Third Generation Solar Cells DSSC

Prof. S. Sivaram
Prof. S. Sengupta
Amitava Das

CH5106-16 AD

Silicon-based single Junction PV modules make up for 95% of the PV Market. The most efficient solar cell currently available has an efficiency of 26.8 %, while the theoretical limit, called the **Shockley-Queisser limit**, is about 32 %. The nature of the bandgap (direct - indirect) influences the number of absorbed photons. The indirect bandgap of silicon is a strong limitation to the ideal efficiency of these solar cells. Three types of losses limit the efficiency of a solar cell:

IPCE (Incident Photon-to-Current Efficiency) — also known as External Quantum Efficiency (EQE) — is a key parameter in photovoltaic and photoelectrochemical device characterisation.

Definition

$$\mathrm{IPCE}(\lambda) = \frac{\textit{Number of electrons collected}}{\textit{Number of incident photons at wavelength } \lambda}$$

or in measurable terms,

$$\mathrm{IPCE}(\lambda) = \frac{1240 \times J_{ph}(\lambda)}{\lambda \times P_{in}(\lambda)}$$

where:

- $J_{ph}(\lambda)$:photocurrent density (A/m²) at wavelength λ
- $P_{in}(\lambda)$:incident light power density (W/m²)
- λ: wavelength (nm)
- 1240 is a conversion constant (from hc/e)

Derivation

Photon energy:

$$E = \frac{hc}{\lambda}$$

where:

•$h = 6.626 \times 10^{-34}\ J$ (Planck's constant)

•$c = 3.00 \times 10^{8}\ m/s$ (speed of light)

•λ = wavelength in meters

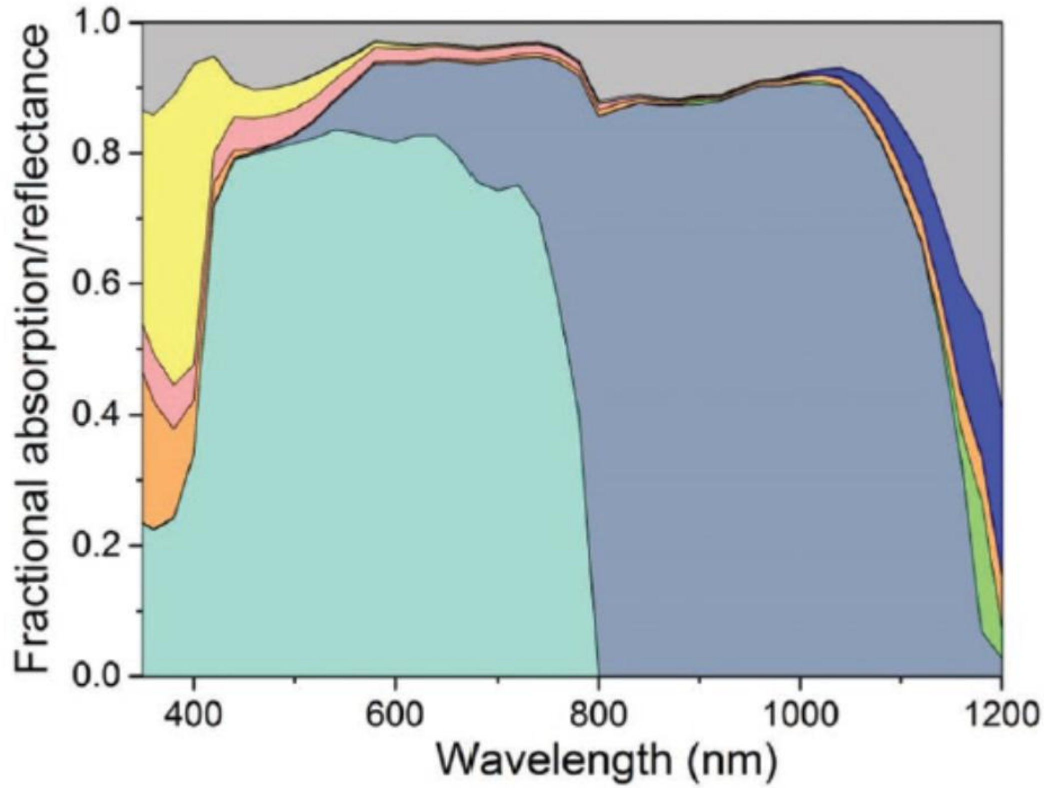
To express E in **eV** and λ in **nm**:

$$E(eV) = \frac{hc}{e\lambda} = \frac{1240}{\lambda(nm)}$$

Here,

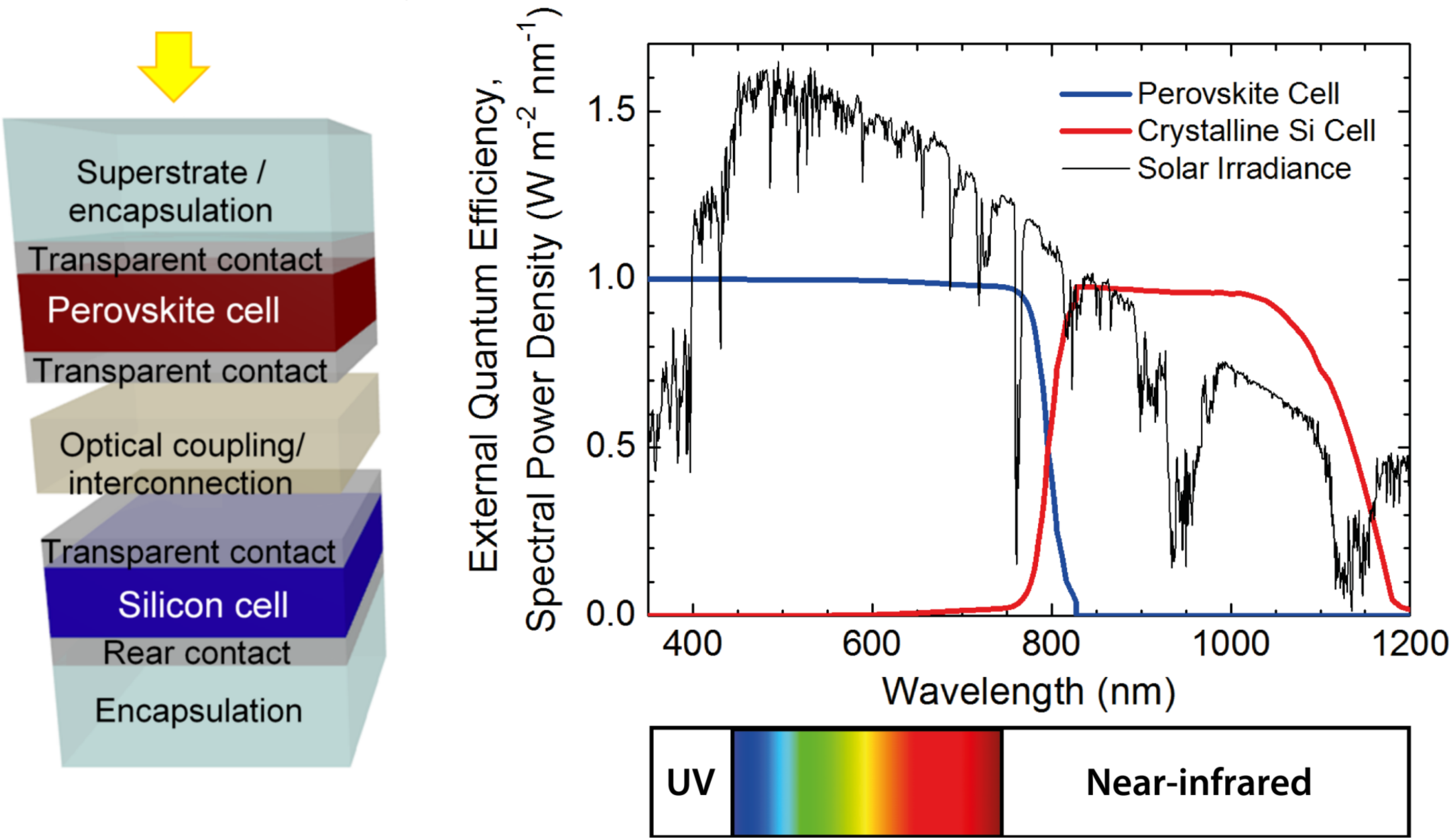
$$\frac{hc}{e} = 1.2398 \times 10^{-6}\ eV = 1240\ eV$$

The development of high-efficient silicon solar cells is, however, approaching its theoretical efficiency limit of 29.4%.



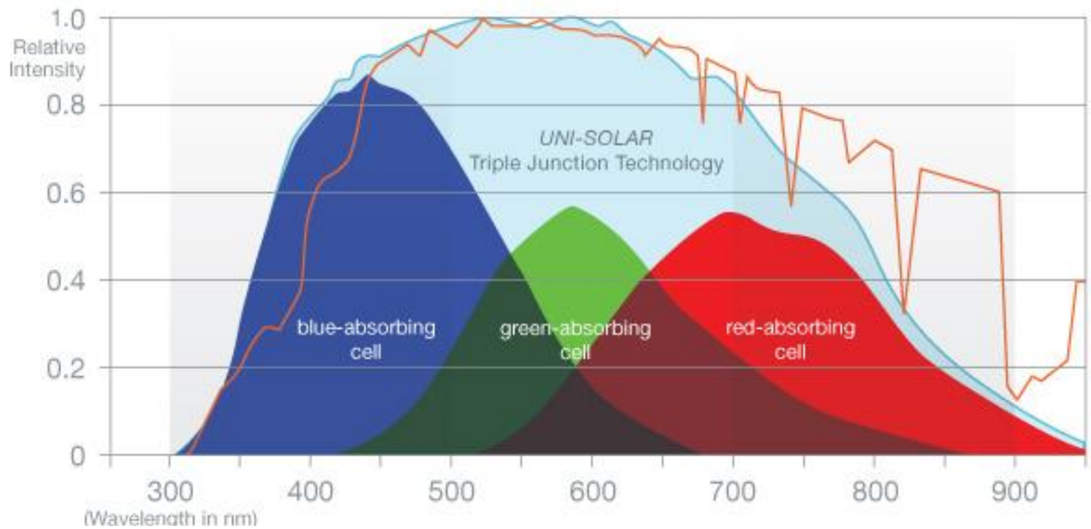
As a next step, the concept of silicon-based tandem solar cells is promising to break this limit. Stacking two solar cells on top of each other, the top cell — with a high band gap (metal halide perovskite having ABX_3 crystal structure) material — utilizes high energy photons while the silicon bottom cell utilizes low energy photons. Perovskite have a tunable band gap — the parameter that determines which part of the solar spectrum is utilized.

Adv. Sci. News, by Patricia Schulze | May 26, 2020

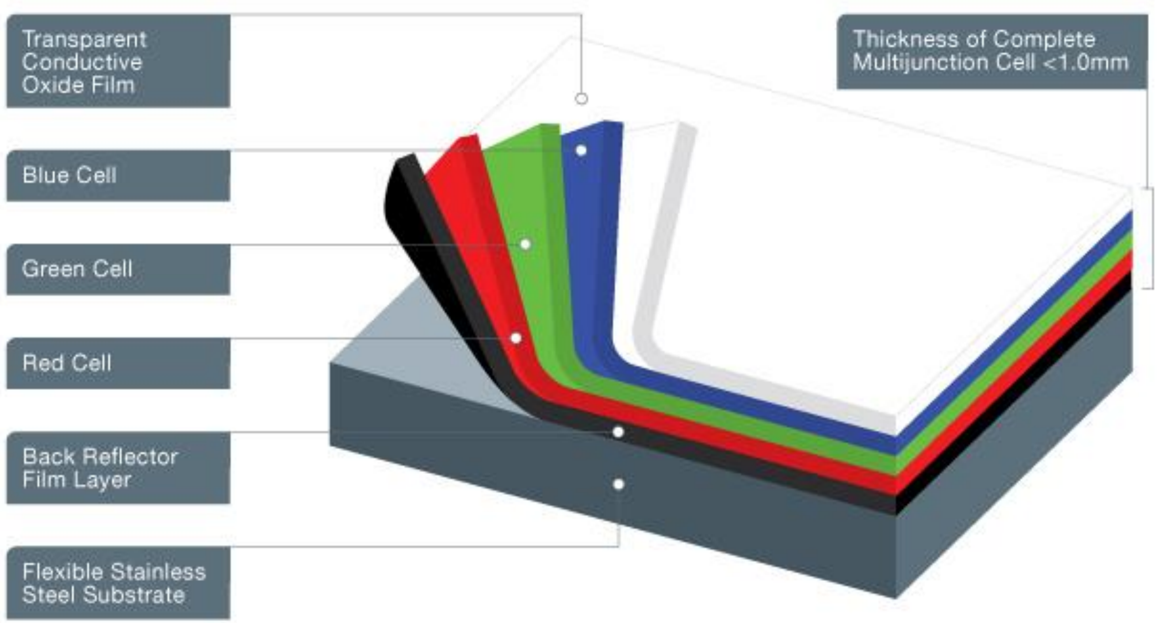


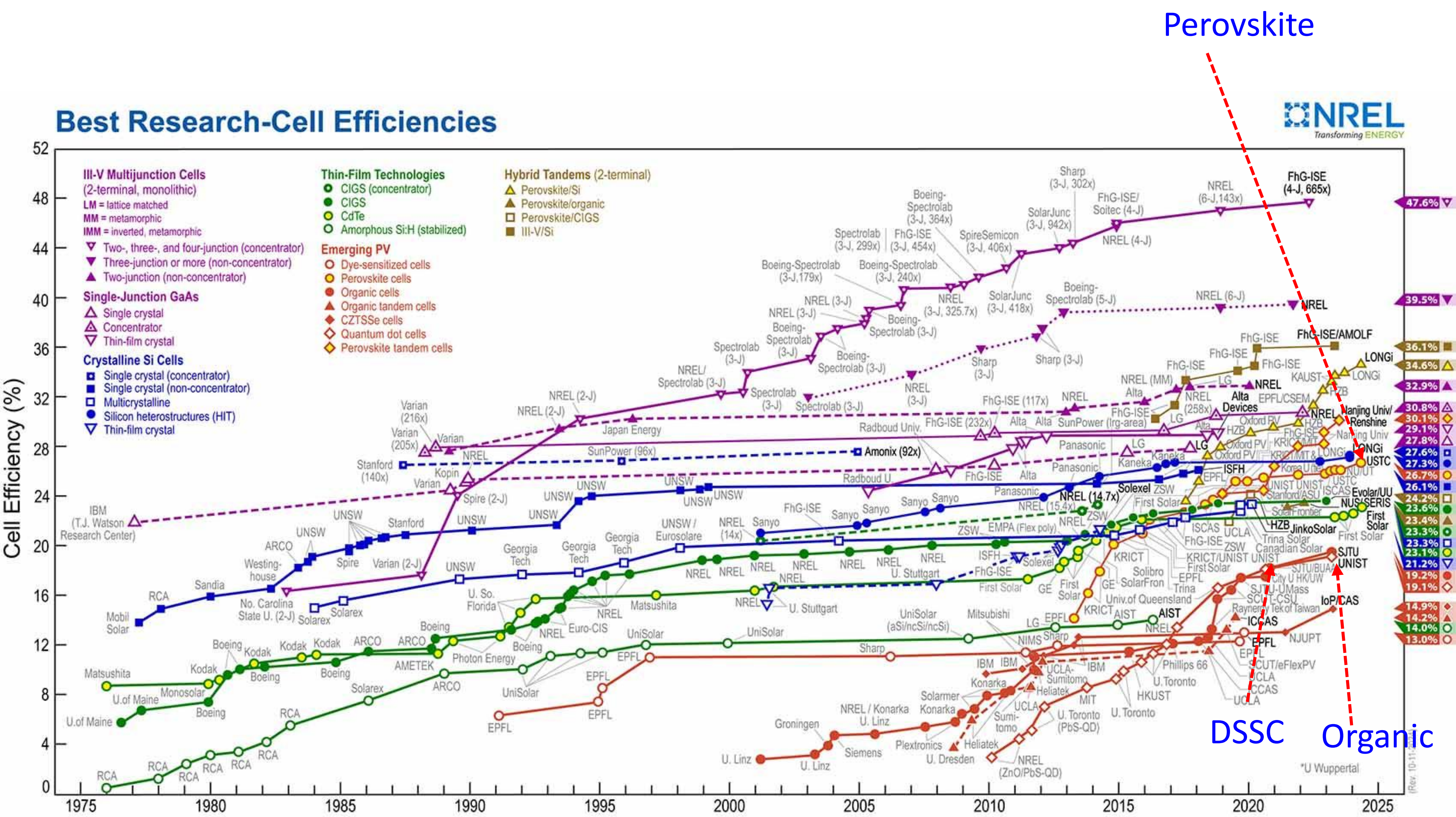
Superstrate / encapsulation
Transparent contact
Perovskite cell
Transparent contact
Optical coupling/ interconnection
Transparent contact
Silicon cell
Rear contact
Encapsulation
External Quantum Efficiency,
Spectral Power Density (W m-2 nm-1)
1.5
1.0
0.5
0.0
400
600
800
1000
1200
Wavelength (nm)
Perovskite Cell
Crystalline Si Cell
Solar Irradiance
UV
Near-infrared

UNI-SOLAR TRIPLE JUNCTION TECHNOLOGY



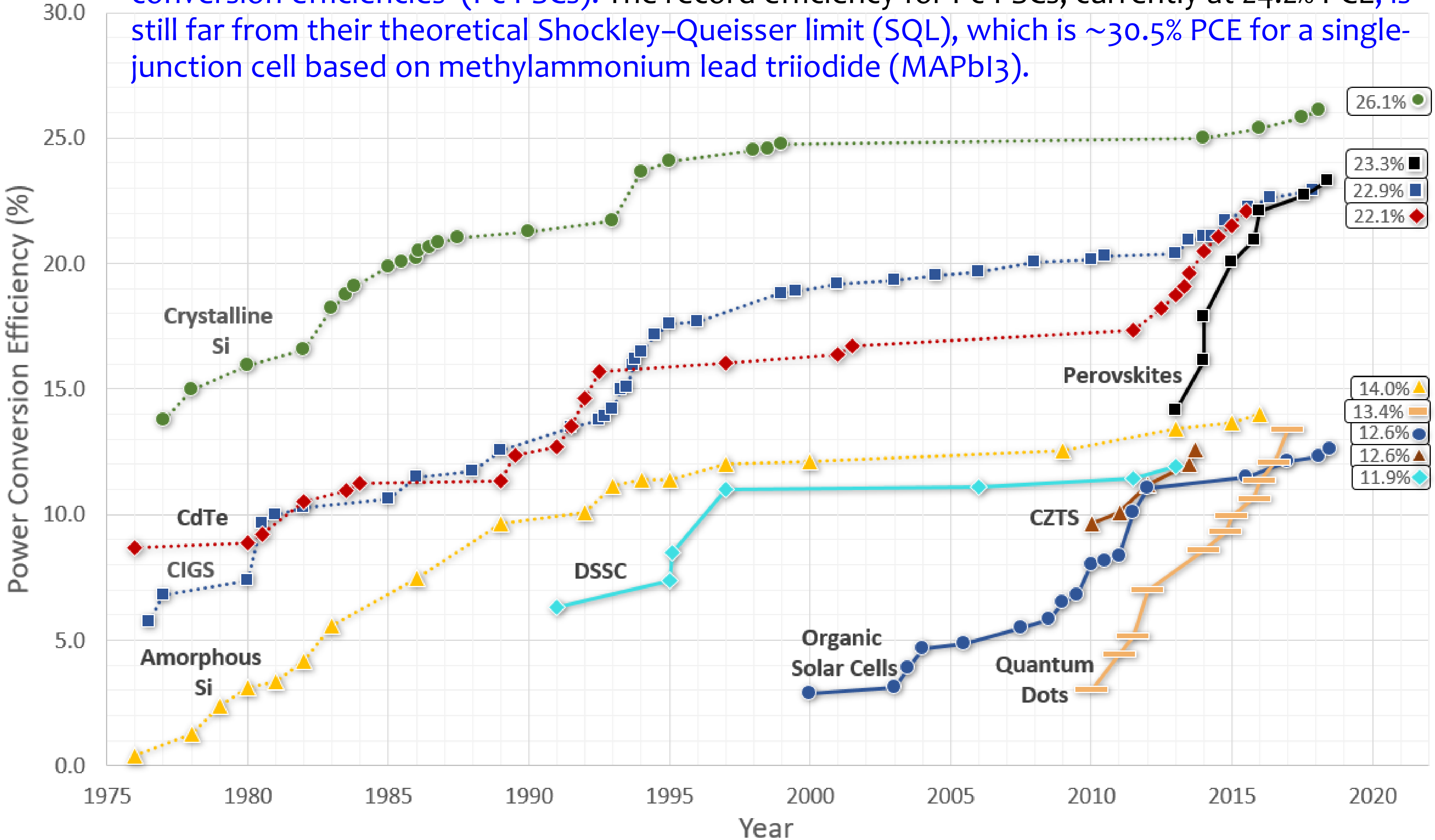
UNI-SOLAR TRIPLE JUNCTION SOLAR CELLS





https://www.nrel.gov/pv/cell-efficiency.html

Studies on perovskite solar cells have principally been on polycrystalline film power conversion efficiencies (Pc-PSCs). The record efficiency for Pc-PSCs, currently at 24.2% PCE, is still far from their theoretical Shockley–Queisser limit (SQL), which is ~30.5% PCE for a single-junction cell based on methylammonium lead triiodide (MAPbI3).



Perovskite solar cells have increased in power conversion efficiency at a phenomenal rate compared to other types of photovoltaics.

Sustainable Energy Fuels, 2020, 4, 528-537

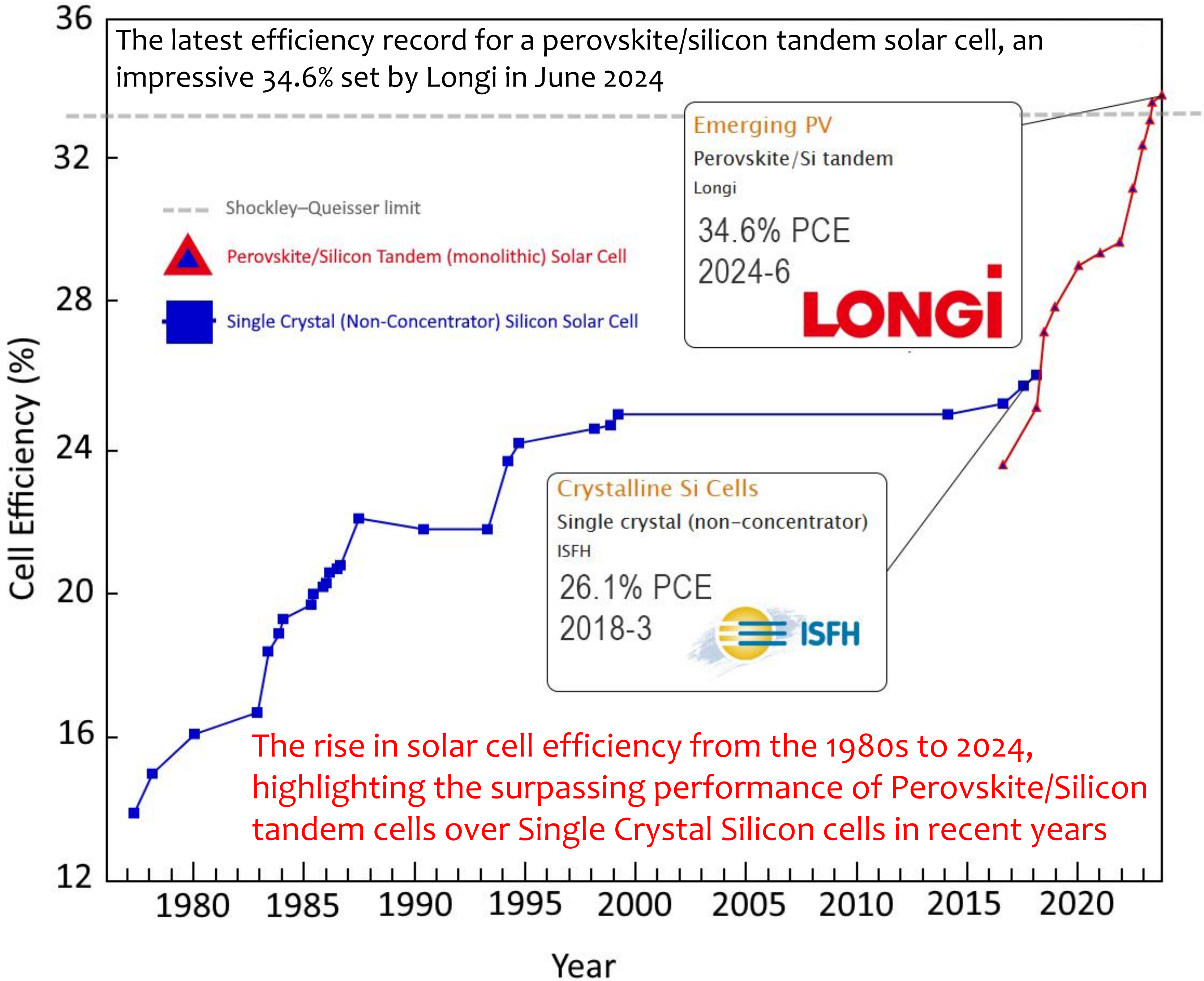
Perovskite Based Solar Cell Efficiency Leader-board

The cell was tested and verified by the [National Renewable Energy Laboratory (NREL; national laboratory of the U.S. Department of Energy)].

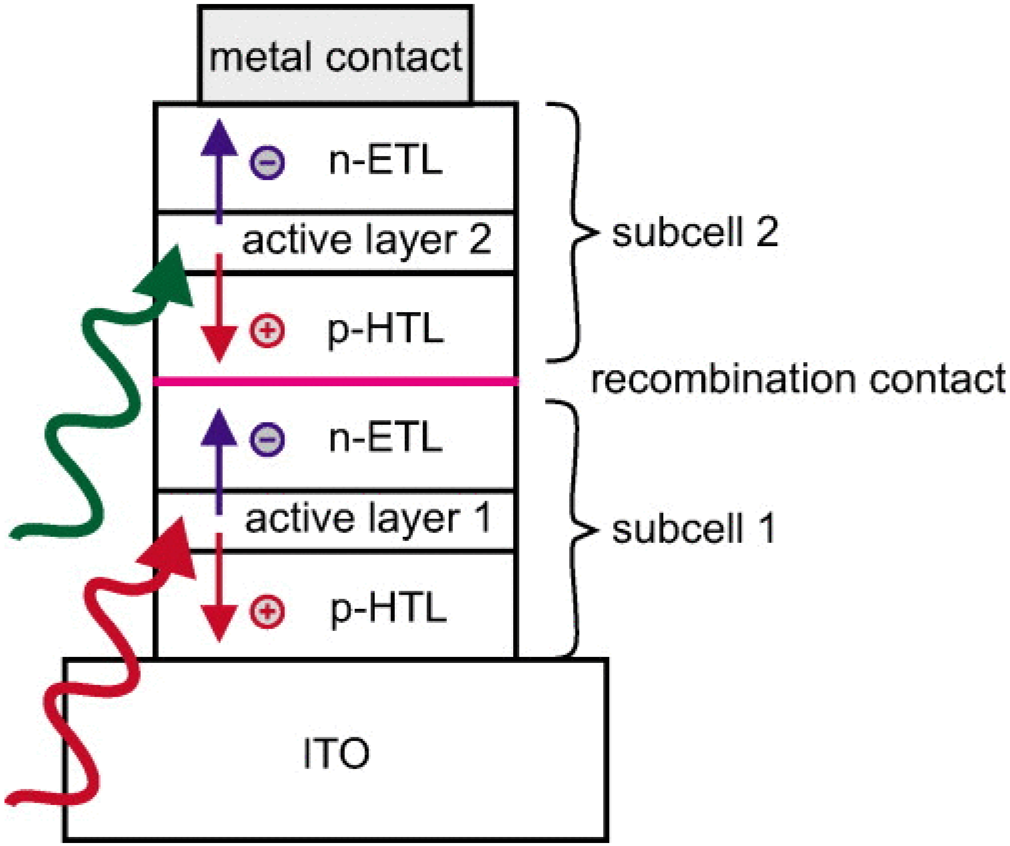
- **PCE:** 26.7%
- **VOC:** 1.193 V
- **Device Area:** 0.052 cm^2
- **Institution:** USTC
- **Certification:** NREL

Cell Type	Efficiency	Area (cm^2)	Year	Institution
Perovskite (Single-Junction)	26.7%	0.052	2025	University of Science and Technology of China
Perovskite-Silicon Tandem	34.85%	1.0	2025	LONGi Solar
Perovskite-Perovskite Tandem	30.1%	0.049	2023	Nanjing University & Renshine Solar

https://www.fluxim.com/research-blogs/perovskite-silicon-tandem-pv-record-updates

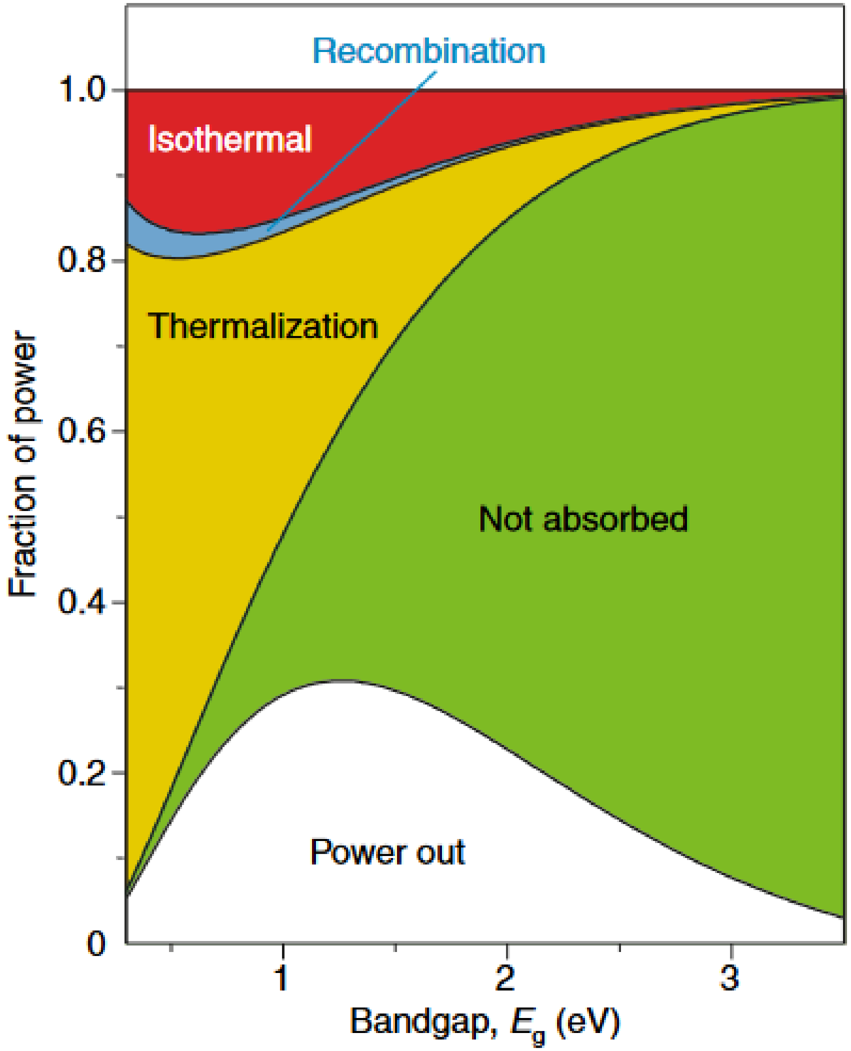


The latest efficiency record for a perovskite/silicon tandem solar cell, an impressive 34.6% set by Longi in June 2024
Shockley–Queisser limit
Perovskite/Silicon Tandem (monolithic) Solar Cell
Single Crystal (Non-Concentrator) Silicon Solar Cell
Emerging PV
Perovskite/Si tandem
Longi
34.6% PCE
2024-6
LONGi
Crystalline Si Cells
Single crystal (non-concentrator)
ISFH
26.1% PCE
2018-3
ISFH
The rise in solar cell efficiency from the 1980s to 2024, highlighting the surpassing performance of Perovskite/Silicon tandem cells over Single Crystal Silicon cells in recent years
Cell Efficiency (%)
Year
12
16
20
24
28
32
36
1980
1985
1990
1995
2000
2005
2010
2015
2020



Energy Environ. Sci., 2009, 2, 347–363

The Limitations of Silicon Solar Cells



•**Optical:** Photons with energy lower than the bandgap are not absorbed. The higher the bandgap, the higher the amount of non-absorbed photons (~ 19% of the total losses).

•**Thermal:** Photons with an energy that exceeds the Bandgap ($E > E_g$) are absorbed. The generated carriers are thermalizing down to the band edge. The excess energy is released as heat to the solar cell (~ 33% of the total losses).

•**Electronic:** Loss due to radiative charge recombination, i.e. the pair recombines and, eventually, a photon is emitted. (~ 15% of the total losses).

•**Isothermal losses**: An additional electronic contribution due to the power dissipation along the band-edge (constant temperature of the carrier).

These losses result in about 68% of the total sunlight not being converted into electricity

https://www.fluxim.com/perovskite-silicon-tandem-pv-record-updates

Beyond the Shockley–Queisser Limit

The Shockley–Queisser limit sets the maximum efficiency of a single-junction silicon solar cell at ~32%.

Commercial silicon modules achieve up to ~26.8% efficiency due to optical, thermal, and electronic losses.

Overcoming the Limit: Tandem and Advanced Concepts

Tandem (Perovskite/Silicon) Solar Cells: Combine materials that absorb different parts of the solar spectrum, surpassing single-junction limits.

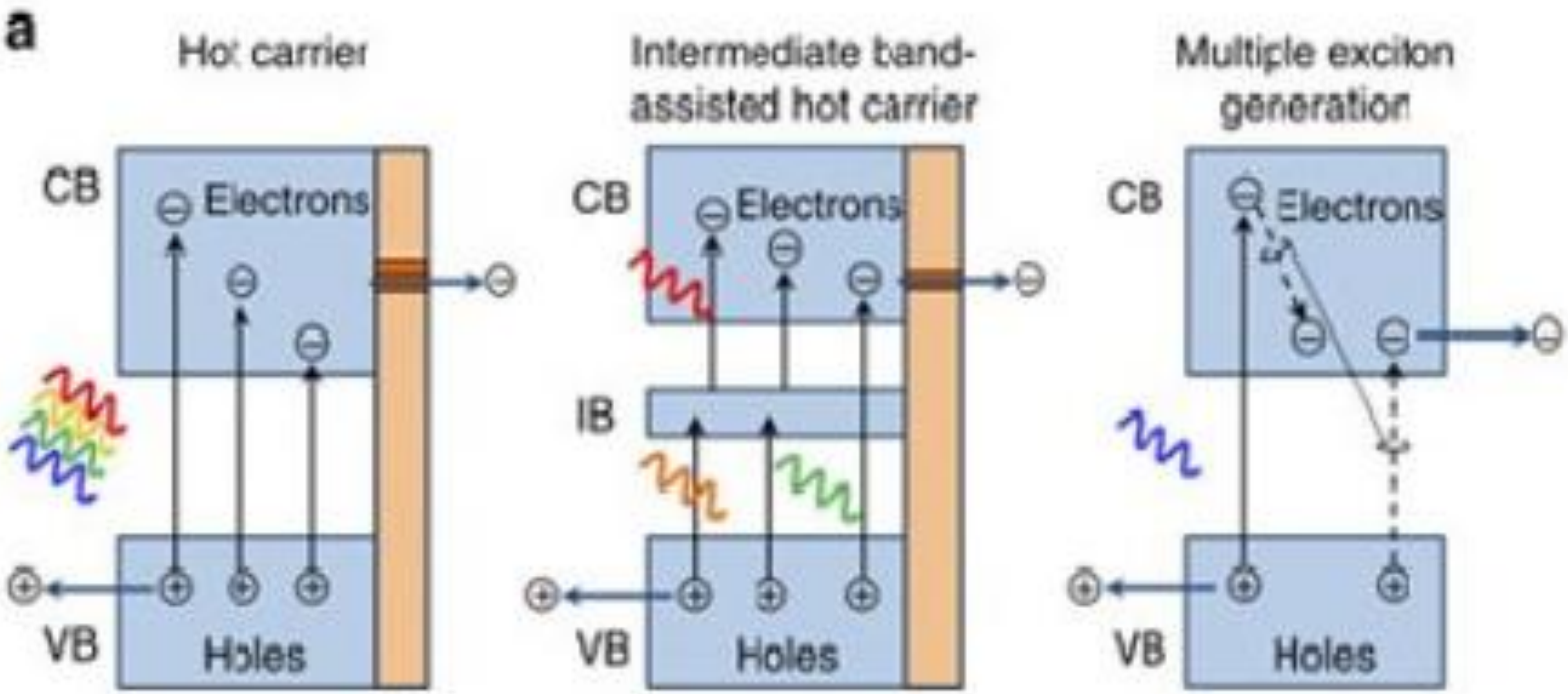
Proposed Approaches to Reduce Silicon Losses

Hot Carrier Solar Cells: Extract high-energy carriers before excess energy is lost as heat.

Intermediate Bandgap (IB) Solar Cells: Introduce an intermediate energy level between valence and conduction bands, allowing absorption of low-energy photons without reducing voltage.

Multiple Exciton Generation (MEG): Convert one high-energy photon into multiple charge carriers, increasing current output.

While these strategies could theoretically boost efficiency, none are yet viable for large-scale commercial photovoltaics.



hot carrier

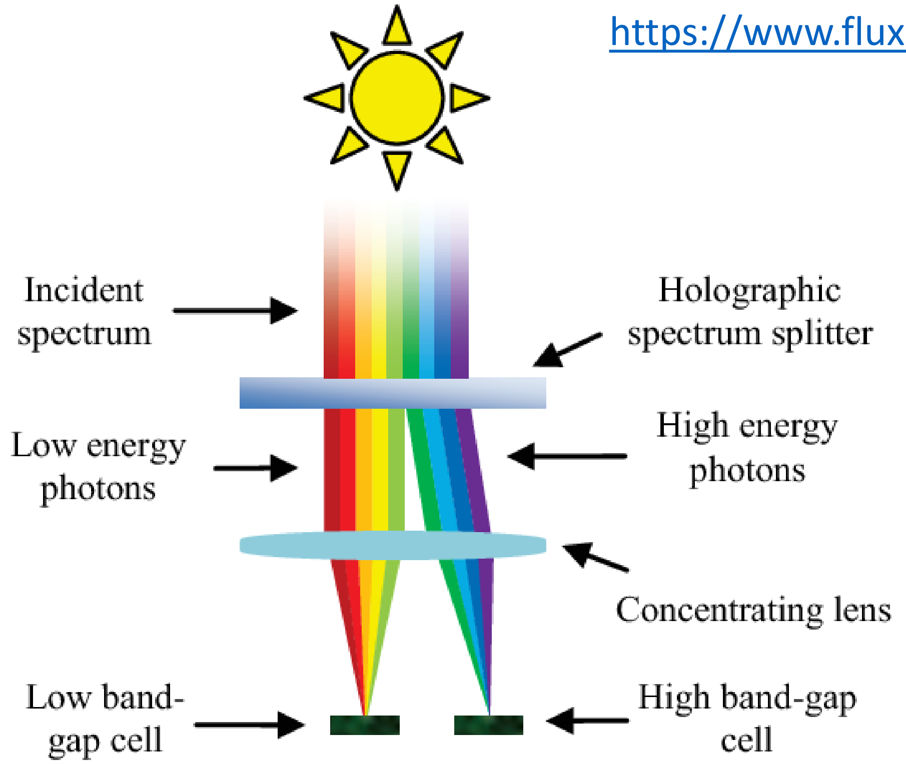
intermediate band transitions

multiple exciton generation

Three advanced solar cell mechanisms: hot carrier absorption, intermediate band transitions, and multiple exciton generation, each enhancing electron excitation and energy conversion efficiency.

https://www.fluxim.com/perovskite-silicon-tandem-pv-record-updates

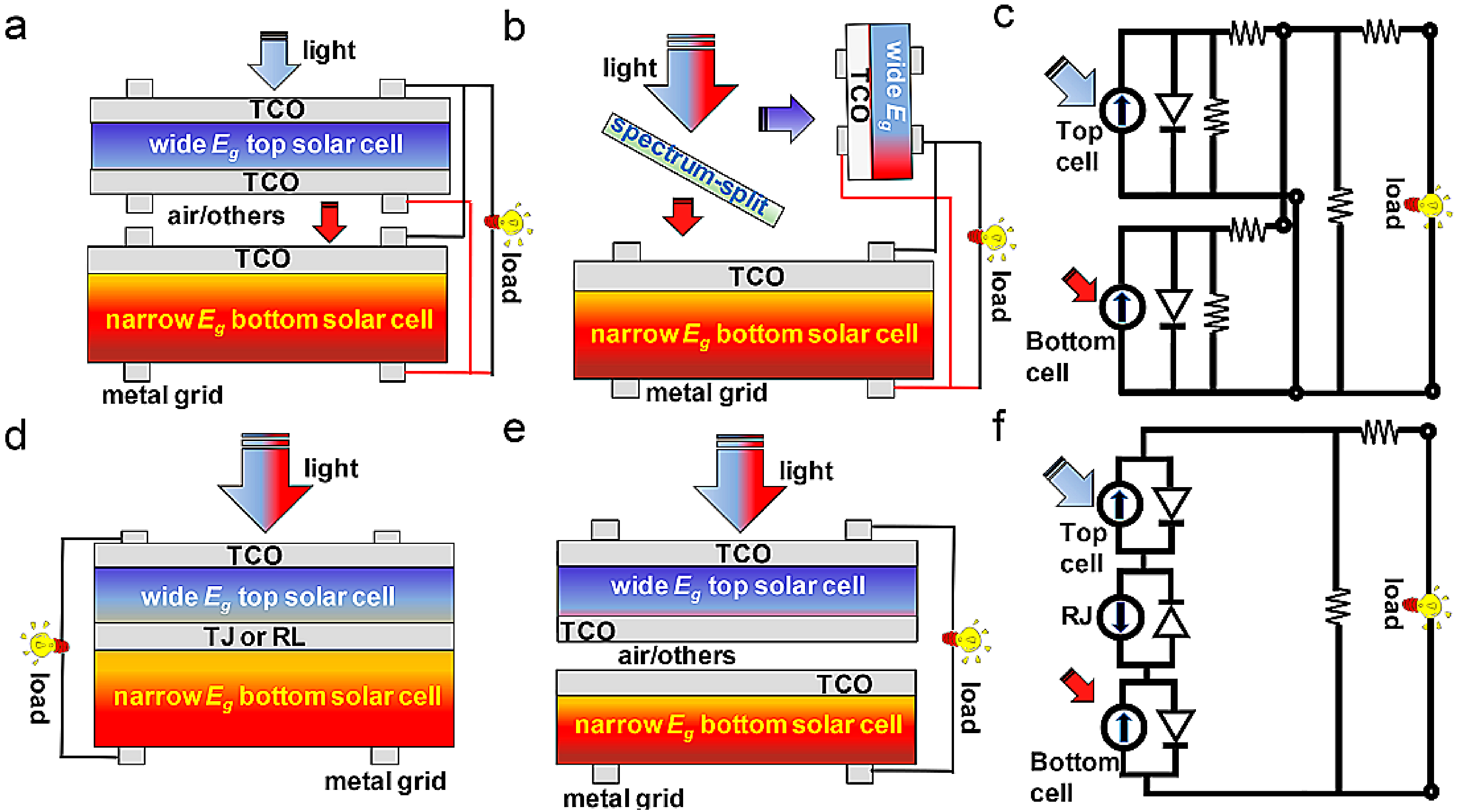
https://www.fluxim.com/perovskite-silicon-tandem-pv-record-updates



A holographic spectrum-splitting solar energy system uses a holographic optical element (HOE) to divide incident sunlight into high- and low-energy photon bands.

- High-energy photons are directed to wide band-gap solar cells, which convert them efficiently into electricity.
- Low-energy photons are sent to narrow band-gap cells, optimized for longer wavelengths.

This spectral division minimizes thermal losses and allows each cell to operate near its optimum efficiency, thereby enhancing the overall photovoltaic performance beyond that of single-junction cells.



Various tandem solar cell configurations and their corresponding electrical circuit diagrams, demonstrating how light management and connectivity affect the overall efficiency and performance of the solar cells

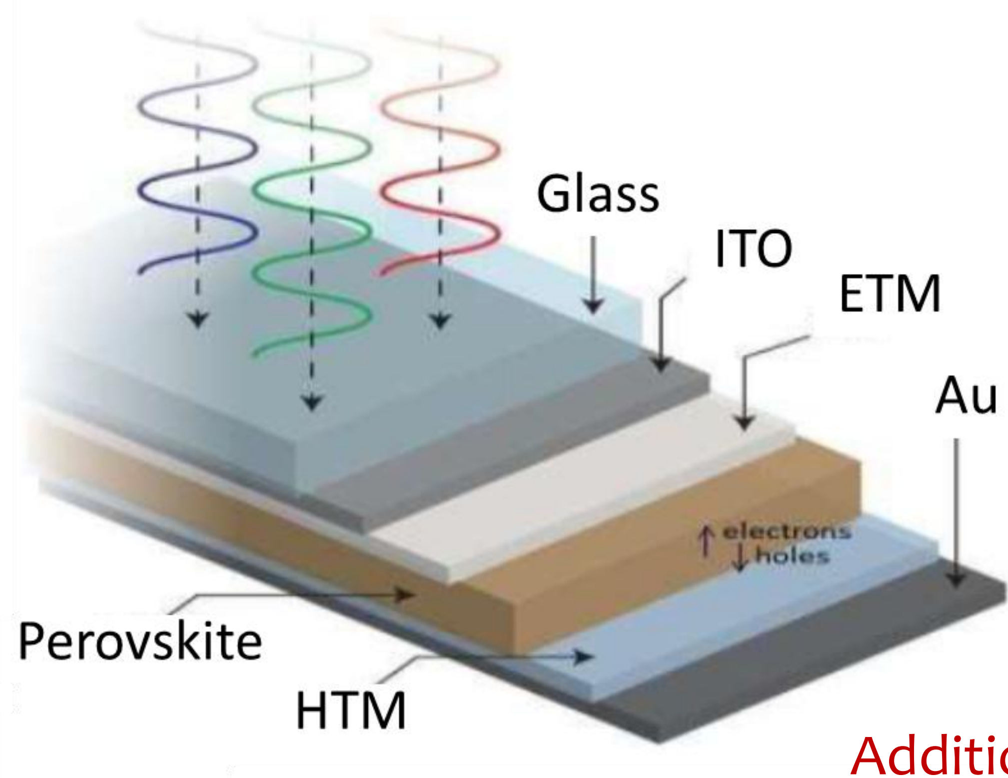
https://www.fluxim.com/perovskite-silicon-tandem-pv-record-updates

Metal Electrode : Gold

Hole Transport Layer : Spiro – OMeTAD

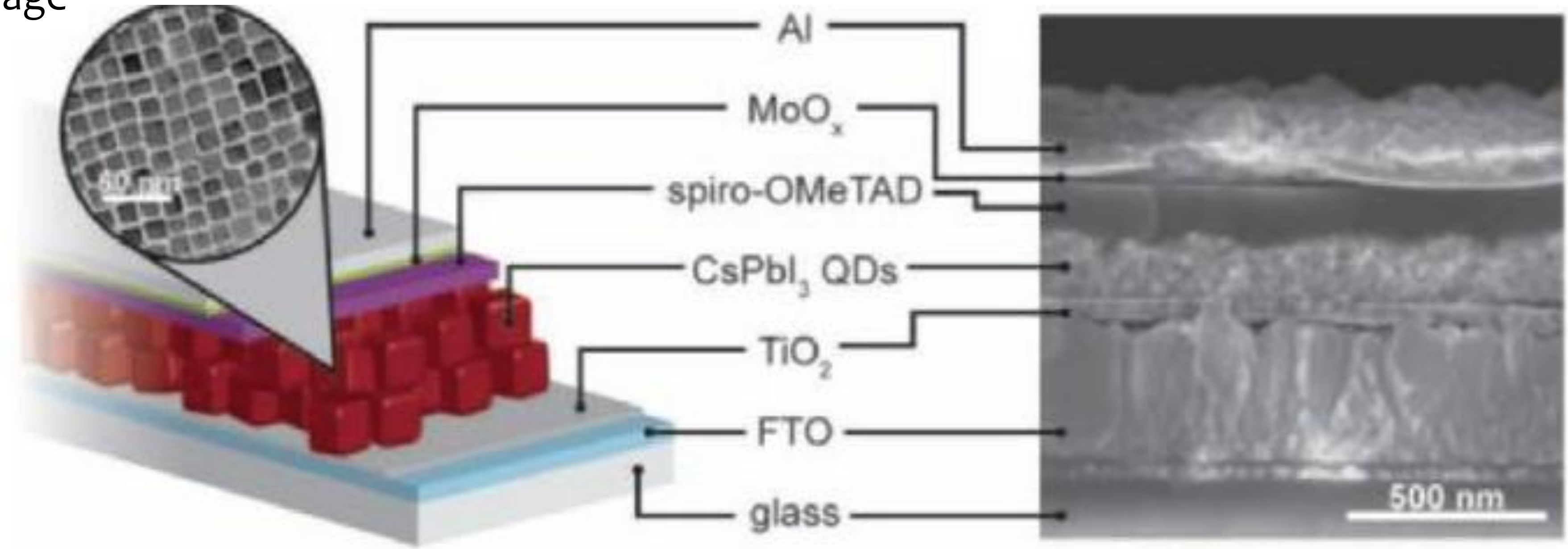
Absorber layer: Methyl Ammonium Lead halide ($CH_3NH_3PBX_3$)
: $CH_3NH_3PbI_3$,$CH_3NH_3SnI_3$, $CH_3H_3PbBr_3$, $CH_3NH_3PbCl_3$

Electron Transport Layer: TiO_2



Additional Read:
ACS Energy Lett. 2019, 4, 2147−2167
Sustainable Energy Fuels, 2020, 4, 528-537

TEM image



Schematic (& TEM image of Perovskite QDs) and SEM cross-section of the CsPbI3 solar cell

Adv. Energy Mater. **2020**, *10*, 2000183

FTO (fluorine-doped tin oxide): A transparent conductive oxide used in solar cells, primarily as an electrode on the sun-facing side to collect electrons while allowing light to pass through

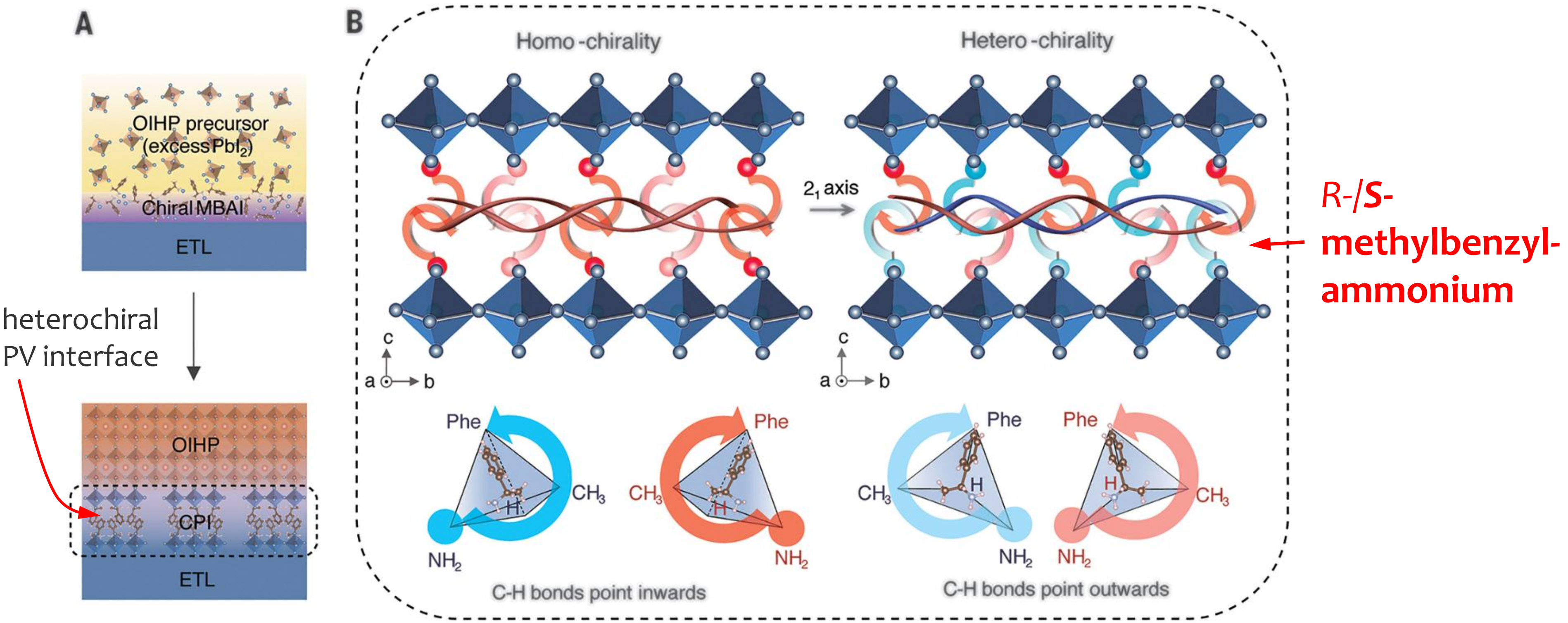
Perovskite Solar Cell Durability

The durability of perovskite solar cells for long time usages is a concern. Some common standards for developing solar cells are as follows:

- Crystalline-Si solar cell needs to last for 25 years in outdoor conditions to be marketable, and have similar efficiencies.
- According to the International Electrotechnical Commision's (IEC) standards, solar cells must perform well under non-laboratory conditions, such as in damp conditions i.e. 85% humidity at 85 degrees Celsius. They must withstand these for more than 1000 hours consistently.

Currently, perovskite solar cells still do not reach these standards. A recent review presents a detailed summary of various studies that have been done on perovskite stability. This includes a triple cation perovskite withstanding 85% humidity for 250 hours, and a methylammonium lead iodine ($MAPbI_3$) perovskite solar cell withstanding 55% humidity for 480 hours [nt J Energy Res. 2021;1–17].

Chiral-structured heterointerfaces enable durable perovskite solar cells



Organic-inorganic halide perovskites (OIHP)

Researchers mimicked the strength of natural chiral structures to enhance the mechanical reliability of perovskite solar cells. The main issue was the weak interfaces between layers with different thermal expansion properties. To fix this, they added chiral-structured interlayers made of R-/S-methylbenzyl-ammonium between the perovskite absorber and the electron transport layer, forming a strong and flexible interface. As a result, the encapsulated cells maintained 92% of their original 26% efficiency after 200 temperature cycles between −40°C and 85°C over 1200 hours.

Science, 2024, 384, 878-884

Si-solar cells: Expensive to purify but cost-effective when volume is high

Perovskite solar cells: Solution processed with lower manufacturing cost.

Cost

26.6 % efficiency in single crystal Si cells

Efficiency ⇔ **Durability**

Si-Solar Cells ~ 25 yrs in outdoor condition

24.2% efficiency in stabilized perovskite solar cells.
Certified efficiency achieved ~22.5%

Longest reported perovskite stability ~ 1 yr

https://www.ossila.com/pages/perovskite-solar-cell-degradation-causes

A bilayer conducting polymer structure for planar perovskite solar cells with over 1,400 hours of operational stability at elevated temperatures. [Nature Energy, 2022, 7, 144–152.]

For more details….
Promises and challenges of perovskite solar cells;
Science 2017; 358, Issue 6364, 739-744; DOI: 10.1126/science.aam6323

ORGANIC–INORGANIC HYBRID PEROVSKITES

- Hybrid Organic Inorganic Semiconductor
- Inorganic - Lead (Strong light absorption, Provide high efficiencies, even above 20 % as per NREL)
- Organic- Methyl Ammonium (Soluble in Polar Solvents, Provides low temperature processing - low cost and energy saving)
- First three-dimensional organic–inorganic hybrid perovskite:

  Replacing Cs^+ in $CsPbX_3$ (X = Cl, Br or I) with MA $(CH_3NH_3)^+$ in 1978.
- $CH_3NH_3PbI_3$ is most common used materials for making high efficiency perovskite solar cells.

Perovskite Solar Cell Durability

The durability of perovskite solar cells for long time usages is a concern. Some common standards for developing solar cells are as follows:

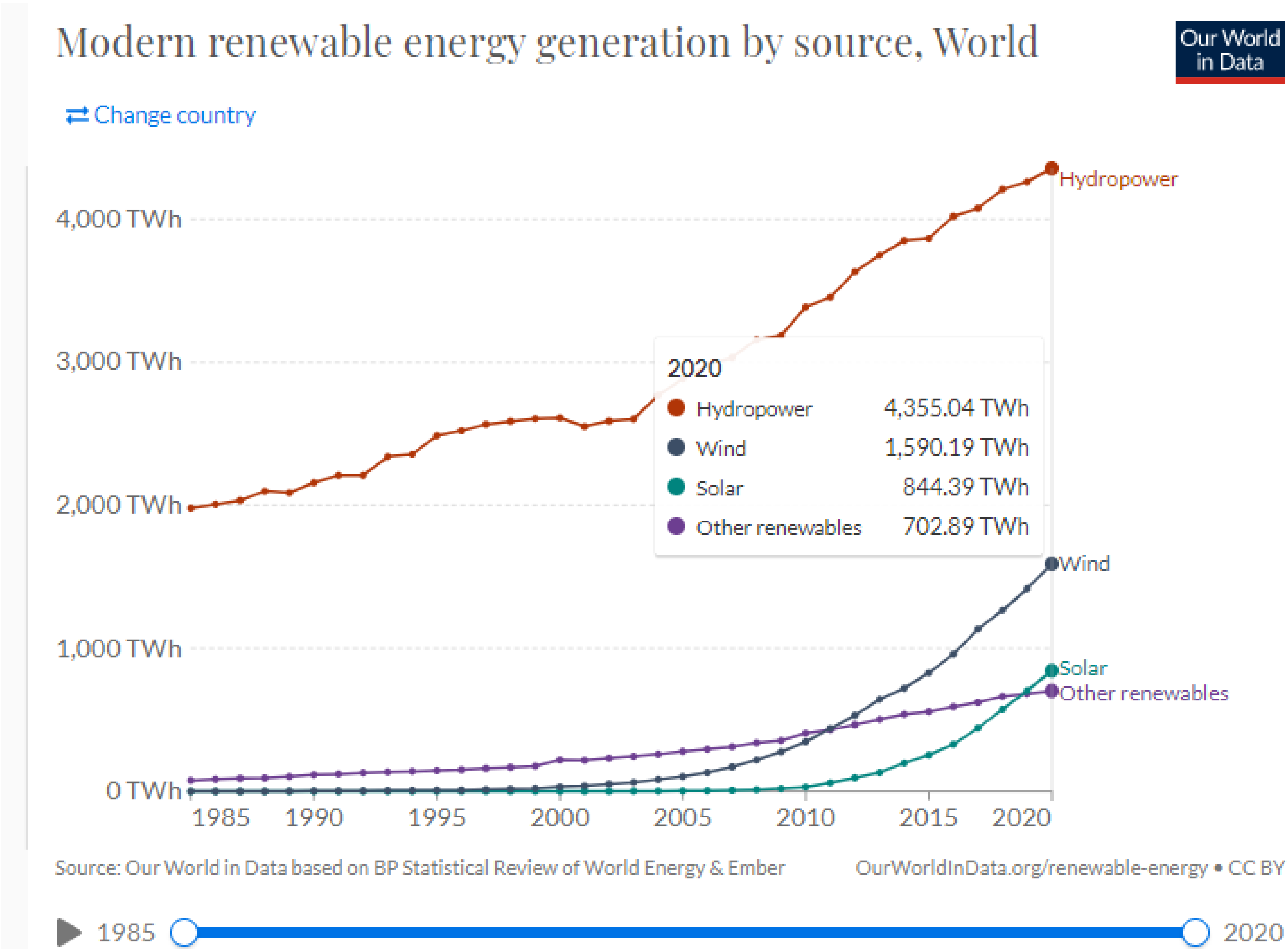
- Crystalline-Si solar cell needs to last for 25 years in outdoor conditions to be marketable, and have similar efficiencies.
- According to the International Electrotechnical Commision's (IEC) standards, solar cells must perform well under non-laboratory conditions, such as in damp conditions i.e. 85% humidity at 85 degrees Celsius. They must withstand these for more than 1000 hours consistently.

Currently, perovskite solar cells still do not reach these standards. A recent review presents a detailed summary of various studies that have been done on perovskite stability. This includes a triple cation perovskite withstanding 85% humidity for 250 hours, and a methylammonium lead iodine ($MAPbI_3$) perovskite solar cell withstanding 55% humidity for 480 hours [nt J Energy Res. 2021;1–17].

There *are* solar modules (and technologies) certified to meet the relevant standard of ~85 °C / 85 % RH for ~1 000 h. For example:

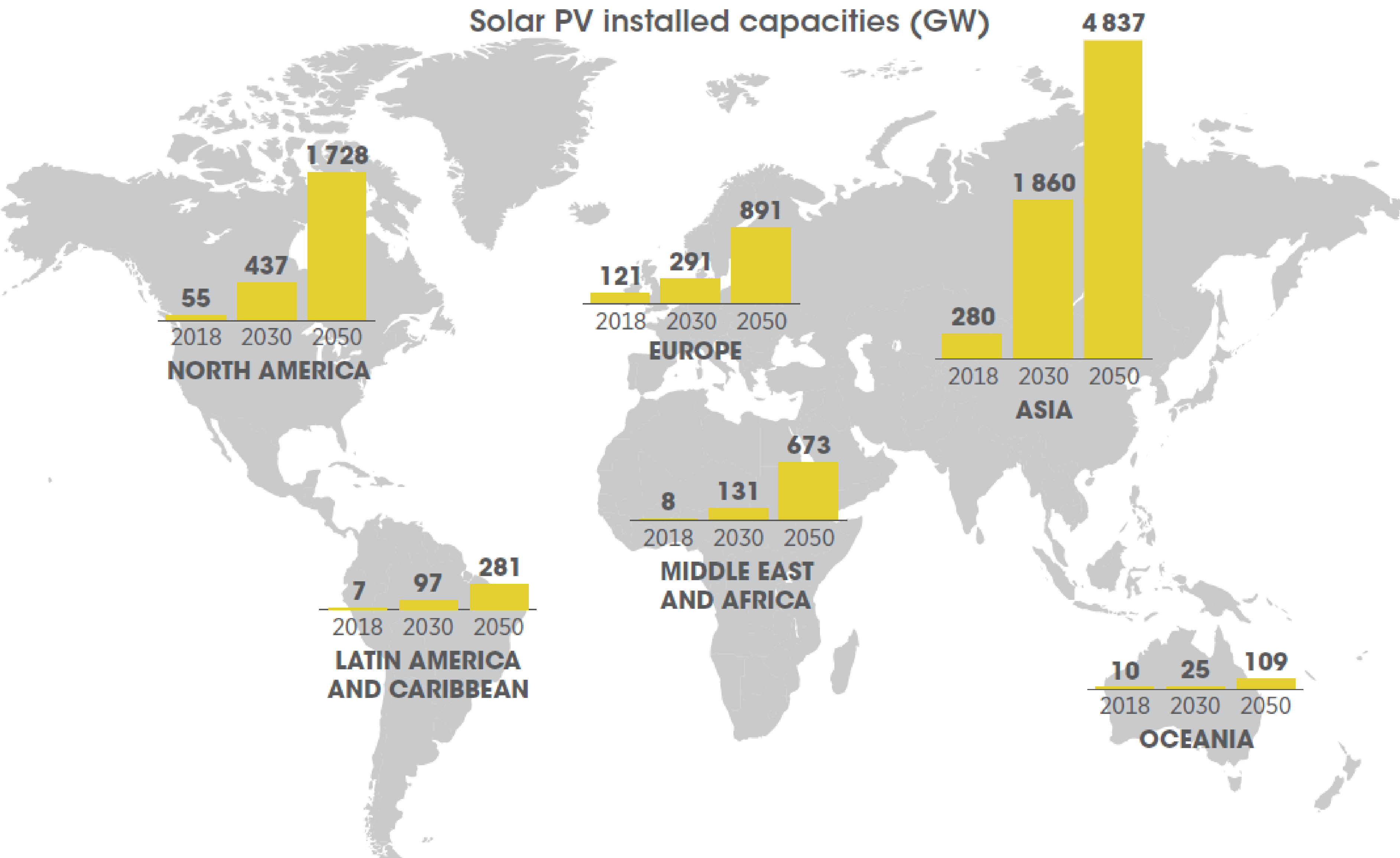
- The standard IEC 61215 (for crystalline silicon PV modules) includes a Damp Heat test of 85 °C and 85 % relative humidity for 1 000 h.
- The website of a PV-certification and testing body Kiwa PVEL states that their "Damp Heat" test exposes modules to 85 °C / 85 % RH for *two periods of 1 000 hours each".
- https://couleenergy.com/understanding-solar-panel-certification-iec-61215-61730-standards-explained; https://www.kiwa.com/us/en-us/about-kiwa/entities/pvel/pqp/dh

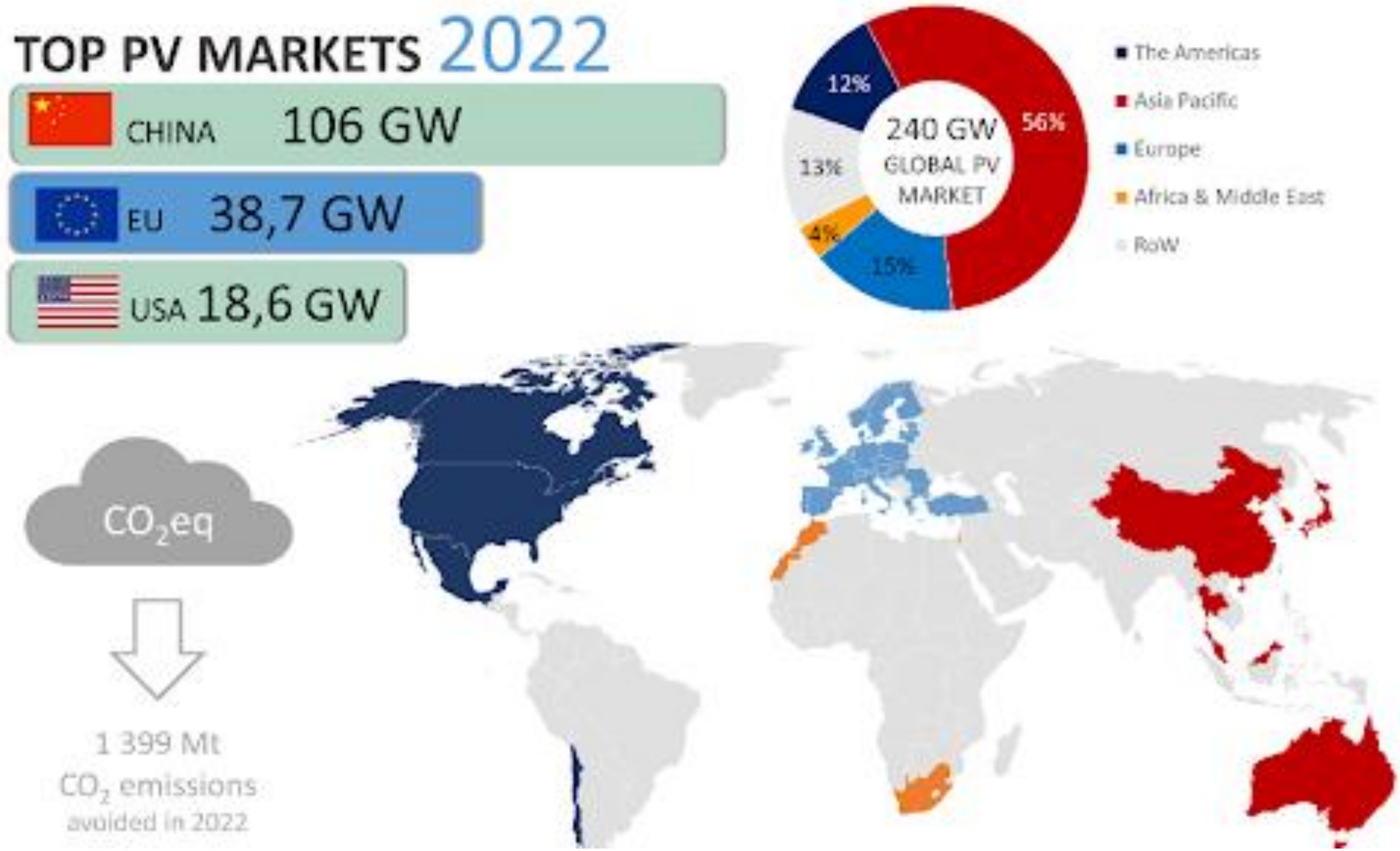
Issue of sustainability



Modern renewable energy generation by source, World
Our World in Data
Change country
Hydropower
4,000 TWh
3,000 TWh
2,000 TWh
1,000 TWh
0 TWh
2020
Hydropower 4,355.04 TWh
Wind 1,590.19 TWh
Solar 844.39 TWh
Other renewables 702.89 TWh
Wind
Solar
Other renewables
1985
1990
1995
2000
2005
2010
2015
2020
Source: Our World in Data based on BP Statistical Review of World Energy & Ember
OurWorldInData.org/renewable-energy • CC BY
1985
2020

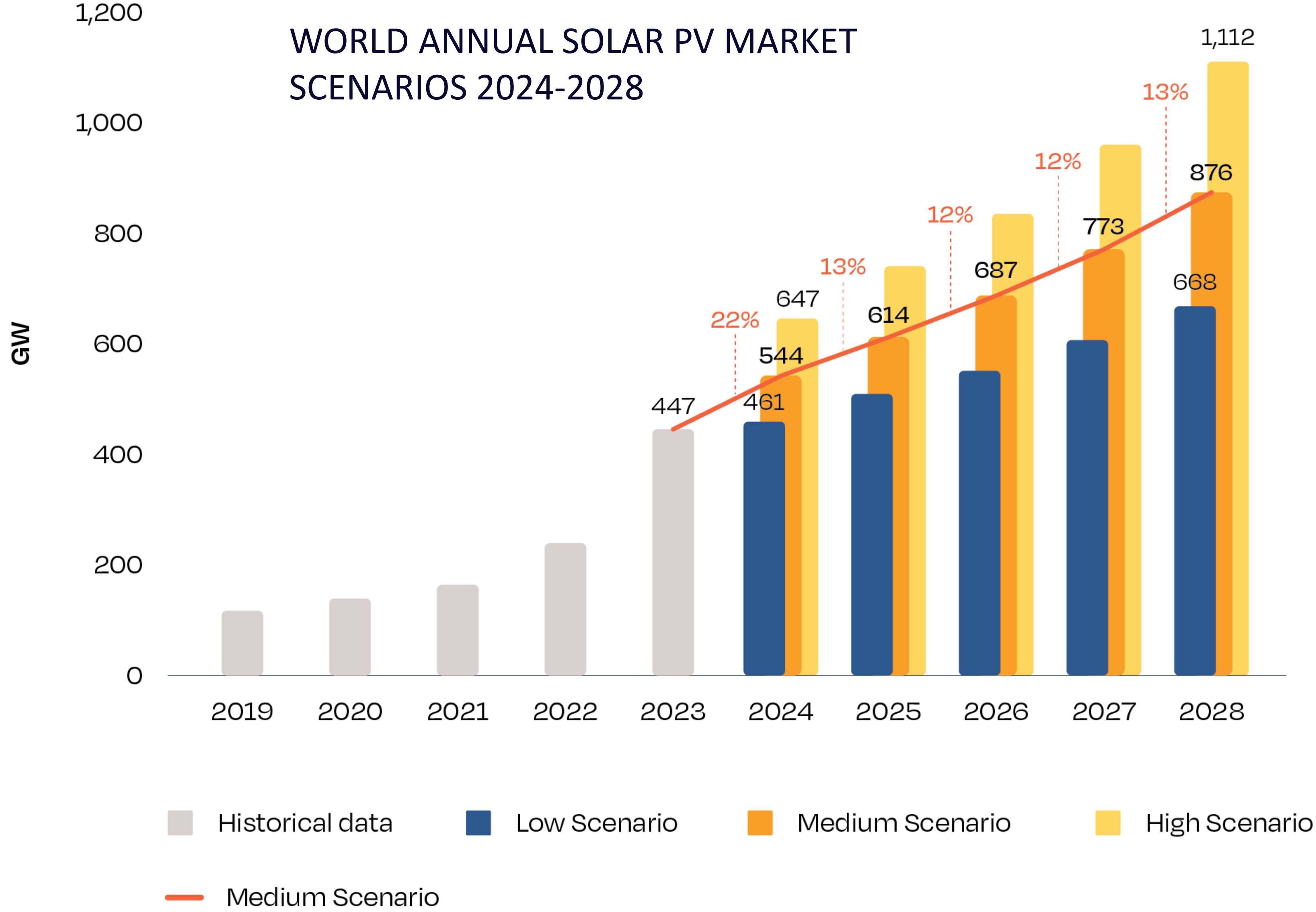
Among the world's regions, Asia is poised to dominate global solar PV installations in the Renewable Energy map scenario, followed by North America and Europe



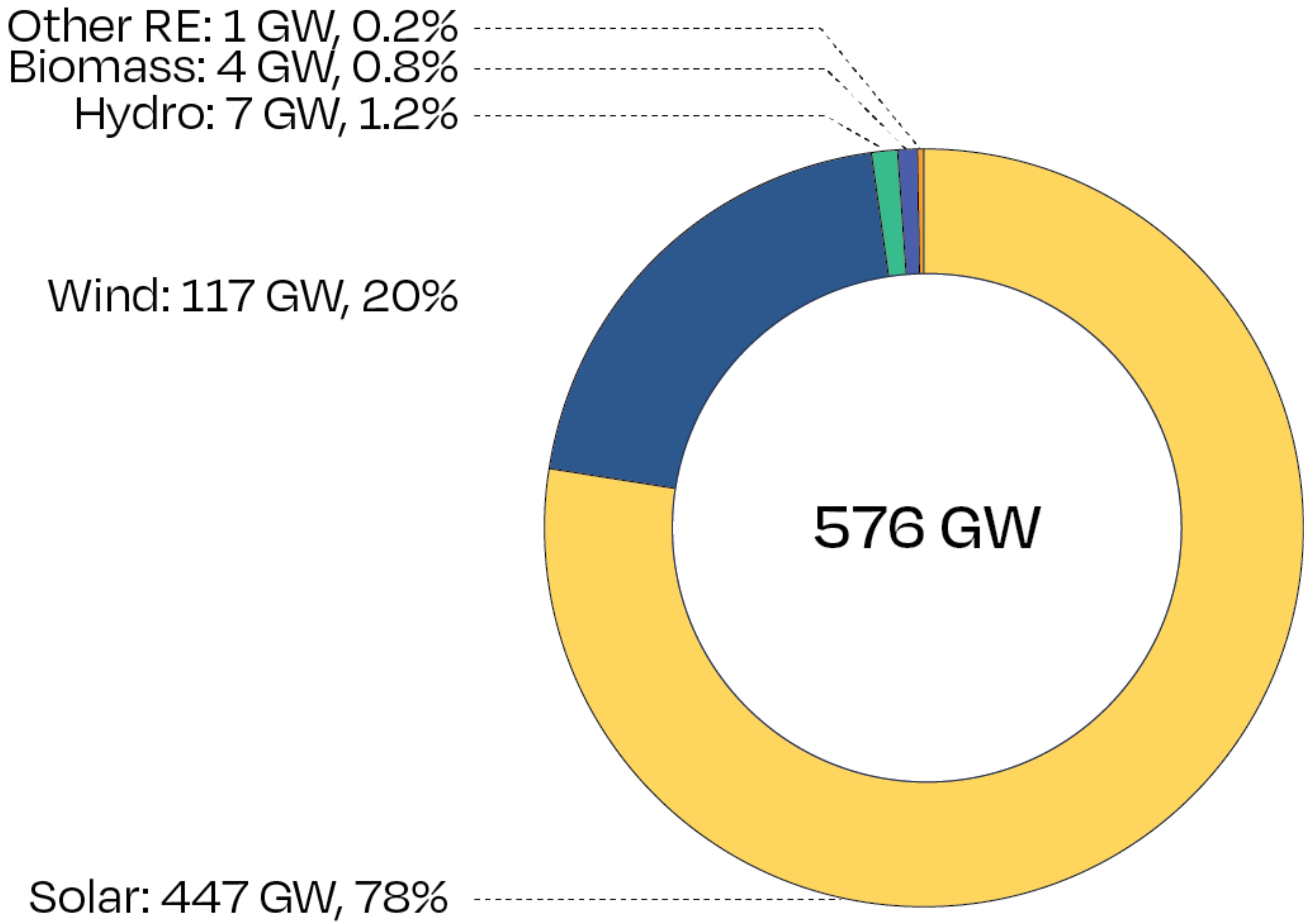


https://www.faistgroup.com/news/snapshot-global-pv-markets-2023/

WORLD ANNUAL SOLAR PV MARKET SCENARIOS 2024-2028



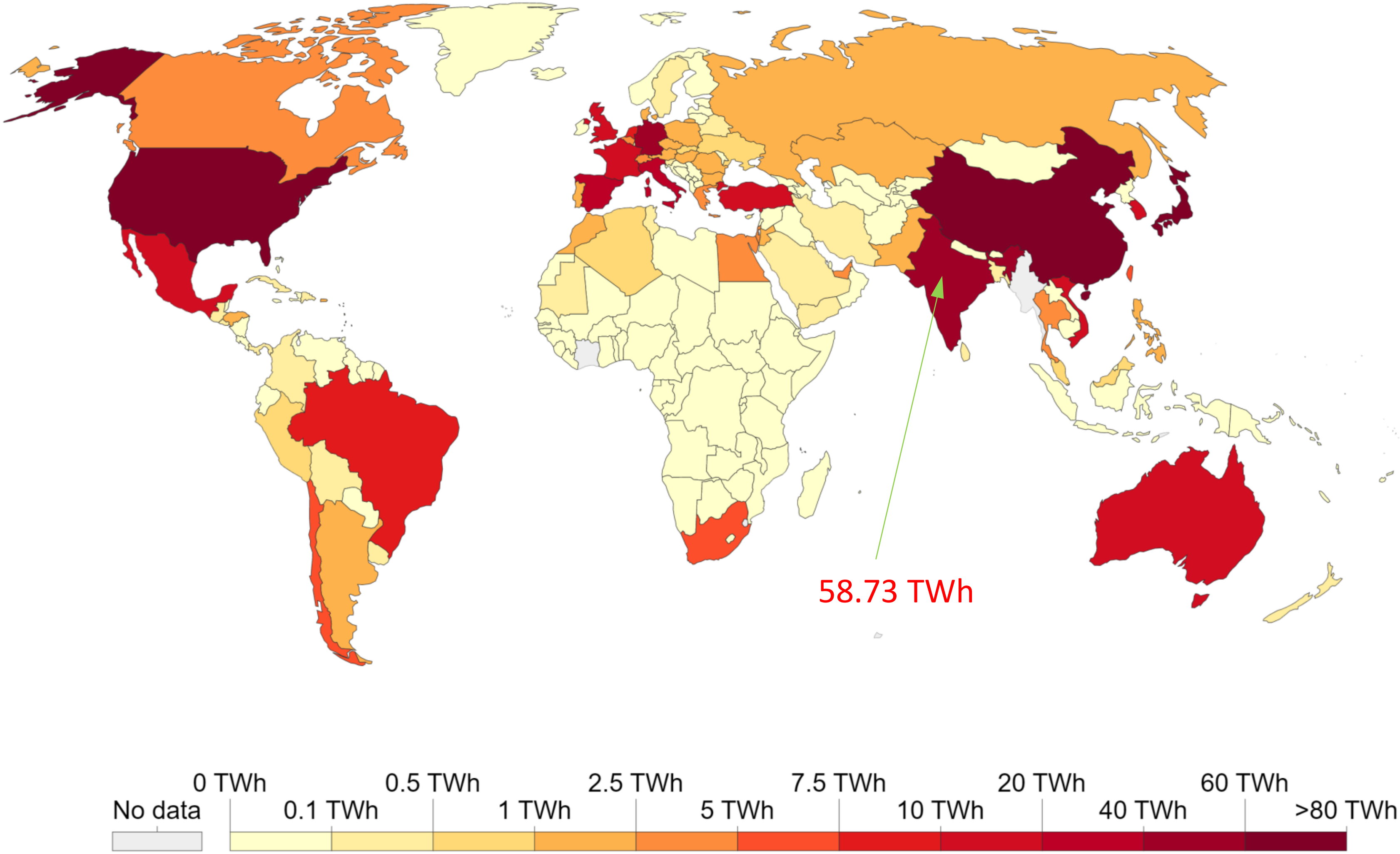
https://www.solarpowereurope.org/insights/outlooks/global-market-outlook-for-solar-power-2024-2028/detail



https://www.solarpowereurope.org/insights/outlooks/global-market-outlook-for-solar-power-2024-2028/detail

Solar power generation

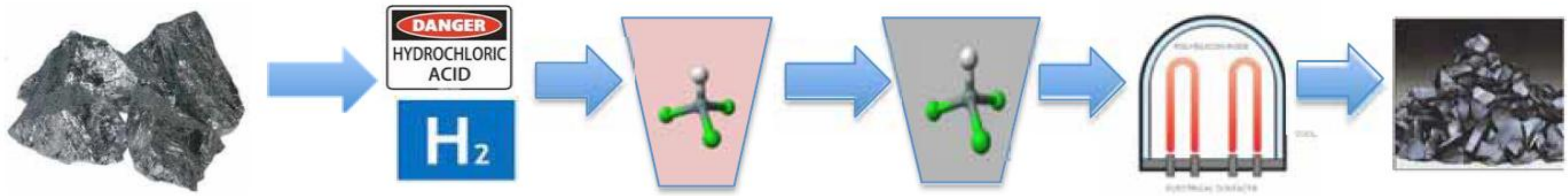
Electricity generation from solar, measured in terawatt-hours (TWh) per year.



Source: Our World in Data based on BP Statistical Review of World Energy & Ember

Si metal to Semiconductor grade Polysilicon

Sandia National Laboratories



MG Silicon Metal
98.0% to 99.5% Si

MG Silicon Metal Is Dissolved In Hydrochloric Acid To Form Trichlorosilane (HSiCl3)

Trichlorosilane (HSiCl3) is Further Refined

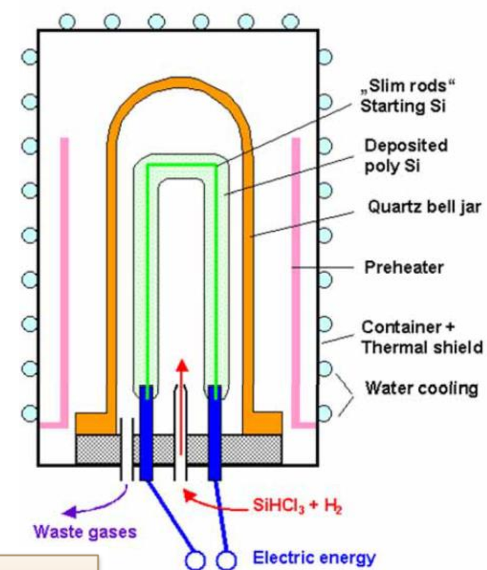
Siemens or FBR Poly Silicon Process

Semiconductor Si
99.999+% Si

$$Si + 3HCl \rightarrow SiHCl_3 + H_2$$

- Purify TCS in distillation columns
- Recover pure Si using Chemical Vapor Deposition (CVD)

$$H_2 + SiHCl_3 \rightarrow 3HCl + Si$$



Cold wall reactor, high energy consumption. TCS conversion per pass is around 15%, recycling and lower productivity

80% of the worlds polysilicon is produced using the Siemen's process developed in the 1950's.

Stephen Maldonado, (View point) ACS Energy Lett. 2020, 5, 3628.

150 kWh/kg

$SiO_2 + C \rightarrow Si + CO_2$

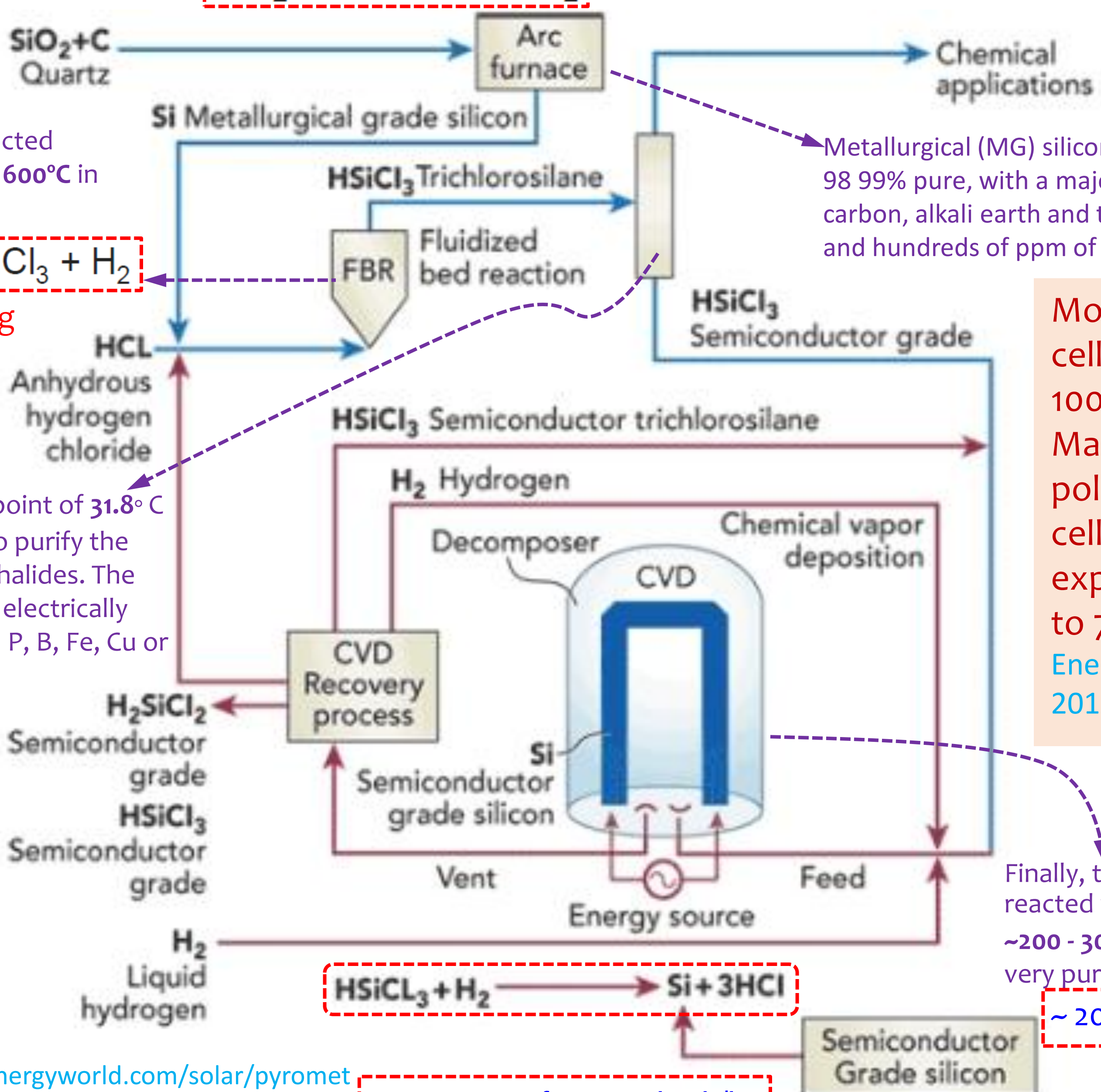
Reaction performed at **2000° C** in an Electrode Arc Furnace. Metallurgical (MG). Carbothermal reduction of SiO2, a 19th century chemical innovation.

Powdered MG-Si is reacted with anhydrous HCl at **600°C** in FBR to form $SiHCl_3$

$Si + 3HCl \rightarrow SiHCl_3 + H_2$

~ (200+ 50) kWh/kg

Metallurgical (MG) silicon is produced with 98 99% pure, with a major contamination of carbon, alkali earth and transition metals, and hundreds of ppm of B and P.



Mono-crystalline cells require up to 1000 kWh/kg-Si. Manufacturing of poly-crystalline cells has energy expenditures of up to 700 kWh/kg-Si. Energy Procedia 33, 2013, 322 – 334.

$SiHCl_3$ has a low boiling point of **31.8°** C and **distillation** is used to purify the $SiHCl_3$ from the impurity halides. The resulting $SiHCl_3$ now has electrically active impurities (e.g. Al, P, B, Fe, Cu or Au) of less than 1 ppb.

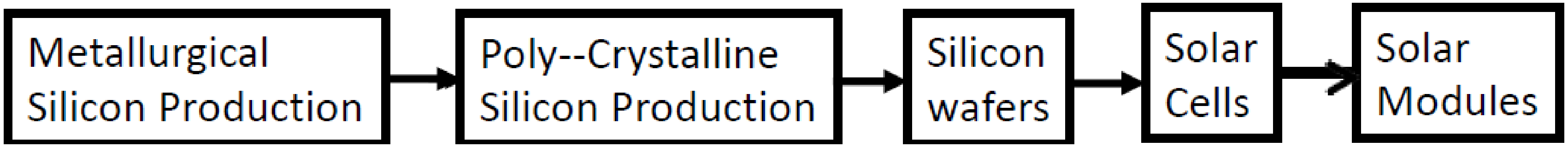
~ (100 + 50) kWh/kg

Finally, the pure $SiHCl_3$ is reacted with H_2 at **1100° C for ~200 - 300 hrs** to produce a very pure form of silicon.

~ 200 kWh/kg

Ingots to wafer: ~ 50 kWh/kg

https://www.renewableenergyworld.com/solar/pyrometers-improve-quality-and-yield-in-silicon-growth/#gref



IS SILICON PV GREEN ENERGY ?

Consider the following facts

- Solar PV manufacturing processes involve converting quartz to metallurgical grade silicon and then to polysilicon ingots which are sliced to form wafers
- Every ton of metallurgical grade silicon production results in 4 tons of silicon tetrachloride; Material utilization efficiency is a mere 30%
- 1 ton of crude silicon production results in 10 tons of CO_2; Purification process results in additional 45 tons of CO_2; for manufacturing in China, 70 g CO_2 is generated per kWh of electricity

Total energy expenditure for solar cell manufacturing

The total energy expenditure for solar cell manufacturing is the sum of the aforementioned processes. Mono-crystalline cells require up to 1000 kWh/kg-Si. Manufacturing of poly-crystalline cells has energy expenditures of up to 700 kWh/kg-Si.

Other Issues:

- Silicon production uses SF_6 (to clean the Siemens Reactor: a potent GHG), HF (to clean wafers and texture the surfaces), 1,1,1 trichloroethane (a persistent pollutant) and large quantities of strong acids.
- Conversion of ingots to wafers requires mechanical sawing, generating up to 10 % waste and a significant amount of fine silicon dust (inhalation hazard)
- Silver that is used for making panels at 5 % of current power demand will consume 50% of current silver produced.
- Little or no recycling of silicon in process waste or end of life panels

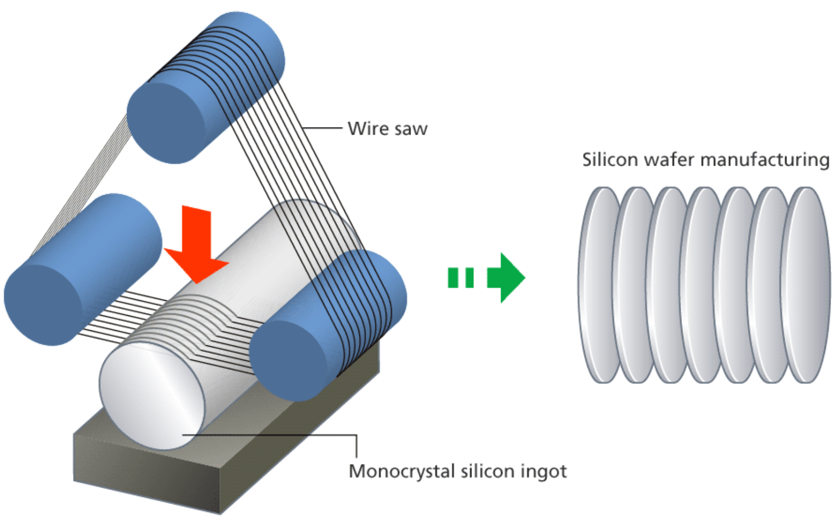
1,1,1 trichloroethane (TCA) remains a persistent pollutant at many sites and some of the daughter products that accumulate from intrinsic decay of TCA have been determined to be more toxic than the parent compound. [Water Research, 2011, 45, 2701-2723]

Table 3. Emissions form photovoltaic module and system.

Energy Procedia 33 (2013) 322 – 334

		SO_2	NO_x	Particles	CO_2	CH_4	N_2O	Source
Emissions (kg/kW_p)	PV Module 1995/1998	5 - 5.5	4.5 - 5.3	No Info	2.7 - 3.8	No Info	No Info	[5, 6]
	Entire PV System 1998	1.9	1.8	0.11	971,000	1.6	0.0031	[3]

Schematic of c-Si PV module supply chain



MAKING SILICON IS AN EXPENSIVE PROCESS

- High temperatures, invariably produced using electrical energy
- Long reaction times
- Several unit & Batch processes
- Large number of waste and by products
- Highly corrosive environment

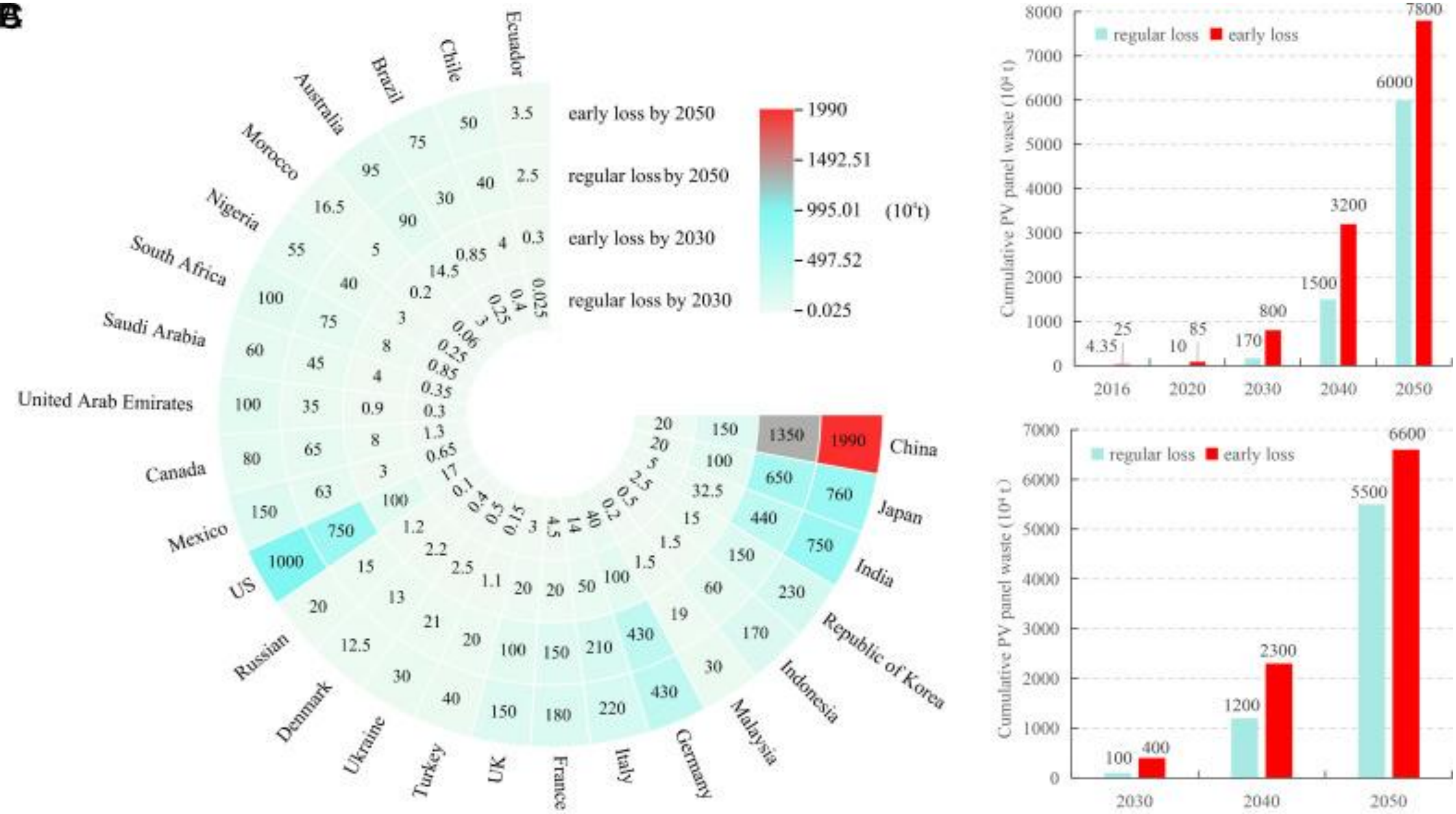
Socio-Economic and Environmental Impacts of Silicon Based Photovoltaic (PV) Technologies; Energy Procedia 33 (2013) 322 – 334

Global capacity for solar grade silicon : ~ 0.5 million tons per annum
Minimum viable economic capacity : 10,000 tons per annum
Highly capital intensive : US $1.5 million per ton of production

By contemporary standards of chemical manufacturing, the process for producing silicon is a highly complex process

- By 2030, the world is likely to face **at least ~1–2 million tonnes** of PV panel waste if current lifetimes hold and major premature retirements don't dominate.
- If lots of panels are retired early (due to fast technology turnover, damage, migration to newer systems, etc.), we could be looking at **several million tonnes** (approaching ~5–10 million tonnes) by 2030.
- The waste problem will surge more strongly after 2030, as many panels installed in the 2010s and 2020s start reaching end-of-life. For example, by 2050 projections go up to ~60-80 million tonnes globally

Proc Natl Acad Sci U S A. 2025 Jul 2;122(27):e2417921122



Proc Natl Acad Sci U S A. 2025 Jul 2;122(27):e2417921122

The future of PV decommissioning. Under regular loss and early loss scenarios, the figure indicates (*A*) modeled results of estimated cumulative waste volumes of EOL PV panels in major countries by 2030 and 2050; (*B*) global PV panel waste projections, 2016–2050; and (C) China PV panel waste projections in 2030, 2040, and 2050 by the China ECOPV Alliance. Image credit: Siyou Xia, plotted from data in refs. 3 and 4.

The boom in installation of solar photovoltaic (PV) panels in recent decades has helped nations tackle their carbon emissions. But the technology has a useful lifespan of about 25–30 years, which means a rapidly growing number of PV panels will soon need to be disposed of (1). And while the environmental impact of their construction has received much attention, what happens at the end of their life cycle has garnered less scrutiny. At present, only about 10% of PV panels are recycled, with the majority being dumped, burned, or buried.

Proc Natl Acad Sci U S A. 2025 Jul 2;122(27):e2417921122

•3. IRENA, IEA, End-of-life management: Solar photovoltaic panels (2016). https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf?rev=49a75178e38c46288a18753346fb0b09. Accessed 20 June 2025.

•4. China ECOPV Alliance, Latest research findings on accurate forecasts for China’s photovoltaic recycling market (2023). http://www.ecopv.org.cn/site/content/1197.html. Accessed 20 June 2025.

Global PV Module Waste Projections to 2050 [Cumulative Waste Estimates]

These numbers account for the expected lifetime of PV panels, historical and projected installations, and potential early retirements.

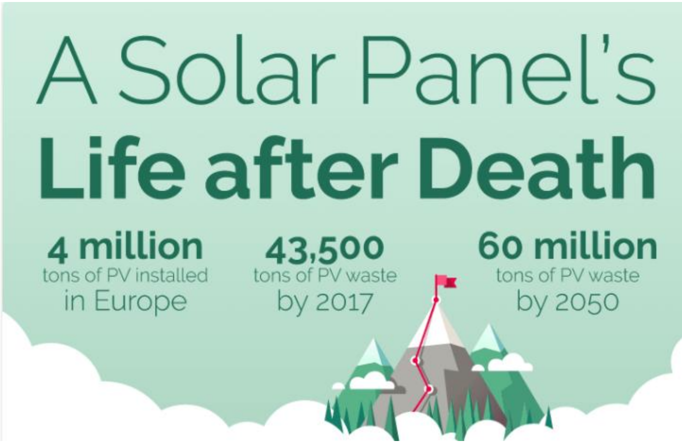
Scenario	Global cumulative PV waste by 2050
Regular-loss (modules last 25–30 yrs)	~60–70 million tonnes
Early-loss / accelerated retirement	~78–80 million tonnes

Key Drivers

1. Aging of early PV installations: Panels installed in the 2000s–2020s will start reaching end-of-life in the 2030s–2040s.
2. Rapid growth of new installations: Solar capacity is expanding fast, especially in Asia, the U.S., and Europe, adding future waste.
3. Early replacement/upgrades: Faster technological turnover (e.g., more efficient modules) accelerates waste accumulation.

Recycling & Circular Economy

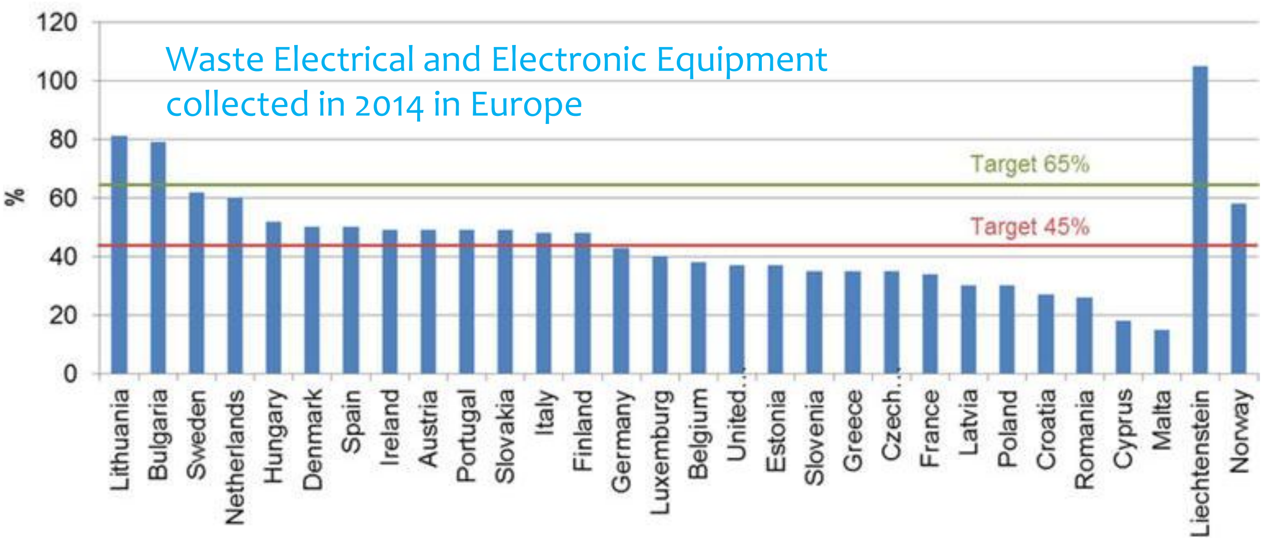
- Current global recycling rates are very low (~5–10%), but new policies (EU, China, U.S.) aim to increase recovery.
- By 2050, **tens of millions of tonnes** of recoverable silicon, glass, and metals (Ag, Al, Cu) will become available.
- Effective recycling and reuse could **reduce environmental impact** and provide **raw materials** for new PV production.



The worldwide solar PV waste is estimated to reach around 78 million tones by 2050

Recycling will help to produce 2 billion new panels without the need to invest in raw materials. Additional capacity of 630 GW of energy can be achieved through use of recycled material.

A typical crystalline silicon (c-Si) PV module contains approximately 75% of the total weight is from the module surface (glass), 10% polymer (encapsulant and back sheet foil), 8% aluminum (mostly the frame), 5% silicon (solar cells), 1% copper (interconnectors) and less than 0.1% silver (contact lines) and other metals (mostly tin and lead). Lead and tin, if leached into soil and groundwater cause health and environmental concerns, while copper, silver, and silicon present a value opportunity if recovered efficiently.



Since February 2014, the collection, transport and recycling of PV modules that reached their end-of-life is regulated in every EU country. Waste Electrical and Electronic Equipment

The EU directive established recycling targets in terms of module weight and also expresses the intention to increase the collection rates to allow the progressive recycling of more material and less to be landfilled.

Among the valuable materials in the panel, silicon presents the best opportunity, given its considerably larger fraction and its ultra-high purity (99.9999% or six nines/6N). The solar-grade silicon from PV waste can be recovered for second-use applications in solar panels or repurposed for value-added application in the anode of the 3b generation of Lithium-ion batteries.

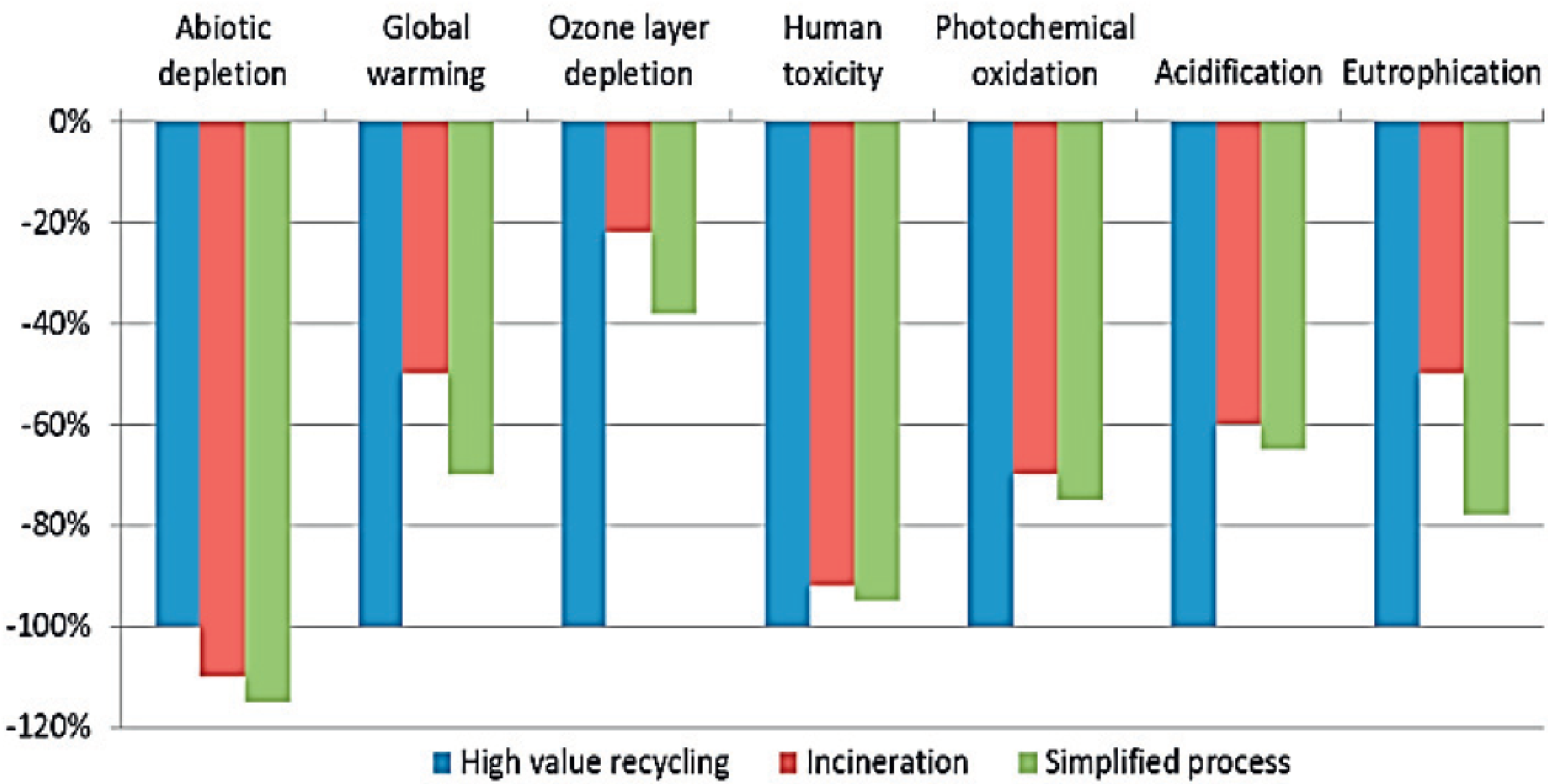
Today's EV batteries are an essential part of the total EV cost (33% to 57% depending on the car), and materials production is the dominant contributor to the energy cost of making the batteries. Cost-cutting strategies rely heavily on innovations at the materials level, i.e. raw materials sourcing and processing.

In 2015, Elon Musk claimed that silicon in Model S batteries increased the car's range by 6%. Ever since, EV companies like Daimler and BMW have also been actively engaged in research and development programs to synthesize battery-grade silicon for EV applications.

4. Environmental impacts of recycling and energy payback time

Following scenarios were analysed to compare the environmental impact of recycling of PV modules (Figs. 8 and 9) [11]:

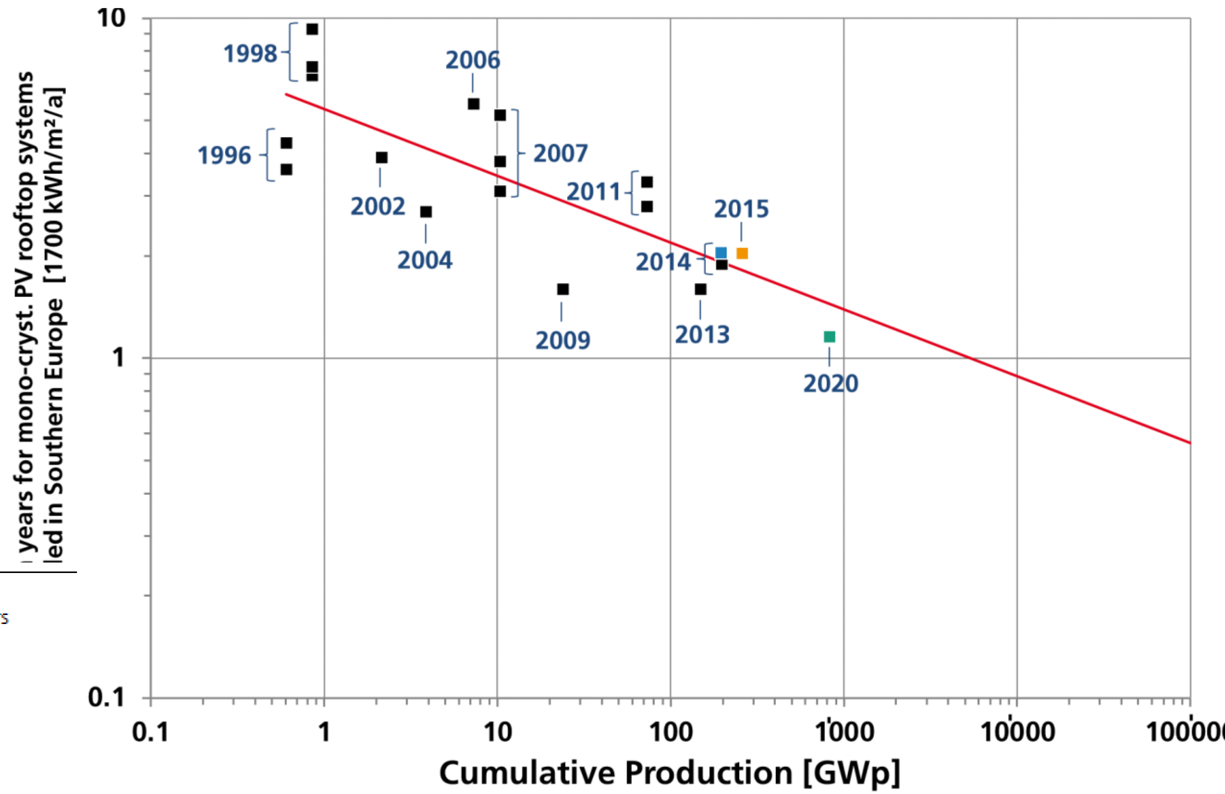
- High value recycling: recovery of silicon and all valuable substances
- Simplified process: crushing, incineration of plastic materials in MWI, disposal of inorganic components
- Incineration of modules without prior material separation



Executive Summary
Price Development

- In Germany prices for a typical 10 to 100 kWp PV rooftop-system were around 14,000 €/kWp in 1990. At the end of 2020, such systems cost only 7.4% of the price in 1990. This is a net-price regression of about 92% over a period of 30 years.
- The Experience Curve – also called Learning Curve - shows that in the last 40 years the module price decreased by 26% with each doubling of the cumulated module production. Cost reduction results from economies of scale and technological improvements.

Learning Rate: Each time the cumulative production doubled, the EPBT went down by 12.8 % for the last 24 years.
Irradiation: 1700 kWh/m²/a at an optimized tilt angle;
Years: Estimated average year of original data.



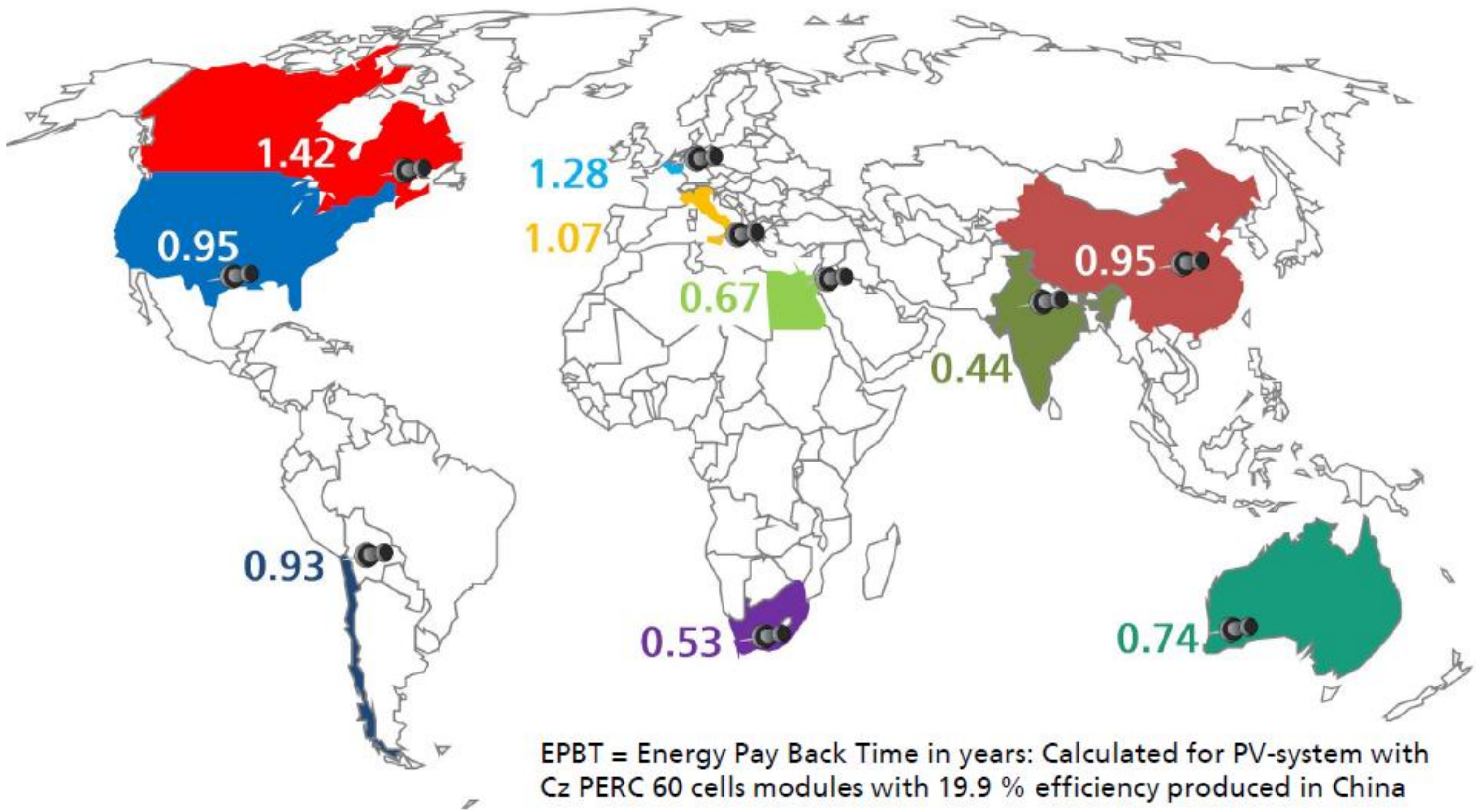
Harmonization methodology
based on Koppelaar (2016) harmonized results and harmonization parameters

1) Performance Ratio	
based on average annual PV yield during lifetime	
PV system lifetime	25
Degradation	0.70%
PR (initial)	80%
PR (incl. average degradation during lifetime)	**73.6%**
2) Grid efficiency	
for converting PV yield in primary energy equivalents	
grid efficiency	**35%**

EPBT of Leccisi (2016), Louwen (2014) and Friedrich (2020) were harmonized with 1) PR (incl. average degradation) and 2) grid efficiency to results of Koppelaar (2016)*

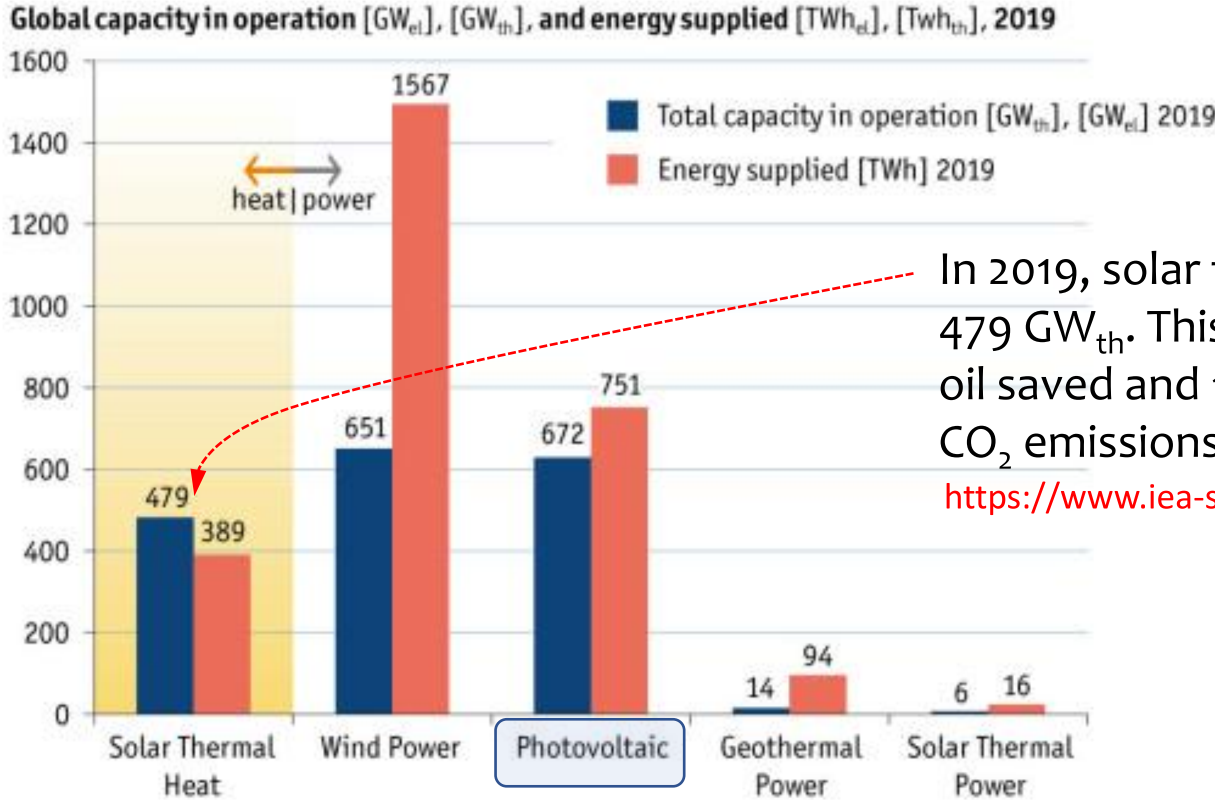
Data: Lorenz Friedrich, Fraunhofer ISE. Graph: PSE 2021

EPBT



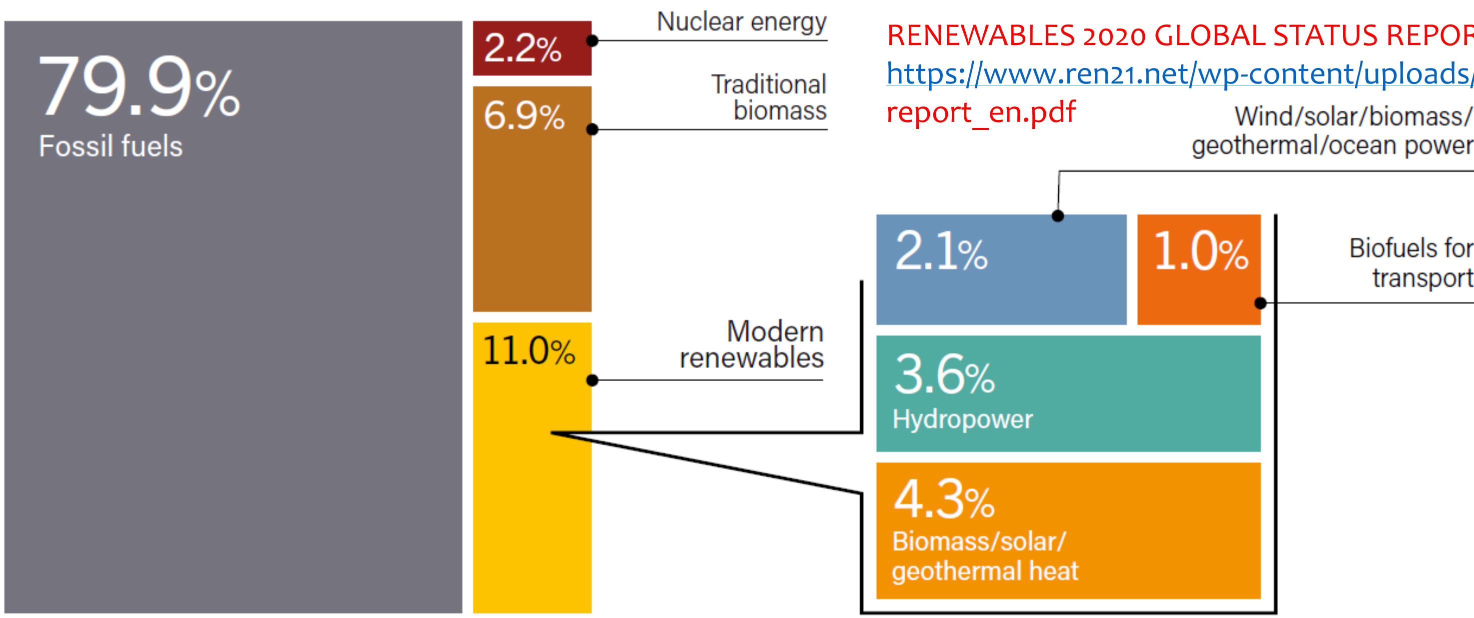
Influencing factors and interpretation:

- Energy Pay Back Time: The lower, the better
- Irradiation: The higher, the better
- Grid efficiency: The higher, the better



In 2019, solar thermal systems produced 479 GW_{th}. This equates to 43 million tons of oil saved and 138 million tons of CO_2 emissions avoided.

https://www.iea-shc.org/solar-heat-worldwide-2020



RENEWABLES 2020 GLOBAL STATUS REPORT

https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf https://www.irena.org/climatechange/Avoided-Emissions-Calculator: 26-8-21

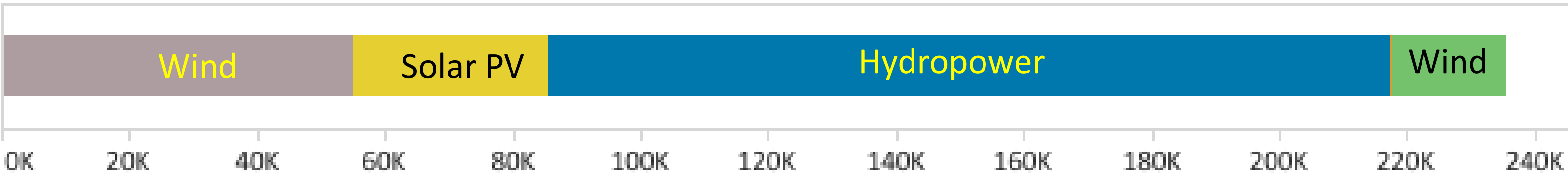
Avoided Emissions Calculator

1. Select Country/area
India

Select Technology
All

Select Year
2018

2. Electricity Generated from Renewables (GWh) (India, 2018)

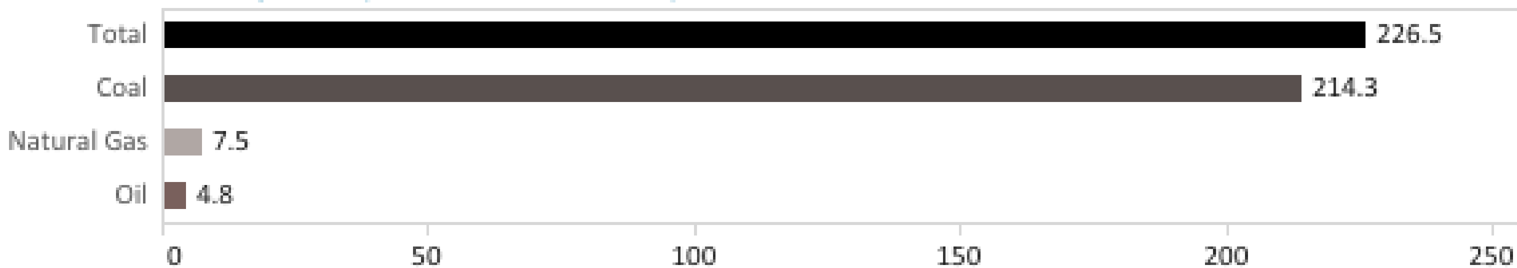


3. Fossil Fuel Mix Replaced

Select your scenario:

	Coal%	Natural Gas%	Oil%
◉ Default Values	*90.8*	*6.8*	*2.4*
○ Define Mix	50	20	30

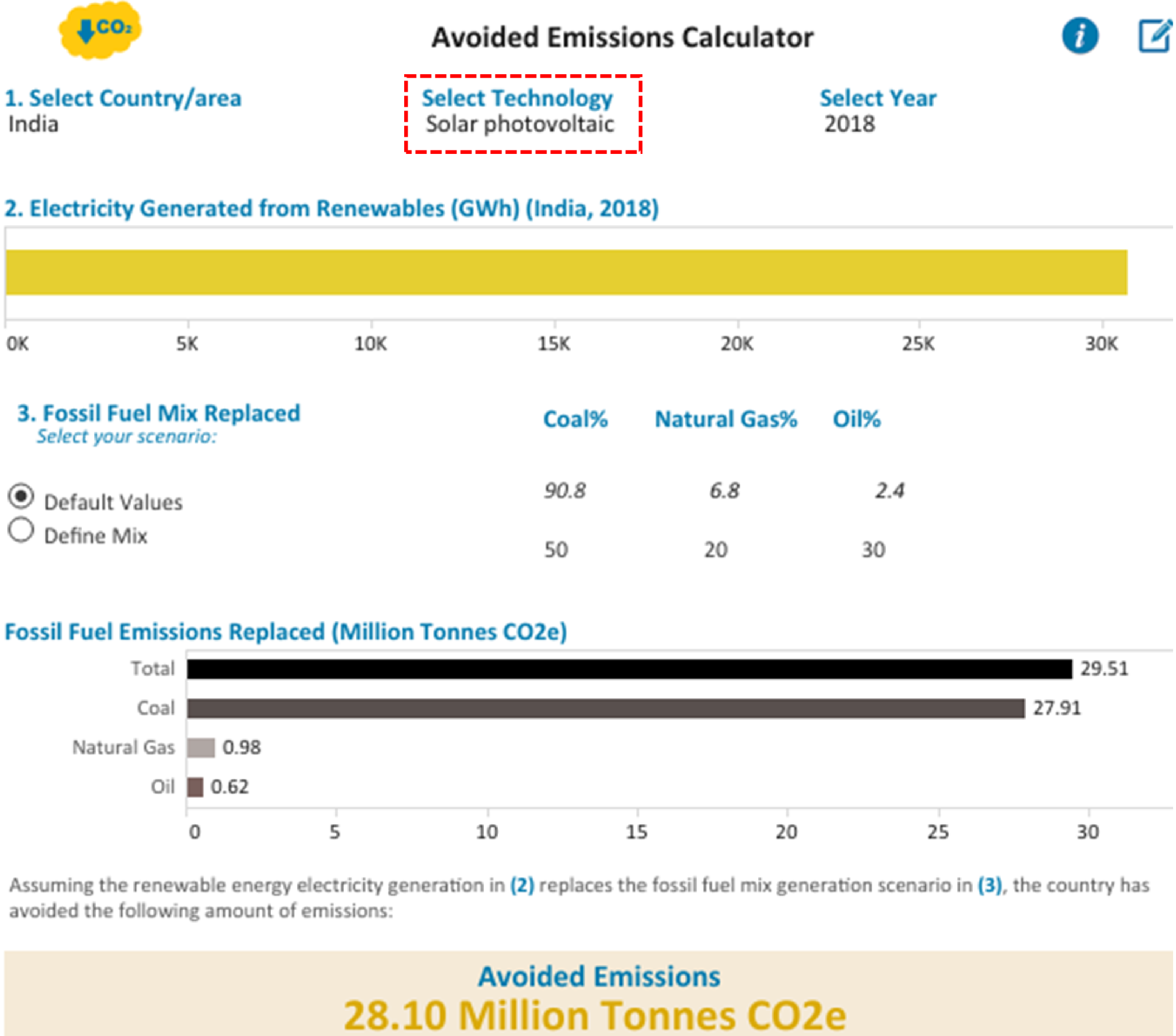
Fossil Fuel Emissions Replaced (Million Tonnes CO2e)



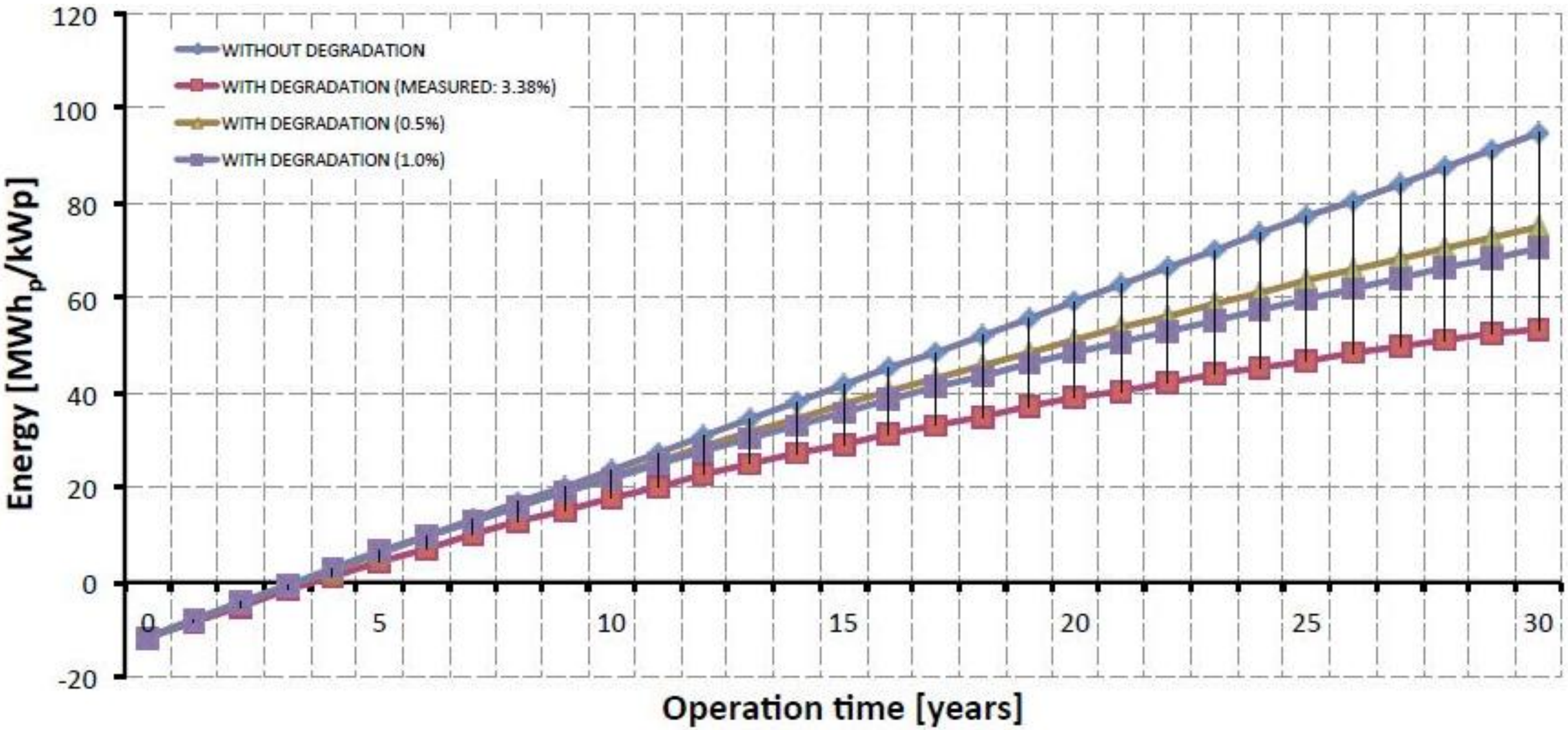
Assuming the renewable energy electricity generation in **(2)** replaces the fossil fuel mix generation scenario in **(3)**, the country has avoided the following amount of emissions:

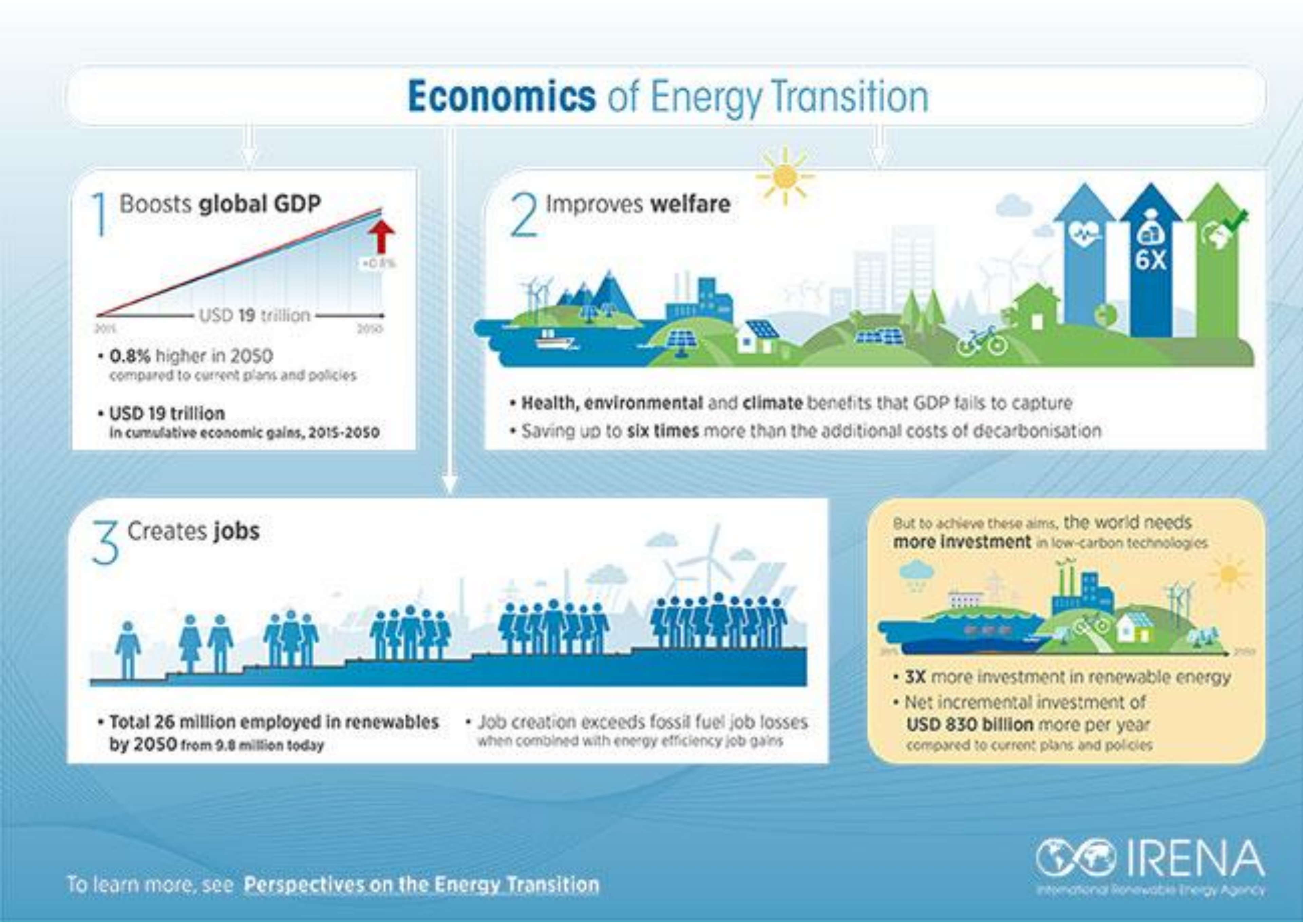
Avoided Emissions
223.6 Million Tonnes CO2e

India: Solar PV [2018]
Elec. Generated: 30,707 GWh
Renewable energy Emissions:
1.4 Million Tones CO2e

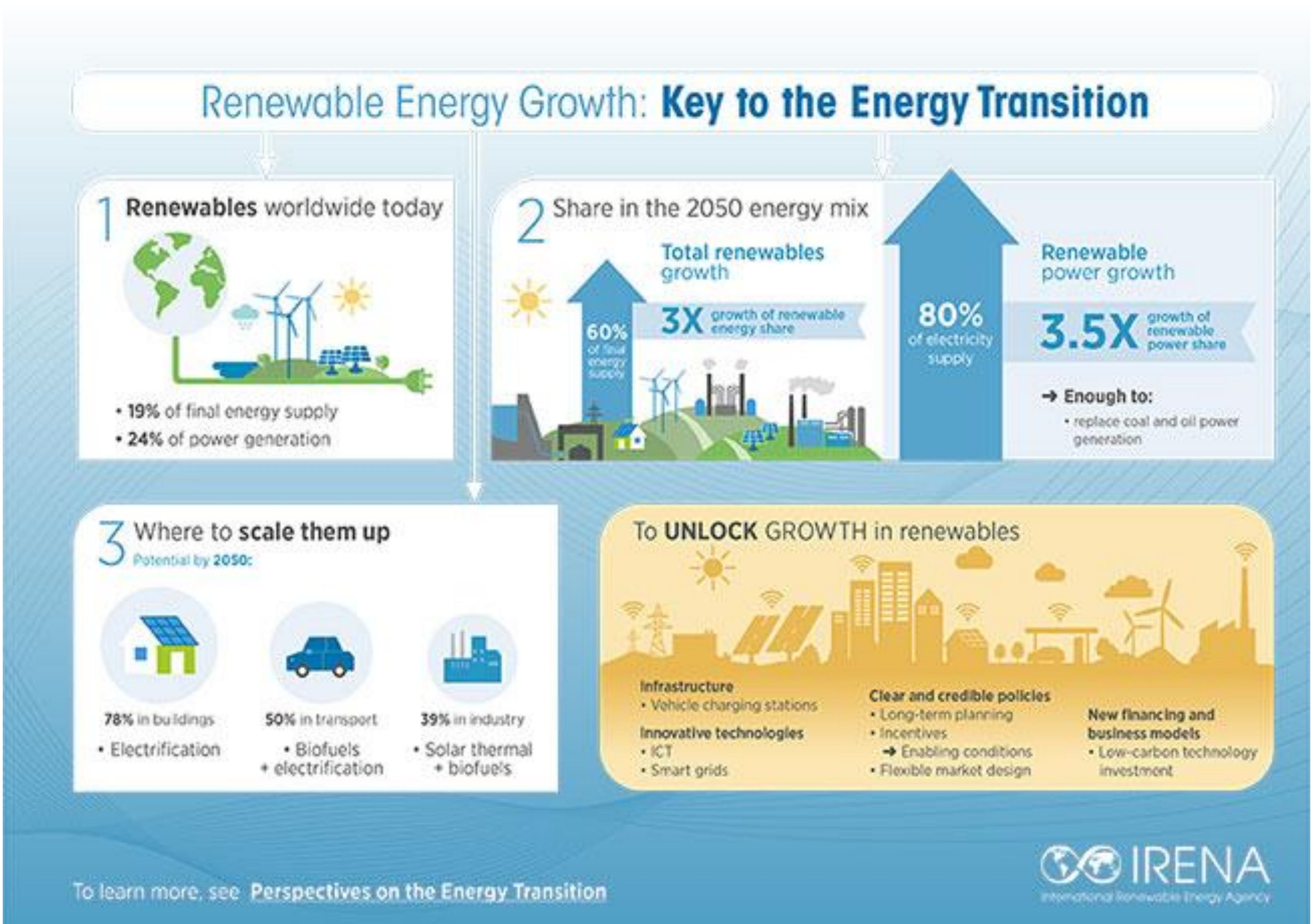

Avoided Emissions Calculator
1. Select Country/area
India
Select Technology
Solar photovoltaic
Select Year
2018
2. Electricity Generated from Renewables (GWh) (India, 2018)
0K
5K
10K
15K
20K
25K
30K
3. Fossil Fuel Mix Replaced
Select your scenario:
Coal%
Natural Gas%
Oil%
Default Values
90.8
6.8
2.4
Define Mix
50
20
30
Fossil Fuel Emissions Replaced (Million Tonnes CO2e)
Total
29.51
Coal
27.91
Natural Gas
0.98
Oil
0.62
0
5
10
15
20
25
30
Assuming the renewable energy electricity generation in (2) replaces the fossil fuel mix generation scenario in (3), the country has avoided the following amount of emissions:
Avoided Emissions
28.10 Million Tonnes CO2e

Hypothetical solar cell with 3.5 years of EPBT

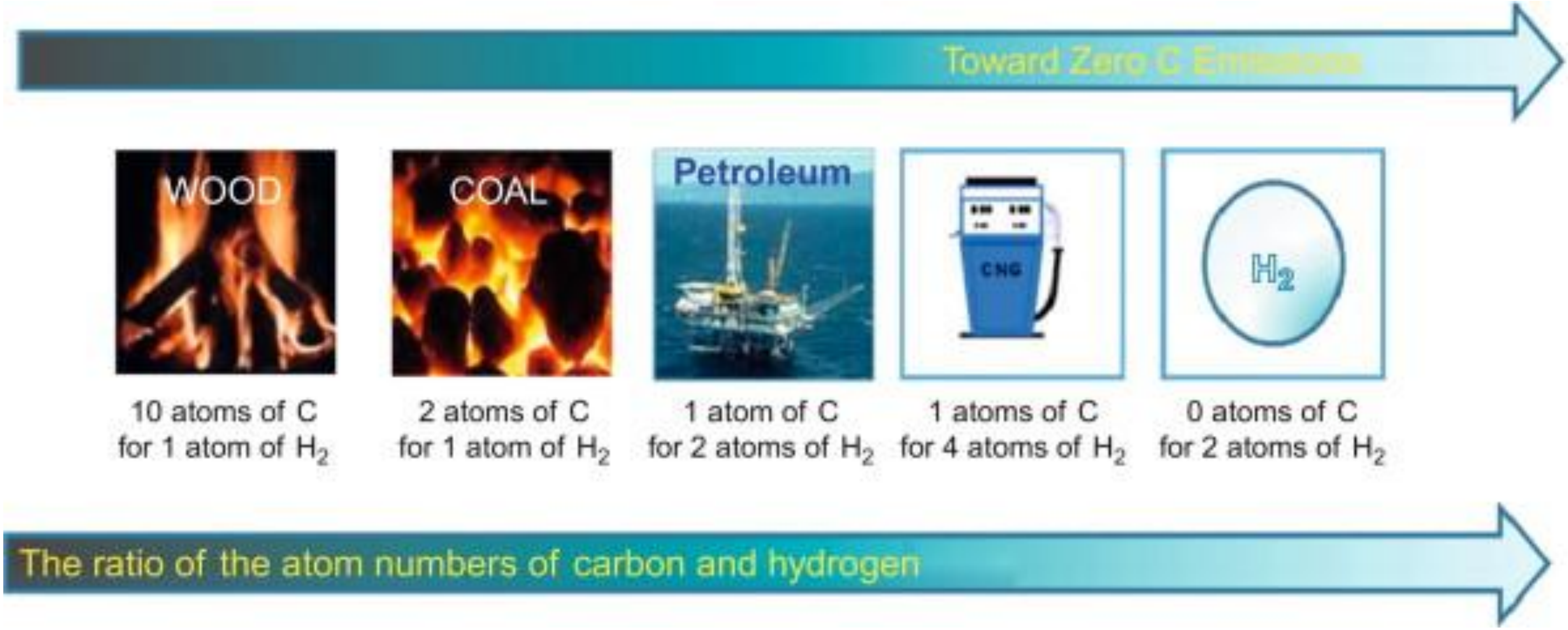




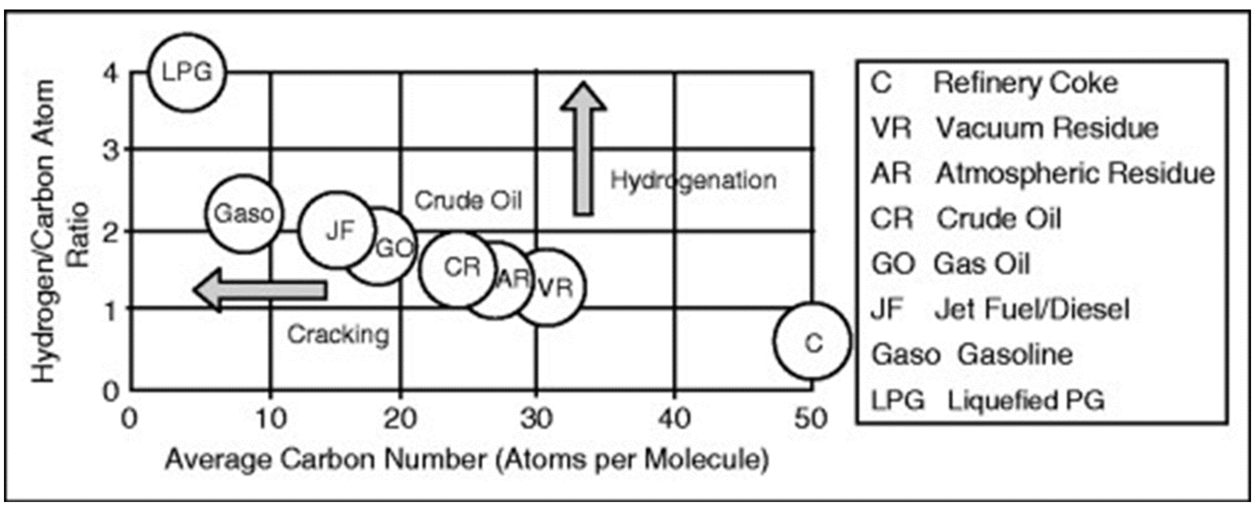
Economics of Energy Transition
1 Boosts global GDP
+0.8%
USD 19 trillion
2015
2050
• 0.8% higher in 2050
compared to current plans and policies
• USD 19 trillion
in cumulative economic gains, 2015-2050
2 Improves welfare
6X
• Health, environmental and climate benefits that GDP fails to capture
• Saving up to six times more than the additional costs of decarbonisation
3 Creates jobs
• Total 26 million employed in renewables by 2050 from 9.8 million today
• Job creation exceeds fossil fuel job losses when combined with energy efficiency job gains
But to achieve these aims, the world needs more investment in low-carbon technologies
• 3X more investment in renewable energy
• Net incremental investment of USD 830 billion more per year compared to current plans and policies
To learn more, see Perspectives on the Energy Transition
IRENA
International Renewable Energy Agency



Renewable Energy Growth: Key to the Energy Transition
1 Renewables worldwide today
• 19% of final energy supply
• 24% of power generation
2 Share in the 2050 energy mix
Total renewables growth
60% of final energy supply
3X growth of renewable energy share
80% of electricity supply
Renewable power growth
3.5X growth of renewable power share
➔ Enough to:
• replace coal and oil power generation
3 Where to scale them up
Potential by 2050:
78% in buildings
• Electrification
50% in transport
• Biofuels + electrification
39% in industry
• Solar thermal + biofuels
To UNLOCK GROWTH in renewables
Infrastructure
• Vehicle charging stations
Innovative technologies
• ICT
• Smart grids
Clear and credible policies
• Long-term planning
• Incentives
➔ Enabling conditions
• Flexible market design
New financing and business models
• Low-carbon technology investment
IRENA
International Renewable Energy Agency
To learn more, see Perspectives on the Energy Transition



Toward Zero C Emissions
WOOD
COAL
Petroleum
CNG
H_2
10 atoms of C for 1 atom of H_2
2 atoms of C for 1 atom of H_2
1 atom of C for 2 atoms of H_2
1 atoms of C for 4 atoms of H_2
0 atoms of C for 2 atoms of H_2
The ratio of the atom numbers of carbon and hydrogen



Hydrogen/Carbon Atom Ratio
Average Carbon Number (Atoms per Molecule)
0
1
2
3
4
0
10
20
30
40
50
LPG
Gaso
JF
GO
CR
AR
VR
C
Crude Oil
Hydrogenation
Cracking
C Refinery Coke
VR Vacuum Residue
AR Atmospheric Residue
CR Crude Oil
GO Gas Oil
JF Jet Fuel/Diesel
Gaso Gasoline
LPG Liquefied PG