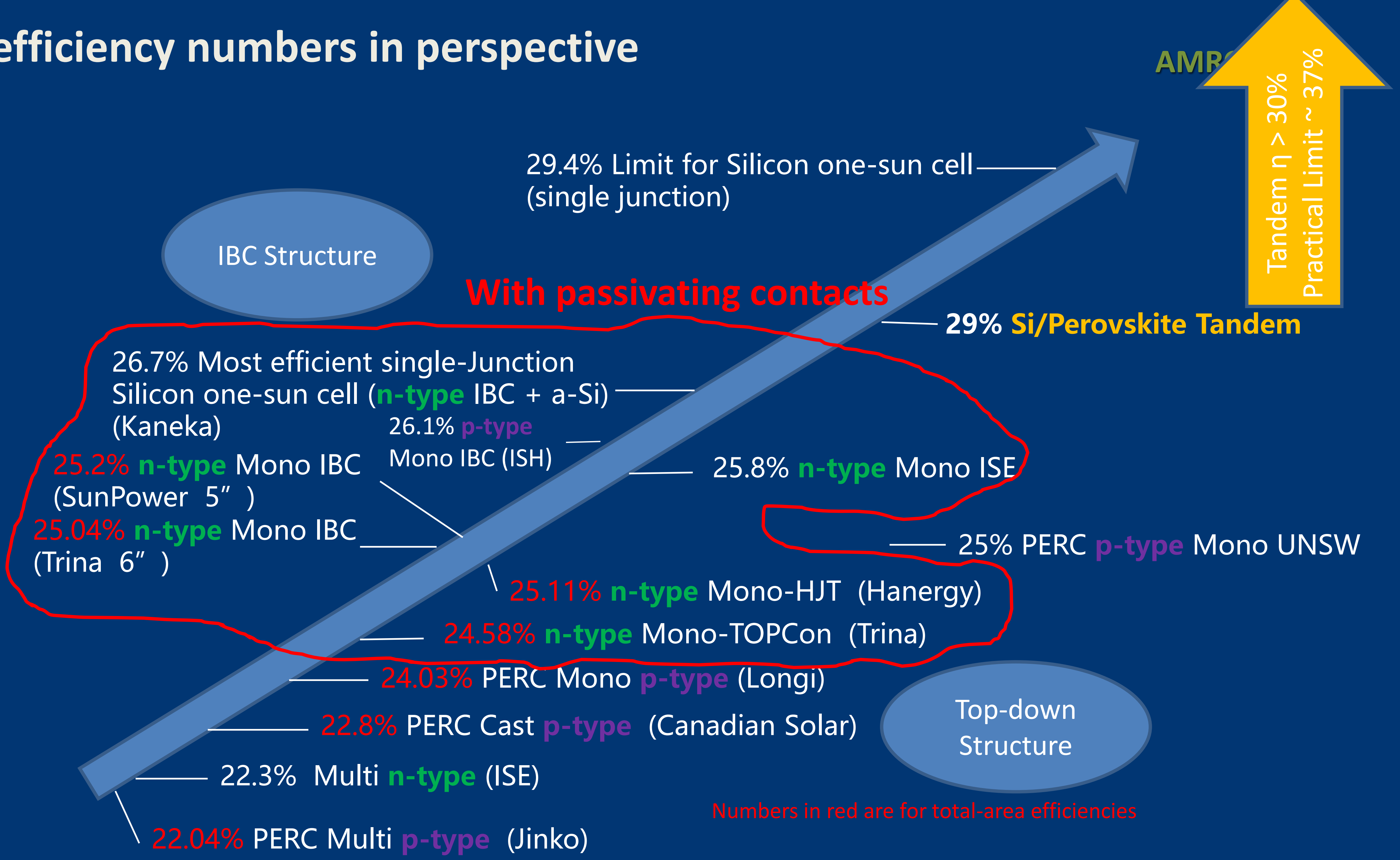
# The Si PV Technology roadmap is well known for many years …




- “Heterojunction cells” are actually “Passivating Contact” cells
- Other technologies: TOPCon, POLO, …

=> Challenges and opportunities in continuing developing the Si PV roadmap

# Putting efficiency numbers in perspective



# Putting efficiency numbers in perspective

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Tandem η > 30%
Practical Limit ~ 37%

### Results from Trend Analysis

- ✓ Any cell with Total-Area Efficiency > 22% and traditional Top-Bottom contacts is a PERC, TOPCon, HJ or multi-junction cell
- ✓ Any PERC cell with Total-Area Efficiency > 22.5% and traditional Top-Bottom contacts is a Mono - PERC cell
- ✓ Any cell with Total-Area Efficiency > 24% has Passivating Contacts (TOPCon, HJ, ..)
- ✓ Any cell with Total-Area Efficiency > 24.5% and traditional Cz substrate is made on a n-type wafer
- ✓ Any cell with Total-Area Efficiency > 25% has a rear junction

skite Tandem

type Mono UNSW

Structure

22.3% Multi n-type (ISE)

22.04% PERC Multi p-type (Jinko)

Numbers in red are for total-area efficiencies

# The PV Industry has “embraced” the road toward higher efficiency

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- ✓ Increase the productivity of manufacturing tools (kW/h)
- ✓ More Watt for every wafer/cell/module handled, transported, stored or installed: => increase efficiency and increase wafer/module size
- ✓ Reduce the cost (per Watt) of components (\$/pc. or \$/$m^2$): Wafers, glass, cable, connectors, Jbox, EVA, Backsheet, ….
- ✓ Reduce the labour cost (manufacturing, installation, maintenance)
- ✓ Driven by the need to increase the power density of PV in heavily populated areas (Singapore, HK, Japan, Belgium, Netherlands, Monaco, …)

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High-Efficiency has never been as important as it is today

# Our Achievements

# Cost of Generation CAPEX is not the main challenge

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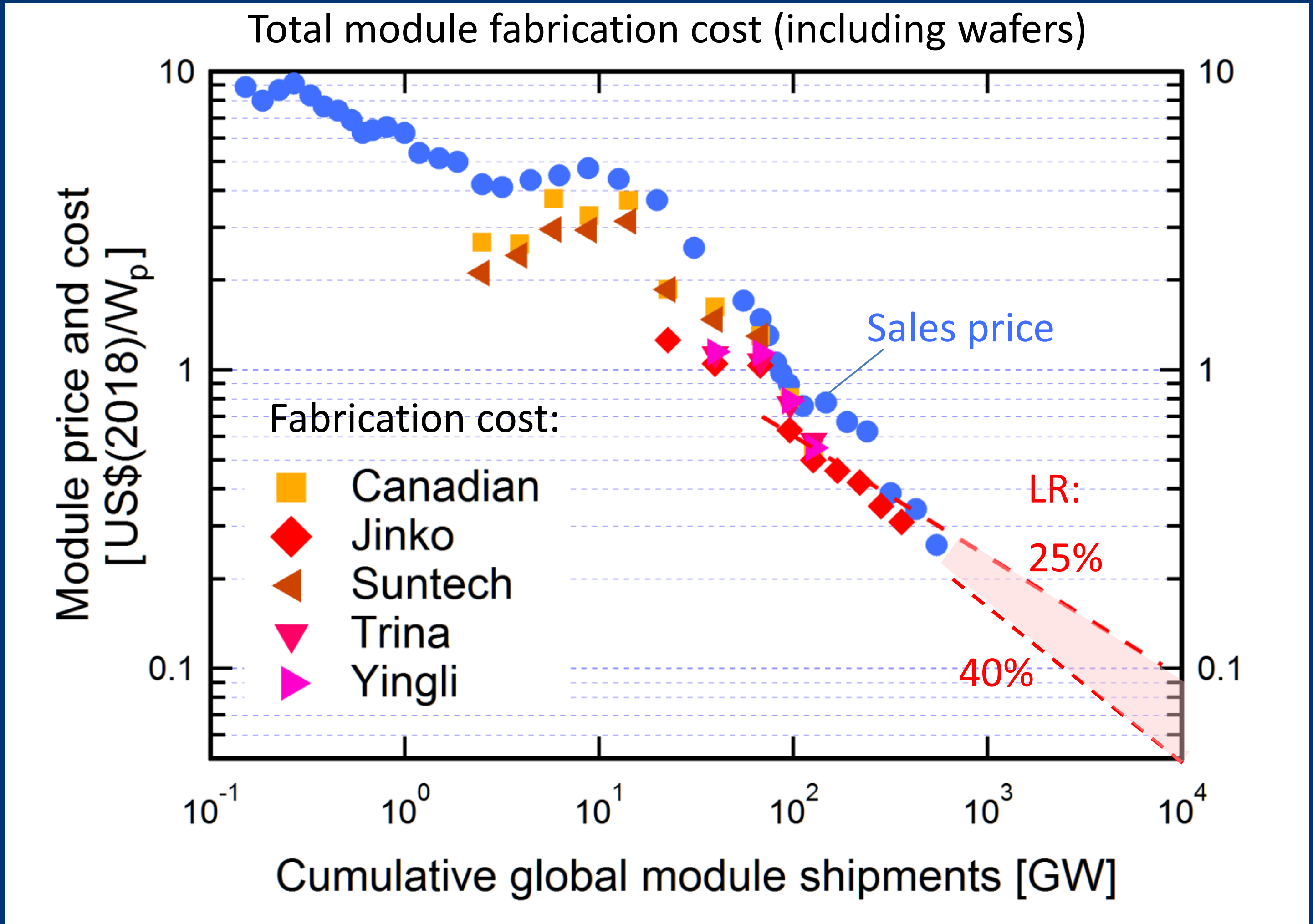


PV is already in many parts of the World the cheapest source of energy, even against the marginal cost of coal.



Graph courtesy of Dr Chen Yifeng (Trina Solar)

# Module efficiency is not the main challenge

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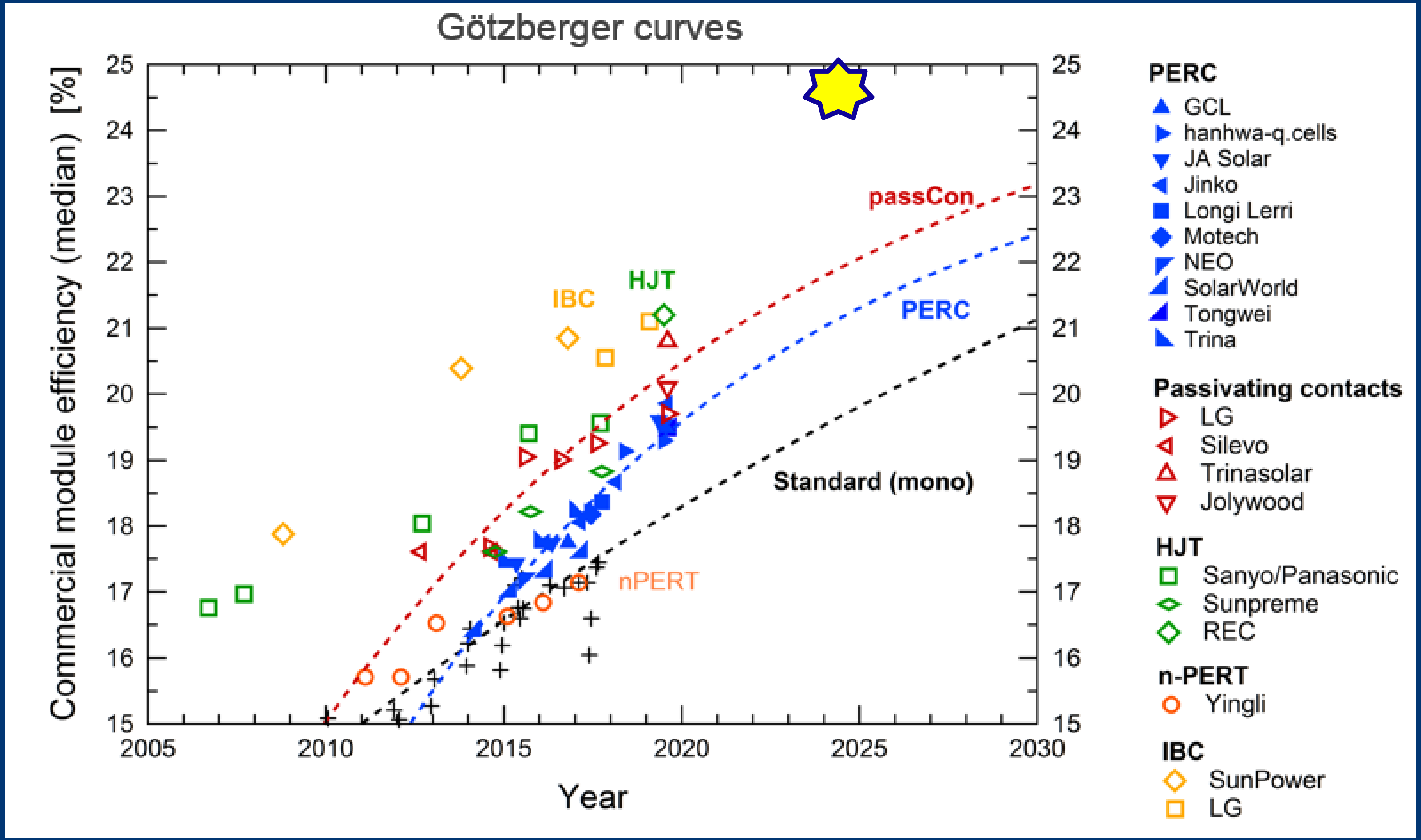


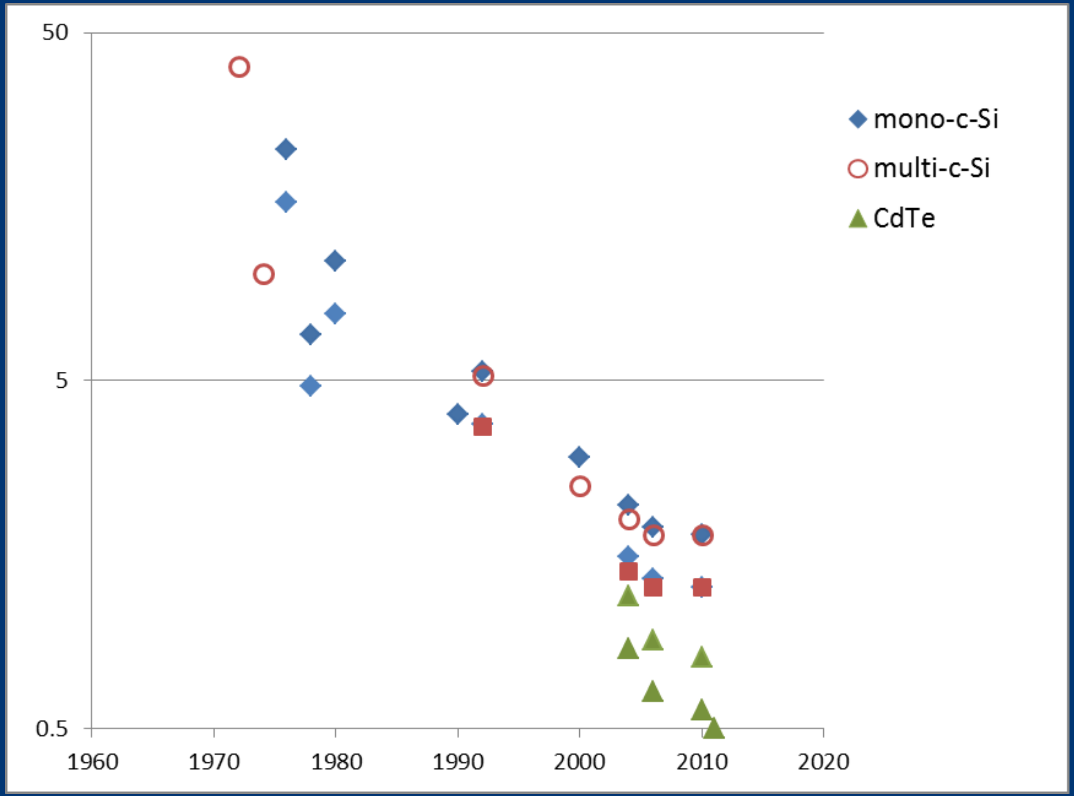

… Silicon-based Tandem cells with efficiency > 26% will soon be commercially available

Y. Chen et al, IEEE J PV 8, 1531 (2018), and updated data from the PV industry
Graph courtesy of Dr Pietro Altermatt, Dr Chen Yifeng

# ✓ Energy Sustainability

Energy Pay-Back Time (EPBT)

$$Growth \leq \frac{1}{EPBT(in\_years)}$$




V. Fthenakis, in book Photovoltaic Solar Energy from Fundamentals to Applications

# ✓ Improved Productivity

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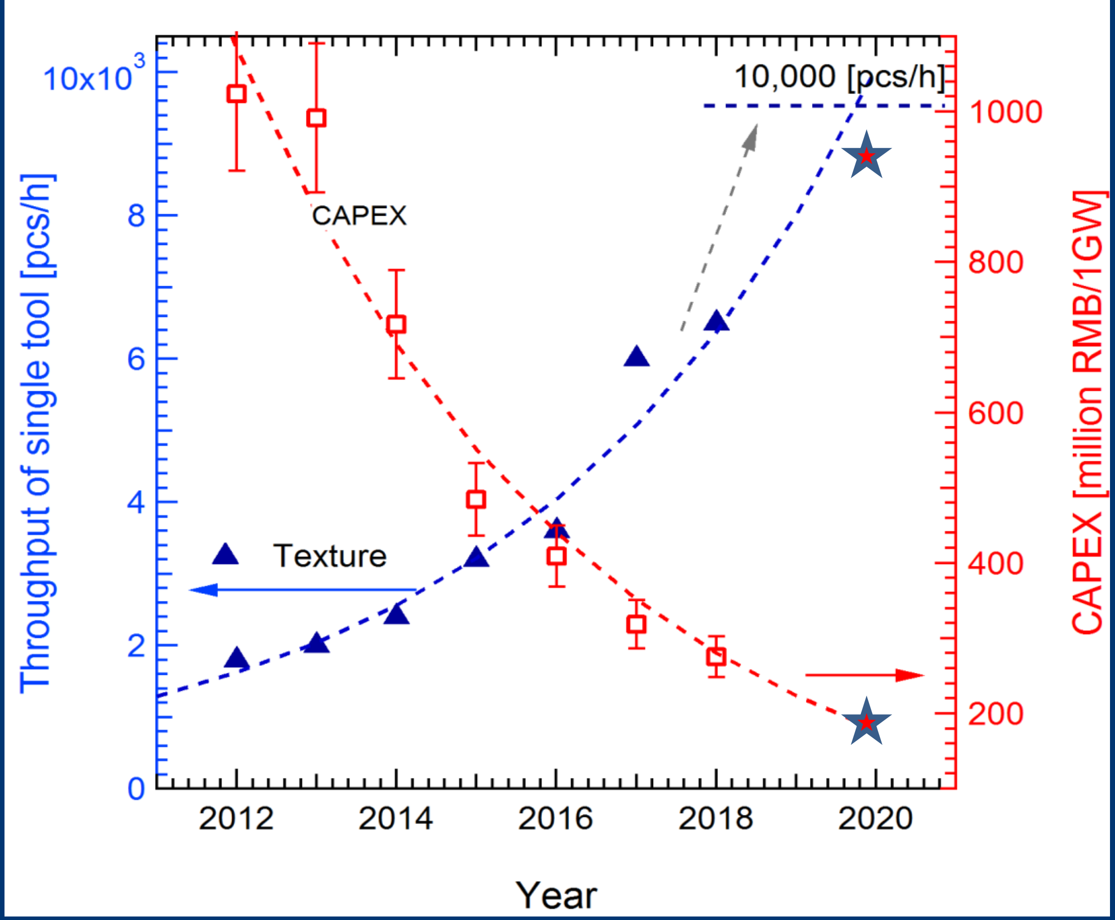
## Typical Facts of a PV Manufacturing Site

- ❖**Typical Fab Unit size ~ 5 to 10 GW**
- ❖**Typical Co. Size ~ 20 GW (doubling every 3 years)**
  - ❖ **4** billion Wafers p.a. (**600k** Wafers start per hour)
  - ❖ **70** million Modules p.a. (**2** modules out per sec)
- ❖**Growth: > 30% p.a.**
- ❖**Cost Reduction: -12% p.a.**
- ❖**Direct Labour < 1 DL/MW**
- ❖**Typ. Takt Time ~ 0.5 to 1 sec**




Graph courtesy of Dr Chen YiFeng, Trina Solar

Typical throughput of a Texture tool and Capex of PERC cell line

# Manufacturing CAPEX is not the main challenge (at least for PERC)

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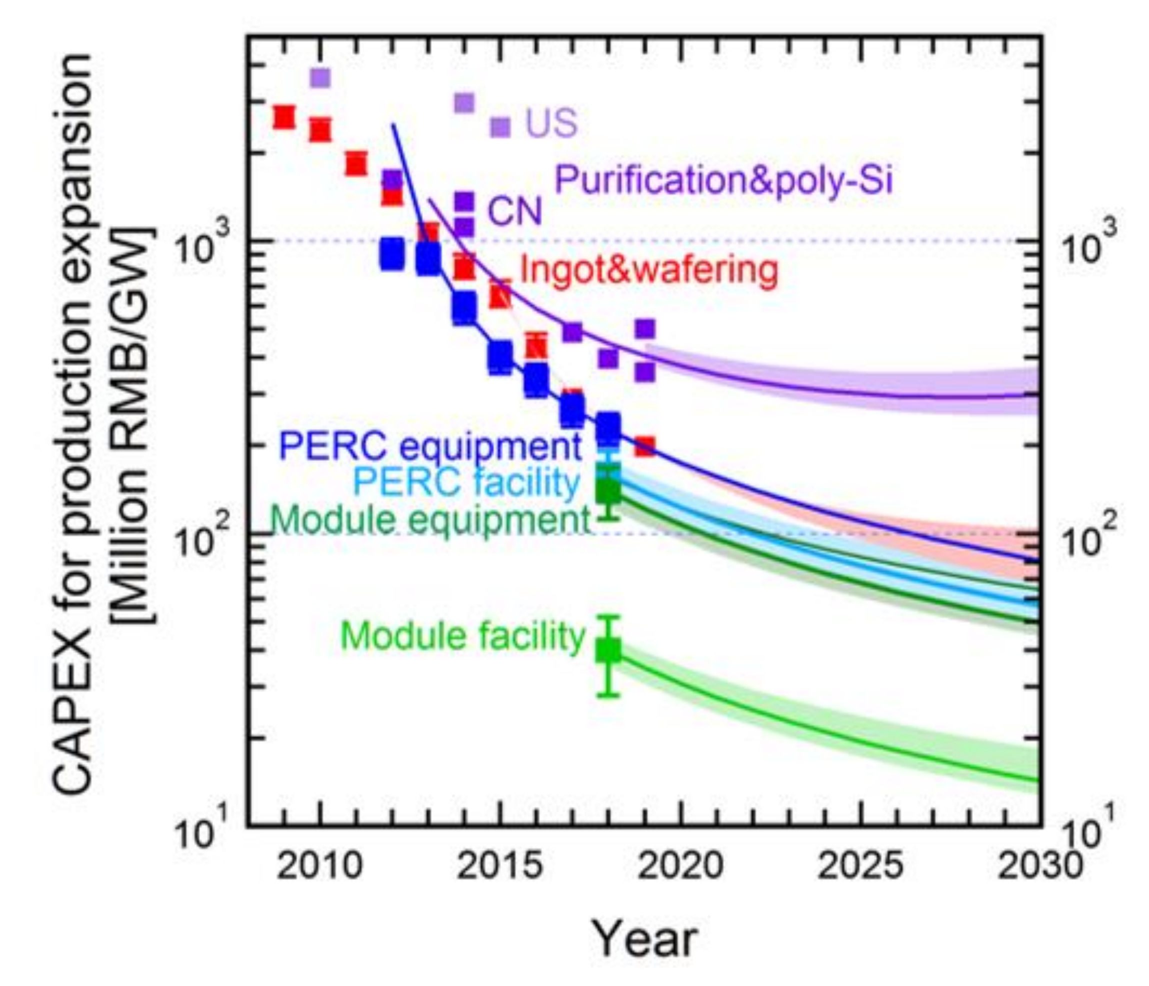


Already reduced by more than one order of magnitude in the last 10 years

| Technology | Cell Production Line* (US$/GW) with 210mm wafers |
|---|---|
| Mono PERC | 25.9 to 27.5 million |
| N-type TOPCon | 29 to 33.6 million |
| N-type HJ | 70.2 to 76.3 million |

The PV Industry is capable to grow PERC capacity even with low Gross Margin

Y. Chen et al, IEEE JPV 8, 1531 (2018)



* New production line in 2021, tools supplied in China

# Our Challenges

# If we do not grow fast enough right now, …

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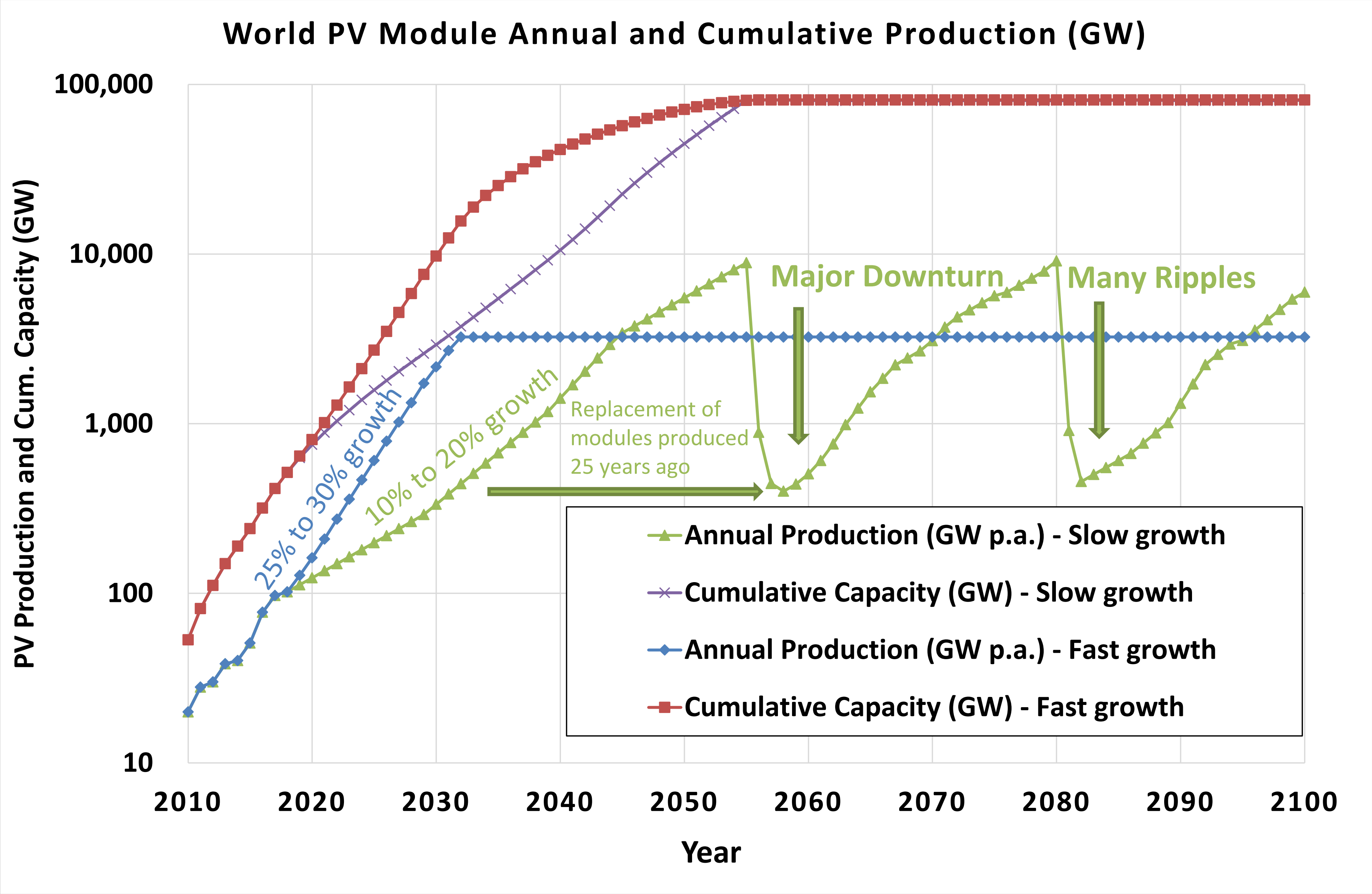


…. the PV industry will not survive such major downturns in the 2050’s

# If we do not grow fast enough right now, …

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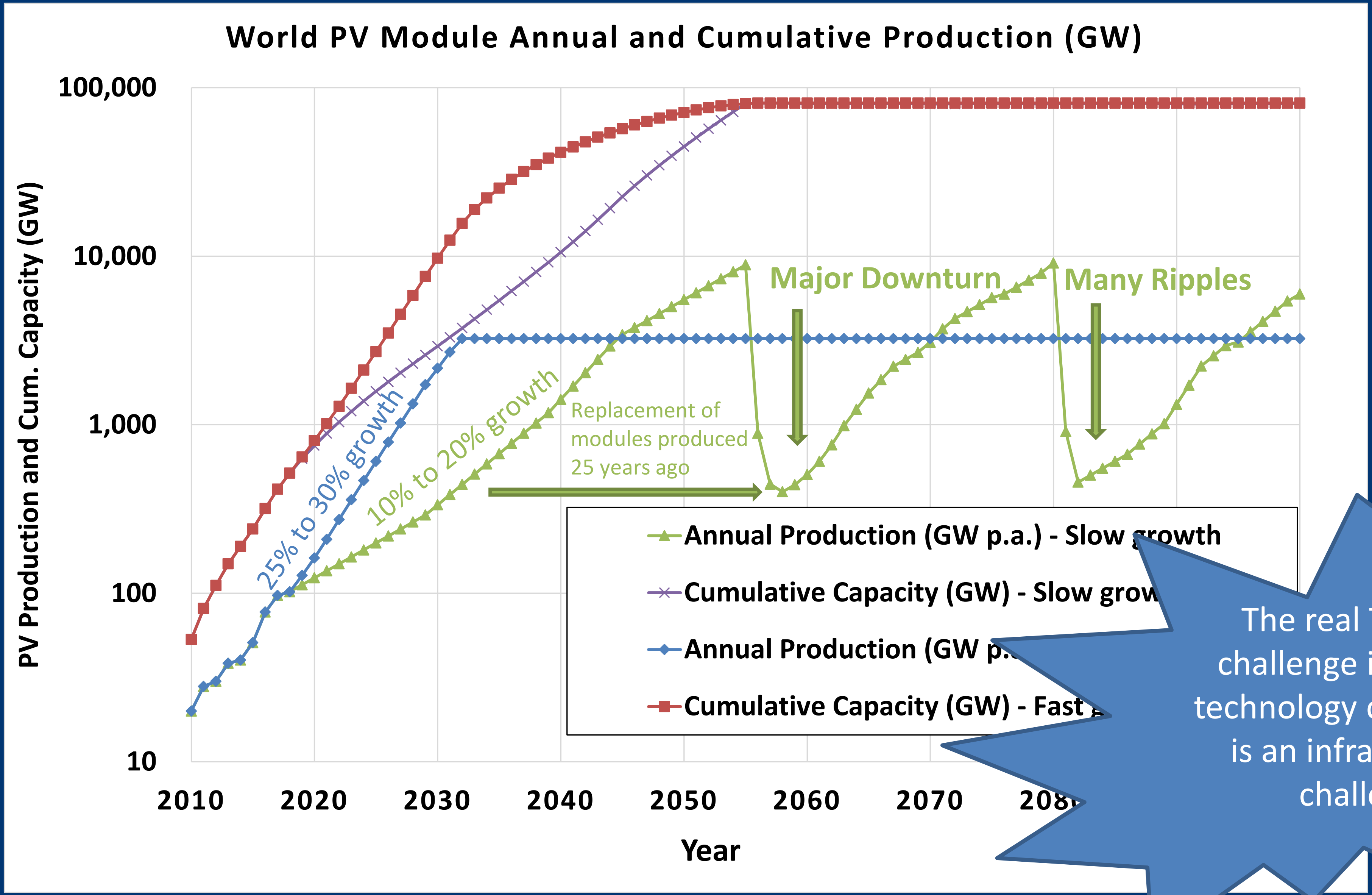


…. the PV industry will not survive such major downturns in the 2050's

The real Terawatt challenge is not a PV technology challenge, it is an infrastructure challenge

# There are many ways to look at Sustainability

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- **Energy**: How many kWh consumed per kWp installed?
  - To manufacture PV modules, inverters, BOS
  - To transport, to install
  - Energy Pay Back Time (EPBT)
  - How fast can we grow this industry? (energy, infrastructure, land)
- **$CO_2$ emissions**: How many kg of $CO_2$ equivalent per PV module? Per kWp? Per kWh?
- Water and chemical **consumption**, solid waste, gas and liquid effluents, pollution
- **Material usage**: availability, scarcity, risk of price increase, speculation
- **Recycling** and Capturing valuable material
- **Financial** sustainability of PV manufacturers
  - Generate enough earning to grow, to build the next production lines
- What is impacting the sustainability of PV systems?
  - Reliability, performance degradation, system lifetime (often depending on climate)
  - Efficiency, PR, Annual irradiance, orientation, partial shading (also impacts reliability)
  - Bifacial or not, tracking or not

# Life Cycle Assessment of PV Systems

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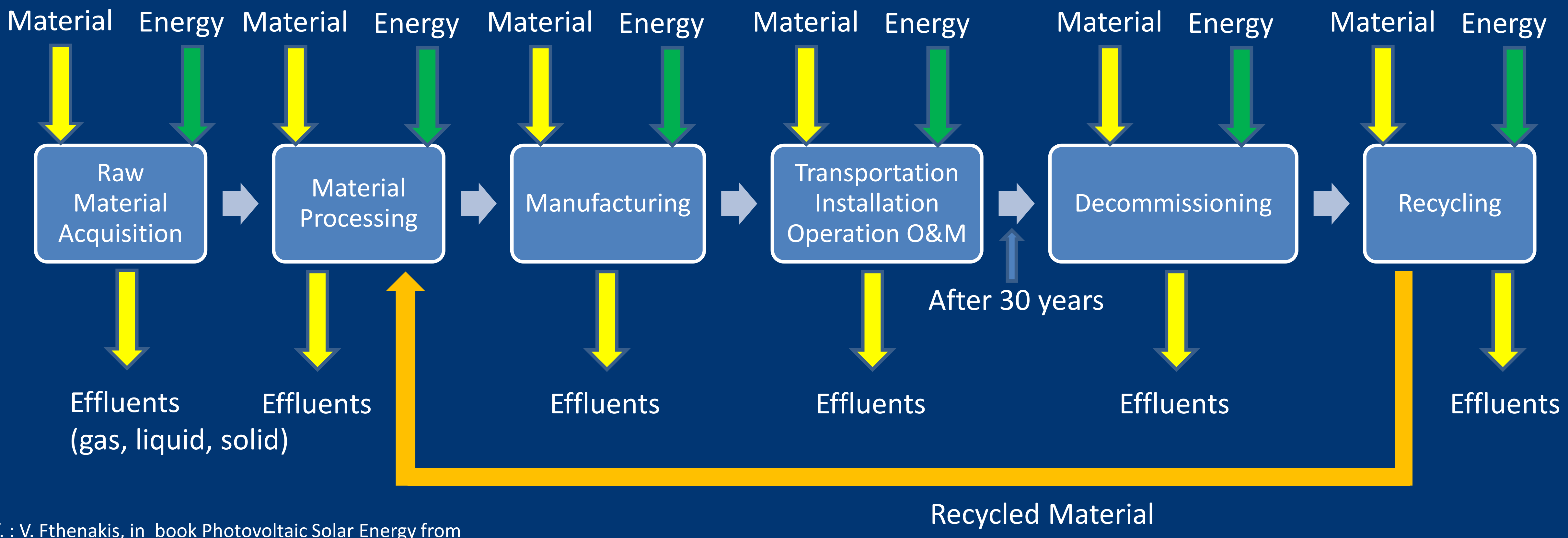
Cumulative (Primary) Energy Demand : $CED = E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL}$

Energy Payback Time : $EPBT = CED / ((E_{agen} / \eta_G) - E_{O\&M})$

Energy Return on Investment : EROI = System Lifetime / EPBT




Ref. : V. Fthenakis, in book Photovoltaic Solar Energy from Fundamentals to Applications, Wiley 2017

# Energy and $CO_2$ Embedded in a 1 TW PV Modules

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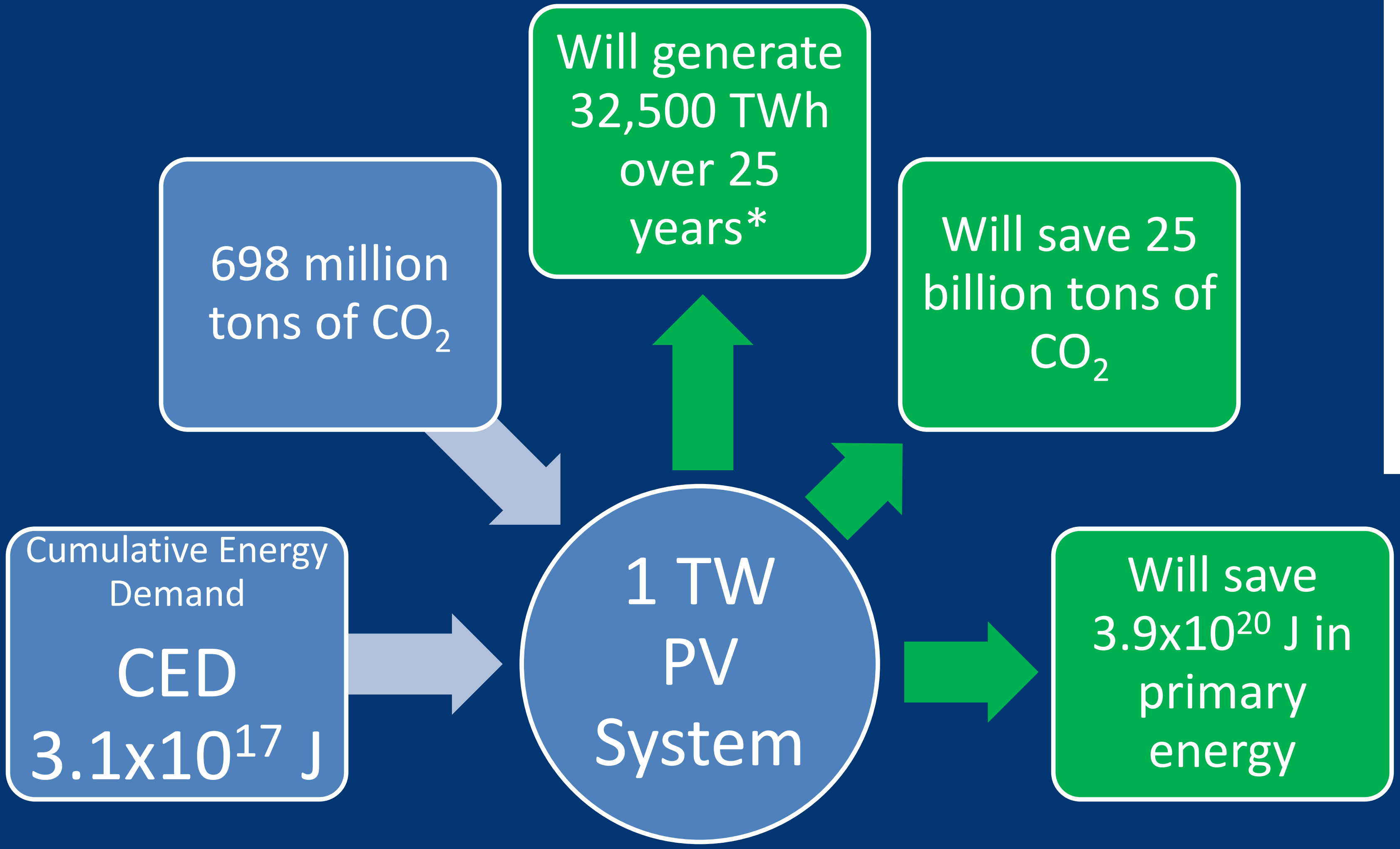


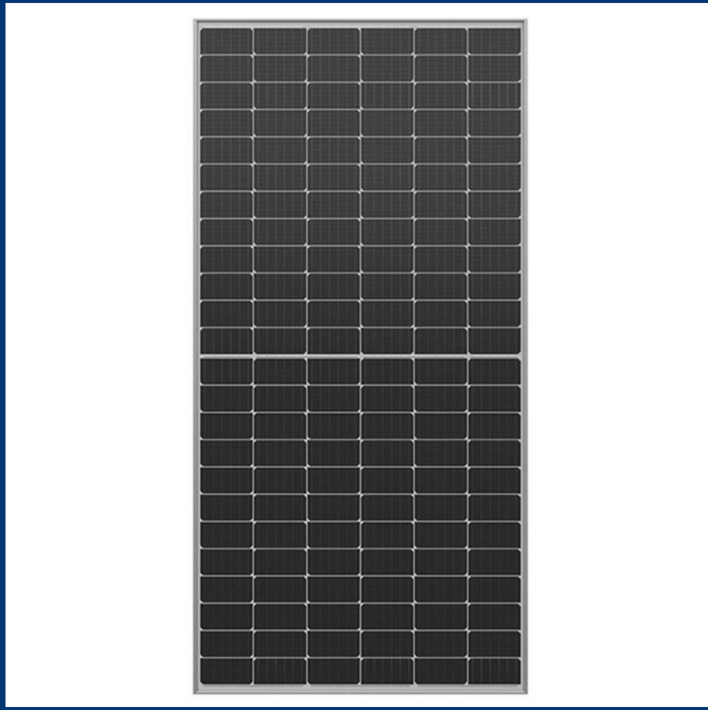

One 400W PV panel (~US$100) will produce the same amount of electricity as 6.9 tons of coal (~US$280)

* Average lifetime of PV power plants is actually 32.5 years

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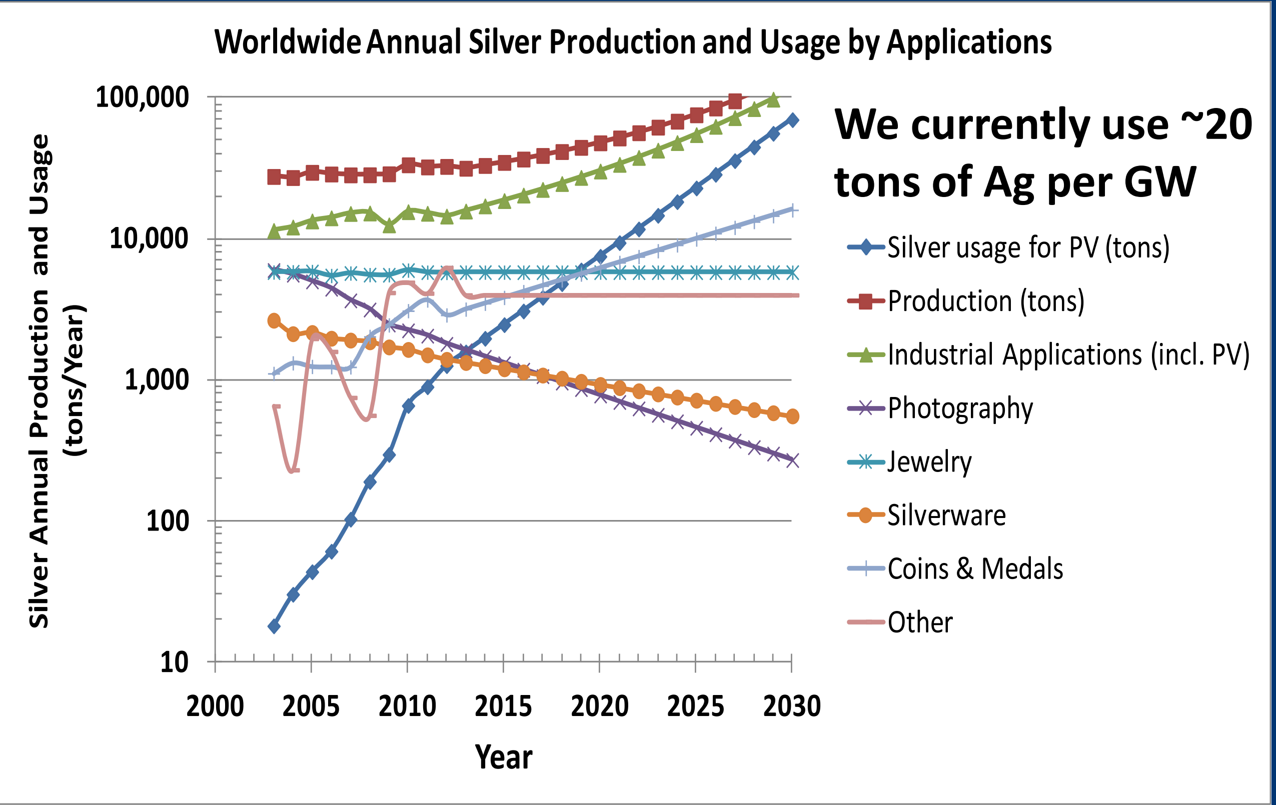
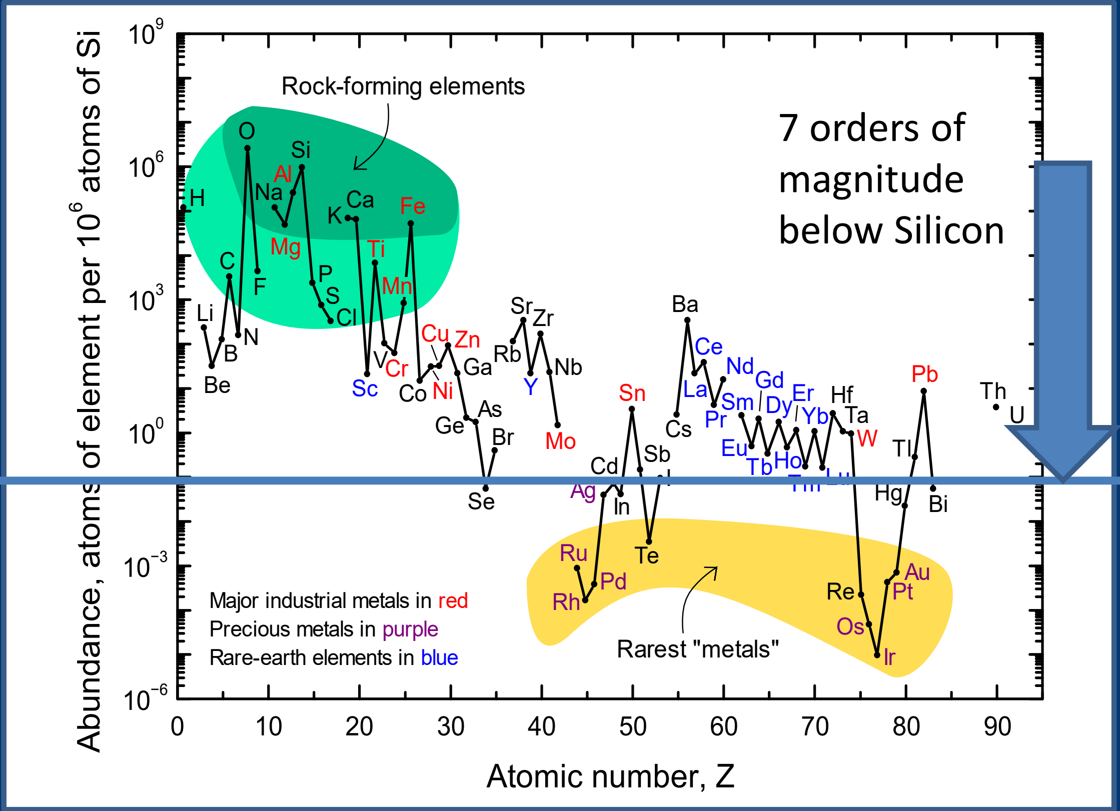
# The Silver Issue

# Material Sustainability




World Production of Ag ~ 30,000 Tons p.a. Recycling does not become significant until 2050.

At 3TW p.a. (~2040) , the usage of Ag must be < 5mg/W (currently ~ 20mg/W)

# Embedded in a 1 TW PV System (Mono PERC, fixed tilt)

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94% of today's worldwide production

29,000 tons of Ag

14% of today's worldwide production

42 million tons of glass

32% of today's worldwide production (of MG Silicon)

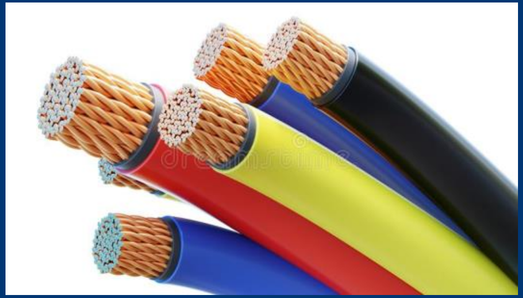
2.3 million tons of silicon

19% of today's worldwide production

12.5 million tons of Al

35% of today's worldwide production

7 million tons of Cu



3% of today's worldwide production

56 million tons of steel

1 TW PV System

1% of today's worldwide production

47 million tons of concrete

# Material Sustainability Ag, In, Bi

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## Silver

| Technology | Current "Best in class" Ag usage | Reasons for difference compared to PERC |
| --- | --- | --- |
| P-type PERC | 15.4 mg/W | |
| N-type TOPCon | 23.5 mg/W | Requires Ag contacts on both sides |
| N-type HJ | 31.5 mg/W | Requires low-temperature Ag paste on both sides |

At a Multi-Terawatt level, the consumption of Ag must be reduced to less than 5 mg/W to be sustainable.

## Indium and Bismuth

| Technology | Current typical In usage |
| --- | --- |
| P-type PERC | N/A |
| N-type TOPCon | N/A |
| N-type HJ | In 15 mg/W (15 tons/GW) |
| Low-temperature solder MBB or SmartWire | Bi 18 mg/W (18 tons/GW) (Bi-Sn solder coating on wires) |

Considering the worldwide annual supply of In (760 tons/year) and Bi (~8,000 tons/year), In or Bi cannot be considered as a sustainable material for PV technology at the Multi-Terawatt level!

# Recycling of PV Systems and Modules

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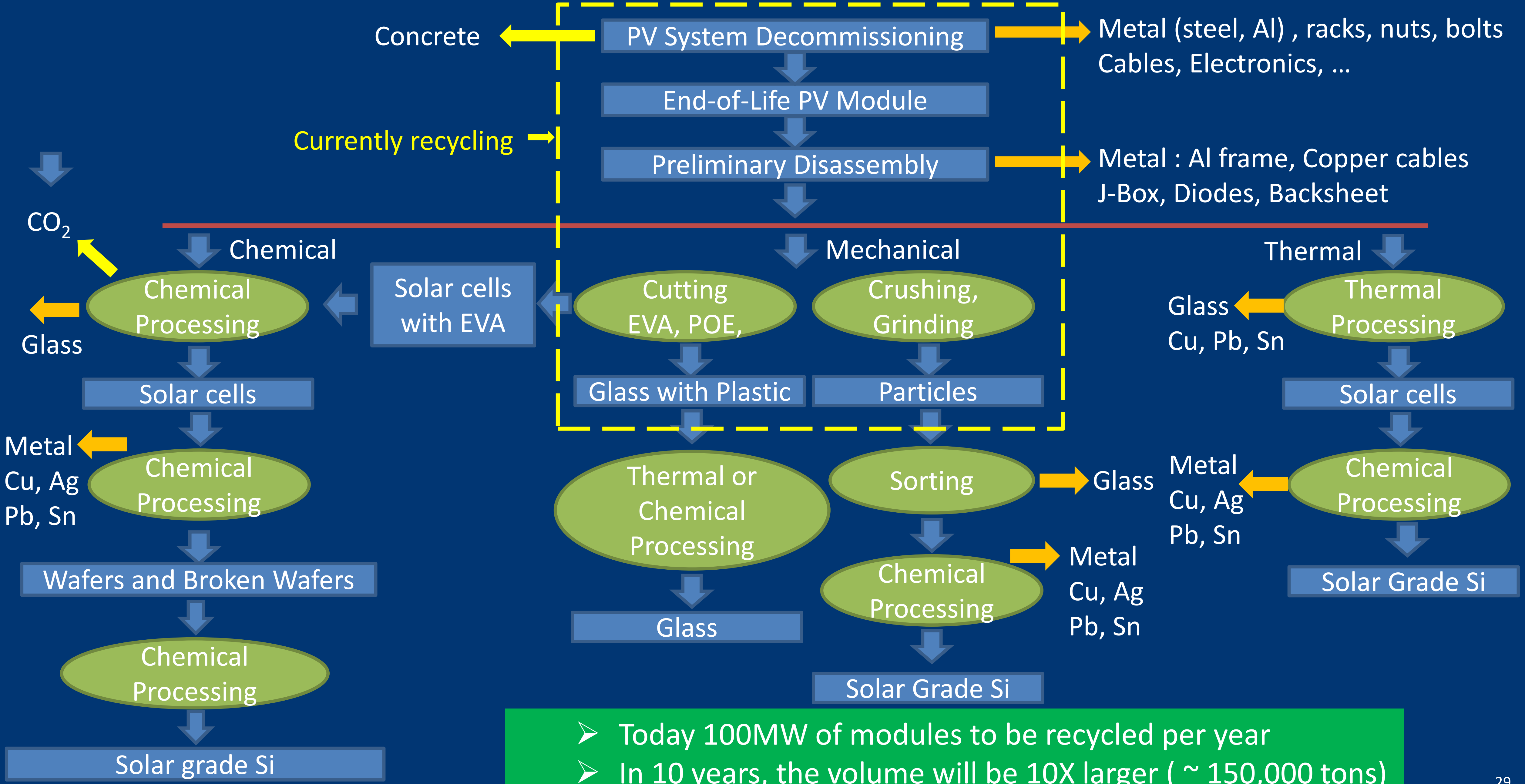


- Today 100MW of modules to be recycled per year
- In 10 years, the volume will be 10X larger ( ~ 150,000 tons)

# Recycling of PV Systems and Modules

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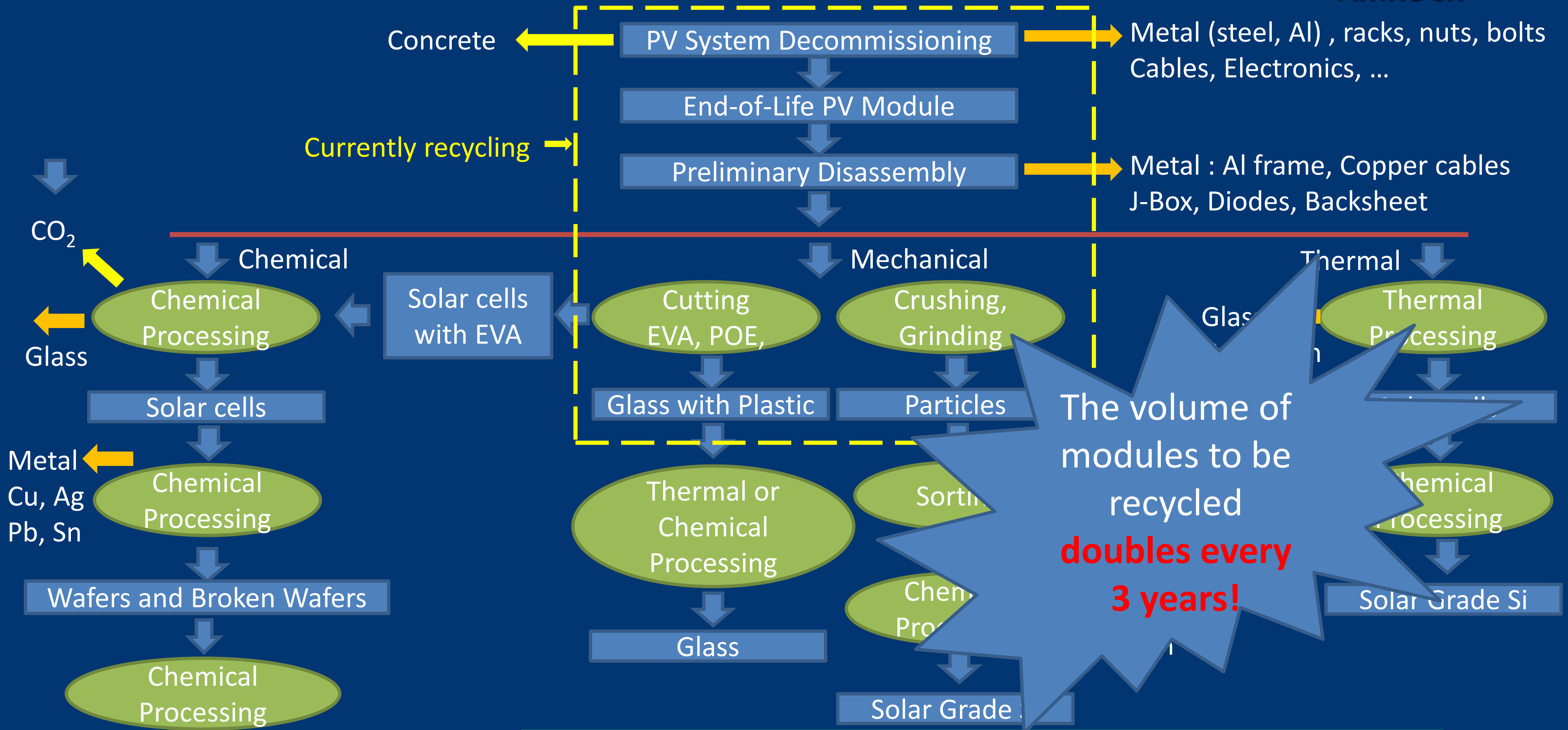


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# Conclusions

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1. Urgency in transforming the Energy Economy to 100% Renewable Energy
   - Missing this objective will have disastrous consequences
   - PV will play a central role
   - We need to keep a fast pace: 25% to 30% growth until 2030
   - Annual Production to stabilize to ~ 3TW p.a. by 2035
   - Cumulative capacity to reach 70-80TW by 2050 (and possibly > 100TW by 2100)

2. Efficiency, Cost of Manufacturing, cost of CAPEX (at least for PERC), EPBT are not an issue

3. Sustainability: At the Multi-TeraWatt level, the consumption of Ag must be reduced < 5mg/W
   - Significant Ag issue with Bifacial, TOPCon and SHJ
   - Significant In issue with SHJ. Not sustainable for PV production at TW level
   - Significant Bi issue with SmartWire or Bi-coated MBB. Not sustainable for PV production at TW level

4. Recycling: Volume doubles every 3 years! Mut be improved to recycle valuable and rare material
   - Considering the 25 year lifetime: First Reduce, then recycle and reuse!

5. The Terawatt challenge is an infrastructure challenge (energy storage, interconnection, Power-to-X)

# Thank You

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