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Scaling Solar

Hyae Ryung Kim, Marcelo Cibie, Max de Boer, Lara Geiger, Isabel Hoyos, Heonjae Lee, Taicheng Jin, Hassan Riaz, and Gernot Wagner

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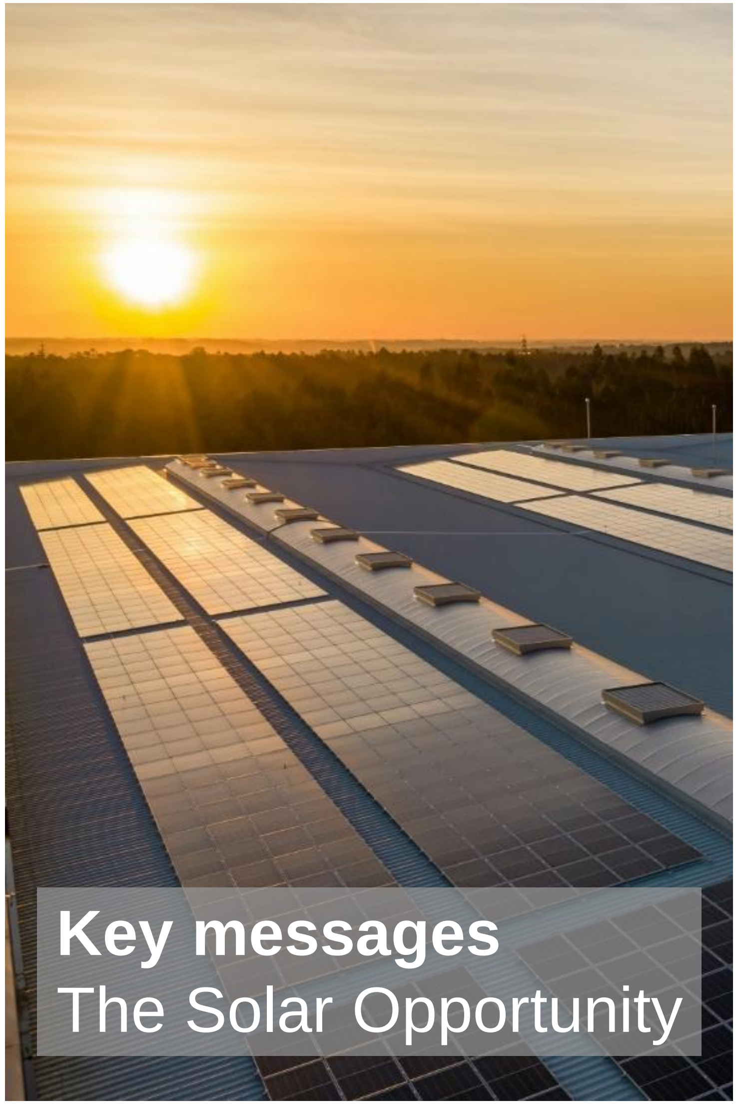
The Solar Opportunity



Key messages
The Solar Opportunity

Solar can abate 5.5 to 10 gigatonnes (Gt) of CO_2e by 2050 in select subsectors, including 24% to 43% of power and heat, depending on the transition scenario.

Solar PV **prices dropped ~99.8% since 1975**, driven by **economies of scale** known as **Swanson's law,** in which each doubling of installed capacity has led to an average price drop of ~20%. This was initially caused by the **improvement of module efficiency;** after 2001, **economies of scale** became a significant driver of cost reduction.

Solar electricity generation reached **~1,600 terawatt-hours (TWh) of global capacity in 2023** with 23% CAGR from 2018 to 2023, exceeding growth expectations at every stage.

Solar PV systems can be classified according to **purpose and size**:

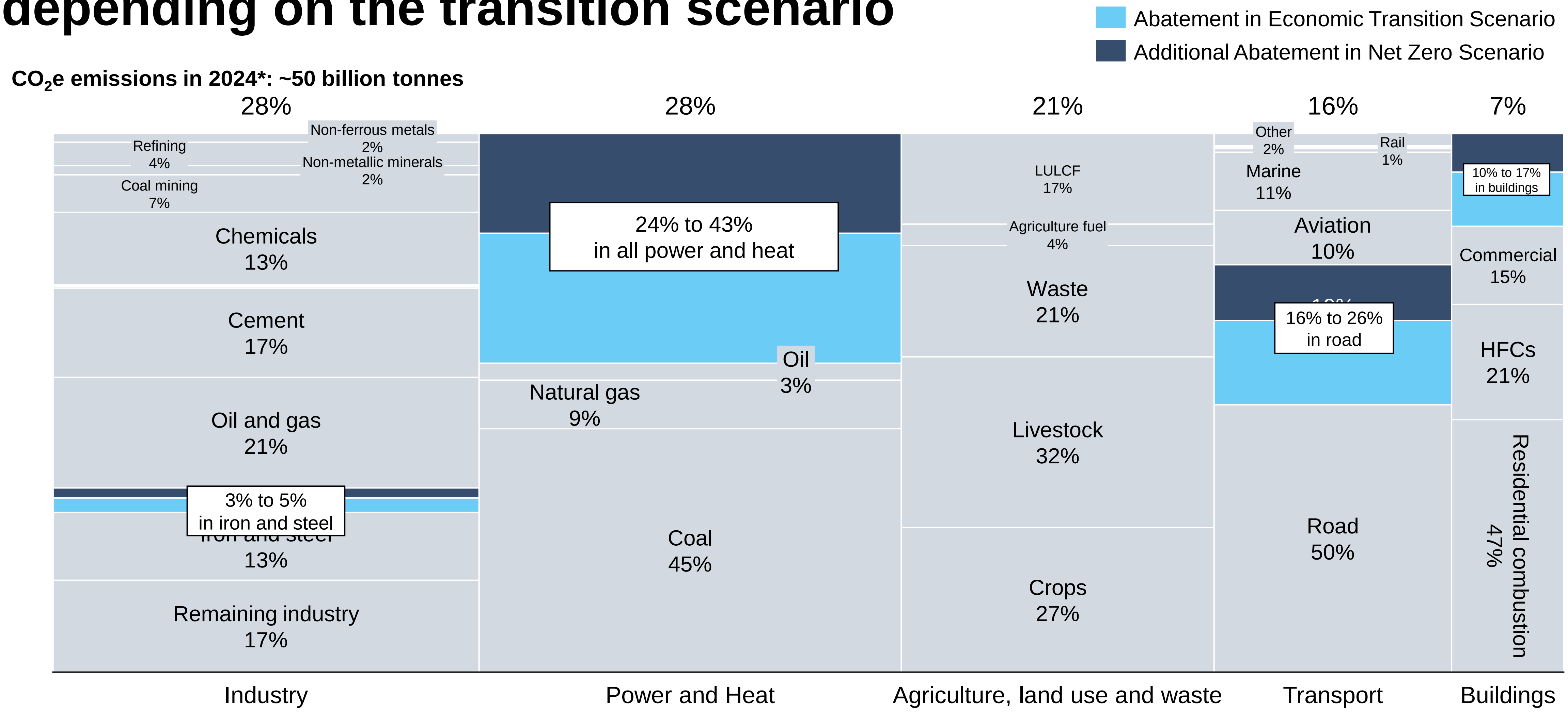
1. **Residential** system typically ~0.002 to 0.02 megawatts (MW); installed capacity is ~357 GW (2024)
2. **Commercial and Industrial** system typically ~0.02 to 5 MW; installed capacity is ~522 GW (2024)
3. **Utility** system typically ~1 to 1,000 MW*; installed capacity is ~1,226 GW (2024)

Solar projects require a **substantial upfront investment** in equipment, installation, and site preparation:

- Typical system cost is ~3.15$/Watt for **residential**; ~1.51$/Watt for **commercial & industrial**, and ~1.12$/Watt for **utility-scale (1Q24)**.
- However, they have **relatively low maintenance costs** relative to other energy sources, and given electricity savings, tax benefits, and potential revenue generation, the payback period typically ranges from ~2 to 10 years.

(*) Exact classification boundaries vary by sources; the authors present a rough estimation from a combination of sources.

Solar can abate 5.5 to 10 Gt of CO_2e by 2050 in select subsectors depending on the transition scenario



(*) 2024 emissions based on projections.
Sources: Rhodium Group, Climate Deck (2024); BNEF, New Energy Outlook (2025); IRENA, Transport (2025); IEA, Net Zero by 2050 (2023); Way *et al.*, Empirically Grounded Technology Forecasts and the Energy Transition (2022).
Credit: Hassan Riaz, Theo Moers, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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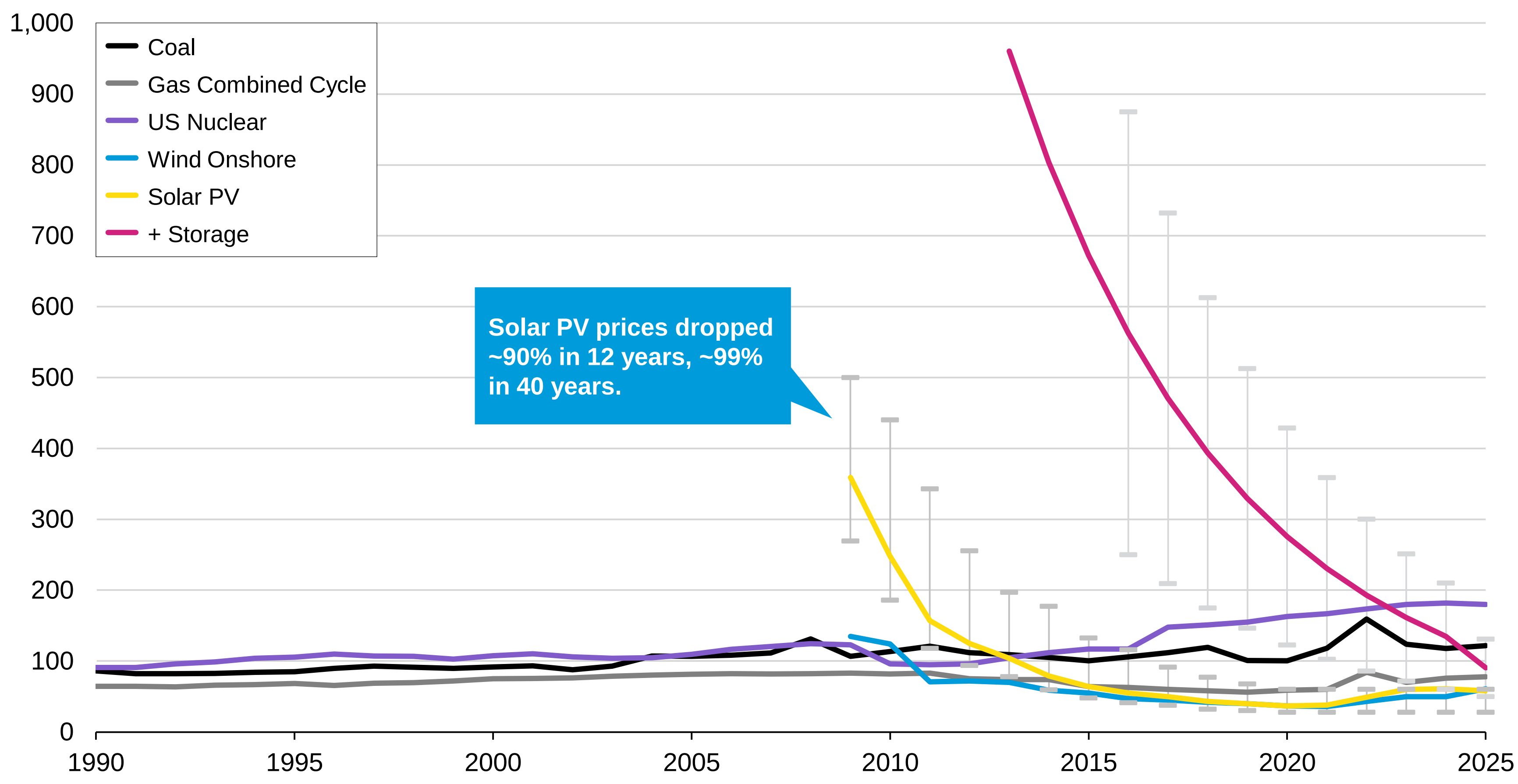
Utility-scale solar and wind now cheaper than fossil fuels, battery storage costs not far behind and falling fast

Levelized cost of electricity (LCOE) & storage (LCOS) ($USD/MWh)



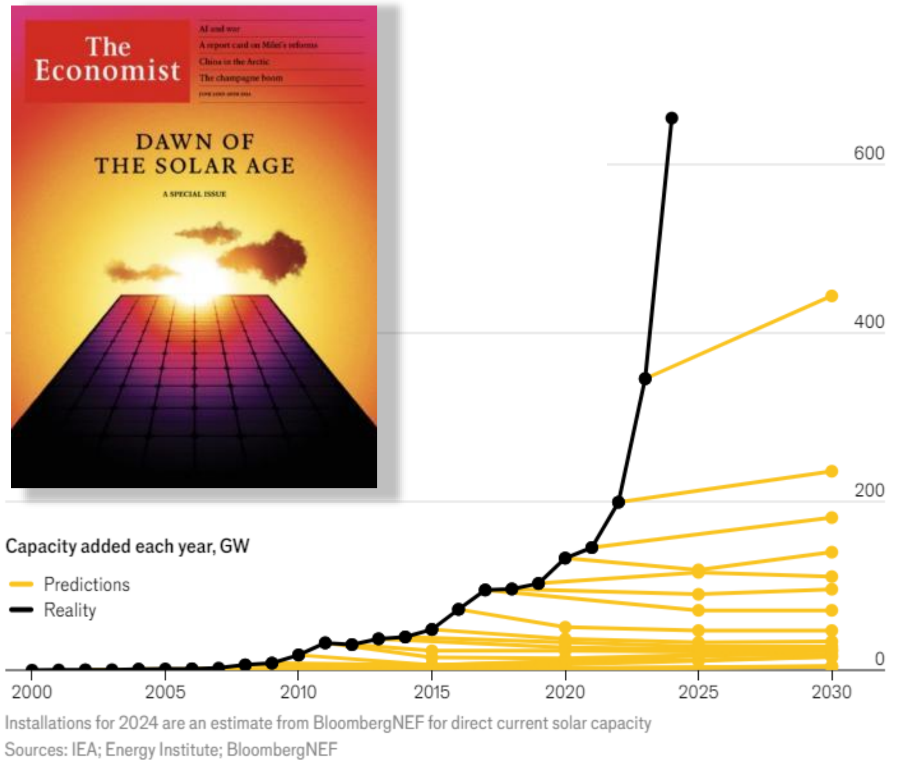
Observations

- **Solar photovoltaic (PV) prices dropped by ~80% in the past decade,** wind by ~70%, and lithium-ion battery costs by ~90%.
  - PV price drop primarily driven by **improvements in module efficiency** and **economies of scale.**
  - **Onshore wind** remained the cheapest for the longest, **now beaten by PV**.
  - Lithium-ion **battery costs fell 20% in 2023** alone.
- **Gas combined cycle** power plants **cheaper than coal**, more expensive than both solar and wind.
  - Rapid scale-up of utility-scale batteries "killer app" to replace gas on grid.
  - **Battery prices expected to continue falling** due to cell manufacturing overcapacity, economies of scale, and switch to lower-cost lithium-iron-phosphate (LFP) batteries.

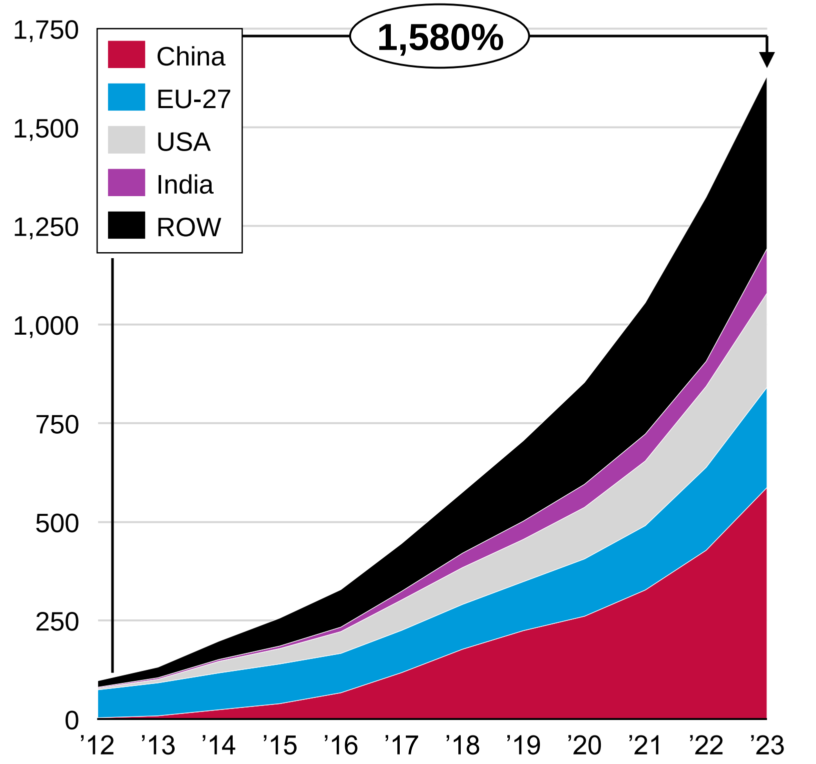
Sources: Lazard, LCOE+ (2025); Our World in Data, Our World in Data (2024); Energy Institute, Statistical Review of World Energy (2024); BNEF, Battery Price Survey (2024); Kavlak *et al.*, Evaluating the Causes of Cost Reduction in Photovoltaic Modules (2018).
Credit: Hyae Ryung Kim, Xiaodan Zhu, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Past solar adoption has exceeded expectations at every stage; China has led most installed capacity growth

Expectation vs. reality for solar deployment

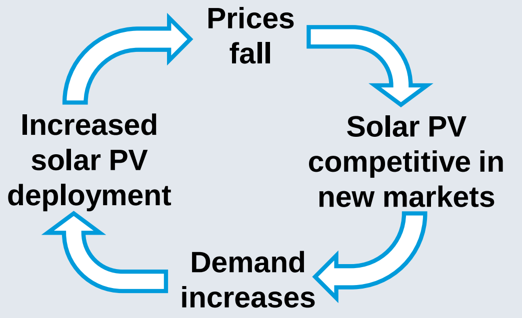


Global installed solar capacity (TWh)



Observations

- Solar PV deployment consistently **exceeds expectations** due to **Swanson's law**; increased deployment and lowered price lead to more demand and more installations:



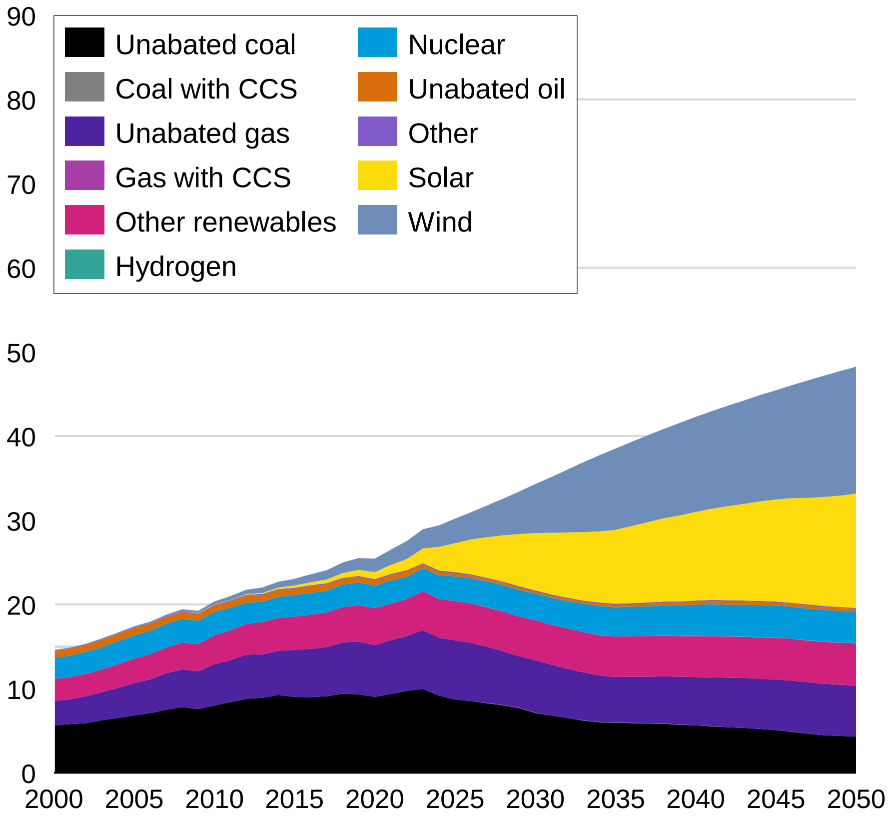
- The **main bottlenecks** for solar deployment are not technological maturity, economics, or supply constraints, but **grid stability, interconnection delays, and supportive policies.**

Sources: Sun Machines, The Economist; Our World in Data using IRENA (2023); Nemet (2009); Farmer and Lafond (2016); Kavlak et al. (2018); Our World in Data using Lafond et al. (2017), IRENA and de la Tour (2013); BloombergNEF (2024); Our World in Data, Our World in Data (2024).
Credit: Taicheng Jin, Hassan Riaz, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

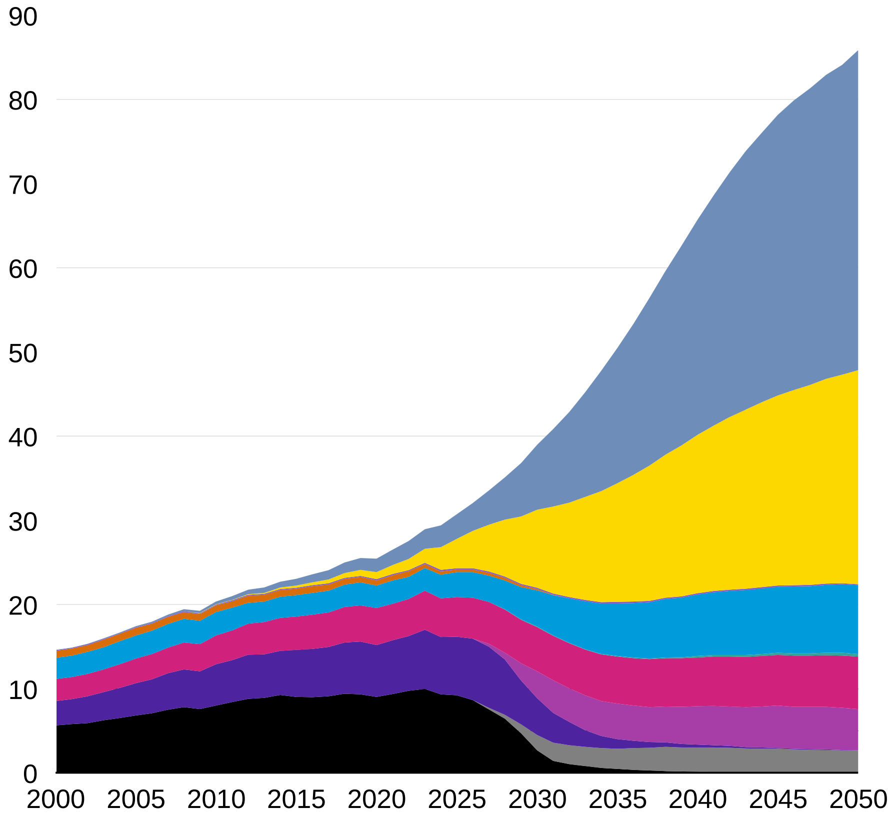
Solar and wind will drive most renewable energy deployment by 2050; must grow 15-fold in IEA's Net Zero Scenario

Solar PV generation must grow from 1,600 TWh in 2023 to 25,000 TWh in 2050

Economic Transition Scenario (ETZ) in thousands TWh



Net Zero Scenario (NZS) in thousands TWh



Observations

- **Electricity generation is the largest source (36%)** of energy-related CO_2 emissions today.
- **Global electricity demand is expected to increase** from ~25,000 TWh in 2023 to ~60,000 TWh in 2050.
- **Increase in electricity demand** is driven by:
  - **Advanced economies:** Increased electrification and expansion of hydrogen electrolysis
  - **Emerging economies:** Population growth and increase in living standards
- In the predicted NZS by 2050 scenario, **solar is forecasted to reach 25,000 TWh of electricity per year** (~100% of today's energy production).
  - Forecast is based on current solar adoption trends, competing economics between other technologies, and total forecasted power generation.

Sources: BNEF, 1Q 2024 Global PV Market Outlook (2024); IEA, Electricity (2025).
Credit: Taicheng Jin, Hassan Riaz, Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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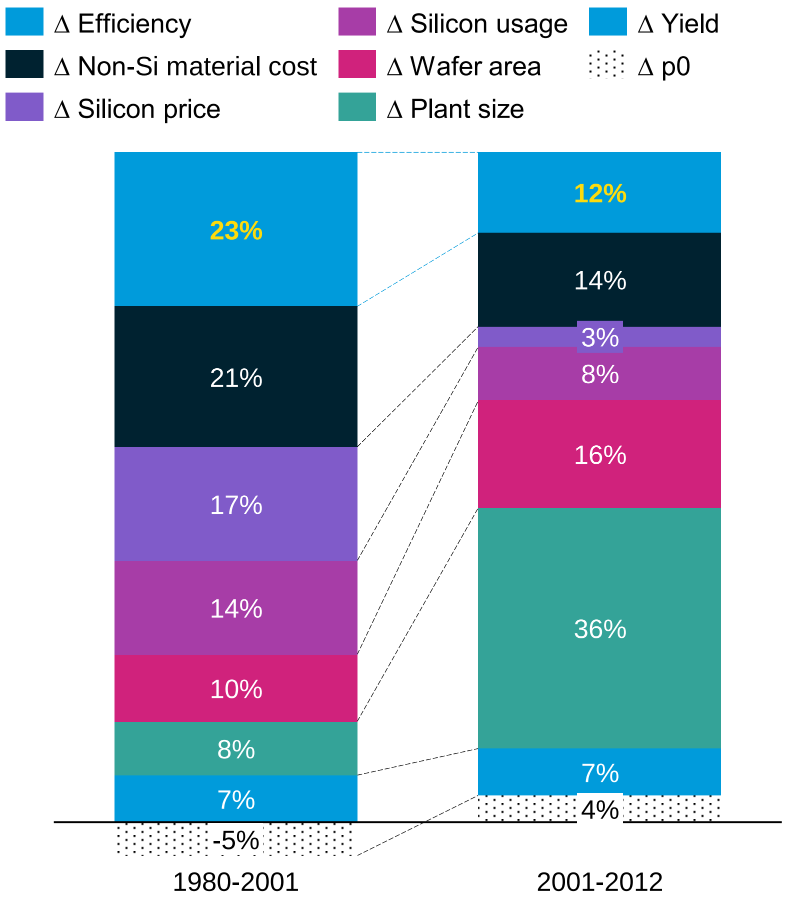
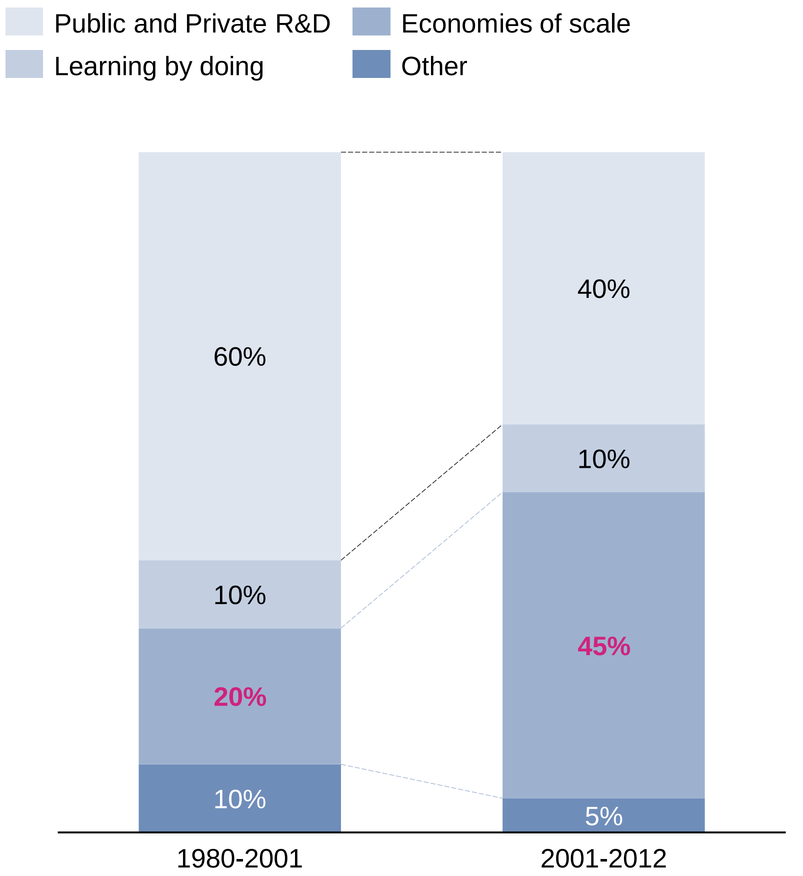
Price decreased initially due to R&D in module efficiency; since 2001, economies of scale has been the main driver

Cost change from technical variables*



Cost change from economic variables*



Observations

- **Technical variables** represent technical improvements, while **economic variables** include public and private R&D, learning by doing, economies of scale, and others.
- **Module efficiency** was the leading technical variable and public and private R&D was the leading economic variable for cost reduction between **1980 and 2001.**
- **After 2001**, **economies of scale** became a **significant driver** of cost reduction as the plant size increased.

(*) 1980-2001 price reductions scaled to 100% and align data with 2001-2012. The pre-factor in Equation (5) reflects the baseline operational costs such as electricity, labor, maintenance, and depreciation for a fixed size plant over time.
Source: Kavlak *et al.*, Evaluating the Causes of Cost Reduction in Photovoltaic Modules (2018).
Credit: Taicheng Jin, Isabel Hoyos, Hassan Riaz, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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Residential, commercial & industrial distinct from utility solar PV

	DISTRIBUTED SOLAR PV		UTILITY SOLAR PV
	Residential	**Commercial & industrial**	**Utility**
			
Description	• **Small systems**, most often on residential **rooftops** • Produce electricity directly for the **homeowners;** could **export and deploy excess amount to the grid**	• **Midsize systems,** often **mounted on the ground** or **flat roofs of commercial buildings** • Produce electricity **directly for the business use; could export and deploy excess amount to the grid**	• **Large, ground-mounted array** that **delivers power to the grid** • Often sell the pre-determined amount through a **Power Purchase Agreement (PPA)** to a utility off-taker • Supply electricity to **the designated customers through the grid**
Typical system size	**~0.002-0.02 MW**	**~0.02-5 MW**	**~1-1,000 MW**
Typical cost per kWh (LCOE*, 2025, US)	**$0.117-$0.282**	**$0.081 – $0.217/kWh**	**$0.038 – $0.078/kWh**
Global cumulative installed capacity (2024)	**357 GW**	**522 GW**	**1,226 GW**

(*) Unsubsidized LCOE (levelized cost of energy) is the average minimum price at which electricity generated must be sold to offset the total cost of production over the project's assumed lifetime.
The LCOE for commercial and industrial is an average of a commercial rooftop and a commercial ground system.
Sources: SEIA, Solar Industry Research Data (2025); IEA, Renewables 2023 (2024); US DOE, SunShot 2030 (2025); Lazard, LCOE+ (2025); Nuveen, Energy Transition Q2 2024 Update (2024).
Credit: Taicheng Jin, Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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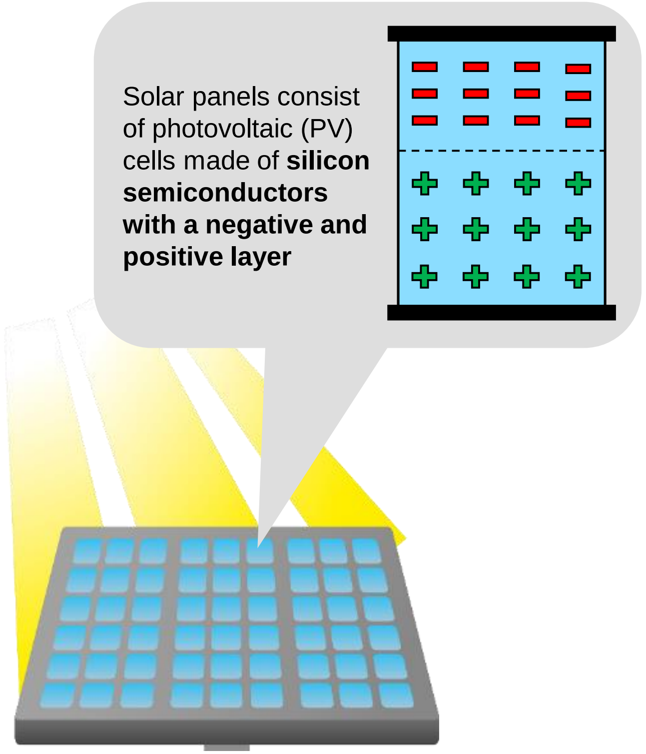
Typical solar project economics result in payback periods ranging from 2 to 10 years

Solar technology 101



Photons from sunlight hit solar cells and **release electrons**

↓

Freed electrons flow through the circuit and **produce an electric charge**

↓

Wiring in the panels **captures the direct electric current (DC)** generated

↓

An inverter converts the DC electricity into **alternating current (AC)** electricity to directly power buildings

↓

The **system is integrated** with the **energy grid** to supply excess AC electricity

Solar expenses

- **High CapEx:** Solar projects require substantial upfront investment in equipment, installation, and site preparation. The average residential system cost is $10,000 to $25,000, with a levelized cost of energy of $0.081 to $0.217 per kWh. Typical LCOE for commercial and industrial is $0.081 to $0.217 per kWh and for utility-scale $0.038 to $0.078 per kWh.
- **(Relatively) Low OpEx:** Low maintenance costs relative to other energy sources and no fuel costs result in low operating expenses.

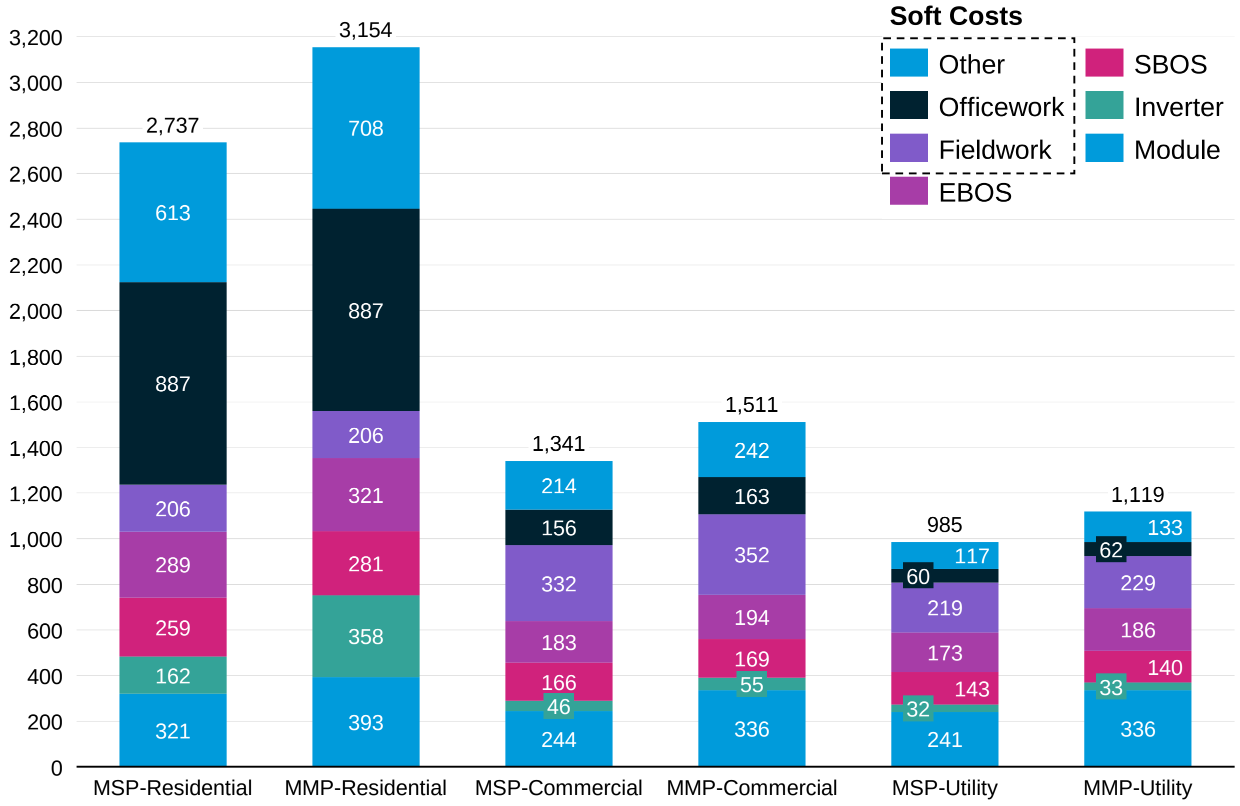
Solar revenue

- **Tax incentives:** Under the IRA, Residential Solar Energy Credit, Investment Tax Credit, and Production Tax Credit reduced ~30% of the initial cost. Other state and local incentives can reduce it further.
- **Long-term savings:** Savings depend on project size and local grid electricity price. Average annual savings could be $1,500 for residential projects and range from $10,000 to $100,000 for commercial and industrial projects. The payback period typically ranges from ~2 to 10 years.
- **Additional revenue:** Net metering allows surplus to be sold, including via Renewable Energy Credits (REC) such as performance based SREC in NJ which require utilities to meet RPS requirements; consumers can access solar revenue through off-site community solar projects.
- **Increased value:** Solar installations can boost property value and commercial appeal, attracting potential buyers, residents, employees, and investors.

Sources: SEIA, Solar Industry Research Data (2024); IEA, Renewables 2023 (2024); SolarKal, What's the Sun's Cap Rate? (2023); Revision Energy, How do Solar Panels Work (2025).

~50% of solar cost structure is soft costs or gross margins for residential and commercial PV

Solar systems cost[1] breakdown, 2024 ($USD/KW)[2]



Observations

- Historically, the price of module is ~10-30% and other components (Inverter, EBOS (Electrical Balance of Systems), SBOS (Structural Balance of Systems)) add ~15-25%; The remaining ~50% is soft costs / gross margins
- Soft costs / gross margins are high in part due to lack of transparency as well as ultra-low conversion rates and high Customer Acquisition Costs (CAC)
- Higher prices are exacerbated in 3rd-party agreements like site leases where complexity adds to the opacity, resulting in lower payments to customers

Case study: SolarKal saves businesses costs through a competitive marketplace model

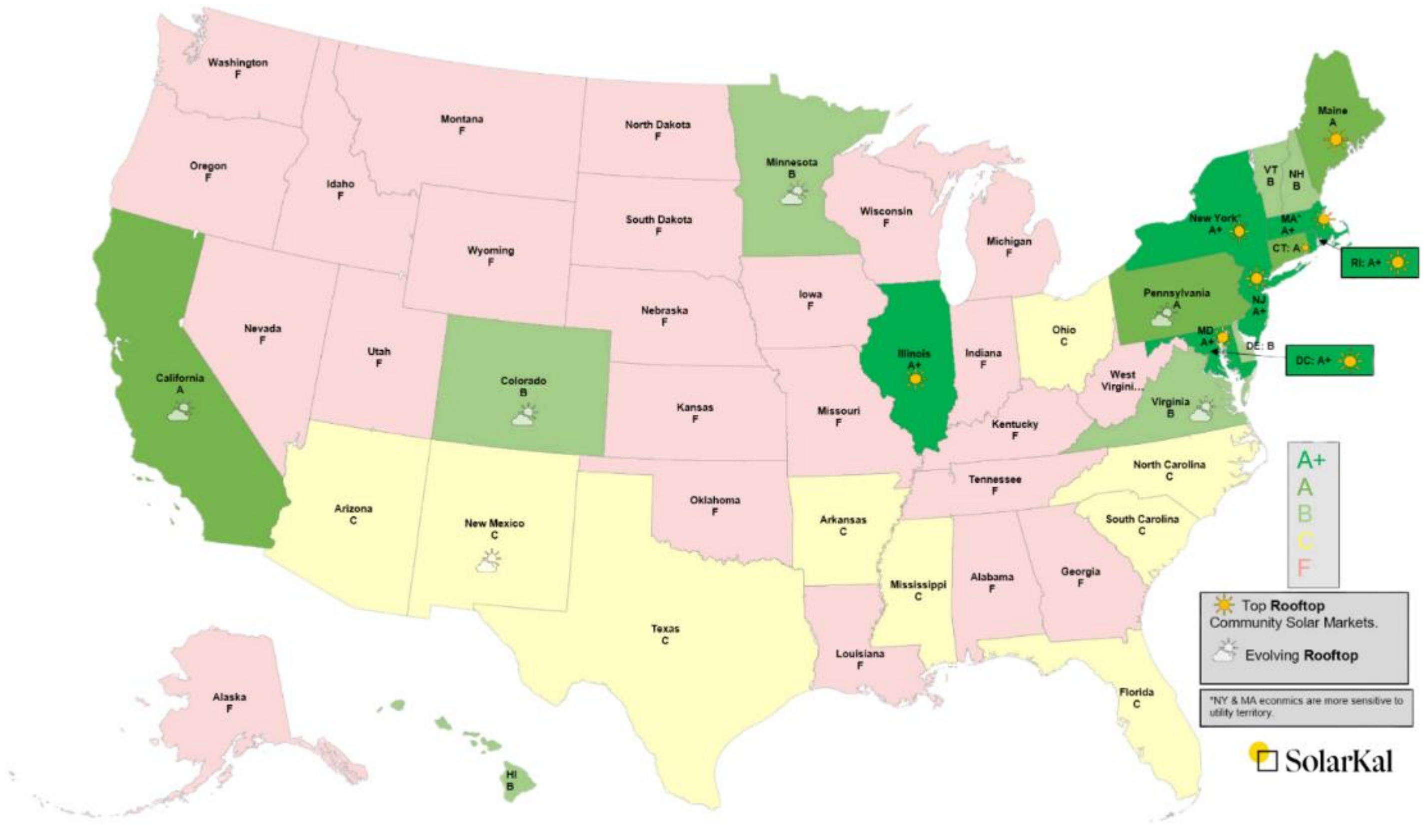
SolarKal acts as dedicated solar advisors for commercial real estate asset owners

- Asset portfolios are evaluated for solar potential by leveraging a database of national pricing, injecting transparency into the marketplace
- By fostering a competitive RFP process involving 200+ pre-vetted and approved vendors, **clients' economics are improved by 43% on average**
- Savings are structural - with an **80% RFP success rate**, higher conversion deal flows reduces CAC and therefore lowers costs

(1) Other costs include permitting, inspection and interconnection, transmission line costs, sales tax, overhead, and profit.
(2) MSP - Minimum Sustainable Price, MMP - Modeled Market Price
Sources: NREL, US Solar PV System Cost Benchmark (Q1 2023) (2023); SolarKal, What's the Sun's Cap Rate? (2023).
Credit: Taicheng Jin, Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Deployment environments differ across states and energy markets, with ISO-NE and CAISO leading in the US

State-level solar receptiveness graded on a letter scale



Observations

- **A state's solar attractiveness** is principally determined by:
  - **Incentives** including state rebates, SRECs (solar renewable energy certificates), and community solar
  - **Electricity rates** determining energy saving, which make up the bulk of the revenue to repay investment
  - **Net metering rules** setting rates utilities pay for returned solar energy; e.g. "net metering" pays the retail unit energy cost (same a customers pay to receive energy), whereas "net billing" applies wholesale rate, reducing revenue a customer receives
  - **Solar irradiation** measuring how much sunshine an area receives, on average, over a period of time
- **CA and Northeastern states** are the friendliest solar states due to state level incentives like NJ's SREC, PA's elevated electricity rates, and NY's offering of Tax Credit Bridge Loans and VDER net-metering arrangement

Note: CAISO is the California Independent System Operator and ISO-NE is the Independent State Operator North-East.
Sources: SolarKal, The 50 States of Solar (2024); NREL, NSRDB (2025); EIA, Electric Power Annual Reports (2024); Berkeley Labs, Queued Up (2024).
Credit: Taicheng Jin, Hassan Riaz, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

ELP Greenport project demonstrates the economics of storage and the delicate balance of community interests

Facts

- Developer: Eight Light Partners
- Location: Greenport, Columbia, New York
- Status: Operating
- Commission date: March 2020
- Capacity: 7 MWac
- Operator: Conductive Power
- Off-takers: Hudson community subscribers

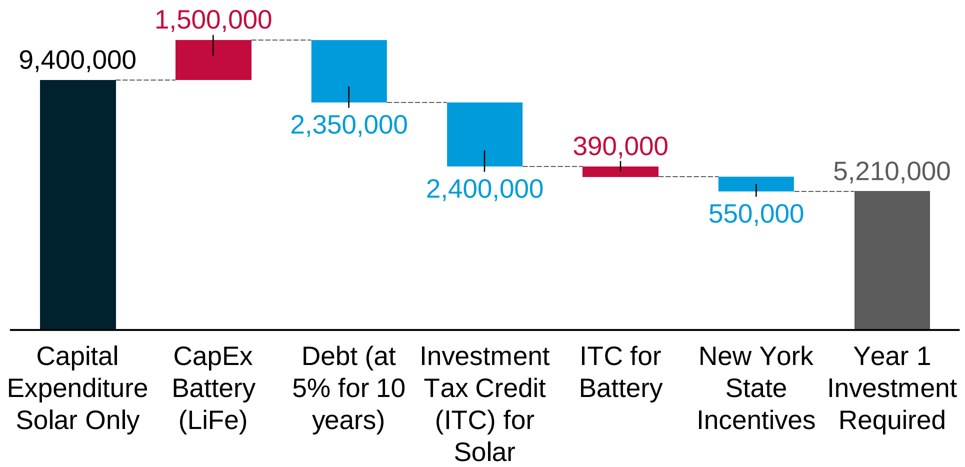
Financials

- Viability and net present value depended on multiple factors: solar generation capacity, CapEx, availability of project financing, New York state's Value of Distributed Energy Resources (VDER)
- Metrics**:**
  - NPV: $23 million
  - IRR: (15% solar; 16% +storage)
  - Margin: ~23%
  - MOIC: ~2.12x

Issues

- **Solar only or + storage?**
  - $1.4M additional equity contribution
  - + 30% generation = $175K additional per year
  - Capital cost of battery = - $1.5M
  - Government incentive for storage ($940K)
    - > $390K from ITC
    - > $550K from NYSERDA
- **Community Opposition and Conservation**
  - Scenic Hudson and Historic Hudson banded together to oppose the construction.
  - Solar field initially sat across from the Oliver Bronson House, a viewshed that gave birth to the Hudson River School of American landscape painters.
  - Consultation was conducted to revise site plan according to the "Clean Energy, Green Communities" guide to relocate visible panels away from the view of house.

CapEx → Required equity contribution (solar PV + storage)



Assumptions: 21% tax rate; -0.5% rate of solar depreciation; depreciation (year 1); 8% discount rate

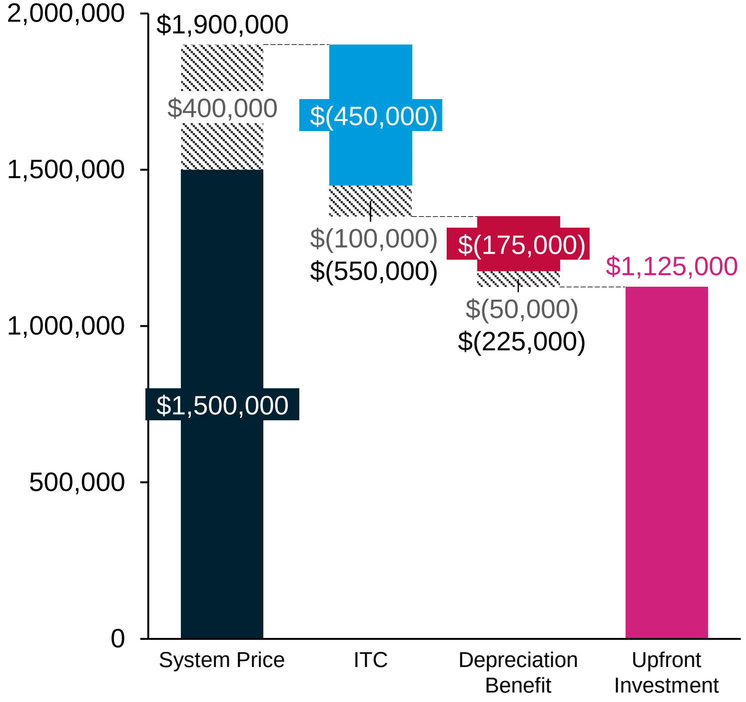
1. Electricity generated (number of modules x watts per module) x the specific production (kWh per year) *kW of installed capacity
2. Rate of $0.09 per kWh to determine revenue of electricity generated
3. Rate of $0.28 per kWh for added value for electricity generated in summer hours between 1 PM and 6 PM (June, July, and August)

Sources: Columbia CaseWorks, ELP Greenport: Scaling Community Solar (2024); Scenic Hudson, At the Historic Bronson House, a Surprising Solar Success (2025).
Credit: Taicheng Jin, Hassan Riaz, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Federal ITCs and PTCs provide limited relief, but state incentives play a crucial role in pushing projects past investors' hurdle rate

REC could boost IRR by 7-15% and cut payback by 2-5 years

Waterfall of a 1MW project without state-incentives



Return Profile if based in:

Annual income in New Jersey
(+) Energy Savings: $150,000
(+) REC Revenue: $125,000
Project IRR: 24-26%
Payback Period: 6 Years

Annual income in Florida
(+) Energy Savings: $128,000
Project IRR: 11-13%
Payback Period: 7 Years

Annual income in Texas
(+) Energy Savings: ~$128,000
Project IRR: ~8-16%
Payback Period: ~5-10 Years

- Diagonal represent additional cost/savings for range estimate.
- Assuming a standard 1 MW solar project (BTM/direct ownership): On-site system, behind the meter, for self-consumption; direct ownership provides full control, access to tax incentives, and long-term savings.

Observations

- Federal incentives provide a significant boost, but **strong state-level incentives can push a project over hurdle rate**
  - **Federal level:** ITC, PTC, Accelerated Depreciation
  - **State level:** state Credits, RECs, rebates, state tax exemption, net-metering, renewable portfolio standards (RPS), interconnection standards
  - **County level:** rebates & grants, buildings standards
  - **Community level:** energy-efficient organizations, regional partnerships
- NJ, FL, and TX offer **varying levels of state-incentives**, resulting in different levels of project IRR
  - **New Jersey:** The **Successor Solar Incentive (SuSI)** program rewards solar energy production with **SREC-II certificates**, valued at **$85-$90 per MWh for 15 years**. Solar equipment is exempt from sale and property taxes, and net metering allows generators to sell excess electricity back to the grid.
  - **Florida:** The state exempts added value of solar energy system from **property taxes and sales taxes**. Statewide net metering policy allows full credit on utility bills. Local utilities offer **$2,000-$4,000 rebates** for solar battery installations.
  - **Texas: Several** utilities provide **$2,500-$3,000 rebates** for solar PV of at least 3 kW. Some utilities and retail energy providers offer **solar buyback programs** that provide bill credits or cash for surplus energy fed back into the grid.

Note: Texas has a larger band of uncertainty around buybacks depending on location
Sources: Solar.com, Solar Incentives by State (2025); Forbes, New Jersey Solar Incentives, Tax Credits And Rebates (2024); Energysage, Texas Solar Rebates and Incentives (2025); Texas Power Guide, Find Your Best Plan (2025); DSIRE, DSIRE (2025); Canary Media, Florida is Now a Solar Superpower (2025); Solarkal, SolarKal (2025).
Credit: Taicheng Jin, Hassan Riaz, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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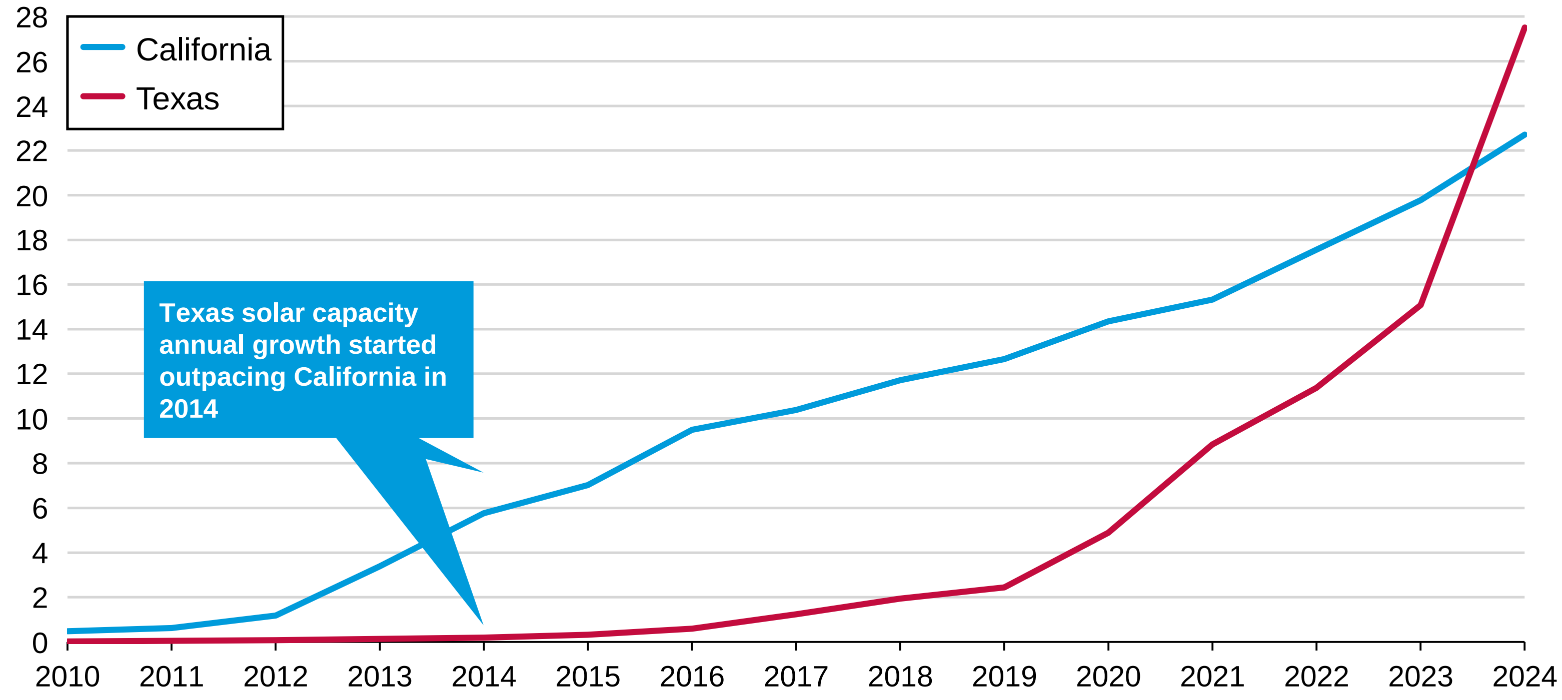
Deregulated Texas energy market boon for solar, surpassing California in 2024

Total installed utility-scale solar capacity in Texas and California (GW)

CAGR '10-'15	CAGR '15-'20	CAGR '20-'24
CA: 71%	CA: 15%	CA: 12%
TX: 87%	TX: 73%	TX: 54%



Observations

- **Texas surpassed California** as leading solar PV state after **adding 1.6 GW in Q2 of 2024** (ACP).
- Texas installed nearly **9 GW of new solar by the end of 2024** – over one-fourth of the U.S. 2024 additions – for a **total capacity of 27.5 GW** (ACP).
- Texas is **expected to install 11.6 GW** new utility-scale solar in 2025 (EIA).
- **Texas' advantage:**
  - ⊕ Deregulated, electricity-only energy market
  - ⊕ Streamlined approval process
  - ⊕ Abundant land
  - ⊖ Minimal state-incentives
- **California's challenge**:
  - ⊕ Strong state incentives
  - ⊖ Strict regulations
  - ⊖ Interconnection delays

Source: ACP, Clean Power in 2024 (2025); EIA, Solar, Battery Storage to Lead New U.S. Generating Capacity Additions in 2025 (2025).
Credit: Hyae Ryung Kim, Taicheng Jin, Isabel Hoyos, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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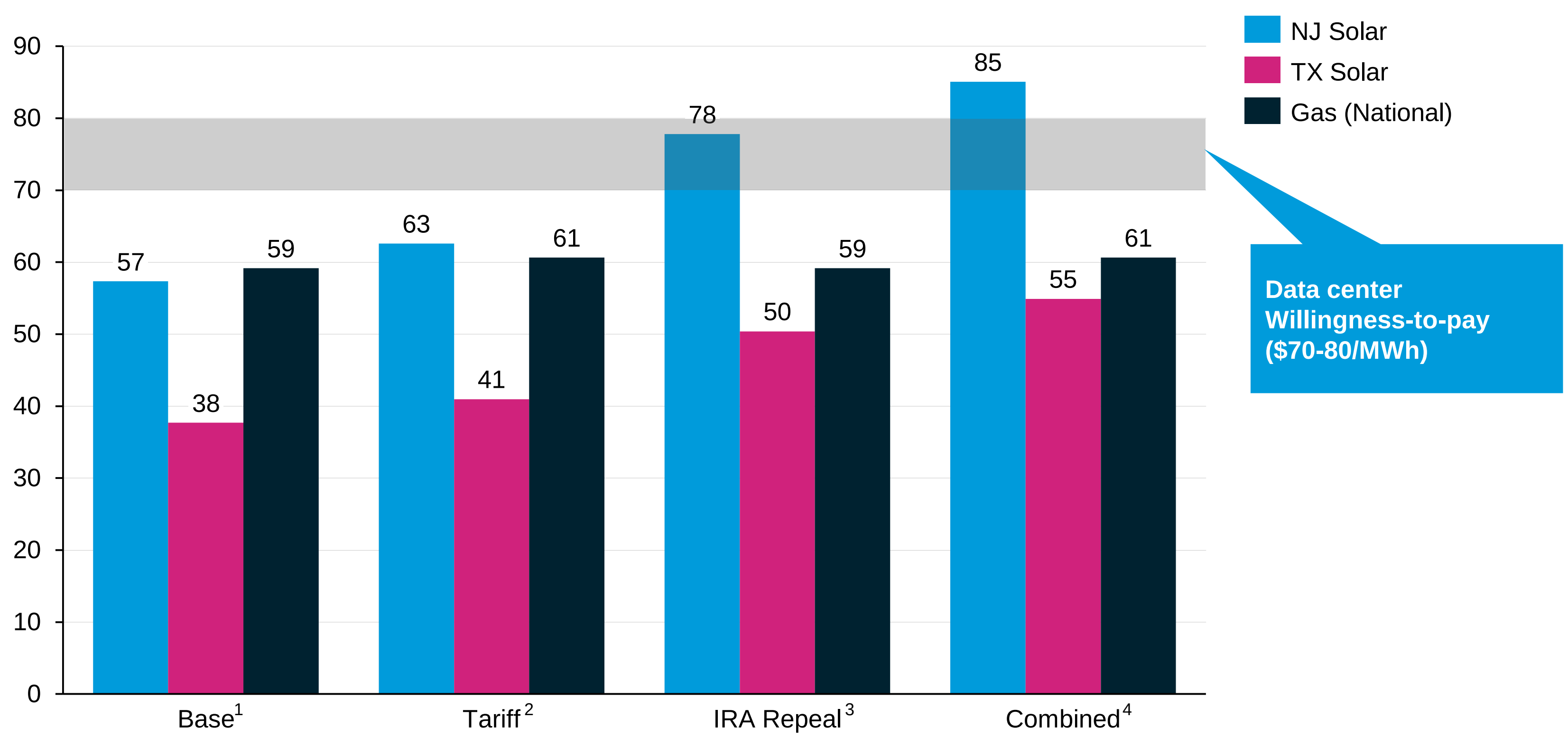
Solar may lose its edge in costly, subsidy-reliant states like NJ with tariffs and IRA repeal, but TX stays competitive

Solar vs. gas LCOE by region and scenario ($USD/MWh)



Observations

- **NJ Vulnerability: High CapEX and REC reliance** push LCOE to **$85/MWh** under tariffs + IRA repeal making solar uncompetitive showing policy risks.
- **TX Resilience: Low CapEX, minimal RECs, and high output** keep LCOE at **$55/MWh** making solar competitive.
- **Data Center Demand:** TX's solar PPAs will be **below data centers $70-80/MWh budget** even under Combined scenario, supporting data center growth.
- **Gas Constraints: Turbine shortages (+75% CapEx) and tariff (+5%)** elevate gas LCOE up to **$61/MWh.**

(1) Base: Reflects current economic conditions with stable policies; Gas assumes turbine shortage (+75% CapEX)
(2) Tariff: Adds a 10% CapEx increase for solar; Gas reflects turbine shortage and 5% Tariff
(3) IRA Repeal: Removes ITC and RECs; Gas has turbine shortage only
(4) Combined: Combines Tariff (+10% solar, 5% gas CapEX) and IRA Repeal (no ITC/RECs); Gas reflects turbine shortage (+75%) and tariff (+5%)
Sources: Lazard, LCOE+ (2025); Morgan Stanley, The BEAT - Outlook (2025); EIA, Annual Energy Outlook (2025); Offgridai, Offgridai (2024).
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Solar Technology Landscape

Two main solar PV cell technologies:

- **Crystalline Silicon (c-Si):** Rigid cells made from either mono- (mono-Si) or polycrystalline silicon (poly-Si), with a commercial efficiency between 17% and 25%; cost ranges between $0.26 for utility-scale projects to $0.6 per watt for residential projects.*
- **Thin-film:** Cells can be flexible**,** have a 7% to 8% commercial efficiency, and cost between $0.75 and $1.10 per watt.*

Trends across the production chain:

- **Polysilicon:** After a recent spike to $39 per kilogram, **prices have come down to about $6 per kg** as production restarted post-COVID. Prices could continue to decline with continued capacity additions.
- **Wafers:** The industry has started to shift to larger wafer sizes, resulting in a **50% decrease in polysilicon use** per watt of capacity, and to N-type wafers.
- **Cells:** Production has **shifted from BSF cells to PERC cells** in the past decade, resulting in an average 1% efficiency gain for mono-Si cells, but could move to TOPCon or HJT in the future. Production has also **shifted from poly-Si cells to mono-Si cells,** driven by higher efficiency and a drop in price.

Innovations in solar PV:

- **Novel technologies:** Silicon heterojunction cells, perovskite cells, and multi-junction cells have not been able to replace c-Si cells at scale yet. However, their growing efficiencies coupled with potential cost improvements could make them more competitive.
- **Panel modifications:** Solar trackers, bifacial panels, and concentrator PV can boost c-Si cell efficiencies by up to 45%.
- **Deployment locations:** New developments in location include building integrated PV (BIPV), floating PV (FPV), agrivoltaics, and vehicle integrated PV (VIPV).

(*) Price estimates are based on US market panel costs; ROW c-Si panel costs range from $0.10 to $0.23 per watt

Solar PV makes up >99% of global installed solar capacity

	1	2
	Solar PV	**Concentrated solar power**
		
Description	Converts sunlight **directly into electricity** using **semiconductors**	Uses focused sunlight to **heat a fluid** (molten salt), which **produces steam** that is used to **drive a turbine** to generate electricity
Advantages	• **Ease of installation** — solar panels can be easily installed in lots of different places • **Little maintenance required** once installed	• Comes with **built-in energy storage** — thermal energy can be stored for up to 16 hours • Can be **integrated with an existing fossil fuel plant** (e.g., to share turbine)
Global installed capacity (2023)	**1,055 GW** 99% of total installed solar capacity	**8.1 GW** 1% of total installed solar capacity
Average cost (LCOE,* global)	**$0.038 - $0.078 per kWh** *(Lazard 2025)*	**$0.118 per kWh** *(2022)*

Main focus of this deck

(*) LCOE (levelized cost of electricity) is a way to compare the true costs of different energy sources.
Sources: IRENA, Solar Energy (2025); Our World in Data, Solar Photovoltaic Module Price (2024); HelioCSP, Cost of Concentrated Solar Power (CSP) Projects Fell from USD 0.38/kWh to USD 0.118/kWh (2023); Renewable Energy World, How Solar PV is Winning Over CSP (2013); Statista, Average Installation Cost for Concentrated Solar Power (CSP) Worldwide (2024); US DOE, SunShot 2030 (2025).
Credit: Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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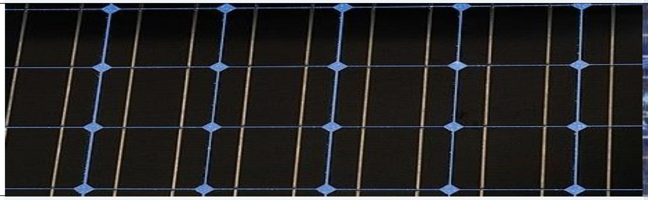
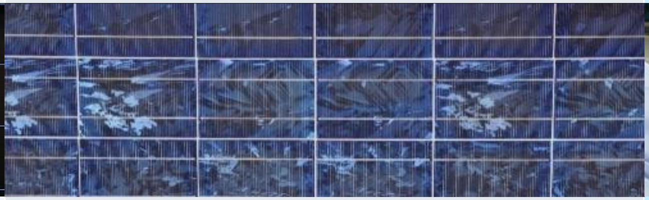
Crystalline silicon (c-Si) is the main cell type, while thin-film is often reserved for highly specific use cases

	CRYSTALLINE SILICON CELLS		THIN-FILM
	Monocrystalline (mono-Si)	Polycrystalline (poly-Si, 'multi-Si')	
			
Description	Cells of polysilicon that have **crystallized into a single Si crystal** (Czochralski process) • One panel is made up of **32 to 96 silicon wafers** • **Black or very dark blue** with **round corners**	• Cells of polysilicon that consists of many square blocks of **multiple Si crystals** • Has a **visible grain,** giving the cell a **blue hue without rounded corners**	• Solar cells produced by depositing **thin layers of photovoltaic material** on a base material • PV material determines color, **potentially flexible** depending on base layer
Commercial efficiency (2024)	**~17–25%**	**~13–18%**	**~7–18%***
Panel cost per watt (2024)	**$0.26–$0.50**	**$0.28–$0.50**	**$0.75–$1.10**
Challenges	• **Limited space** or need for **maximum output** subject to a surface area constraint	• **Price is a main concern**	• **Price is a main concern**

(*) Peak commercial efficiency of copper indium gallium selenide (CIGS) thin-film cells has reached 22% in lab settings and 18.7% in field tests.
Sources: PVPS, Trends in Photovoltaic Applications (2022); Encyclopedia Britannica, Thin-film Solar Cell (2024); Benda, A Comprehensive Guide to Solar Energy Systems (2018); NREL, US Solar PV System Cost Benchmark (Q1 2023) (2023); InsideClimateNews, Solar Panel Prices Are Low Again. Here's Who's Winning and Losing (2024).
Credit: Max de Boer, Lara Geiger, Marcelo Cibie, Taicheng Jin, Hassan Riaz, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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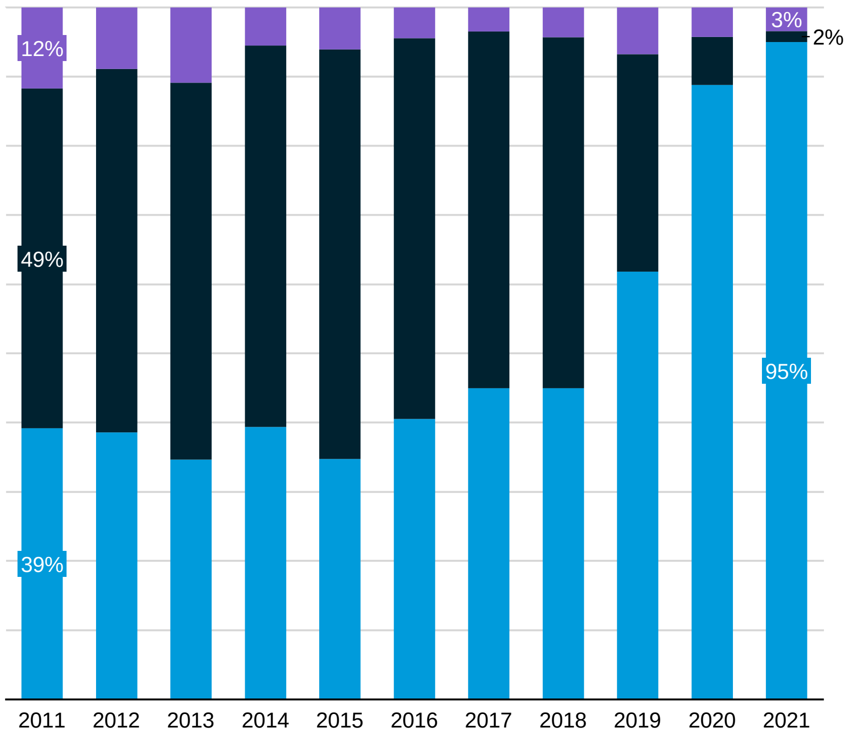
The industry shifted to mono-Si and larger wafer sizes, driven by higher efficiency and cost reduction

Mono-Si makes up ~95% of solar PV production

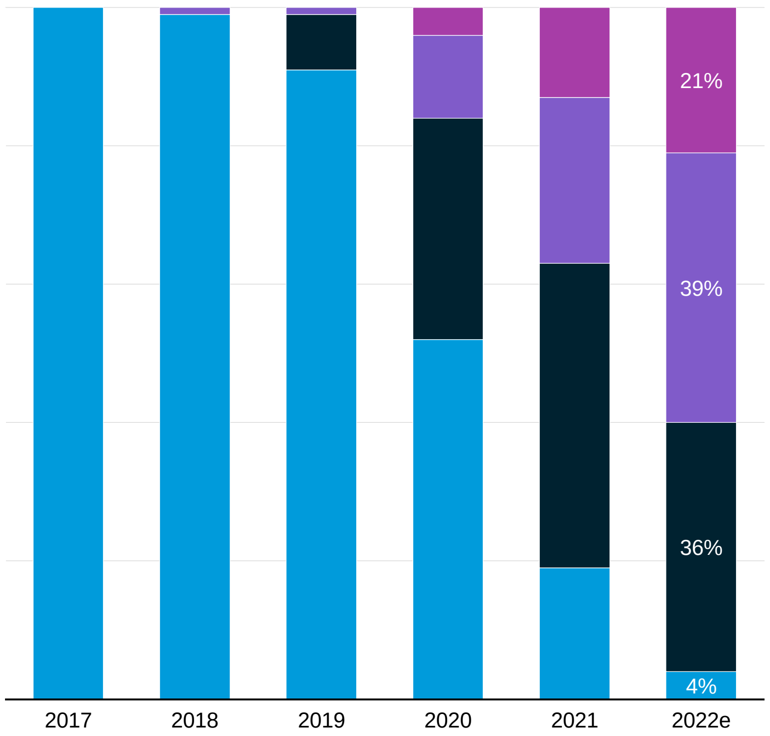
Mono-Si Poly-Si Thin-film

Global PV module production by technology (in % of total GW)



Wafer sizes have increased since 2017

< 158.7 mm 182.0 - 210.0 mm
158.7 - 166.0 mm 210.0 mm



Observations

- From 2018 to 2021, **c-Si cell production has shifted dramatically** from **poly-Si** to **mono-Si**.
- This shift has been driven by the **higher efficiency of mono-Si cells** as well as **efficiency improvements in manufacturing process**, leading to **lower prices**.
- **Thin-film production has increased slightly over time** as its **applications in special use cases** continue to grow.
- Global wafer production **shifted from <158.7 mm wafer sizes to larger sizes** (210 mm max. size).
- The shift to larger wafer sizes has been one of the main drivers of the **decrease in polysilicon,** resulting in **cost savings**.

Sources: IEA, Solar PV Global Supply Chains (2022); PV Magazine, Polysilicon Costs Have Slid by 96% Watt Over Past Two Decades (2023).
Credit: Taicheng Jin, Hassan Riaz, Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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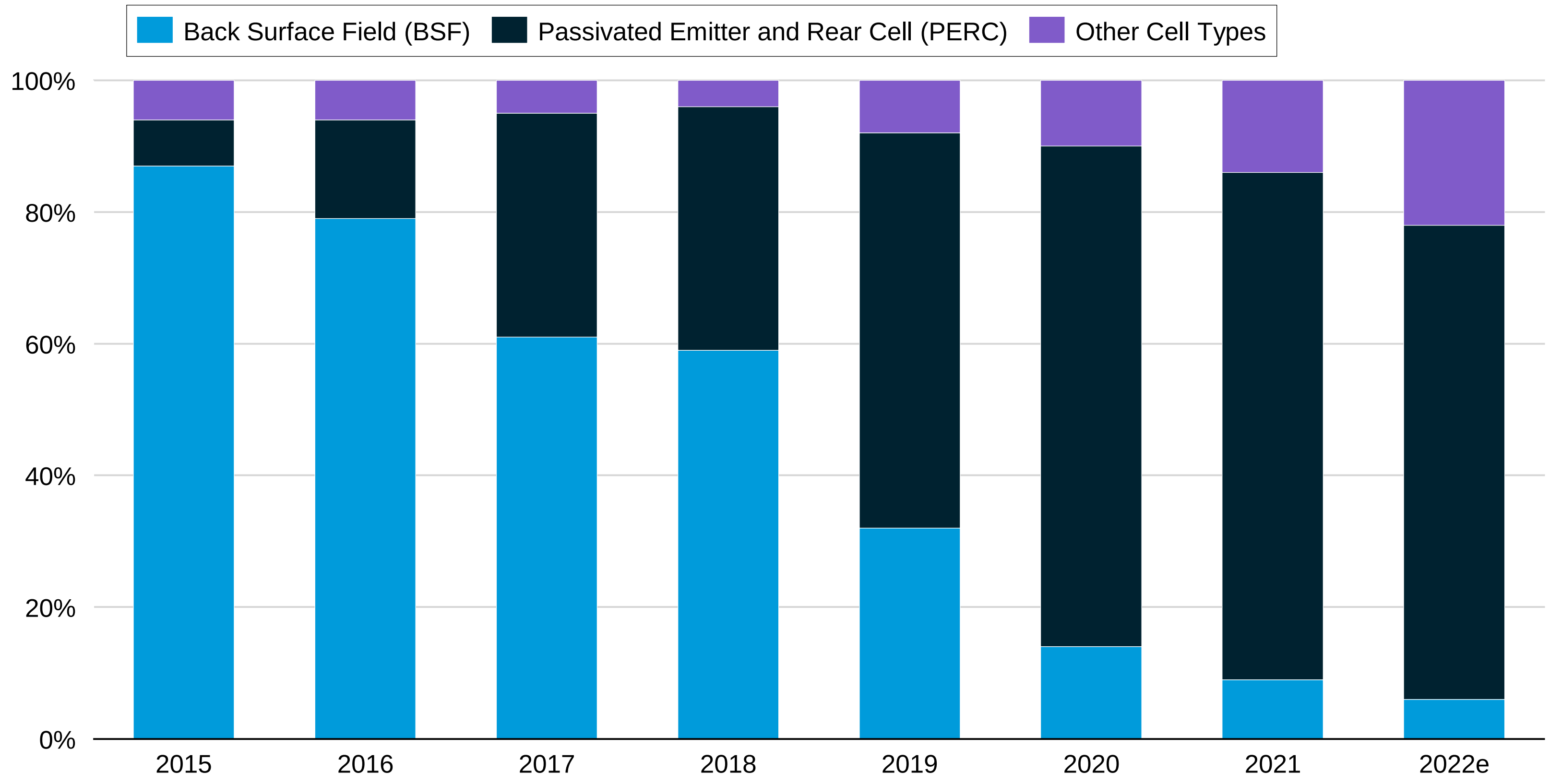
PERC cells have gained 65% market share, quickly replacing BSF (-81%) since 2019, but TOPCon looms large

P-type mono PERC has become the dominant cell type since 2019



Observations

- **Cell type** refers to the **materials and configurations applied** to the **polysilicon wafer** to **transform it into a functional PV cell**.
- **Since 2015,** we have seen a **shift in cell production** where the **BSF cell type** has been **gradually replaced** by the **PERC cell type**.
  - **BSF solar cells:** Traditional crystalline silicon cells with an aluminum layer at the back that creates a back surface field. This reduces recombination losses and slightly improves efficiency.
  - **PERC solar cells:** An advanced version of BSF cells. In addition to the aluminum back, they have a passivation layer and a dielectric layer that reflects more light back into the cell, improving efficiency.
- The **PERC cell type** boosts the **efficiency of monocrystalline cells** by **about 1%**.
- The **share of other cell types** is **projected to keep increasing** (TOPCon cells boost efficiency of PERC by about 2%).

Note: Other cell types include TOPCon, heterojunction technology, and back contact.
Sources: IEA, Solar PV Global Supply Chains (2022); Solar Magazine, A Complete Guide to PERC Solar Panels (2022); Solar Magazine, TOPCon Solar Cells; The New PV Module Technology in the Solar Industry (2023).
Credit: Taicheng Jin, Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

HJT, perovskite, and multi-junction cells boast higher efficiency but have yet to replace c-Si at commercial scale

	1 Silicon heterojunction cells (HJT)	2 Perovskite cells	3 Multi-junction cells
Description	• HJT incorporates **thin layer(s) of** undoped and doped amorphous Si (a-Si:H) on **both sides** of the **crystalline silicon (c-Si) core used in regular solar PV cells**. • **Indium tin oxide** is the preferred **transparent conductive oxide** layer.	• **Perovskites**, or halide perovskites, are a family of **metal-based halides** that have a **distinct octahedral crystal structure** with **the** potential to replace **crystalline silicon in PV cells**.	• Whereas **traditional solar cells** have only **one layer of crystalline silicon**, **multi-junction solar cells** contain **multiple layers of photovoltaic material**. • **Each layer** is **specifically designed** to absorb a **different sunlight wavelength**.
Efficiency	**~26–29%**	**~26–34%(1)**	**~30–47%(2)** (depending on number of layers)
Estimated cost per watt	**~$1.10–$1.60** *(~10% more expensive than monocrystalline cells)*	**~$0.32–$0.37** *(~70% cheaper than monocrystalline cells)*	**~$300** *(~240x more expensive than monocrystalline cells)*
Pros and cons	⊕ • **Has better performance** at **higher temperatures** than crystalline silicon cells; – useful in desert environments, for example ⊖ • Requires **more expensive materials** for electrical contacts than regular silicon cells	⊕ • Can be **produced at much lower temperatures** than crystalline silicon, leading to **lower costs** ⊖ • **Degrade** when **exposed to moisture and oxygen,** leading to **shorter cell life spans**	⊕ • Require **much less space** because of **higher efficiency** — therefore, can be used in satellites, for example ⊖ • **Different layers made of rare elements** are **much more expensive** than crystalline silicon

(1) Highest efficiencies achieved for perovskite cells that also incorporate a crystalline silicon layer in a multi-junction setup; pure perovskite cell efficiency is ~26.1% (2023).
(2) Highest efficiencies achieved in combination with concentrators.

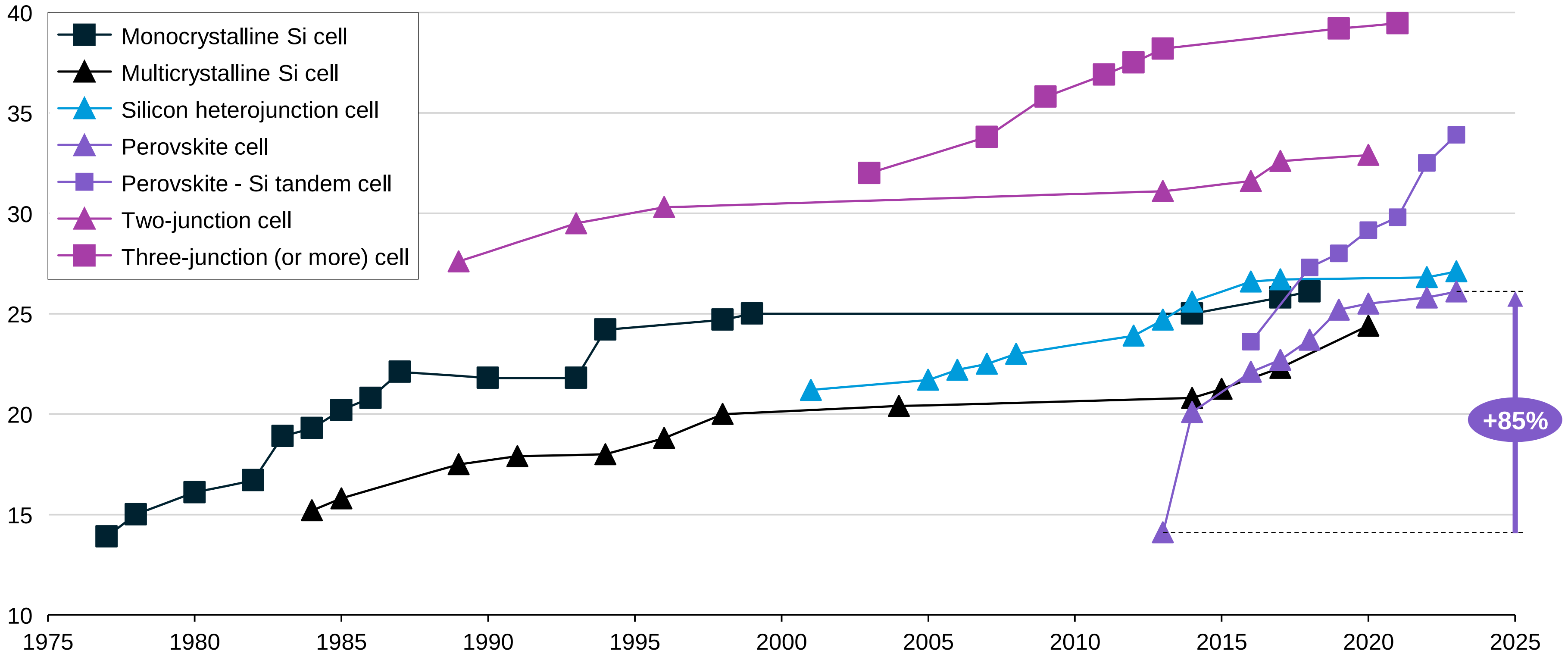
Sources: Akkerman and Manna, What Defines a Halide Perovskite? (2020); US EERE, Perovskite Solar Cells (2025); IEA, ETP Clean Energy Technology Guide (2025); NREL, Photovoltaics Research (2025); NREL, Crystalline Silicon Photovoltaic Module Manufacturing Costs (2020); PV-Manufacturing.org, Silicon Heterojunction Cells (2025); SolarReviews, Exciting New Solar Technologies that Actually Matter (2025); US DOE, Multijunction III-V Photovoltaics Research (2025); US DOE, Perovskite Solar Cells (2025); Z. Song *et al.*, Manufacturing Cost Analysis of Perovskite Solar Modules (2018).

Credit: Taicheng Jin, Hassan Riaz, Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Efficiency of perovskite cells increased ~85% over 10 years (6% CAGR) vs. multi-Si's ~61% gain over 40 years (1% CAGR)

Significant efficiency gains have been achieved for most cell types in past 10 years

Highest confirmed cell efficiency for research solar PV cells in lab conditions (in %)



Observations

- **Poly-Si cells** have still **improved somewhat in recent years**, but **efficiency gains for mono-crystalline cells have been minimal since the 1990s.**
- **Perovskite cells** have booked the **most impressive efficiency gains**:
  - **Regular perovskite cells'** efficiency improved by **12%** between 2021 and 2023 to **26%**.
  - **Perovskite - Si tandem cells**, which consist of a perovskite cell layered on top of a regular c-Si cell, improved by **10%** between 2015 and 2023 to **34%**.
- In **multi-junction cells**, **most efficiency** gains have been booked recently for **three-junction (three layer) cells** (7% since 2002) — even **getting close to four-junction cells.**

Note: For the sake of simplicity, many nascent technologies have been left out of this chart. For the full interactive version of this chart, please see here.
Source: NREL, Photovoltaics Research (2025).
Credit: Taicheng Jin, Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Panel modifications such as tracker and concentrators could increase efficiency by an additional 40+%

	1	2	3
	Solar trackers	**Bifacial solar PV**	**Concentrator PV (CPV)**
			
Description	• **Single-axis trackers** follow the position of the sun as it moves from **east to west**; more common in **utility projects**. • **Dual-axis trackers** follow the sun **both east to west and north to south**; more common in **commercial projects**.	• Bifacial solar modules have **solar cells** on **both sides of the panel**. • **The backside** uses **light that is reflected off the ground**.	• Panels consist of a **large array of mirrors** angled at a **single solar PV cell**, which is often **a more efficient and expensive cell** like a multi-junction cell. • **Panels work** only in **areas with strong direct sunlight** and **need trackers** to achieve the **highest efficiency**.
Estimated efficiency gain	Single-axis tracker: **+25–35%** Dual-axis tracker: **+35–45%**	**Up to +30%**, depending on the surface below the panels	Monocrystalline cell**: +5–10%** Multi-junction cell**: +10–20%**
Estimated additional cost	Residential scale**: +40–100%** Utility scale**: +7–10%***	**+10–20%**	**Price estimates vary** — **up to 30% cheaper** in the right circumstances.

(*) For utility-scale, single-axis tracker.

Sources: California Energy Commission, Self-Tracking Concentrator Photovoltaics (2020); EnergySage, Is a Solar Tracking System Worth It? (2023); NREL, A Bottom-Up Cost Analysis of a High Concentration of PV Module (2015); Marketwatch, A Guide to Bifacial Solar Panels (2024); Renogy, Bifacial Solar Panels (2024); Penn State, Utility Solar Power and Concentration (2025); PVPS, Trends in PV Applications 2022 (2022); SolarReviews, What Is a Solar Tracker and Is It Worth the Investment? (2025).

Credit: Taicheng Jin, Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Scaling Solar” (14 August 2025).

Solar has been tested in many deployment scenarios, integrating with agriculture, urban architecture, and personal mobility

Building integrated PV (BIPV)

- BIPV serves a **dual purpose**: **generating electricity** and **insulating building** from the environment.
- Panels can be **retrofitted**; the **greatest value** is gained by **including** them **in the initial building design**.

(+) **Aesthetically pleasing:** Blends seamlessly to a building's façade and roof, or when integrated into windows using semi-transparent thin-film

(−) **Generation efficiency**: Tends to be less efficient than traditional PV

Floating PV (FPV) or floatovoltaics

- FPV consists of **panels placed on water**, often near hydroelectric dams.
- The panels can **be rotated to track the sun**; **water below keeps the panels cool**, increasing efficiency.

(+) **Space efficiency:** Doesn't require scarce land, and available water surfaces are abundant; Japan, with scarce land, is a leader in FPV

(−) **Higher costs:** Currently, requires higher upfront investment and maintenance costs than traditional PV

Agrivoltaics

- **Agrivoltaics** refers to the **colocation** of **PV panels** and **crops**, **grassland, or animal husbandry**.

(+) **Space efficiency:** By coexisting with existing farmland, expands available space for PV installation

(+) **Dual income:** Provides diversified income streams for farmers

(−) **Higher costs:** Currently, requires higher upfront investment in BoS components vs. traditional PV

Vehicle integrated PV (VIPV)

- VIPV refers to the **integration of thin-film PV** into the **roof or bonnet of electric vehicles**.
- VIPV modules **blend seamlessly** into the vehicle's exterior and **connect to the electric loads or battery**.

(+) **Increases mileage**

(+) **Decreases load on charging infrastructure**

(−) **Generation efficiency:** Vehicles are not oriented to optimize for the utilization of solar energy

Sources: BBC, The Floating Solar Panels That Track the Sun (2022); Fraunhofer ISE, Vehicle-Integrated PV (2025); PVPS, Trends in PV Applications 2022 (2022); SEIA, Photovoltaics (2025); US DOE, The Potential of Agrivoltaics for the US Solar Industry, Farmers, and Communities (2023).
Credit: Isabel Hoyos, Max de Boer, Lara Geiger, Marcelo Cibie, Hassan Riaz, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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Solar Supply Chain

Key messages
Solar Supply Chain

The solar panel production process consists of five main steps:

(1) The carbothermic reduction of quartzite (SiO_2) to form metallurgical Si

(2) Creation of polysilicon through CVD or FBR

(3) Slicing of casted ingots into wafers

(4) Transformation of wafers into cells

(5) Combination of cells into panels, which are stacked, laminated, and fitted with frames and junction boxes

---

Silicon and silver make up >50% of the material costs of solar c-Si panels, with other major material costs being glass (~13%), aluminum (~11%), polymers (~9%), and copper (~9%).

Currently, **manufacturing capacity exceeds demand along each step of the production process** by at least 70%. Overcapacity is expected to persist until at least 2030.

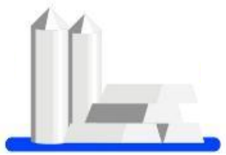
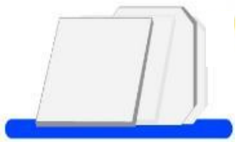
Over time, **China has become the dominant player** along every step of the solar panel production chain, with **at least 75% market share** in every step. China's market dominance is driven by low production costs and high investment barriers.

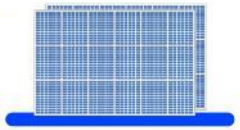
U.S. manufacturing capacity has grown rapidly from **~7GW in 2020 to over ~58 GW as of May 2025, driven by billions in public and private investment unlocked by IRA.**

Solar **module production is the most localized step of the supply chain**, with 19 countries having more than 1 gigawatt of assembly capacity.

SiO_2 is refined to produce ingots, which are cut into wafers and then assembled into cells and modules

Polysilicon → **Ingots** → **Wafers** → **Cells** → **Panel/Modules**



Process

Polysilicon

- Polysilicon is produced by refining SiO_2 into metallurgical-grade silicon, then purifying it via the **Siemens process** to achieve ultra-high purity (7–10N)

Ingots

- Polysilicon chunks are melted into ingots - either as multicrystalline blocks or monocrystalline columns using the **Czochralski process** for higher purity and efficiency

Wafers

- Polysilicon ingots are sliced into **ultra-thin wafers (≈200 µm)** using diamond wire or slurry-based methods, with **diamond wire** increasingly favored for its efficiency

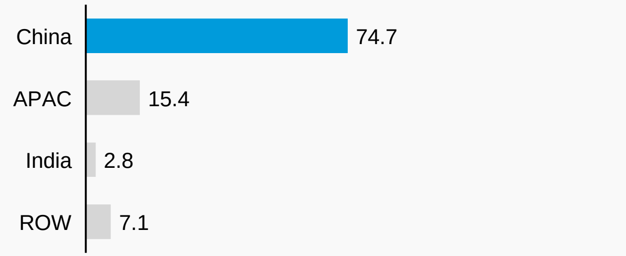
Cells

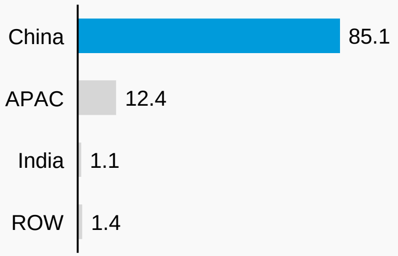
- Wafers become **solar cells** through doping (with boron or phosphorus), adding **metal contacts** for conductivity, and applying an **antireflective coating** to boost sunlight absorption

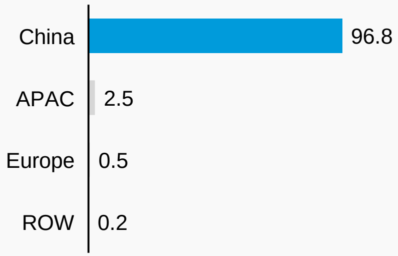
Panel/Modules

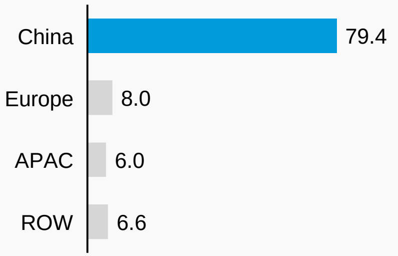
- In the final step, solar cells are **soldered into arrays**, encapsulated with **protective layers**, mounted in a metal frame, and fitted with a connector to form a complete solar panel

Regions (%)





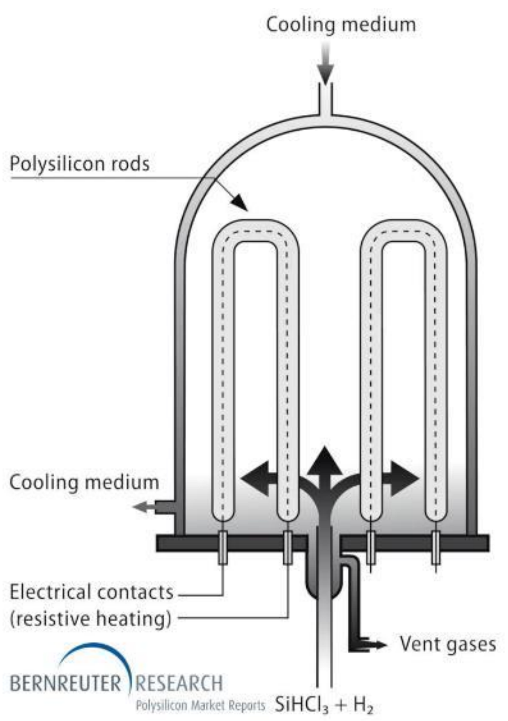




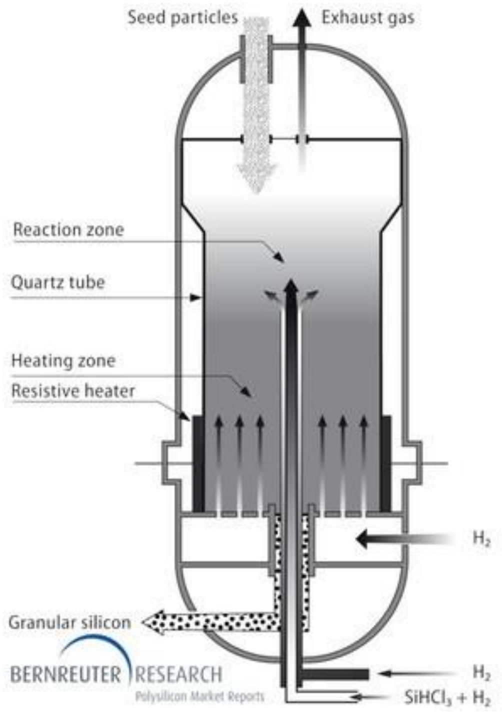
Sources: IEA PVPS, Trends in Photovoltaic Applications 2024 (2024); PV Education, Refining Silicon (2025); PV Manufacturing, Wafering (2025); images from IEA, Solar PV Global Supply Chains (2022); IEA, Solar PV Manufacturing Capacity by Country and Region (2021).
Credit: Taicheng Jin, Hassan Riaz, Max de Boer, Lara Geiger, Marcelo Cibie, Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Demand for fossil fuels in the refinement step contributes most of the CO_2 in the supply chain

Siemens dominates 80% of production



… but FBR is catching up



- **Left figure:** The Siemens process, which uses trichlorosilane, reacts with H_2 and accretes on rods through chemical vapor deposition.
- **Right figure:** Silicon-containing gas is injected together with hydrogen (H_2) through nozzles at the bottom to form a fluidized bed that carries tiny silicon seed particles fed from above.

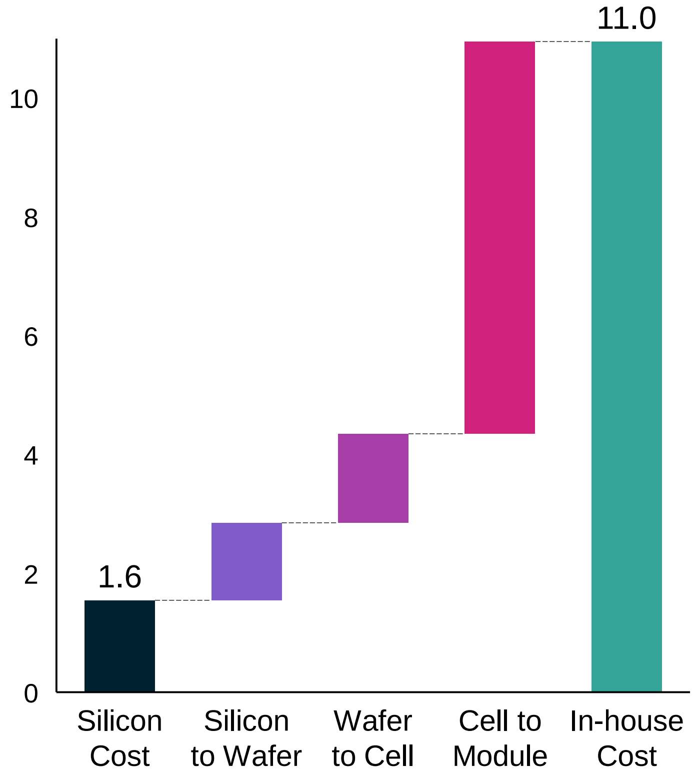
Observations

- Silica undergoes **carbon-thermic reduction**, which requires arc furnaces to be heated up to **~1500 to 2000 degrees Celsius**.
- Next, Poly-Si is refined either through **the Siemens process** (left) or the **FBR process** (right)
- The exergetic efficiency of silicon production is around 0.33 - 0.41, which means only about **one-third of the available energy is successfully converted into useful work**.
- The high energy consumption of sustaining **electro-arc furnaces means access to cheap energy sources**, which until now has largely been **fossil fuel-sourced electricity**, is further contributing to GHG emissions.
- Some look to **FBR for energy reduction** (10-12%). GCL-Poly's 10K MT plant **reduced CO_2 emission** by 130,000 tonnes (-74% to the Siemens process).
- Most carbon emissions are in the **production** phase, specifically **41% from poly-Si refinement**.
- PERC P-mono has a **10% higher life-cycle carbon emission** than PERC P-poly.

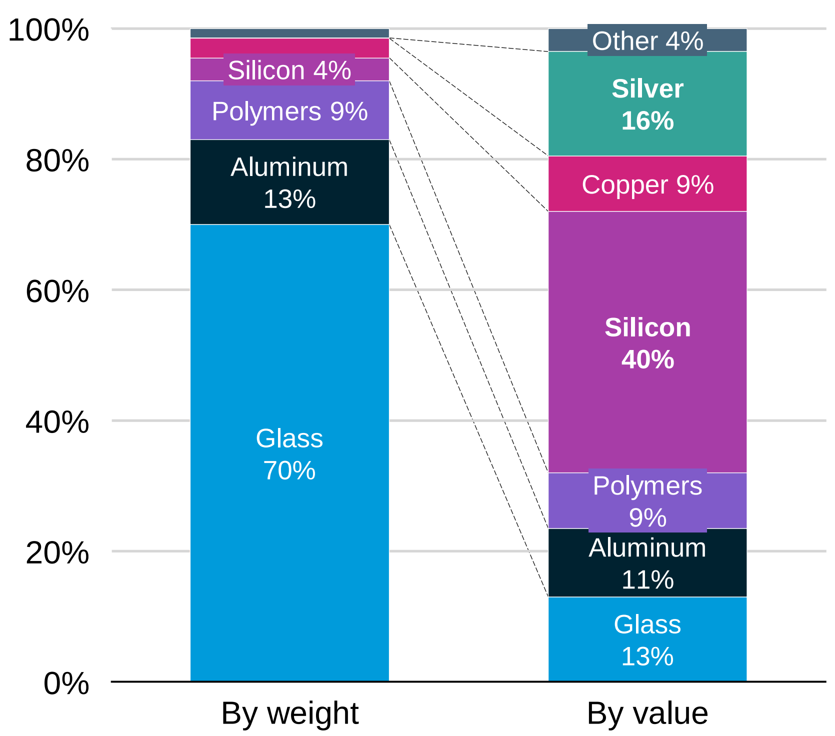
Source: Bernreuter Research, Bernreuter Research (2025); Takla *et al.*, Energy and Exergy Analysis of the Silicon Production Process (2013); PVTech, GCL-Poly Touts FBR Silicon Matching Siemens Process on Purity (2021); Yin *et al.*, Carbon Emission Analysis of Two Crystalline Silicon Components Throughout the Life Cycle (2021).
Credit: Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Silicon and silver make up the bulk of material cost; cell-to-module assembly represents the largest chunk of in-house cost (~60%)

Breakdown of total cost (cents per watt) – (Q3, 2023)



Material composition shares of c-Si solar panels (in %) – (world, 2021)



Observations

- **Silicon input** accounts for around **15%** of total in-house cost:
  - **Silicon and silver make up >50% of materials costs of solar c-Si panels,** but material use is becoming more efficient.
  - **Polysilicon intensity** for c-Si cells dropped by **more than six times between 2004 and 2020** thanks to cell efficiency improvements.
- Cell to module is nearly **60%** of total in-house cost.
  - Cells are stringed and placed between sheets of EVA (ethylene vinyl acetate) and **laminated**; the structure is then supported with **aluminum frames**.
- **Big, integrated companies** can exert pressure on small players that have less **cost control**.
  - Companies with **cost advantage** and **cash holdings** will end up expanding market share.

Notes: Cash cost assumes in-house production from polysilicon modules to integrated solar makers, D&A, SG&A excluded; median used for silicon cost: $6 ~$7/kg, $2.14/g polysilicon, $1=¥7 when referring to mainland China factories.

Source: Sinovoltaics, Solar Panel Manufacturing Process (2025); IEA, Solar PV Global Supply Chains (2022); PV-Manufacturing.org, Photovoltaic Manufacturing and Technology (2025).

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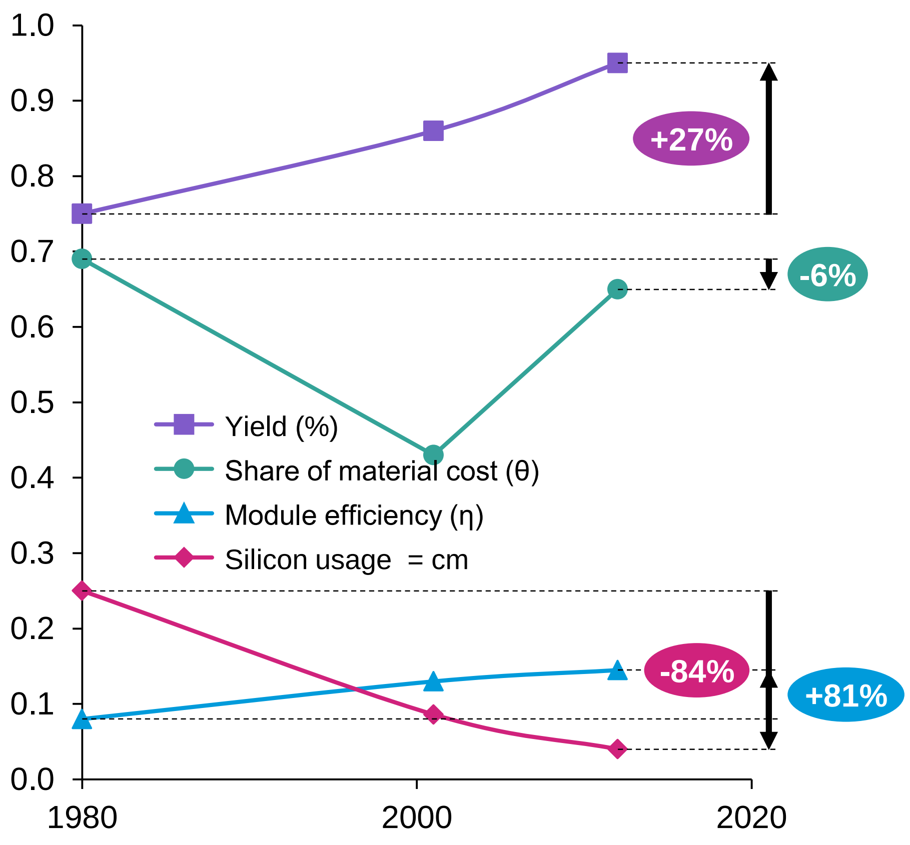
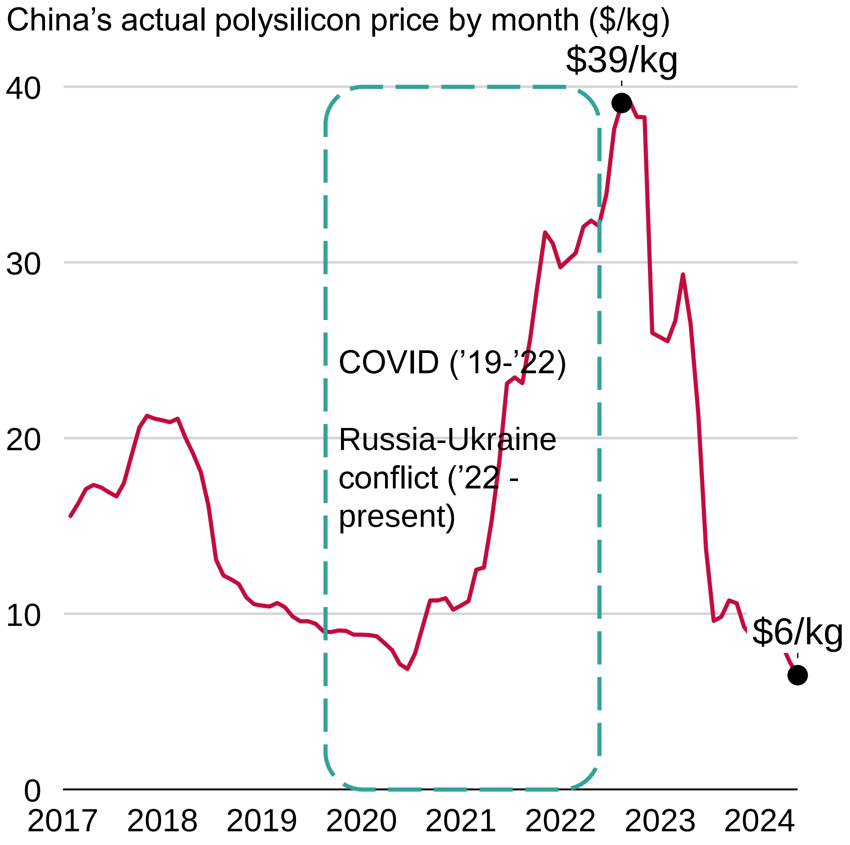
~60% cost reduction from R&D efficiency improvements, ~20% from economies of scale, ~10% from yield from learning by doing

Change in manufacturing parameters ('80-'20)



Polysilicon prices peaked in 2022



Observations

- Polysilicon prices **rose to $39 per kilogram** due to COVID-related **closures of Chinese production facilities** between 2020 and 2022; **as restrictions eased** and **new production capacity** grew, **prices fell back to less than $10 per kg**.
  - With **new capacity still being added**, analysts estimate the price could drop under **$7 per kg in China** in the near future.
- Global wafer production has **shifted from <158.7 mm wafer sizes to larger sizes** since 2017.
- Larger wafer sizes use **fewer grams of polysilicon per watt**, driving **considerable cost savings**.
- **Manufacturing overcapacity** may **temporarily decline in coming years** as factories pause for upgrades needed to produce larger wafer sizes.

Source: Our World in Data, Solar Photovoltaic Module Price (2024); Nemet, How Solar Energy Became Cheap (2019); Farmer & Lafond, How Predictable is Technological Progress? (2016); Kavlak *et al.*, Evaluating the Causes of Cost Reduction in Photovoltaic Modules (2018); Our World in Data, Learning Curves: What Does It Mean for a Technology to Follow Wright's Law? (2023); BNEF, 1Q 2024 Global PV Market Outlook (2024); IEA, Solar PV Global Supply Chains (2022), Business AnalyticIQ, Polysilicon Price Index (2025); PV Magazine, Polysilicon Prices Can Hit All-time Low (2023).
Credit: Taicheng Jin, Isabel Hoyos, Hassan Riaz, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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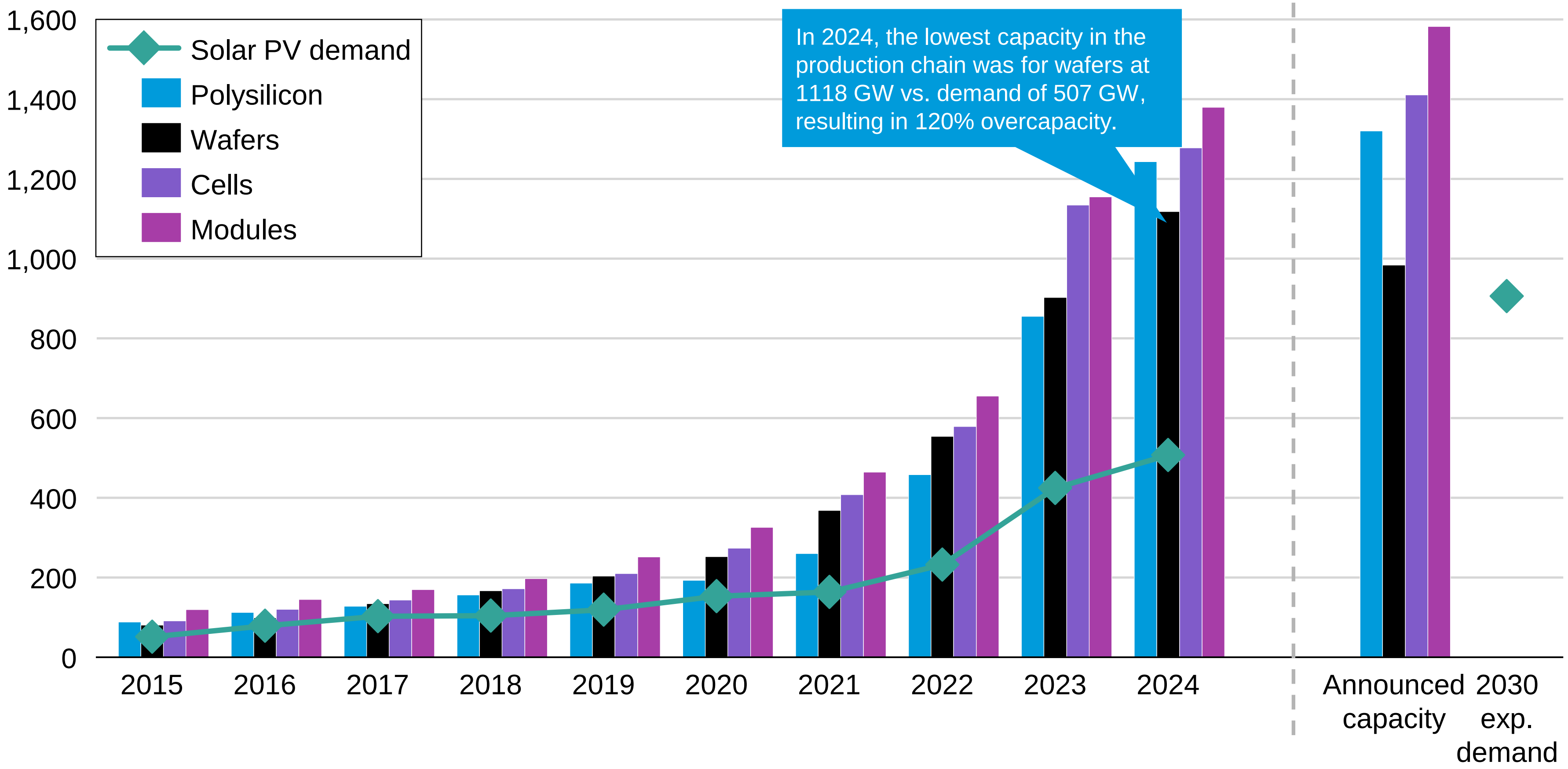
Solar PV manufacturing capacity exceeds demand at every step by at least 70%; overcapacity is expected to last at least until 2030s

Since 2017, solar PV manufacturing capacity has outstripped demand

Global solar PV manufacturing capacity along steps of the value chain (in GW)



Observations

- Since 2015, **global solar PV manufacturing capacity** has **consistently exceeded demand**.
- **Global capacity** is expected to **more than double** in the **next five years**, based on **investment announcements** and the **expected impact of industrial policies**:
  - **IRA** – United States
  - **The Green Deal** – EU
  - **Production Linked Initiative** – India
- With **demand in 2030** expected at **900 gigawatts per year**, all currently announced production capacity would result in a **9% overcapacity in 2030**.

Note: Expected demand in 2030 is based on IEA's Net Zero Emissions (NZE) scenario.
Source: IEA, Solar PV Manufacturing Capacity (2025).
Credit: Yosafat Partogi, Taicheng Jin, Hassan Riaz, Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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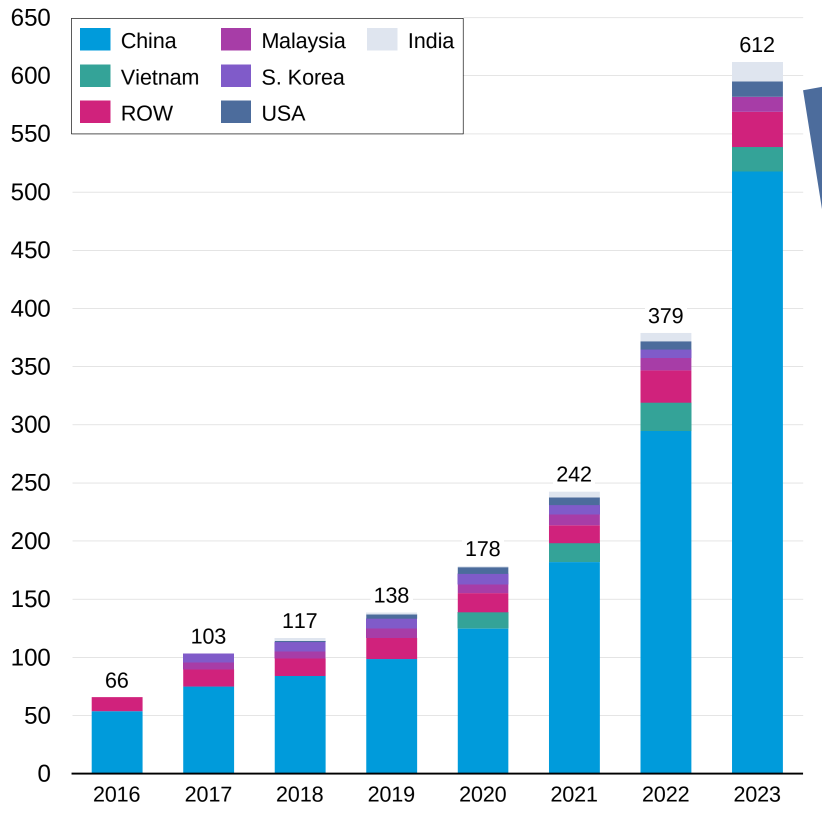
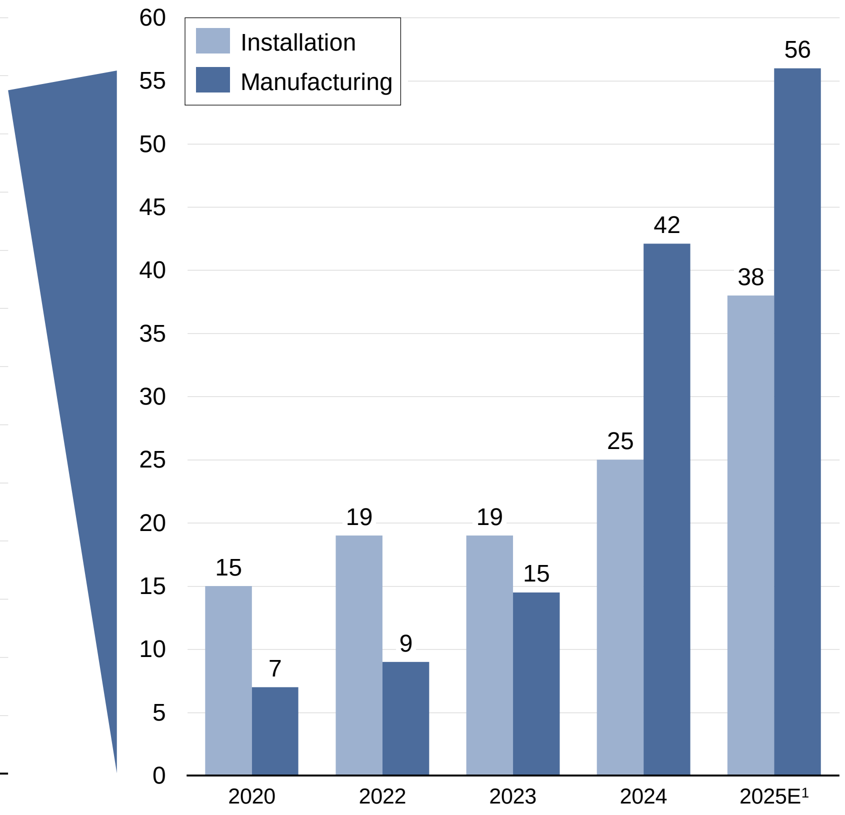
Bolstered by the IRA, the United States' solar PV manufacturing capacity grew ~50% annually since 2020

Global solar PV panel production (GW)



US PV manufacturing & installation capacity (GW)

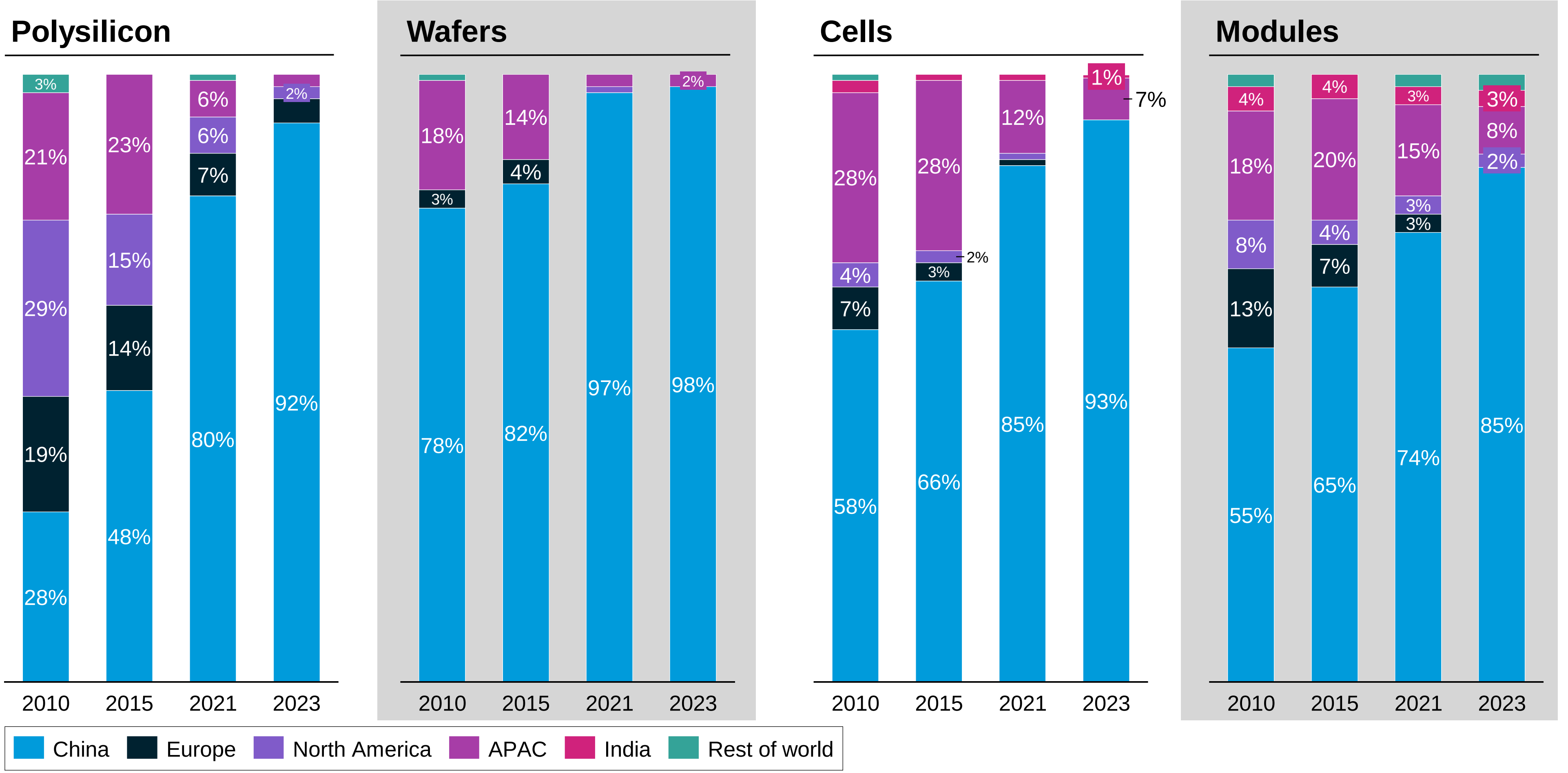


Observations

- **China still dominates the global market:**
  - As of 2025, China's manufacturing capacity exceeds 1,200 GW/year which accounts **for 80-90% of the global supply** across key stages (polysilicon, wafers, cells, modules).
  - China has aggressively increased **solar module production** along with producing in countries in APAC region such as Vietnam, Malaysia, and S. Korea.
  - China benefits from **economies of scale, vertically integrated supply chains and low productions costs.**
- **US manufacturing capacity is growing rapidly:**
  - US module manufacturing capacity grew from ~7 GW in 2020 to over 56 GW as of May 2025.
  - The **IRA was a game changer** unlocking billions in public and private investment.
- **China's market faces headwinds** as overcapacity and price crashes in 2024/2025 are pressuring Chinese manufacturers.
- While the **US cannot match China's scale**, the country strategically built high-quality, incentivized and politically supported capacity from 2022 to 2025, starting to **position itself as a strategic alternative supplier in the West to mitigate geopolitical and supply chain risks.**

(1) US solar PV manufacturing & installation capacity as of May 2025 (SEIA, 2025)
Source: SEIA, Solar Industry Research Data (2025); IEA PVPS, Trends in Photovoltaic Applications 2024 (2024); IRENA, Stats Tool (2025).
Credit: Yosafat Partogi, Heonjae Lee, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Despite increased geographic diversification, China firmly sustains market dominance across entire solar supply chain



Observations

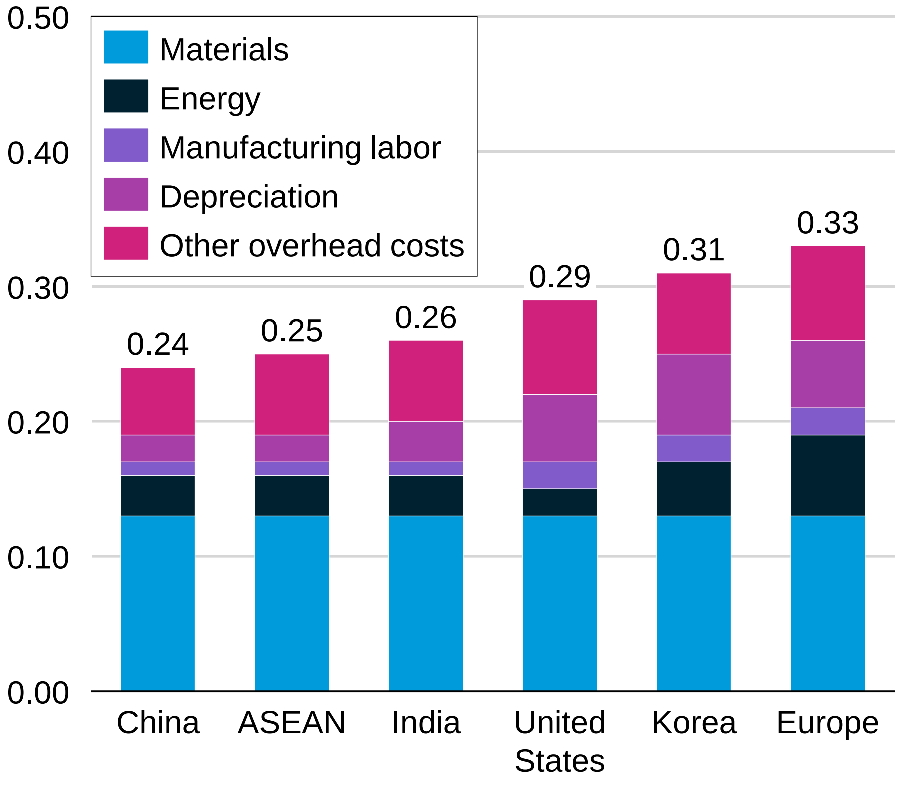
- **China's share** in **all solar PV manufacturing stages exceeds 75%** - **more than double its 36% share in global PV demand**.
- In 2025, solar module manufacturing in the United States surpassed **50 GW of capacity**
  - U.S. solar and storage manufacturing has reached **$40.6 billion since Q3 2022**
- China faces **cells and modules competition** from Vietnam, Malaysia, and Thailand.
- With increased incentives, **North America and India** are **projected** to scale **wafer, cell, and module production by 2027**.

Sources: IEA, Solar PV Global Supply Chains (2022); IEA, 2027 Solar PV Global Supply Chain Projections (2022); SEIA, Solar & Storage Supply Chain Dashboard (2025); IEA PVPS, Trends in Photovoltaic Applications 2024 (2024).
Credit: Shaurir Ramanujan, Taicheng Jin, Max de Boer, Lara Geiger, Marcelo Cibie, Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

China's low production costs are enabled by vertical integration and a focus on mega-scale plants

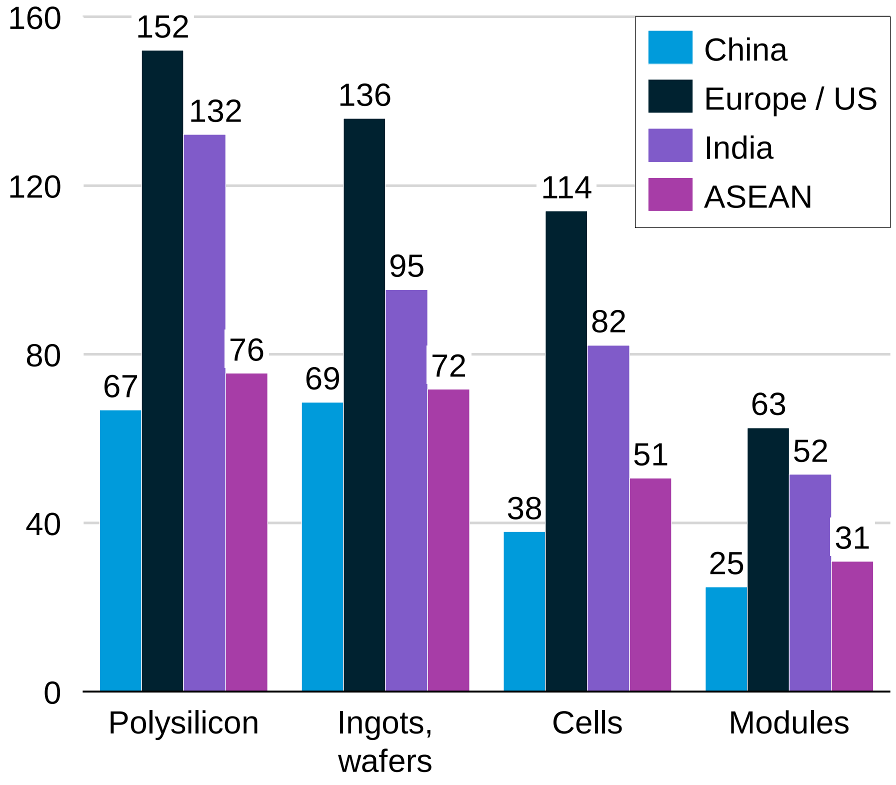
Lowest production costs globally

Total production costs for mono PERC c-Si solar components by input (2022, USD per watt)



Lowest investment costs for new plants

Investment required for new solar PV production capacity (in USD millions per GW of production capacity)



Observations

- Driven by **government investments in the early 2000s**, China built an **enormous lead in solar PV manufacturing**
- Over the past 10 years, producers have also **vertically integrated along the value chain** to realize further economies of scale
- Finally, China now has **extensive expertise** in **developing mega-scale PV manufacturing facilities** that no other country can match

Source: IEA, Solar PV Global Supply Chains (2022).
Credit: Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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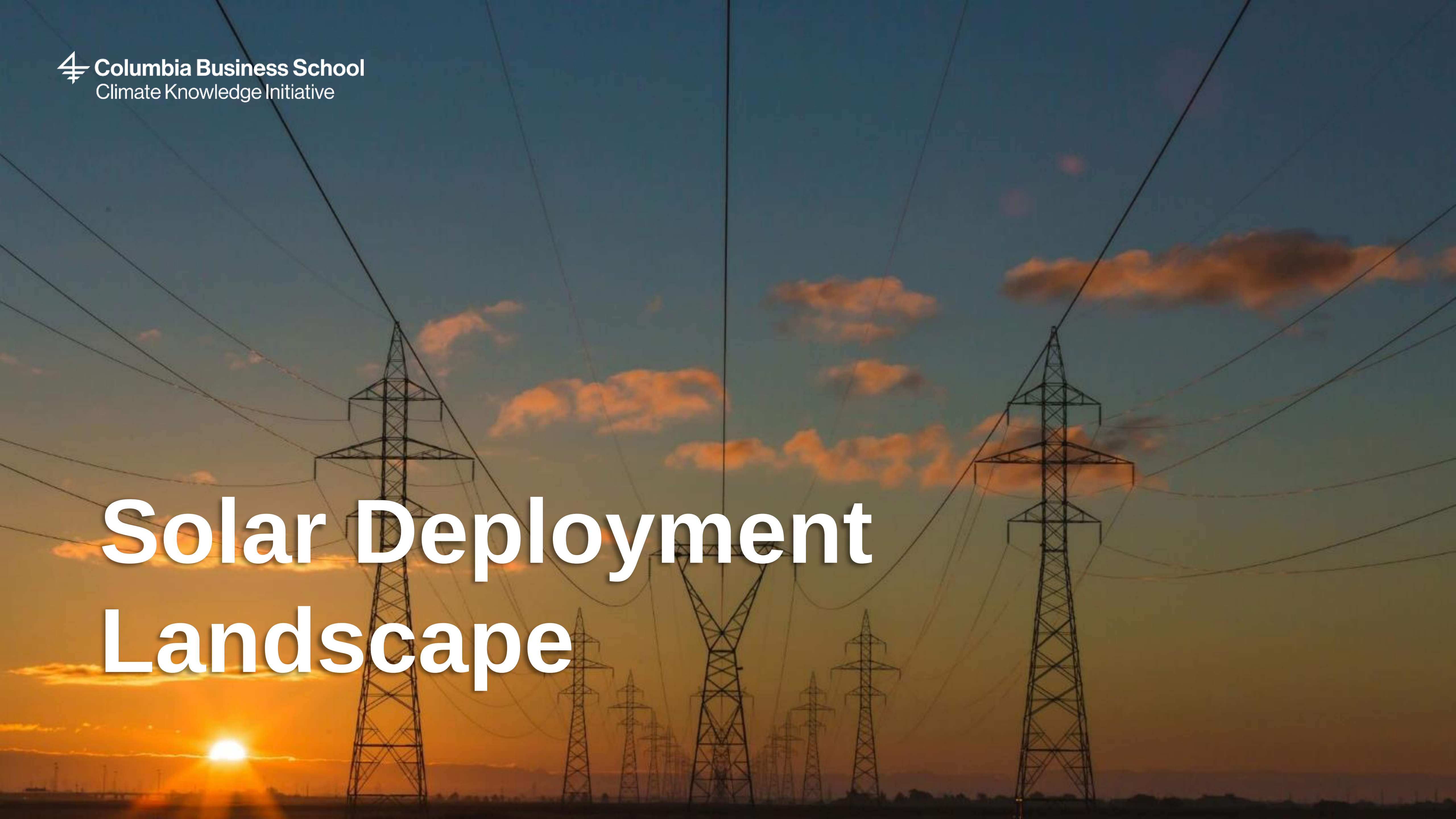

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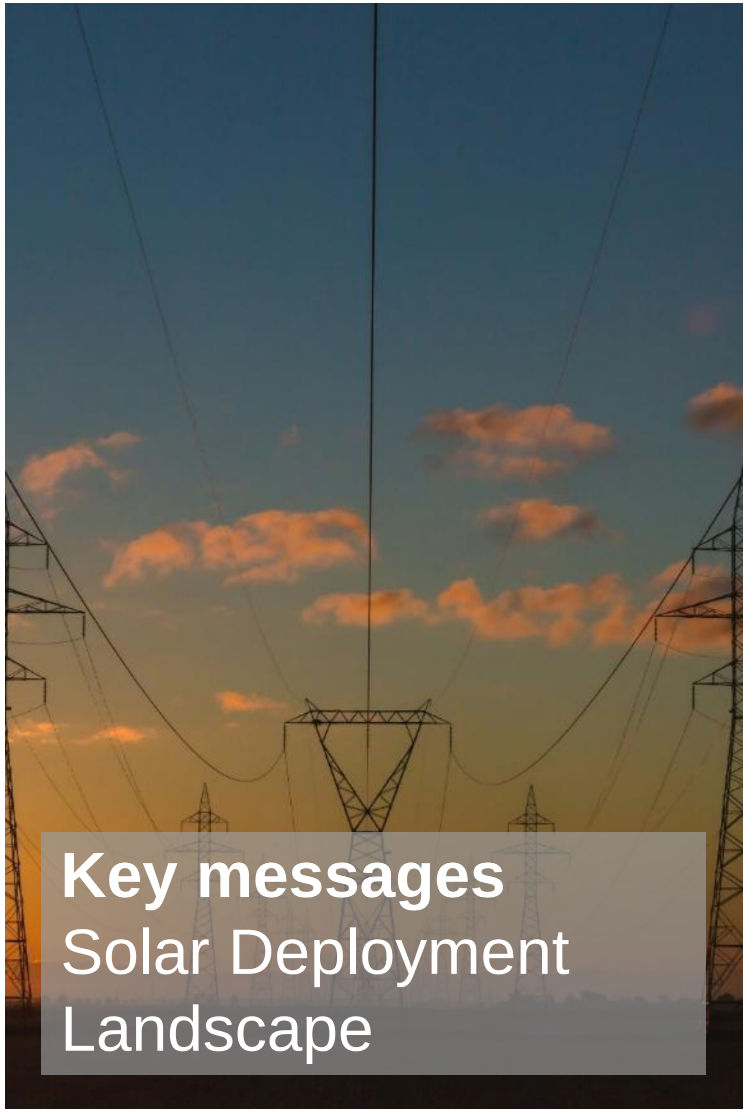
Solar Deployment Landscape



To achieve net zero by 2050, **solar PV capacity must grow 15-fold** — from 1,600 TWh in 2023 to 25,000 TWh in 2050.

- Only **55% of global solar PV generation capacity** has been deployed by **utility companies**.
- **Residential capacity** has **proportionally grown the fastest at +31% ('17–'22 CAGR)**, while **utility capacity has grown the most in absolute terms** from **230 TWh to 961 TWh (+731 TWh '17-'22)**.

Residential solar challenges include **financing access**.

- Recently in the United States, **solar loans and direct purchases** gained traction over once-dominant third-party ownership models.
- Utilities either **pay homeowners directly** for their power (direct payment mechanisms) or give **credits to offset future consumption** (credit systems).
- Community solar projects are a different way for **non-homeowners to get access** to solar PV.

Commercial and industrial players can opt for on-site installation of solar panels, signing a **power purchase agreement (PPA)** or opting for a **solar lease** with a solar PV provider.

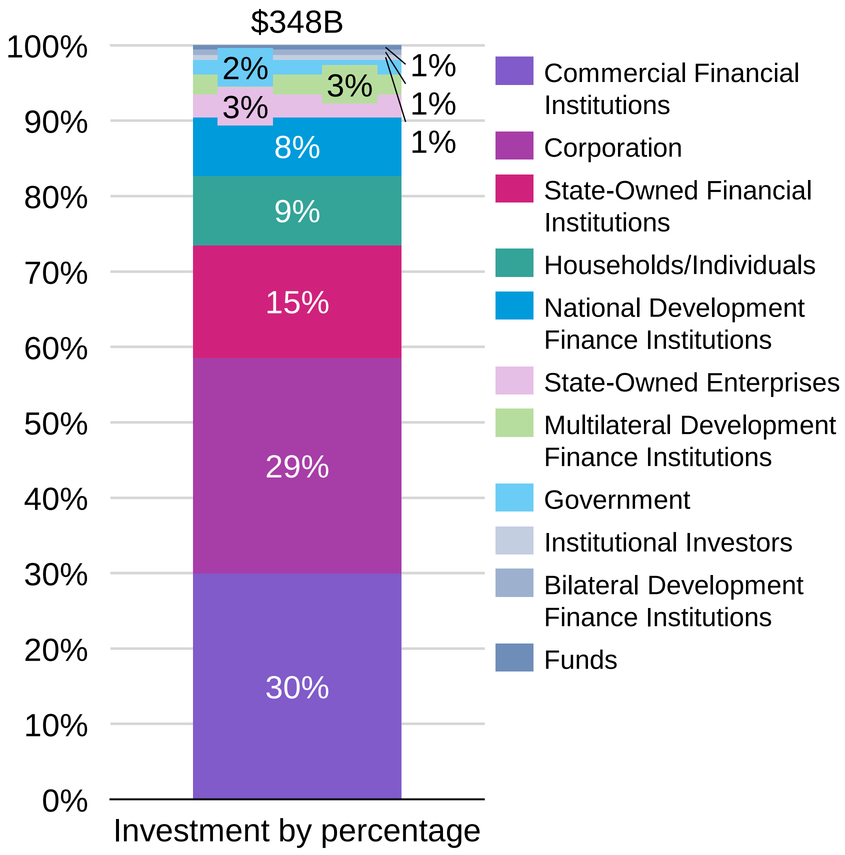
- **PPAs** have surged in popularity recently, with global volume covered by PPAs growing from 14 GW to 110 GW from 2016 to 2021.
- **Solar leases** have also grown in popularity in the Northeast corridor and recently California with very attractive lease rates ranging from $68,000 to $100,000 a year per 100,000 square feet.

Project finance has become an increasingly popular financing method for **utility-scale solar PV projects** given a surge in projects covered by PPAs. Project finance benefits include:

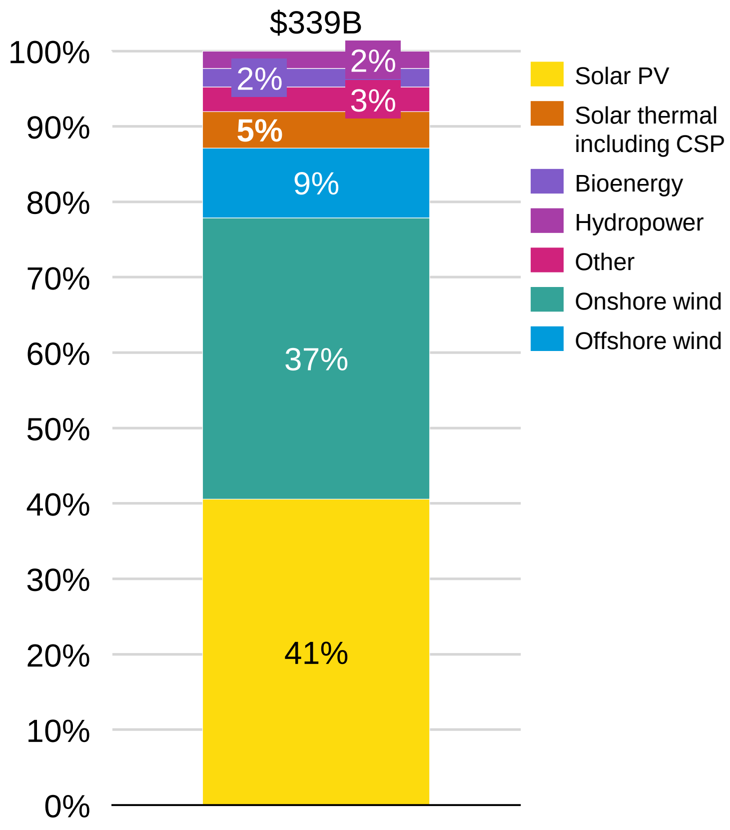
- **Risk isolation**
- **Ability to optimize capital structure**

~70% of solar PV investment comes from private sources, mostly commercial financial institutions and corporations

Global renewable energy finance, by type of investor (2020)



Global renewable energy finance, by technology (2020)



Observations

- In 2020, **68% of funding for solar PV came from private sources**.
  - Private capital tends to flow to regions with low risk, making public investment in regions like Sub-Saharan Africa necessary.
  - State-owned financial institutions and national development finance institutions provided most of the public funding for renewable energy in 2020.
- **Households and individuals** accounted for 10% of investment in all renewable energy in 2020 — **85% of that for solar PV**.
- **Commercial financial institutions** and **corporations** accounted for **~59%** of all renewable energy investment in 2020.
- **Institutional investors** accounted for only 1% of investment in renewable energy in 2020 and tend to favor established technologies like solar PV and onshore wind.
  - In 2020, solar PV accounted for 74% of renewable energy funding by institutional investors.

Sources: CPI and IRENA, Global Landscape of Renewable Energy Finance 2023 (2023); IRENA, Investment Trends (2023).
Credit: Isabel Hoyos, Taicheng Jin, Hassan Riaz, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Residential solar incurs relatively high soft costs; commercial & industrial and utility-scale face long permitting processes

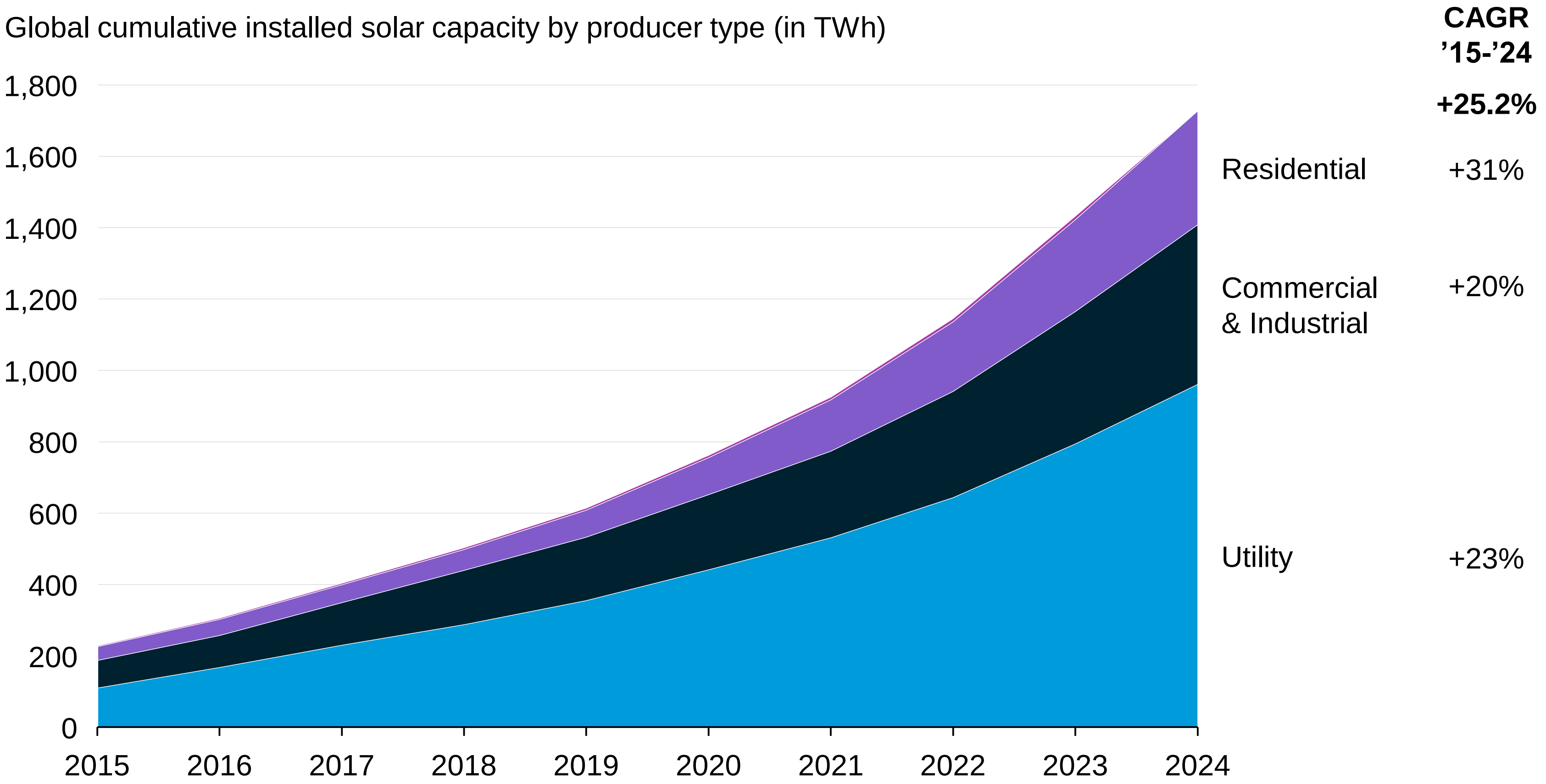
	1 Residential	2 Commercial & industrial	3 Utility-scale
Description	• Powers a single residence • Typically installed on rooftops or backyard, consisting of an average of 8 to 20 panels • 2–10 kW	• Powers a commercial business, including small businesses and large manufacturing facilities • Typically installed on rooftops or adjacent land • 10 kW–10 MW	• Large-scale solar projects that generate power to feed the energy grid, supplying a wide array of potential off-takers (spot market, commercial, industrial, and utility companies) • 10 MW or larger
Global cumulative installed capacity, 2024	**357 GW**	**522 GW**	**1,226 GW**
US system price ($ per watt), 2024	**$3.36**	**$1.46**	**$1.05–$1.18**
Deployment options	• PPAs • Lease • Loan • Direct purchase	• PPAs • Direct purchase for on-site installation • Lease	• Project-level financing (equity or debt) • Balance sheet (equity or debt) • Grants • VPPAs
Stakeholders	• Homeowners (off-takers) • Financial institutions • Contractors and installers • Solar and energy storage equipment manufacturers	• Corporate and industrial customers (off-takers) • Project developers and EPCs (engineering, procurement, construction) • Project financiers • Contractors and installers • Local government agency project owners • Solar and energy storage equipment manufacturers • Solar project owner	• Off-takers • Project developers and EPCs (engineering, procurement, construction) • Project financiers • Contractors and installers • Local government agencies • Solar and energy storage equipment manufacturers • Solar project owners
Challenges	• **Relatively high soft costs** • **Relatively high cost per watt**	• **Relatively long permitting process** • **Interconnection roadblocks**	• **Relatively long permitting process** • **Interconnection roadblocks**

Sources: SEIA, Solar Industry Research Data (2025); IEA, Solar PV-Technology Deployment (2025); Wood Mackenzie, US Solar Market Insight (2025).
Credit: Isabel Hoyos, Taicheng Jin, Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

~55% of installed solar PV capacity comes from utility, rest from commercial and residential

Strongest growth in recent solar PV deployment comes from residential projects

Global cumulative installed solar capacity by producer type (in TWh)



Observations

- Residential solar PV trends:
  - **Governments support residential solar PV rollout** through **net metering** and **tax breaks and credits**.
  - **Electricity price increases in Europe** make residential solar more attractive.
  - **Self-sufficiency** concerns return to US.
- Large-scale (C&I and utility) trends:
  - **High electricity prices in the EU** (as a result of natural gas) drive **profits for renewables**.
  - **Considerable growth in China:**
    - > **New business models** in China, like power transmission via underutilized **ultra-high-voltage transmission** lines, enable faster solar PV rollout.
    - > **Rising electricity prices** in China, due to **internalization of externalities** from coal-electricity, speeds up PV deployment.

Note: Off-grid capacity in 2022 is 9 GW.
Sources: IEA, Renewables 2022 (2022); IEA, Solar Power PV Capacity (2025).
Credit: Taicheng Jin, Hassan Riaz, Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Residential solar can be financed with different structures — key difference is actual ownership

	Description	Who owns the system?	Upfront costs	Long-term benefits for homeowner	Example companies (US)
Solar PPA	• Agreement where a company installs a solar system on a homeowner's property. **The company owns the panels** and is **responsible for maintenance**. • **The homeowner buys the generated electricity from the company**, at a rate that is often lower than the retail grid rate.	**Company**	**None**	**Lower** Also highly dependent on contract terms	sunrun, nrg, TESLA, sunnova, SUNPOWER
Solar lease	• Agreement where a company installs a solar system on a homeowner's property. **The company owns the panels** and is **responsible for maintenance**. • The homeowner pays the lease company **a fixed monthly lease fee**, giving them **the right to use the produced electricity**. • **Revenue from excess electricity production** is allocated to **either the company or homeowner**, based on the **lease agreement**.	**Company**	**None**	**Lower** Also highly dependent on contract terms	
Solar loan	• The homeowner **borrows money** from a **bank or other institution** to **finance the purchase and installation** of a solar system on their home. • The homeowner **repays the principal and interest over time**.	**Homeowner**	**None – Low**	**Higher**	WELLS FARGO, LENDINGPOINT, upgrade, SoFi
Direct purchase	• **Direct purchase of a solar system by a homeowner**, without the involvement of any other third party.	**Homeowner**	**High**	**Highest**	Not applicable

In the United States, the residential solar PV market has shifted over the past 10 years from third-party ownership models (PPA and lease) to solar loans and direct purchases.

Sources: EnergySage, Solar Leases: What to Know Before You Sign (2025); NREL, Residential Solar PV: Comparison of Financing Benefits, Innovations, and Options (2012); SEIA, Solar Power Purchase Agreements (2024); SolarReviews, An Expert Guide to Solar Leasing: Pros, Cons, and Red Flags (2025).
Credit: Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Consumers can receive either direct payments or credits for surplus electricity produced

	Direct payment mechanisms	Credit systems
		
Description	• Homeowners receive **direct financial compensation** for **all the electricity they produce**. • Typically, **homeowners pay the retail rate** for **any electricity they themselves use**. • **Financial compensation** can be set **below, at, or above** the **retail rate of electricity** depending on policy goals.	• Homeowners receive **credits** for any **surplus electricity** their **solar panels feed back into the grid, which can** be used to **offset future consumption**. • When the **received credit** is **valued at the retail price of electricity**, we call it **net metering**; if the **value is lower** (e.g., at wholesale rate), it's called **net billing**.
Examples	Feed-in tariffs, value-of-solar tariffs	Net metering, net billing

Sources: EnergySage, Feed-in Tariffs (2023); EnergySage, Net Metering vs. Net Billing (2022); NREL, Value of Solar Tariffs (2014).
Credit: Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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Pay-as-you-go structure can bring affordability, expand service, and improve financial inclusion

Roles and responsibilities of different stakeholders

Energy service provider	Financier	Mobile network operator
Provides **system components**, **installation**, and operations and management, and collects payments from customers	Provides **funding** to the ESP for installing solar home systems **Receives payment from user**	Provides machine-to-machine tech and monitoring **Provides mobile services** to enable payments

Process: *Installation → Payment by user with Mobile Money → Activation code sent by ESP → User input coded into PAYG → System unlocked for a set allowance*

Observations

- **Electrification** is a priority, but grid expansion is **expensive and has a long lead time**. Therefore, **distributed solar PV**, coupled with pay-as-you-go (PAYG) could be an answer.
  - Kenya and Tanzania represent 85% of market share, but deployment is also in other countries, including Ethiopia, Uganda, Sierra Leone, Malawi, and Zimbabwe.
- **PAYG structure: A home solar system** that customers pay for using mobile payment technologies and **mobile phone credit**.
  - Certain rural populations have access to mobile internet and ample solar potential but don't have access to financial accounts.
- Combination of **payment rules** and **ownership** and financing schemes:
  - **Lease to own: C**ustomers pay for the entire generation capacity (i.e., solar home system) in small installments over a period of one to three years.
  - **Usage-based:** Customers prepay for the electricity supply (in kilowatt-hours).

Sources: IRENA, PAYG Models (2020); USAID, PAYG Solar as a Driver of Financial Inclusion (2017).

Commercial companies can install panels or buy electricity through a power purchasing agreement

On-site solar installation

Description

- Companies can **deploy larger solar systems on their properties** (e.g., flat roofs of manufacturing halls) **typically around ~500 kW**, in contrast to 5 to 20 kW for residential setups.
- These systems often operate **"behind the meter,"** with energy either **consumed on site** or **sold back to the grid** with **feed-in tariffs**.

Pros

- ⊕ **Significant cost savings**, as all produced energy comes at a marginal cost of zero dollars
- ⊕ Often allows company to **make use of tax benefits** (consisting of federal investment tax credit and accelerated depreciation)

Cons

- ⊖ **Requires CapEx** for purchase and installation and **has maintenance costs over time**
- ⊖ **Continued dependence on grid electricity** at wholesale rate when panels are not producing electricity

PPA

Description

- An **agreement between a company** and **an owner of a solar installation** (e.g., a utility or a financial institution) to **buy energy directly**.
- This **long-term agreement** locks in a **fixed rate**, ensuring **stability for the provider** and often **securing discounted rates for the buyer** compared to current wholesale prices.

Pros

- ⊕ **Fixed prices** provide **certainty and stability** for **financial planning**
- ⊕ **Company has no concerns about installation or maintenance**, which is all done by the solar installation owner

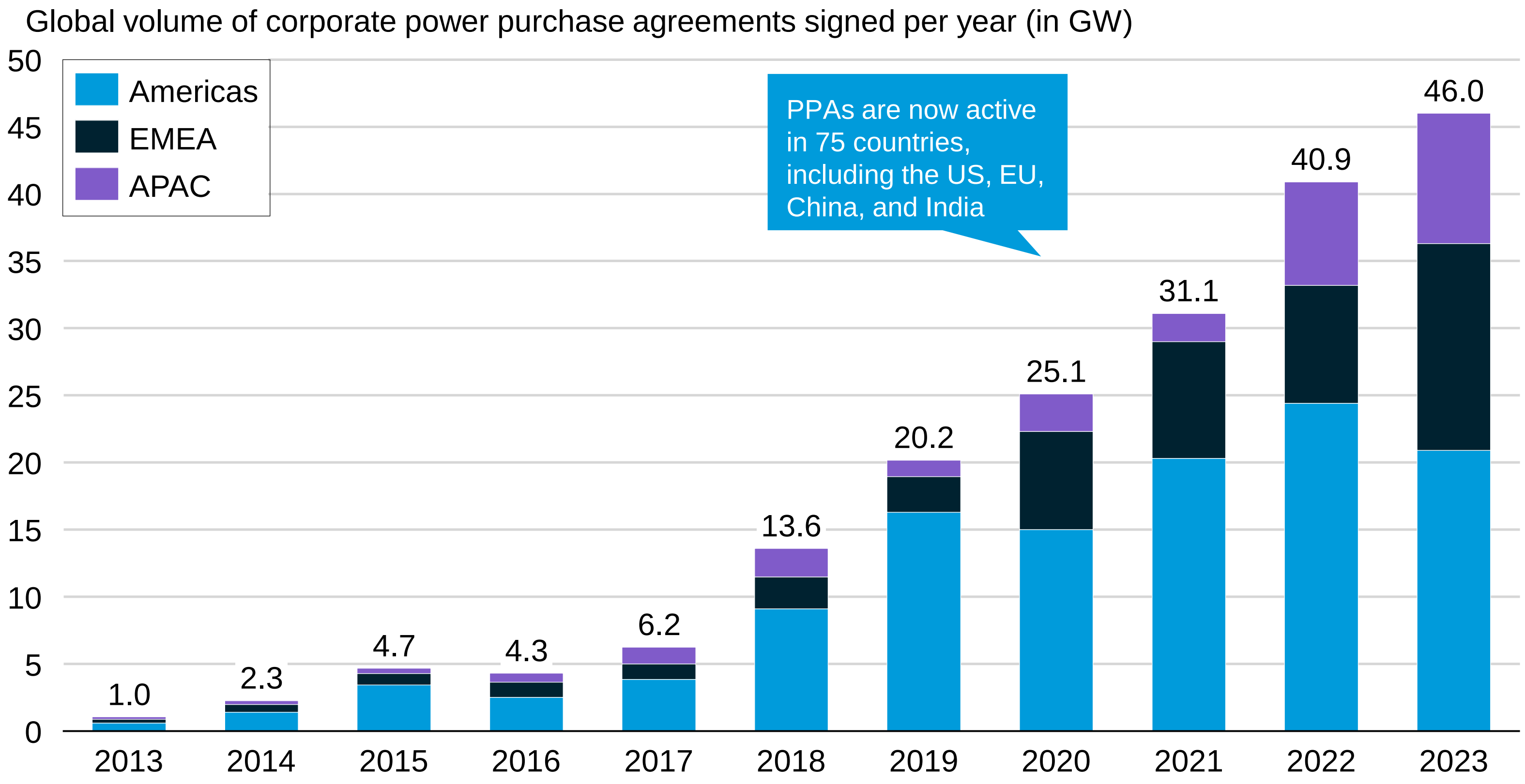
Cons

- ⊖ **Requires long-term commitment** (10 to 20 years)
- ⊖ Company **will not benefit financially** if **energy prices drop**

Sources: Avana Capital, How Does a Commercial Solar PPA Work (2019); Coldwell Solar, What Is a Commercial Solar PV System (2025); US DOE, Power Purchase Agreement (2025).
Credit: Max de Boer, Lara Geiger, Marcelo Cibie, Hassan Riaz, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

PPAs have surged in popularity over the past few years, driven by companies looking to make credible sustainability commitments

Strong growth in the signing of PPAs over past 5 years, especially in US



Observations

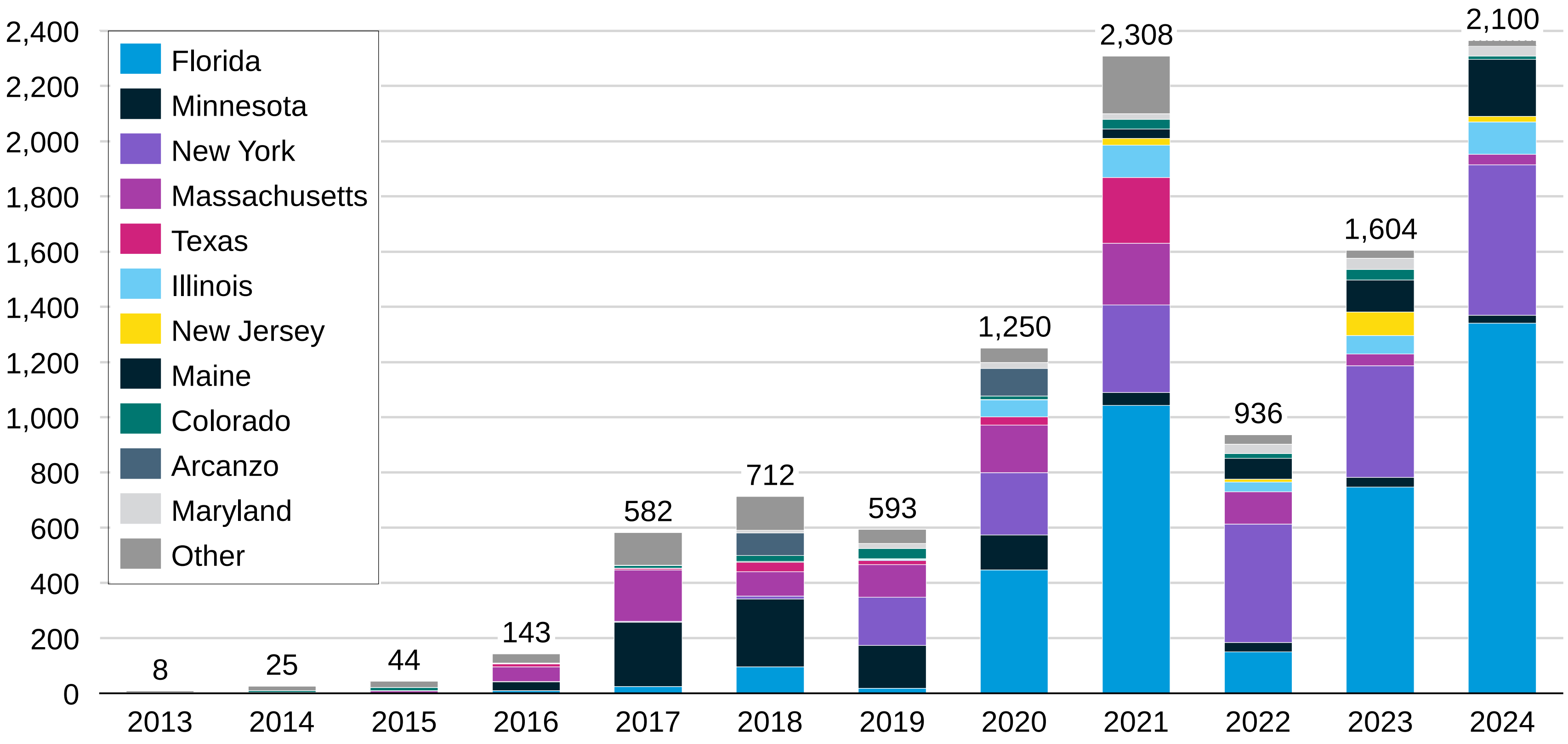
- Corporate power purchase agreements have become **increasingly popular**.
  - Companies are **setting public sustainability goals** with renewable energy as a focal point.
  - A growing focus on **additionality**, which prioritizes **adding new capacity** over using existing ones, is shifting companies from buying green energy certificates to PPAs.
- There is still **potential for growth:** Columbia University's Center for Global Energy policy estimates that **only 3% of the US commercial and industrial energy market is covered by PPAs.**
  - Despite being the **largest PPA market, the US has seen deals decrease by 16%** from a record high in 2022 **due to interest rate and PPA price** CGEP.
- **Regulatory challenges** also remain a barrier in many markets, with issues ranging from **state-controlled utilities** to **restrictions on transporting electricity** to the end user for PPAs.

Note: Graph excludes on-site PPAs. Pre-reform PPAs in Mexico and sleeved PPAs in Australia are excluded.
Sources: CGEP, The role of Corporate Renewable PPAs (2021); Climate Group RE100, 2024 RE100: Annual Disclosure Report (2024); WEF, Clean Energy CPPAs (2021).
Credit: Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Community solar is an increasingly popular way for more consumers to access the benefits of residential solar PV

Community solar deployment focused on small number of states

New community solar capacity added by year and state (in MWac)



Observations

- Community solar is a solar project an **asset owner pursues** with **residential participants signing up** to receive a **share of the benefits and funding the project**.
- Homeowners, renters, and businesses can have equal access to community solar, **including low- to moderate-income customers**. This builds a stronger, more distributed, and more resilient electric grid.
- Customers either **buy or lease a part of a larger, off-site solar PV site**.
- A utility company buys the electricity generated by the community solar project. In return, the **participants receive credits to offset their own electricity bills**.

Sources: NREL, Community Solar Deployment (2024); NREL, Community Solar 101 (2020).
Credit: Isabel Hoyos, Hassan Riaz, Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Scaling Solar” (14 August 2025).

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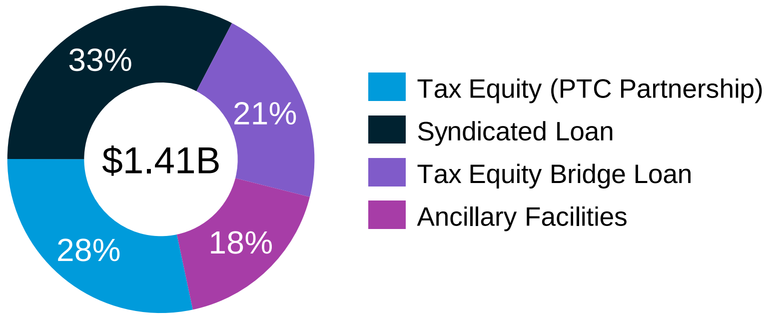
Utility-scale PV can take a variety of equity-debt structures, but project finance with tax equity remains a preferred staple

Typical project finance waterfall (accounts)

- **Project Revenues**
- **Construction / Operating** → **C&O expenses**
- **Debt Payment** → **Fees, interest / principal**
- **Debt Service Reserve** → **Maintain debt service reserve**
- **Maintenance Reserve** → **Maintain maintenance reserve**
- **Subordinated Debt** → **Payment of sub-debt**
- **Distribution** → **Distribute to equity holder**

Excelsior Energy's $1.41 billion package for **Faraday Solar**



Typical lending fees for project financing:

(i) 2–6% of the aggregate loan commitment as an arranging or structuring fee

(ii) 1% of aggregate loan commitment as a syndication fee

(iii) $75,000 annual administrative agency fee

(iv) $50,000 annual collateral agency fee

(v) Facility fees to each lender in the syndicate in an amount between 0.75–1.5% of each lender's commitment.

In addition, the project company will be required to pay the professional fees and administrative expenses of each of the lenders in evaluating the transaction, negotiating the loan documents, and providing the loans.

Observations

- Since 2013, the **share of debt financing in global renewable investments has increased from ~23% to ~55%**, primarily driven by increased cash flow visibility through PPAs
- Since 2004, project finance has become an established financing alternative, increasing its share from **~15% to ~35% of renewable energy asset finance**
- Project finance offers **two main benefits to renewable projects** vis-à-vis balance sheet alternatives:
  - **Corporate or balance sheet financing**: Decision is based on the entire balance sheet
  - **Project finance**: On the cash flow generating capacity of a special purpose vehicle (SPV)
  - Use of an **SPV, legally and commercially separate** from the project developer
  - SPV financed with **limited guarantees from the project developer; lenders do not have recourse** on the other businesses of the project developer and rely on the project's cash flows for repayment

Sources: FS-UNEP, Global Trends In Renewable Energy Investment 2020 (2020); CPI and IRENA, Global Landscape of Renewable Energy Finance 2023 (2023); Steffen, The Importance of Project Finance for Renewable Energy Projects (2018); PV Magazine, Utility-scale Solar Projects Secure Billions in Financing (2023); WSGR, Project Finance Primer for Renewable Energy and Clean Tech Projects (2010).

Credit: Isabel Hoyos, Taicheng Jin, Hassan Riaz, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

There are many options for utility-scale solar to raise debt, each with its advantages regarding debt load, rate and tenor, and risks

Options for utility project to raise debt

Syndicated and club loans (BSL)

- Coordinated by one or more arranger bank, whereas in club deals, a handful of lenders take equal roles in leading
- A group of banks each take a portion of a larger loan so minimize the risk
- Syndicated loan structures are often preferred to accessing the capital markets through 144A offerings because:
  - Capital markets investors are generally less likely to assume construction risk
  - The disclosure documentation for a 144A offering is generally more extensive than that prepared in connection with syndicating a commercial loan

Project bonds (144A)

- Private placement through 144A offerings:
  - Exempt from registration with the SEC if the purchasers are “qualified institutional buyers under the Securities Exchange Act of 1933
- Amount raised disbursed at closing, leads to negative carry
- Less restrictive covenants
- Issued in relatively small amounts (making them ideal for smaller project financing)
- Fixed rate with certainty → removes the upside potential of floating rates that are available pursuant to commercial bank loans
- Faster to execute andless inexpensive than BSL

Term loan B (TLB)

- Shorter tenors and lower or delayed amortization, often with **bullet payments** due at maturity
- Higher risk profiles and usually were non-investment grade
- Terms and conditions less onerous than traditional project debt that amortized over a longer period
- As a result of the subprime lending crisis and the subsequent credit crunch, TLB market all but disappeared

Construction loans

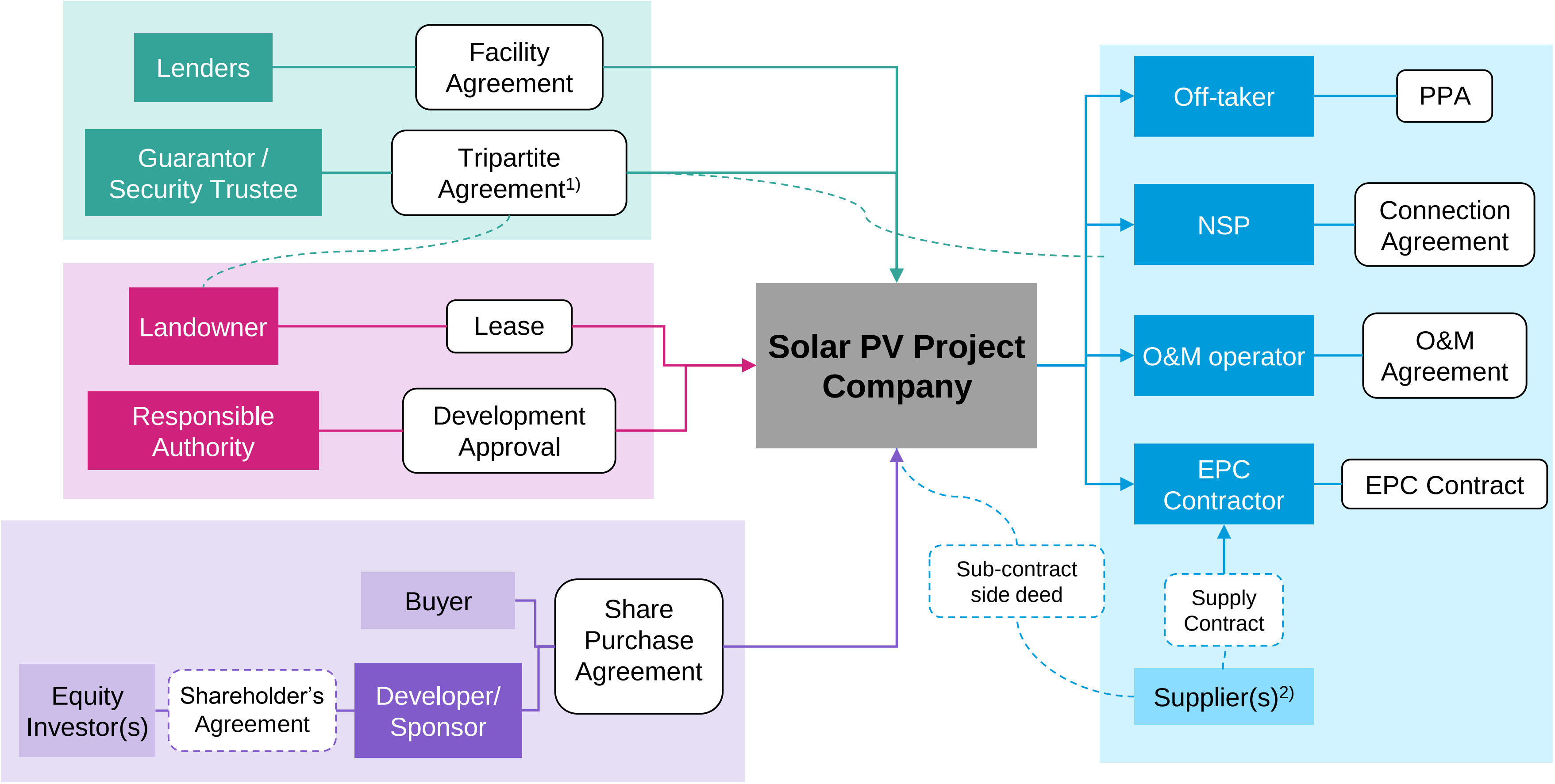
- Used only for the period in which the project is under construction
- Interest rate can be higher vis-a-vis a term loan (reflecting increased risk to lenders during the construction period), but more frequent drawdowns of construction loans permitted
- At the end of the construction loan availability period, construction loan usually converts to a term loan

Working capital loans

- Primarily for ordinary course expenses such as inventory purchases
- Sized smaller than construction or term loans and subject to a maximum available amount tied to the value of a project company’s inventory and cash (often 80%)
- Usually revolving in nature, meaning amounts borrowed can be reborrowed once they are repaid

Source: WSGR, Project Finance Primer for Renewable Energy and Clean Tech Projects (2010).
Credit: Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Scaling Solar” (14 August 2025).

Parties to a ‘bankable’ project generally include a sponsor, lender(s), the project company, and an off-taker



Advantages of Project Finance

- **Easy project management::** Customers invest **less time and resources** in the project than if they were to do it themselves. And contracting with the same company for operations and management later could mean (1) legal enforceability and (2) **less of a learning curve with its own installment**.
- **Better financing terms:** Less need for owner's equity contribution allows access to debt, as a cheaper form of capital financing; risk offloading also increases lenders' appetite.
- **Risk allocation:** The project risk is shifted to the EPC contractor. The contractor is responsible for all project activities from the design phase through to the turnkey moment.

(1) Tripartite agreements are between the project company, the security lender/guarantor, and one of: landowner, contractor, O&M, NPS, and off-taker.
(2) Key supplies could be directly purchased and allocated to the EPC by the project company.
Source: PwC, EPC Projects in the Solar Industry (2022).
Credit: Taicheng Jin, Hassan Riaz, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Scaling Solar” (14 August 2025).

Project finance sequesters risk, optimizes cap structure, and offers alignment of interests for all parties involved

Advantages of project finance

Risk isolation

A special purpose vehicle (SPV) **isolates risks,** commercially and legally, and provides separation from project developer.

The only risk for the project developer is its invested capital.

If the project encounters difficulties, **lenders would have claim only against the project's assets**, not the broader assets of the developer.

Alignment of interests

By creating a distinct project entity, all stakeholders, from investors to suppliers, hold aligned **incentivized for its success**, as **returns are tied to project performance**, not the developer's broader assets.

Optimized capital structure

Predictable cash flows from fixed-rate power purchase agreements can support a **higher debt load**.

Debt financing allows retaining of equity and overall is a **more cost-effective form of capital** with certain **tax advantages**.

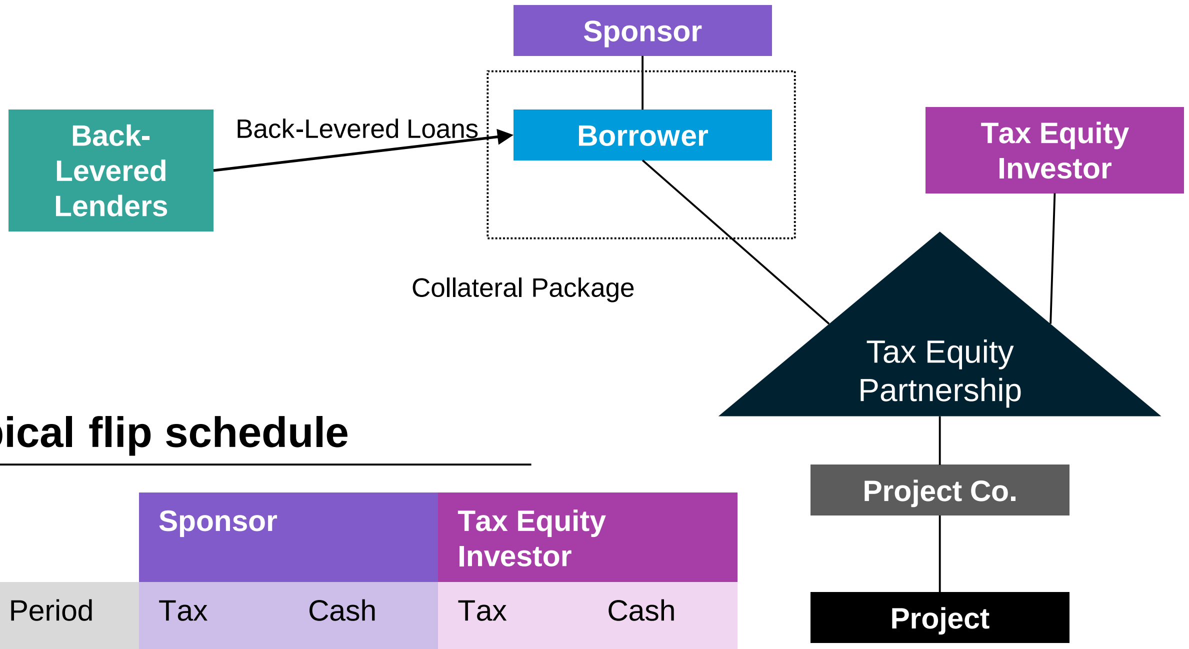
Flexibility in ownership

A **distinct project entity** offers **easier transfers in ownership** or **sales of the project** to third parties at various stages of the project.

Sources: FS-UNEP, Global Trends In Renewable Energy Investment 2020 (2020); Steffen, The Importance of Project Finance for Renewable Energy Projects (2018).
Credit: Taicheng Jin, Isabel Hoyos, Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Scaling Solar” (14 August 2025).

Most of operating period term loans in the US are back levered to tax equity, a unique form of equity with loan-like characteristics

Typical back-leverage financing structure



Typical flip schedule

	Sponsor		Tax Equity Investor	
Period	Tax	Cash	Tax	Cash
1	1%	Majority share	99%	Minority share
2	95%	95%	5%	5%

Observations

- Projects have high levels of contracted revenue, limited variable OpEx, and relatively predictable cash flows, often held in an LLC and taxed as partnerships.
- Tax equity typically **covers 35% of the cost** of a typical solar project, plus or minus 5%.
- **JPMorgan and Bank of America dominate 80% to 90% of the market** but could face headwinds as capital requirement* is set to quadruple under Basel III.*
- The market is forecasted to grow from $20 billion to $50 billion with recent innovations in transferability of tax credits.
  - Blackstone's Foss & Co. ITC transfer.
  - Bank of America's launch of a tax credit transfer desk in 2023

Typical Structures

- **Partnership flip (P-flip):** Investors contribute cash for tax benefits up to a certain date (~5 years), after which the partnership terms **flip**. The developer instead receives the bulk of the tax benefits and cash.
- **Sale leaseback (SLB):** The developer sells the solar system to a tax equity investor that leases the system back to the developer.

(*) Currently at 100% risk weight if bank's total equity investments are below 10% of its capital. The excess equity investments exceeding 10% of a bank's capital would be assessed at 400% risk weight.
Sources: US DOE, US DOE (2025), GoCardless, Tax Equity Definition (2021), YSG, Solar Tax Equity (2025).
Credit: Taicheng Jin, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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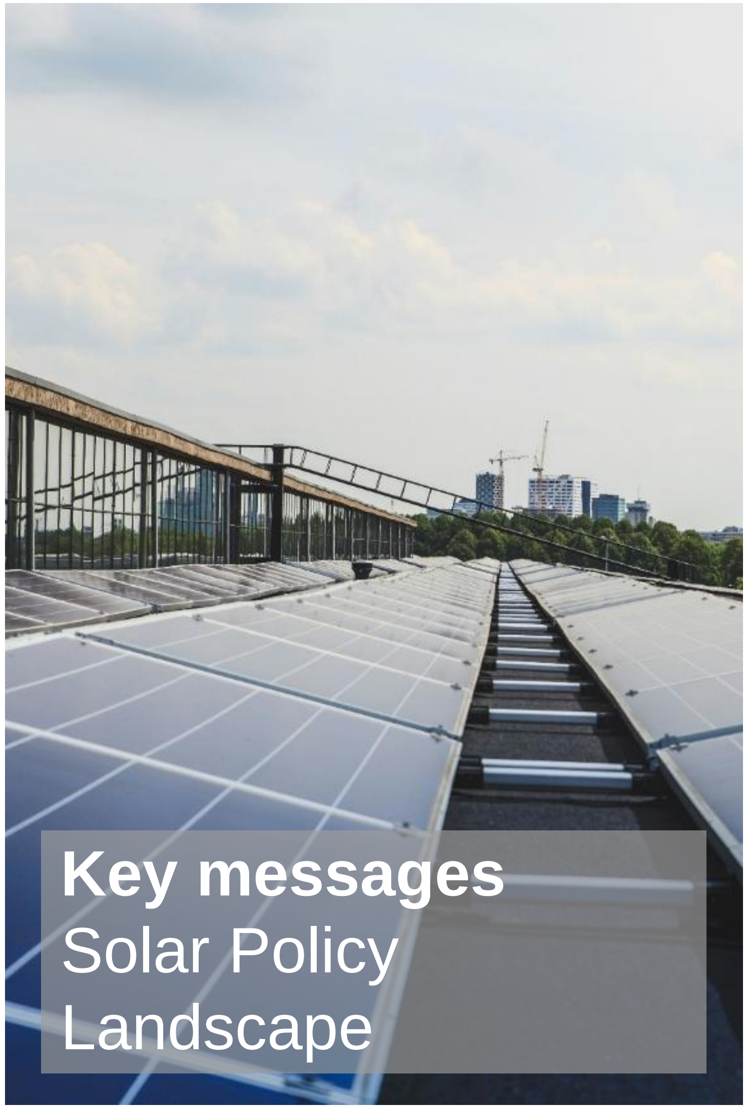
Solar Policy Landscape



Governments worldwide have implemented solar PV supportive policies, including **subsidies and tax breaks, feed-in tariffs, and net metering**. In 2010, feed-in tariffs backed 85% of global solar PV; by 2021 that dropped to only 28%, with other policies covering 49% and 23% operating without support.

China has an installed solar capacity of ~6 GWh in 2023 (21% of total power generation capacity).

- China's 11th to 14th Five-Year Plans, from 2006 to 2021, focus on electrification, supply-side support for renewable energy, and a "great push" for solar and wind.

In response to China's market dominance, the US has introduced **advanced manufacturing tax credits**, put **tariffs on imported solar PV components**, and included a **domestic content bonus in the solar tax credits** for businesses to encourage domestic production.

By extending and increasing solar tax credits, the **US Inflation Reduction Act of 2022 has mobilized $42 billion** from 2022 to 2024 and was projected to **generate an additional ~50% (~160 GW)** of solar capacity by 2033 before the Trump Administration's repeal.

- **Residential Solar Energy Credit:** 30% of the expenses of an installed solar PV system can be subtracted from federal income taxes
- **Solar Investment Tax Credit (ITC):** 30% (up to 50% if certain conditions are met) of the expenses of an installed solar PV system can be subtracted from federal income taxes*
- **Solar Production Tax Credit (PTC):** ¢2.75 per kWh (up to ¢3.35 if certain conditions are met) of produced solar energy can be subtracted from federal income taxes*

**ITC and PTC were mutually exclusive*

Most solar energy policies focus on risk reduction or subsidies

Policy	Description	Can be used to encourage: Residential	C&I	Utility
Direct subsidies and tax breaks	• Consists of governments providing **direct financial support** either in the form **of subsidies** or **tax breaks** for the **purchase of a solar PV system**	✓	✓	✓
Feed-in tariff (FiT)	• A **long-term, guaranteed price** (often above prevailing market prices) for generated electricity from a renewable source • Fixed price **eliminates market price risk** for developers	✓	✓	✓
FiTs through tender	• Developers **bid on FiTs they will accept** for specified generation capacity • Government picks the **lowest bid**, leading to **lower overall costs** while still **eliminating market price risk for developers** • **Similar tender setup** can be used for **commercial power purchase agreements**		✓	✓
Net metering (self-consumption)	• Policy allowing a utility customer to **subtract any power they generate from renewable sources** from the **power they consume** • Customer **billed only for the difference**, regardless of when the power was produced	✓	✓	
Renewable Portfolio Standard (RPS)	• A **regulatory mandate** that requires **a certain percentage of electricity produced by utility providers in an area** to **come from renewable sources** • A common feature of RPS is the **Renewable Energy Credit (REC) trading system**, which can **reduce compliance costs** • A utility that generates more renewable electricity than required **may sell RECs to other utilities** that do not meet the RPS requirement			✓

Sources: Clean Energy Solutions Center, Solar Power Policy Overview and Good Practices (2015); PVPS, Trends in PV Applications 2022 (2022); US EIA, Portfolio Standards (2025).
Credit: Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

US Inflation Reduction Act included solar investment and production tax credits, since repealed by Trump administration

The residential and commercial solar investment tax credits have helped the US solar industry **grow by a factor of more than 200x** since it was implemented in 2006, with an average annual growth of 33% over the past decade alone

Homeowners

Residential Solar Energy Credit

30%

of the **expenses of an installed solar PV system subtracted from federal income taxes**

- **Expenses covered by the tax credit include**:
  - Solar PV panels or cells
  - Contract labor for installation
  - Balance-of-system equipment
  - Energy storage
  - Sales tax
- The tax credit can also be used **against participation in an off-site community solar project**

Businesses

Solar Investment Tax Credit (ITC)

30%

of the **expenses of an installed solar PV system subtracted from federal income taxes**

*(up to **50%** if certain conditions are met)*

- **Expenses covered by the tax credit include**:
  - Solar PV panels, inverters, racking, balance-of-system equipment, and associated sales and use taxes
  - Installation costs
  - Step-up transformer, circuit breakers, and surge arrestors
  - Energy storage devices
  - Interconnection costs (for projects of 5 MW or less)

Solar Production Tax Credit (PTC)

¢2.75 per kWh

of produced solar energy can **be subtracted from federal income taxes**

*(up to **¢3.35** if certain conditions are met)*

- The tax credit **begins phasing out in 2032** and **ends by 2035**, or when the US treasury secretary determines there has been a 75% reduction in annual greenhouse gas emissions.
- Large-scale utility farms that have access to ample sunshine are likely to benefit from the PTC.

Business owners cannot claim the ITC and PTC for the same solar PV installation. In general, large-scale projects that are expected to generate lots of electricity benefit more from the PTC.

Sources: IRS, Residential Clean Energy Credit (2025); SEIA, Solar Investment Tax Credit (ITC) (2025); US DOE, Homeowner's Guide to Going Solar (2025); US DOE, Federal Solar Tax Credits Resources (2022).
Credit: Taicheng Jin, Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

New transferability rule provides simple fungibility to investors, reducing soft costs and eliminating uncertainties

Direct transfer reduces uncertainties, but tax equity structure could still be valuable to capture depreciation and basis step-up

Factors that favor using direct transferability	
Loan proceeds	Debt is "front" leverage, sized against more cash flow; less subordination and no forbearance, reduced interest rate and DSCR → WACC ↓
Equity proceeds from cash flow ↑	Without tax investor cash allocation, more cash for equity buyer to value
Equity proceeds from target return ↓	Simpler structure with less subordination and bigger check size → equity returns will compress further
Soft costs ↓	Eliminates or reduces legal-, independent engineer-, insurance consultant-related costs
No tax investor buyout	Eliminates uncertainty of cash equity to make assumptions about details around buyouts in 5 to 10 years
Factors that favor sticking to full tax equity structures	
Credits purchased at discount	Transferrable credits often sold at discount (95 on the dollar)
Accelerated depreciation	Value of MACRS/bonus depreciation and the TVM of avoided taxes is lost
Basis step-up (↑)	Opportunity to step-up ITC basis in SLB/LPT
Q: Avoided soft costs + lower WACC > ITC buyer discount + lost MACRS + basis step-up value	

Observations

- **IRA allowed sponsors without tax appetite to sell ITC to a third party, but direct transfer has disadvantages for the sponsor**.
- New hybrid structures, in addition to the traditional P-flip, inverted lease, and sale leasebacks, help address challenges.
- **A solution to the chicken-and-egg problem:**
  - Elegant solution to various risks that plague development (EPC, off-take, and financing), increasing project value & viability through decreased risk premium & debt load.
  - Tax appetite prompts a tax equity check which help assure lenders and secures construction financing, positively (albeit indirectly) impacting a project viability.
- **Transferability's value to sponsors:**
  - **Lowers sponsor's aversion to construction risk**, who will **fund a large portion of the CapEx** of the project, but demand **seniority** under the pre-negotiated cash-flow waterfall.
  - Taxpayers who claim the business solar ITC could use an accelerated depreciation schedule (MACRS curve), which allows for a greater depreciation expense in the early years of the life of an asset, reducing tax liabilities; full tax basis — half the ITC depreciated over a five-year schedule using a half-year convention.
- **Transferability's value to developers:**
  - **Long-term commitment** helps **raise construction finance** and facilitate entrance of **large buyers**.
  - Transferability rule **diffuses this problem** because construction lenders will underwrite loans **without a hard tax equity commitment** with a more liquid, simpler tax equity market.

Sources: ACORE, The Risk Profile of Renewable Energy Tax Equity Investments (2023); Bloomberg Tax, Insight: Tax Equity Remains an Under-Utilized Tool for Corporate Tax Strategy (2019); David Riester, Segue, The End of Tax Equity as You Know It (2022); White & Case, Clean Energy Tax Credits – Transferability and Deal Structure Alternatives (2024).
Credit: Taicheng Jin, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Adders over next 10 to 12 years aimed to boost domestic content and labor and increase deployment in low-income areas

Step-down schedules and adders for ITC and PTC[1] [2]

			Start of Construction (year)						
			’06-’19	’20-’21	’22	’23-’33	’34 (2+)	’35 (3+)	’36 (4+)
ITC	Full (Base)	Base	30% (-)	26% (-)	30% (6%)	30% (6%)	22.5%	15% (3%)	0%
		Domestic Content				10%	7.5% (1.5%)	5% (1%)	0%
		Energy Community				10%	7.5% (1.5%)	5% (1%)	0%
	Low-income adder	<5 MW (LMI)			None	10%	10%	10%	10%
		Qualified Projects	No Incentive			20%	20%	20%	20%
PTC	Full (Base)	Base			¢2.75 (¢0.55)	¢2.75	¢2.0(¢0.4)	¢1.3(¢0.3)	¢0
		Domestic Content				¢0.3	0.2 ¢ (¢0)	¢0.1(¢0)	¢0
		Energy Community			None	¢0.3	0.2 ¢(¢0)	¢0.1(-)	¢0

Observations

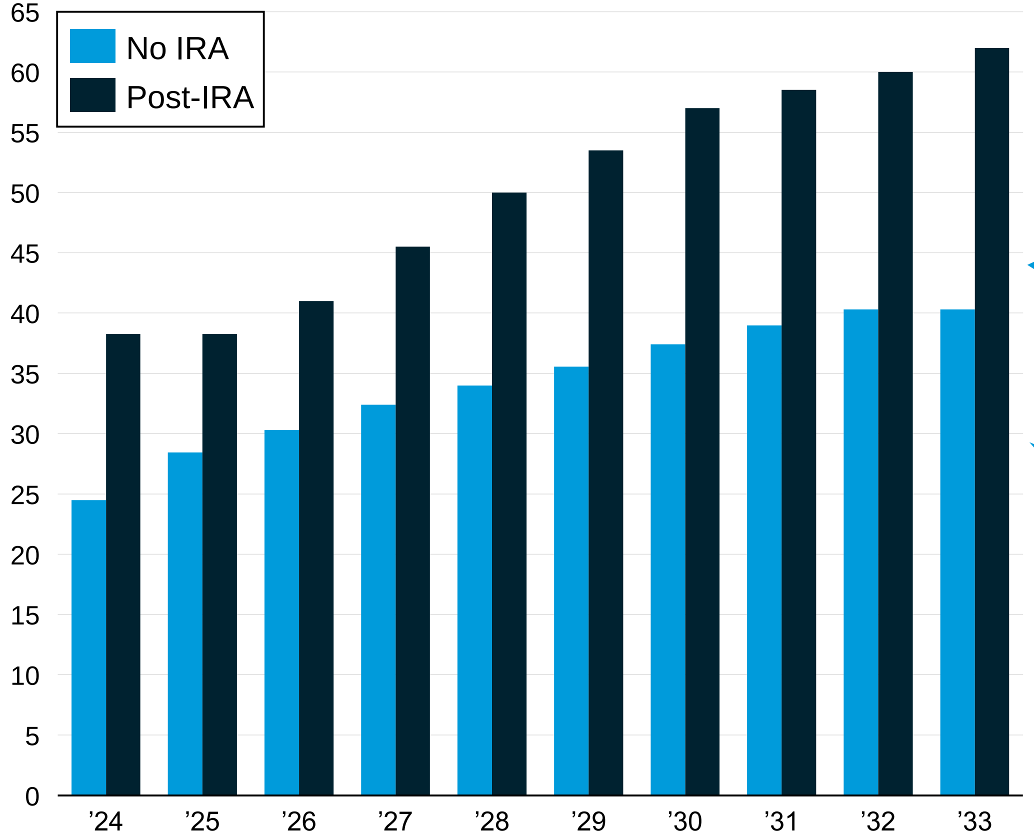
- **Base – bonus two-tier** setup:
  - Adders boost **domestic content** sourcing, **energy communities**, and **qualified areas**.
  - **Prevailing wage and apprenticeship** allow company to claim under **full case.**
- Step downs motivate enterprises to take advantage of construction **when need is critical through reduction in tax liabilities.**
- But step downs could **create logjams** and leave developers and consumers frustrated.
- The 2035 to 2036 expiration indicates a compact timeline (10 to 15 years), while many utility solar projects may need long lead-in time.

(1) Applicable date is either as after 2032 or when US treasury secretary finds that 75% reduction in annual GHG emission has been achieved compared to 2022 baseline.
(2) Base rate refers to scenario if **project does *not* meet labor requirement** (prevailing wage and apprenticeship requirement).
Source: US DOE, Summary of Investment Tax Credit (ITC) and Production Tax Credit (PTC) Values Over Time (2023).
Credit: Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Scaling Solar” (14 August 2025).

IRA mobilized $42B from 2022 to 2024; projected to add ~50% (~160 GW) of solar capacity by 2033, before Trump repeal

Post-Inflation Reduction Act (IRA) solar projections

Annual US solar installations (GW)



The IRA is projected to drive an additional 160 GW of solar deployment over the next 10 years when compared to a non-IRA scenario, according to the SEIA

Projections include over $565 billion in new investment over the next decade, a $144 billion increase from baseline

Actual Post-IRA Solar Growth

- From August 2022 to August 2024, $42 billion in investment was realized, 33 GW of solar capacity was added, and 95 new solar manufacturing facilities were announced.
- **Residential clean energy credit** adoption has surpassed expectations, boosting deployment of residential solar.
  - Over 1.2 million Americans used residential clean energy tax credits
  - The government budgeted $2 billion in 2023, but actual spending was more than triple
  - 30% more people filed for energy efficiency and/or rooftop solar tax credits in 2022 tax returns compared with 2021
- **Utility-scale** solar expansion is leading clean electricity expansion post-IRA, generating the majority of renewable energy capacity additions. However, clean electricity is at risk of falling short of post-IRA growth projections.
  - The IRA has made **renewable electricity cost competitive with coal and natural gas**. With reduced cost barriers, tackling remaining non-cost barriers like permitting, intermittency, and supply chain is critical to achieving climate change mitigation goals.
- **Clean energy investment is growing fastest in so-called energy communities** — areas with coal mine or plant closures, brownfield sites, or previously high fossil fuel employment and high unemployment.

Sources: Wood Mackenzie, US Solar Market Insight (2025); IRENA, Stats Tool (2025); Wood & Mackenzie, The Inflation Reduction Act and Its Impact So Far (2023); US Department of Treasury, The Inflation Reduction Act (2024) The Inflation Reduction Act (2023); HEATMAP, The First IRA Tax Credit Data Is In (2024); SEIA, Impact of the Inflation Reduction Act (2022); Rhodium Group, Clean Investment in 2023 (2024); American Clean Power, Investing in America 2024 (2024).
Credit: Taicheng Jin, Isabel Hoyos, Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Scaling Solar” (14 August 2025).

Trump administration tightens import tariffs and tax incentives conditioned on local labor and content requirements

2012 and 2015: The US Commerce Department under President Obama placed an **AD/CVD of about 30%** on Chinese solar cells and modules, alleging that the **Chinese government was subsidizing solar PV producers**.

2018: The United States imposed a **section 201 tariff** (sunset in 2026, starting at 30% and declining to 15%) on **all imported solar cells and modules,** not just Chinese made (includes Canada, Mexico, Indonesia, etc.), in part to **counteract Chinese firms avoiding tariffs** by producing in Southeast Asia.

February 2022: President Biden announced that the **section 201 tariffs would be extended** (at 15%) to provide **continued support for the domestic solar industry.**

June 2022: US Border Control banned imports suspected of having input from **Xinjiang**.

May 2024: Investigation began for a **fourth AD/CVD** on cells from Cambodia, Malysia, Thailand, and Vietnam.

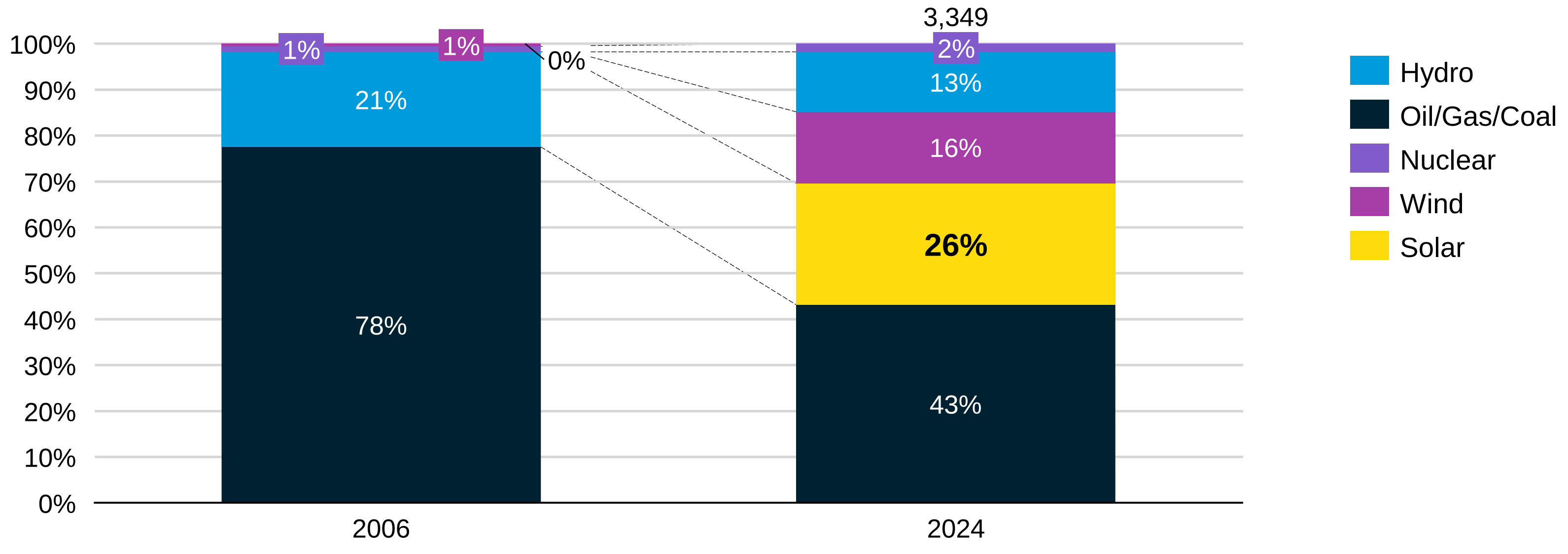
April 2025: Tariffs as high as 3,500% are targeted towards Chinese-owned solar cell manufacturers in response to American manufacturers accusing Chinese companies of flooding the market with cheap goods.

Sources: Reuters, US Finalizes Tariffs on Southeast Asian Solar Imports (2025); Enel, Unlocking the Domestic Content Bonus Tax Credit (2023); New York Times, President Biden Extends Solar Tariffs (2022); The Conversation, To Understand Why Biden Extended Tariffs on Solar Panels, Take a Closer Look at Their Historical Impact (2022); US ITA, Commerce Initiates Antidumping and Countervailing Duty Investigations of Crystalline Silicon Photovoltaic Cells from Cambodia, Malaysia, Thailand, and the Socialist Republic of Vietnam (2024).
Credit: Taicheng Jin, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

From the 11th to the 14th Five-Year Plan (FYP), China's solar strategy adapts through each iteration from 2006 to 2021

11th FYP (2006)	12th FYP (2011)	13th FYP (2016)	14th FYP (2021)
• **Electrification** through (1) cleaner coal, (2) larger plants, (3) new hydro, (4) nuclear, and (5) grid capacity and west-east transportation corridors • **Rapid expansion into renewables** through financial incentives, for the first time making solar a priority	• Solar again in focus (both **PV and CSP**); need for more detailed guidance on **materials innovation** and **electric vehicles** and **plug-in hybrid electric vehicles as strategic sectors**	• "Energy **revolution** that builds a clean, low-carbon, safe, efficient, modern energy system" through improved **supply-side support** • Building comprehensive **energy "bases"** and pushing for **smart "management systems"** on the demand side that interacts with **traffic net and internet**	• A **"great push"** for wind and solar, acceleration in distributing across east and central China • First target of 20% energy demand from renewables; still a **heavy focus on coal** for stability and security but willing to push to replace with **electrification**

China's total installed power generation capacity (2006 vs. 2024, *GW*)



Observations

- China's strategy is motivated by industrial competitiveness as **a slowdown in GDP growth**, **rising labor costs**, and **pollution**.
- Energy bases that combine wind and solar arrays in areas with low populations are excellent learning projects.
- **Utility SOEs** pushed to **learn by doing**, often politically backed to stomach **upfront CAPEX costs through easy access to debt financing**
- Strategy was looking **up the supply chain**, all the way to **mining** and **processing** of the rare earth and strategic minerals.

Sources: Chinapower, CEC China (2024); Climate Energy Finance, Monthly China Energy Update (2025).
Credit: Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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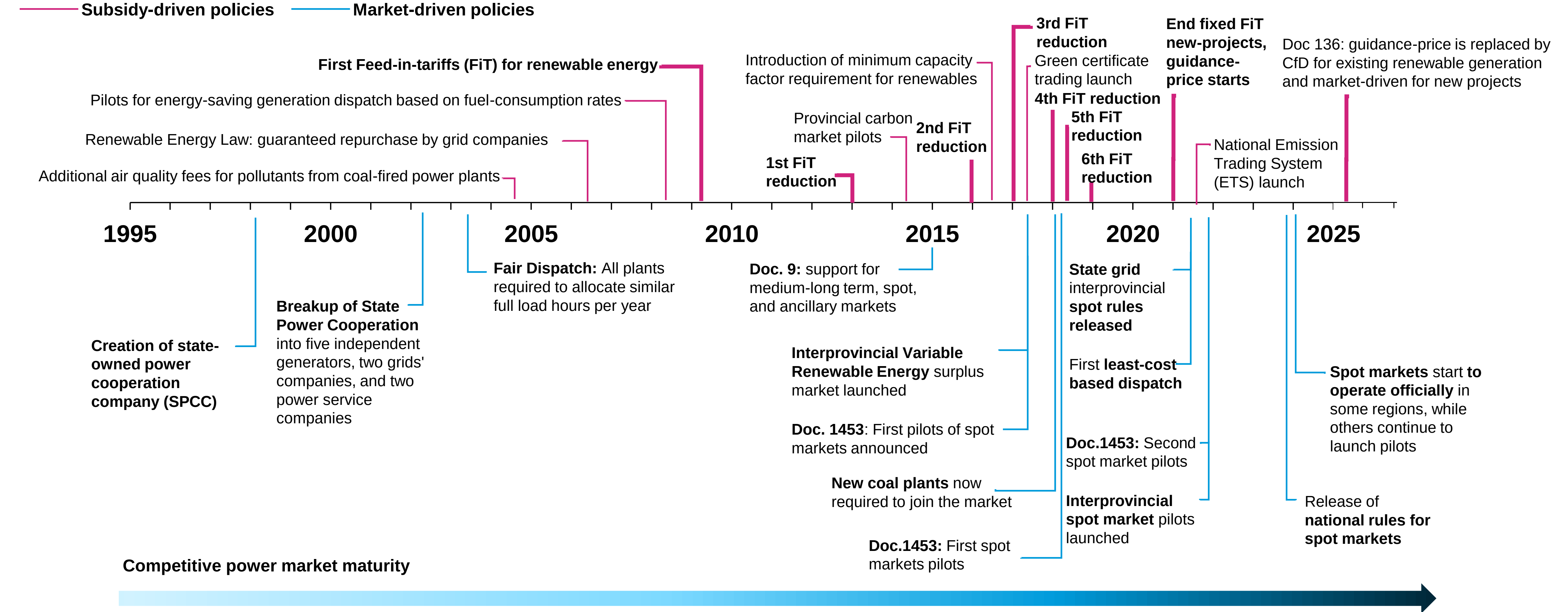
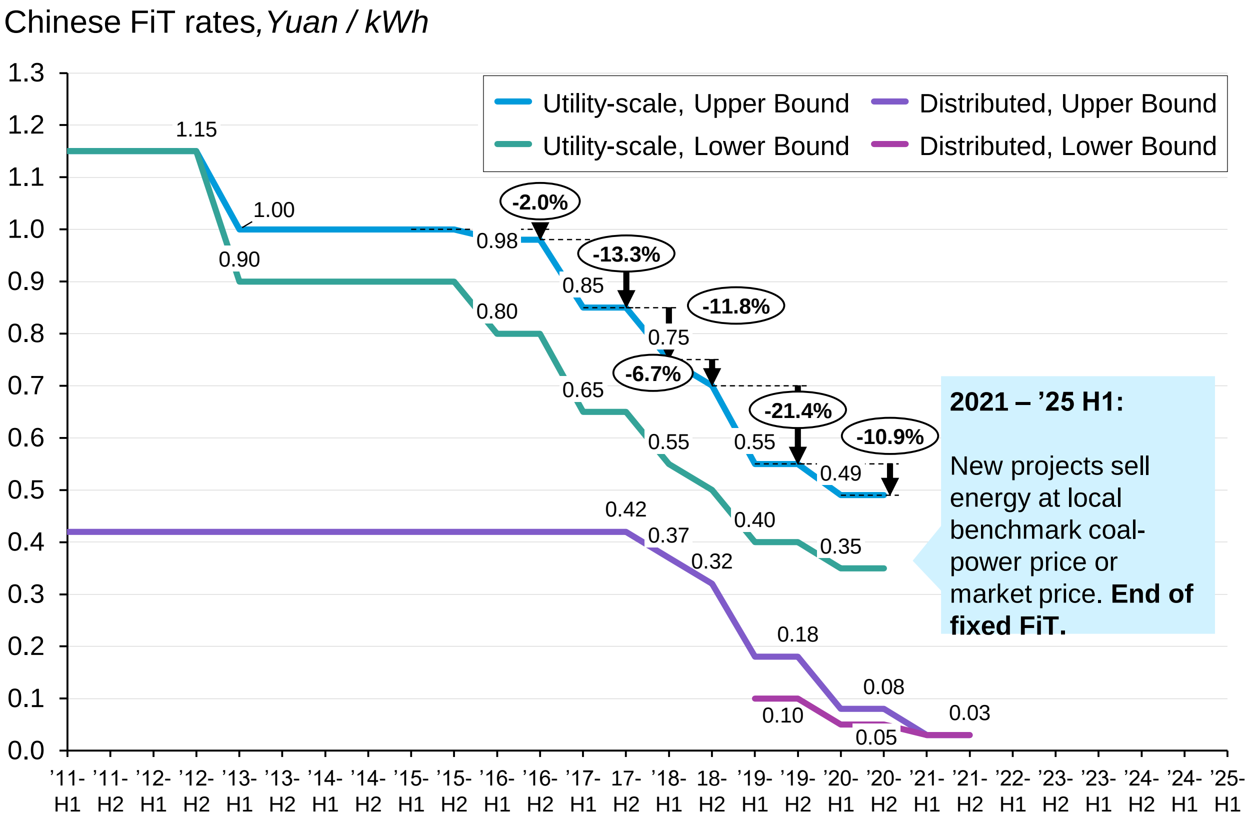
China’s FIT phase-out is part of a national shift from subsidy- to market-driven energy policy

Timeline of China’s key energy policies

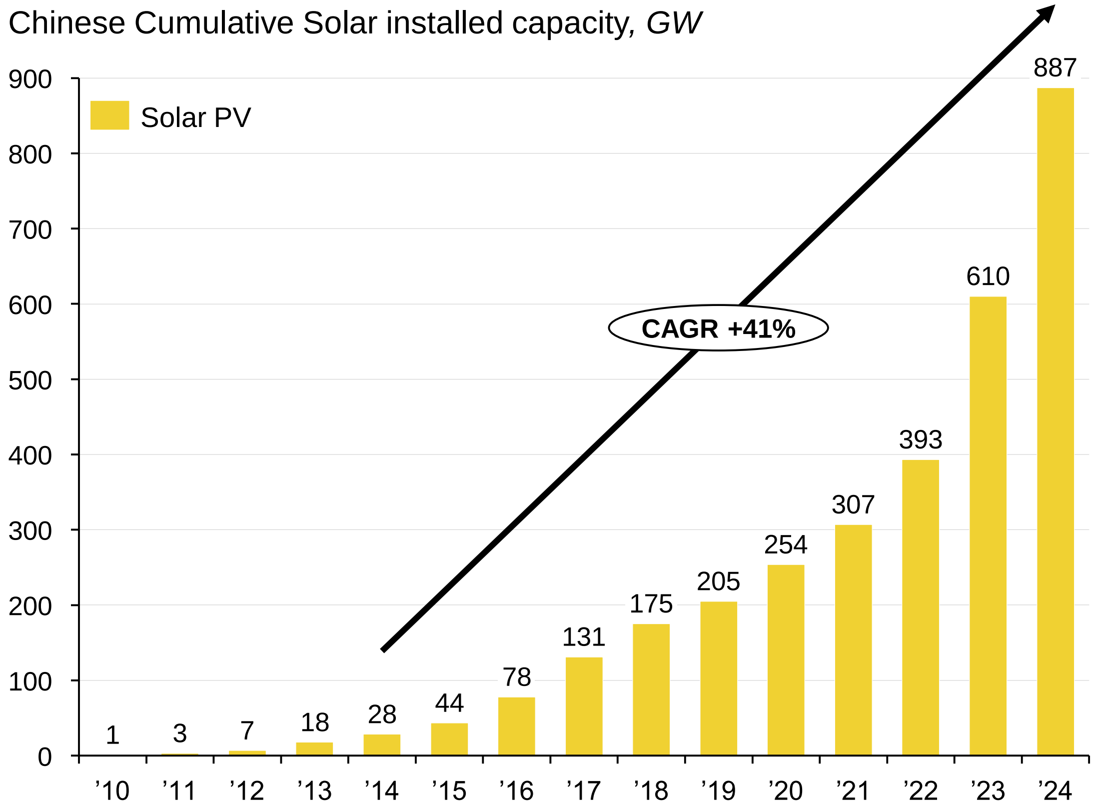


Chinese Feed-in-Tariffs (FiT) in place since 2011, with gradual, planned phase-out since 2013; solar capacity >50x since then

China's FiT were introduced in 2011 and began a planned phase-out in 2013



Despite the FiT phase-out, solar PV capacity has grown with >40% CAGR over past decade



Sources: IRENA (2024), Energy Brainpool (2017), IEA-PVPS (2024).
Credit: Brenda Rain, Nicolas Herrera Isaza, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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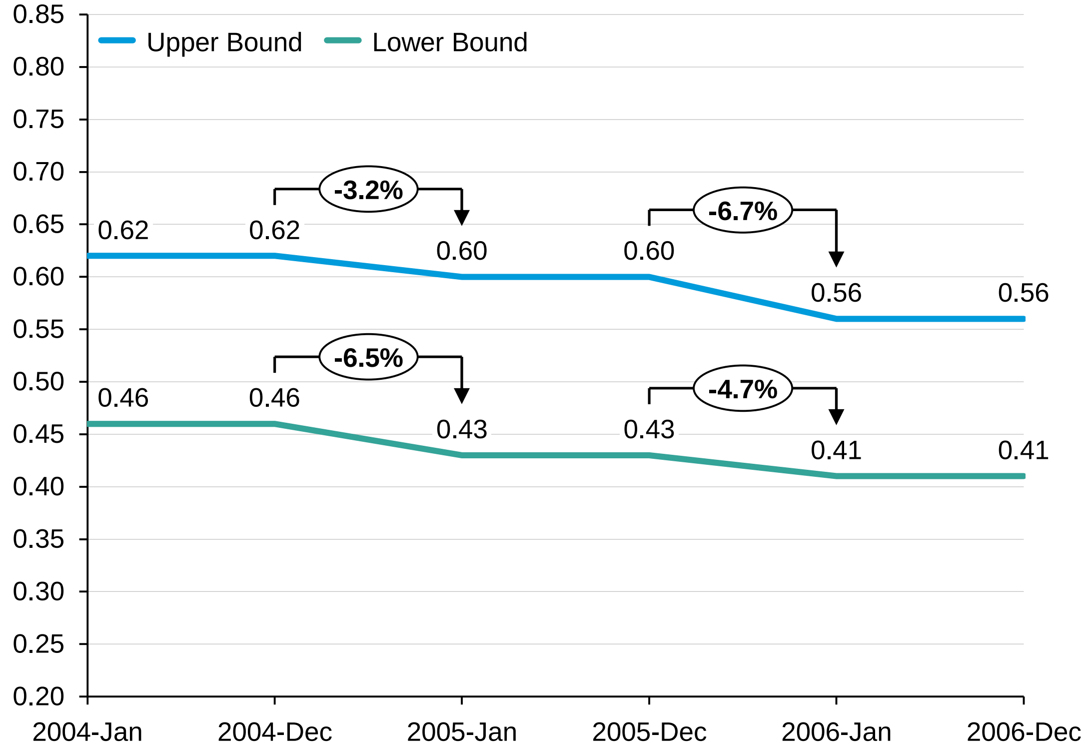
Ambitious German FiT introduced in 2004, phased out starting 2005; renewables capacity >9x in two decades since

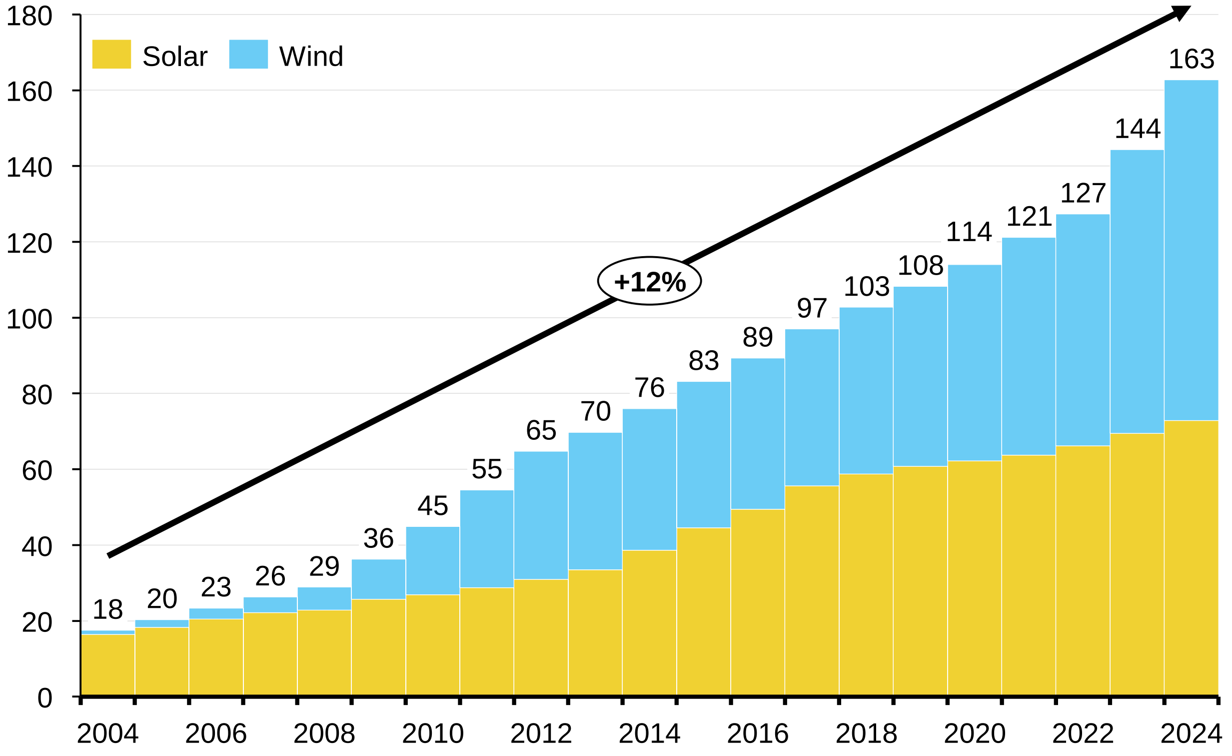
Germany increased its FiT to €0.62/kWh in 2004, with a planned phase-out of 3% to 7% annually from 2005

German FiT rates, *Euro / kWh*



Despite the FiT phase-out, solar PV and Wind capacity has grown with a ~12% CAGR since 2004

Germany's cumulative solar and wind installed Capacity, *GW*



Sources: Deutsche Bank Group (2011), IRENA, (2025)
Credit: Brenda Rain, Nicolas Herrera Isaza, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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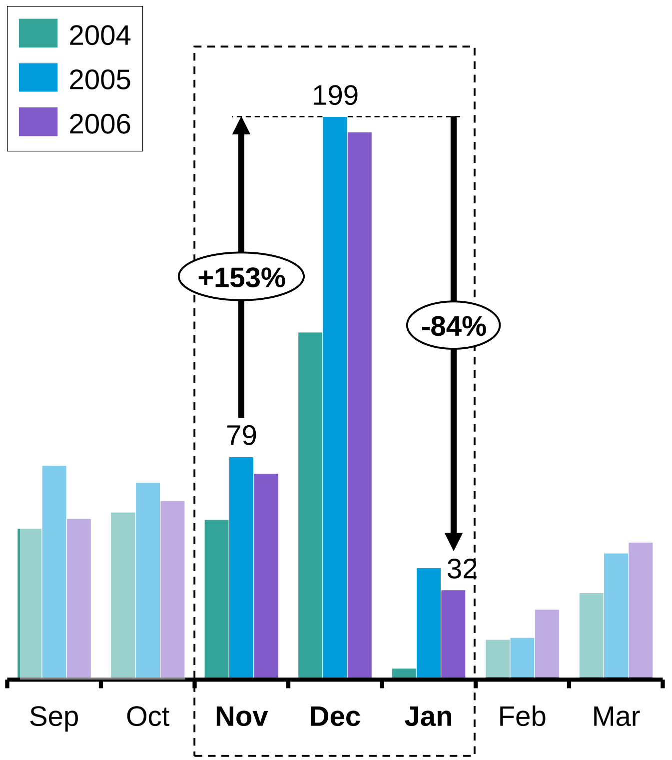
Spikes in 2025 Chinese solar deployment mirror effects of gradual FiT phase-out in Germany from 2004 to 2006

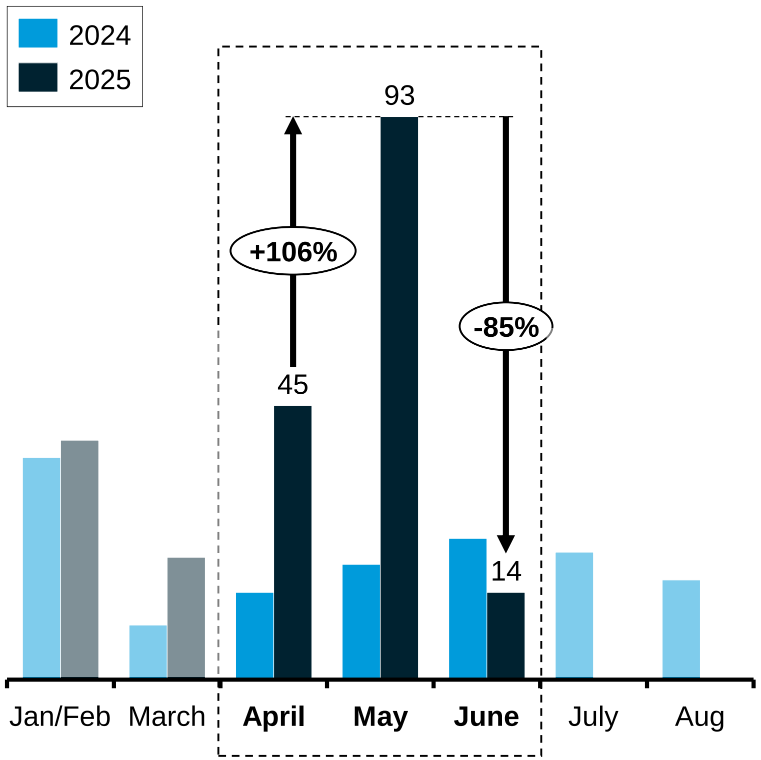
German FiT phase-out led to capacity spikes in December, before rate decreases

Germany's monthly solar capacity additions, *MW*



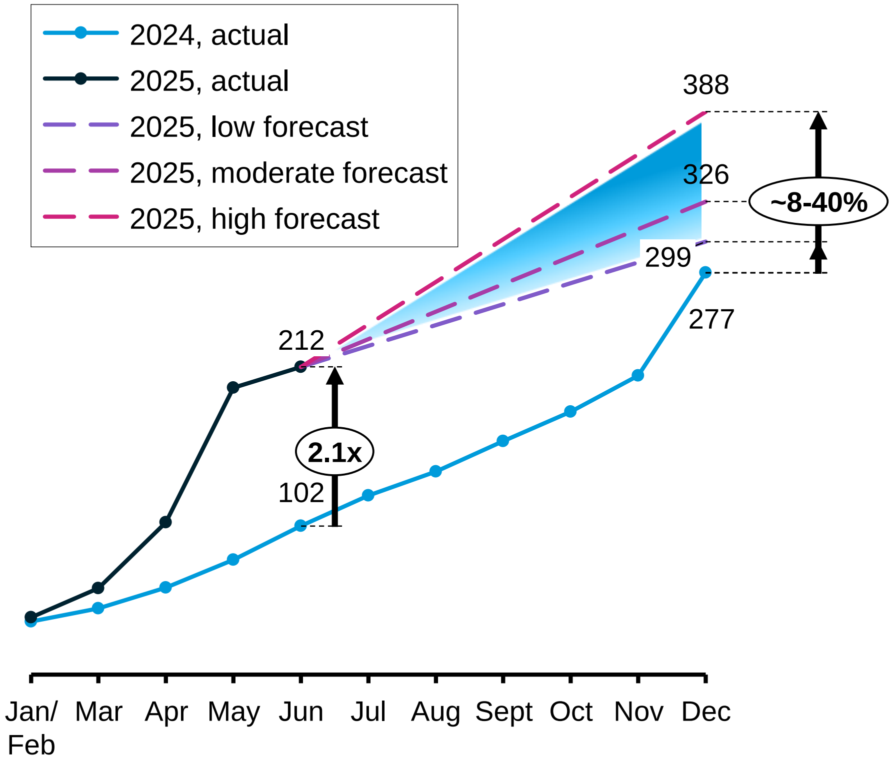
Recent Chinese FiT phase-out saw spike in May before decrease, then large drop in June

China's monthly solar capacity additions, *MW*



Chinese deployment proceeds apace, ~2x same period last year, on track to surpass 2024 deployment ~8-40%

China's cumulative solar capacity additions, *MW*



Sources: CKI Analysis, IRENA, (2025); Open Power System Data, (2020); PV Tech (2025)
Credit: Brenda Rain, Nicolas Herrera Isaza, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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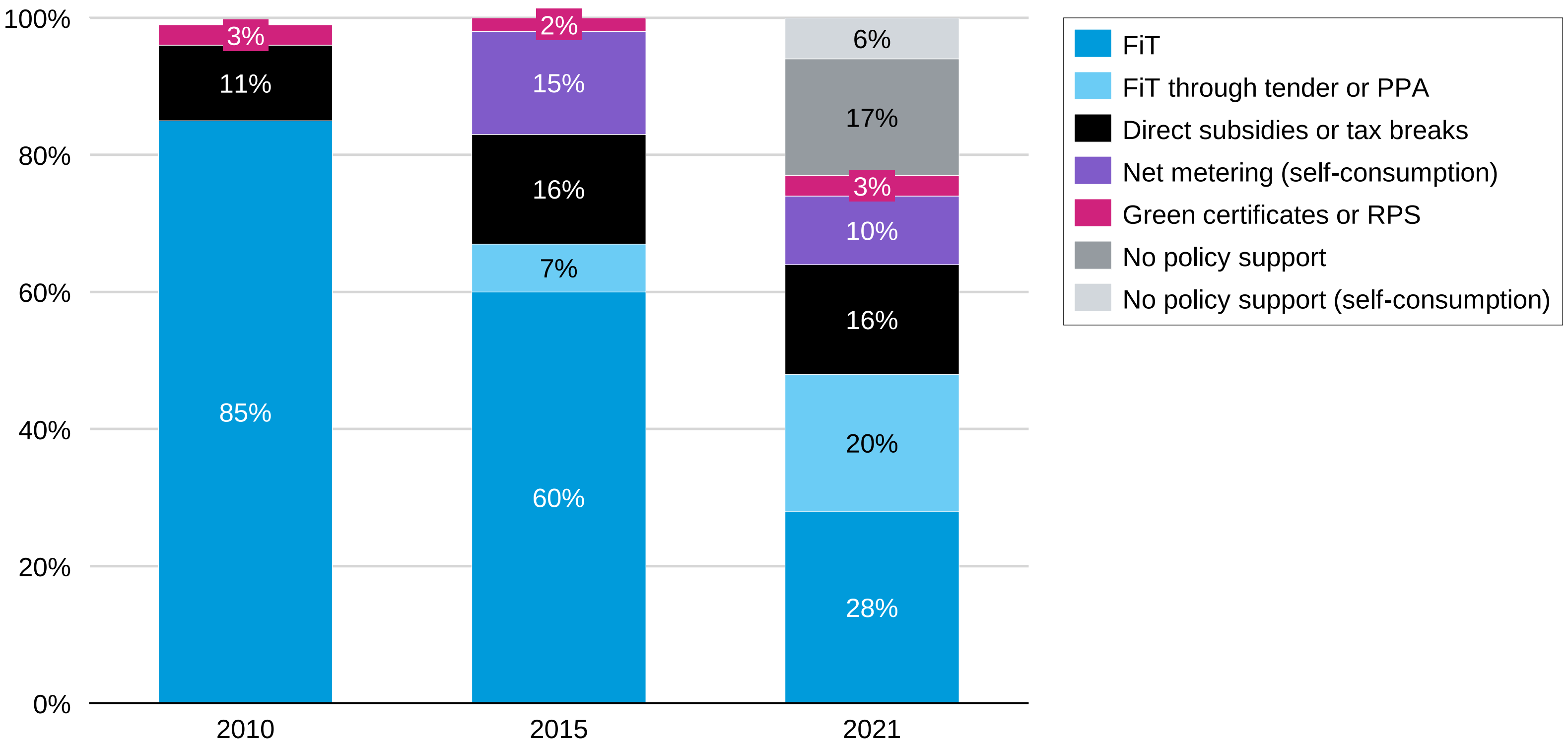
Feed-in tariffs (FiT) used to be the predominant form of support; now phased out in favor of other policies or no support at all

Less solar PV requires policy support

Evolution of solar PV global policies over time (in % of global GW of solar PV covered)



Global trends

- A significant increase has been observed for **non-incentivized solar PV** (generated energy is **sold at the market rate,** also called merchant PV).
- **FiTs** are becoming **less popular**. Existing tariffs are **reduced** or **replaced with new pricing mechanisms**:
  - **Feed-in premiums:** Instead of guaranteeing a fixed price, government guarantees a fixed premium on top of prevailing market prices.
  - **Contracts for difference:** These also guarantee a fixed payout per energy unit, with the government covering the gap between the agreed upon and market price.
- **FiTs through tender** are evolving to **encourage competition** and **shifting away from single focus on price:**
  - **Tech-neutral tenders** specify an amount of generation capacity but do not specify what renewable energy technology must be used. This puts solar PV in direct competition with wind and other forms of renewable energy.
  - **Multiple-factor tenders** add criteria on factors such as environmental protection and local origin of components.

Sources: Clean Energy Solutions Center, Solar Power Policy Overview and Good Practices (2015); PVPS, Trends in PV Applications 2022 (2022).
Credit: Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Scaling Solar” (14 August 2025).

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Solar PV: Overcoming Future Challenges

Key messages
Overcoming Future Challenges

Delays caused by interconnection (connecting new solar PV projects to the grid) are now one of the biggest obstacles **preventing new solar PV capacity from coming online**.

- Solar and energy storage made up **80% of the US interconnection queue** in 2022.
- New rules by the US Federal Energy Regulatory Commission force grid operators to **study projects in batches instead of individually** and prioritize those closest to construction to combat this problem.

Delays caused by permitting issues like zoning issues, environmental studies, complex regulations, and appeals are also significant obstacles to capacity deployment.

- **The United States** proposed the **Bipartisan Permitting Reform Implementation** rule in the summer of 2023 to speed up environmental assessments.
- **The EU** updated its **Renewable Energy Directive** to make permitting easier and appealing harder.

Solar PV is an **intermittent source of energy**.

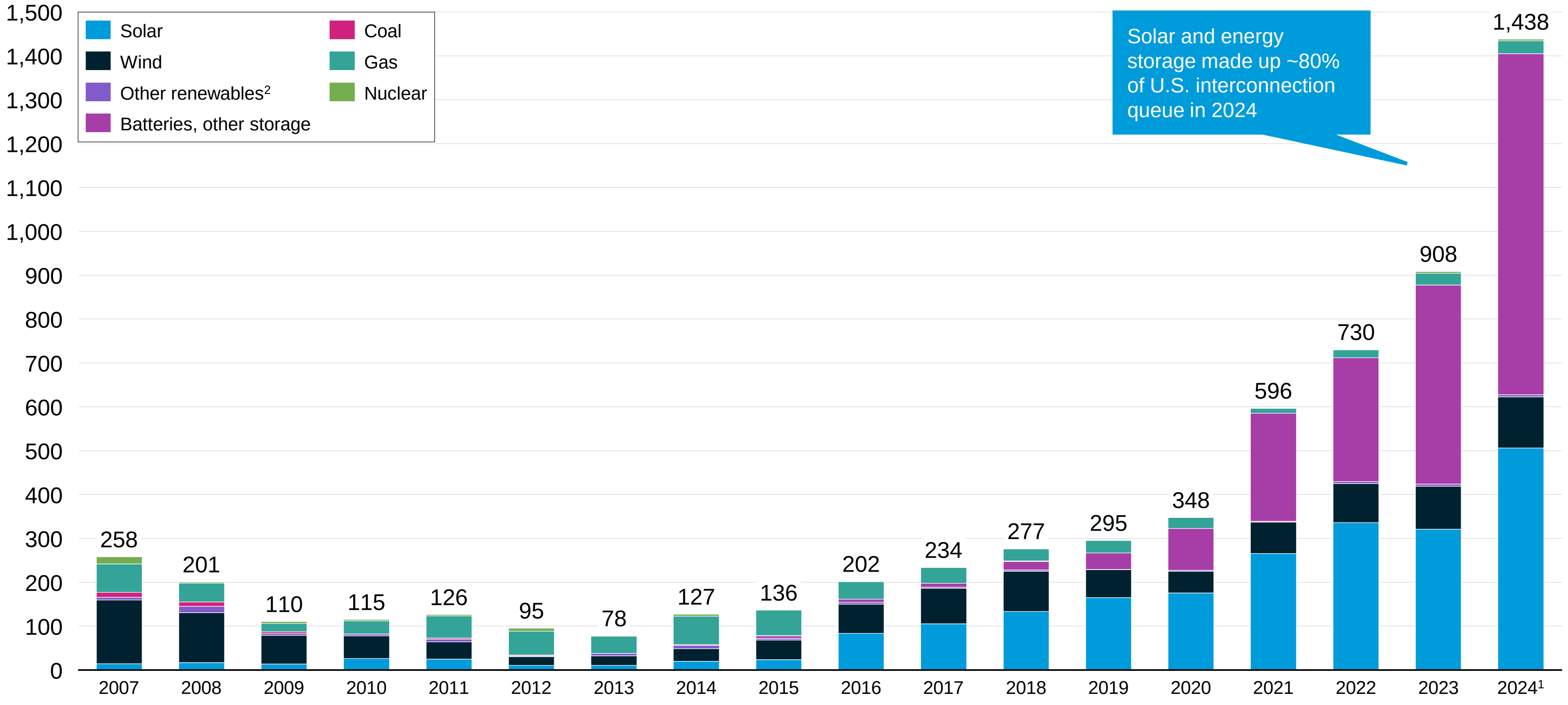
- **Demand response** can **incentivize power consumers** to **time their daily consumption** during peak solar PV production hours.
- **Energy storage** in the form of **batteries or pumped hydropower** can help address both daily and seasonal variations in solar PV output.

The annual number of **solar panels reaching end of life will grow 25x** in the next 30 years.

- EU panel producers are directly responsible for the **costs of collecting and recycling** end-of-life panels.
- China announced a **national recycling program** as of 2025.
- The United States has not announced a recycling initiative yet.

Interconnection delay is one of the main obstacles preventing new solar capacity coming online

Breakdown of US interconnection queues by energy source (GW)



Observations

- Connecting new solar PV projects to the grid is **one of the largest obstacles in both the US and EU.** These delays are caused by**:**
  - **Long feasibility studies by grid authorities**, which were designed **when only a handful of new coal or gas plants** would **connect to the grid each year.**
  - **Grids at maximum capacity**, meaning project developers need to **pay for new transmission lines and other upgrades** or **wait for grid authorities to expand the grid.**
- To reduce interconnection delays, the US Federal Energy Regulatory Commission now **requires grid operators to study projects in batches** vs. individually and to **prioritize those closest to construction.**

(1) 2024 data estimated on '14-'23 CAGR.
(2) Other renewables include geothermal; hydro; solar and wind; solar, wind, and battery; unknown and other.
Sources: Berkeley Lab, Generation, Storage, and Hybrid Capacity in Interconnection Queues (2025); FERC, FERC Transmission Reform (2023); US DOE, Tackling High Costs and Long Delays for Clean Energy Interconnection (2023); Eclareon, RES Policy Monitoring Database (2025).
Credit: Taicheng Jin, Max de Boer, Lara Geiger, Marcelo Cibie, Heonjae Lee, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Permitting issues can cause serious delays as well, but both US and EU are taking steps to streamline the process

Typical permitting issues

Zoning issues

- For many types of suitable land (e.g., agricultural land), **using it for solar PV requires rezoning**.
- **Rezoning can take a long time**, especially when there is the **opportunity for appeals**.

Environmental studies

- Studies assess the **environmental impact** of a solar PV project.
- In the **US**, an environmental impact study for **utility solar PV on federal land** can take **2 to 4 years**.

Complex regulations

- In the US, **counties set regulations** while following **state guidelines**, leading to **strong variations**.
- In the EU, countries set their **own solar PV deployment regulations**.

Appeals

- **NIMBYism*** can lead to residents **appealing against solar PV projects** in their neighborhoods.
- Even if an appeal does not lead to overturning a project approval, it can still cause **significant delays**.

The US aims to shorten environmental reviews

- The Biden administration proposed the **Bipartisan Permitting Reform Implementation rule** in 2023 to **speed up environmental assessments**.
- Proposed changes include:
  - **Two-year limit on environmental impact studies** and a **page limit on documents that need to be submitted** for an environmental review
  - **Clarification of the roles of leading and cooperating agencies** in conducting environmental reviews
  - **Climate change effects** as consideration to environmental impact studies

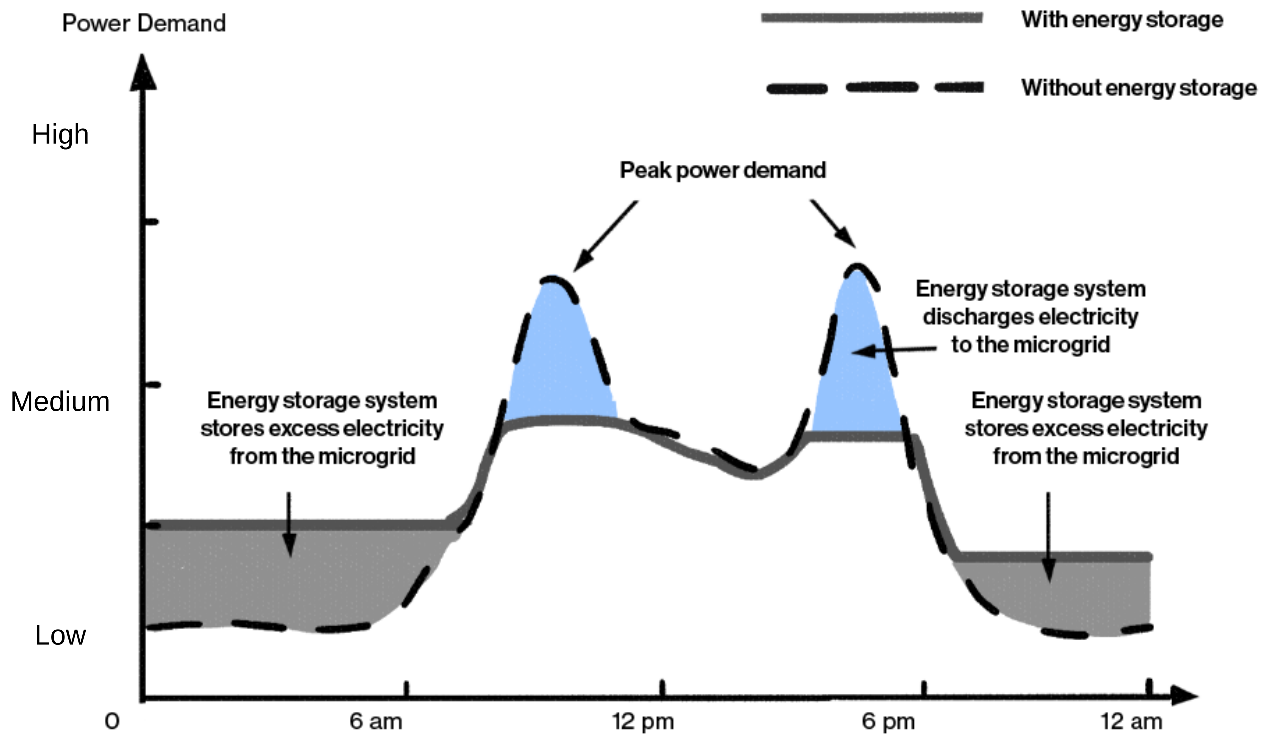
The EU makes applying easier and appealing harder

- In response to the Russian invasion of Ukraine, the **EU updated its Renewable Energy Directive,** which outlines goals nation-states must achieve:
- Proposed changes include**:**
  - **Two-year maximum duration** for the **permitting of new solar and wind projects**
  - Solar and wind classified as **projects of overriding public interest**, which **reduces** (but doesn't eliminate) **the possibilities for appeals**
  - Governments required to **digitize the solar and wind permitting process**

(*) NIMBYism refers to "Not in my backyard" syndrome.
Sources: Popular Science, Outdated Zoning Laws (2022); Eclareon, Barriers and Best Practices for Wind and Solar Electricity in the EU27 and UK (2022); SEIA, Utility-Scale Solar Power on Federal Land Permitting Process (2025); Reuters, Europe on Verge of Permitting Leap for Wind, Solar Farms (2023); White House, Reform to Modernize Environmental Reviews (2024).
Credit: Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Daily and seasonal intermittency requires battery storage to smooth consumption

Energy storage helps smooth out the intermittency of output



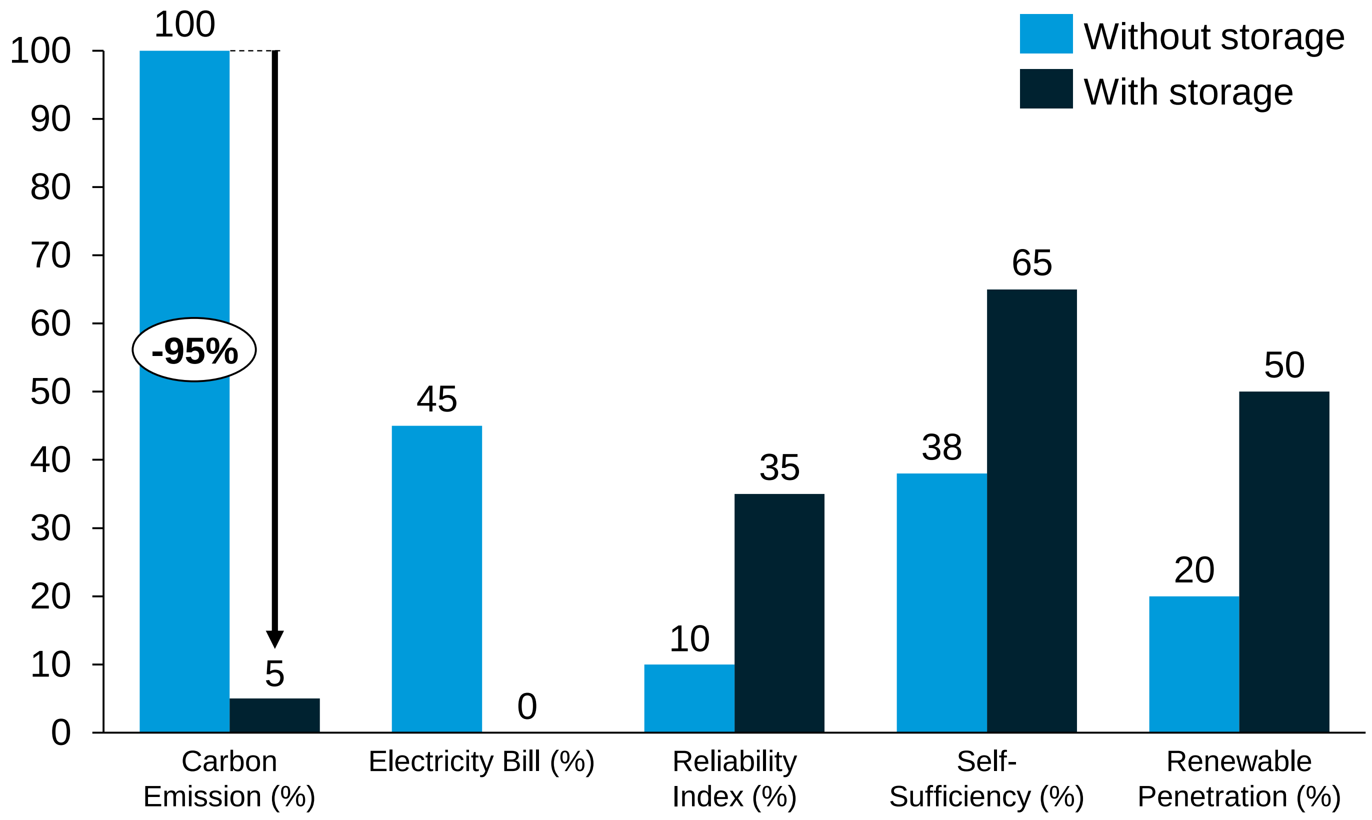
Observations

- As the sun moves across the sky during the day, it **changes the angle** at which the sunlight hits the panels. Generation typically **peaks around noon**, when sunlight directly strikes the panels.
- **Weather conditions** also affect daily power generation. **Overcast skies** or **fog** reduce the amount of sunlight that reaches the solar panels.
- Direct seasonal variation comes from the fact that the position of the sun in the sky changes throughout the year. In **winter, days are shorter and the sun is lower** in the sky, leading to less solar power generation.
- This effect is more pronounced at **higher latitudes**. In regions closer to the poles, days shorten more drastically in winter.
- Seasonal weather patterns also impact annual solar generation (e.g., less solar generation during **rainy season** in Southeast Asia).

Sources: Scientific American, Renewable Energy Intermittency (2015); Solar4ever, Solar Power Calculator Australia (2025); US EIA, Total Energy Overview (2025); Tencent, Running on Sunshine (2024).
Credit: Taicheng Jin, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Integrating Battery Energy Storage Systems (BESS) lowers emissions, reduces bills, and boosts reliability and self-sufficiency

Comparison of project parameter with and without storage component



Observations

- Without energy storage, **fossil fuels** will be used to support energy deficit.
- Solar can significantly **reduce carbon emissions** by up to 95%.
- Solar-only systems designed with 100% usage usually offset only ~55% of the original bill. With storage, it is expected to offset the **entire electricity bill**.
- The reliability as measured by LOLP can **improve from 10% to 35%**.
- Integrating energy storage can improve residential self-sufficiency **from 38% to 65%**.
- With energy storage, the renewable penetration could increase from between 20% and 25% to 50% in California.

Sources: Solar.com, What is the Carbon Footprint of Solar Panels? (2025); Solar.com, Electrum's New NEM 3.0 Savings Calculations Show Path to Maximum Bill Reduction in California (2023); Singh and Fernandez, Reliability Evaluation of a Solar Photovoltaic System With and Without Battery Storage (2015); Ciocia *et al.*, Self-Consumption and Self-Sufficiency in Photovoltaic Systems (2021); NREL, Energy Storage Requirements for Achieving 50% Solar Photovoltaic Energy Penetration in California (2016).
Credit: Xiaodan Zhu, Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Batteries and pumped hydro are two ways to store energy

	Batteries	Pumped Hydropower
		
Description	Solar PV power is stored as **chemical energy** in (most frequently) **lithium-ion batteries** and discharged later.	Excess solar energy is used to **pump water from a reservoir** of lower elevation to one of higher elevation. Later, the water is released and flows through a **turbine to generate electricity**.
Cost ($ per MWh)	**\$350 to \$1,000 per MWh of annual energy output** *(Lithium-ion batteries)*	**\$200 to \$260 per MWh of annual energy output**
Pros	⊕ **Increasing mass production of batteries** (related to demand for electric vehicles) leading **to continuing cost declines** ⊕ **Modular design allows for scalability**, from residential systems to large-scale utility projects	⊕ **Longest duration storage** compared to alternatives like batteries ⊕ Tends to be **cheaper at present than batteries** for overnight and longer term storage
Cons	⊖ At present, batteries are still the **more expensive option** ⊖ **Limited lifespan of batteries** (currently about 5 to 15 years) requires replacement of equipment	⊖ **Land-, water-, and capital-intensive to construct;** dam construction may **permanently damage surrounding ecosystems** ⊖ Can be implemented only in **certain geographies** due to **elevation required**
Example installation	**Victoria Big Battery** in Victoria, Australia (300 MW storage capacity)	**Kidston plant** in Queensland, Australia (250 MW storage capacity)

Sources: AEI, Solar Panel Battery Storage (2022); BNEF, Top 10 Energy Storage Trends in 2023 (2023); Greentech Media, Pumped Hydro Moves to Retain Storage Market Leadership (2020); ABC News, Batteries, Solar, Wind, Hydropower (2022); The Conversation, Batteries Get Hyped, but Pumped Hydro Provides the Vast Majority of Long-term Energy Storage Essential for Renewable Power (2022); Victoria, Victorian Big Battery (2023); Renewable Energy World, Commercializing Standalone Thermal Energy Storage (2016); Entura, Batteries vs Pumped Hydro (2017).
Credit: Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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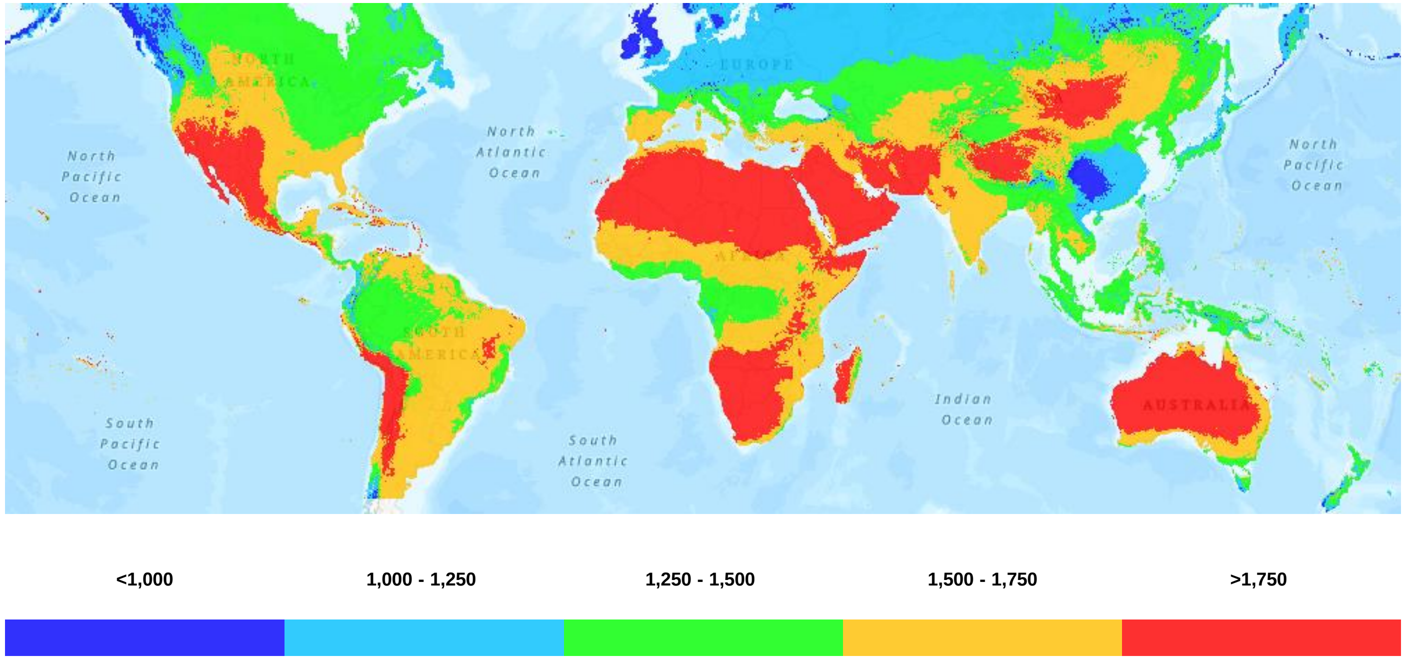
Developing countries with high solar irradiance and low seasonality can benefit from solar PV deployment

Average global solar potential (kWh/kWp)



Most developing countries exceed 1,500 kWh/kWp

Concentration of Solar PV Power

- In approximately 70 countries worldwide, the solar PV daily output is at least **1,500 kWh/kWp**. Most of the countries that demonstrate the highest energy production are in the Middle East, Sub-Saharan Africa, and North Africa, as well as desert regions in major countries.
- High-potential countries tend to **have low seasonality in solar photovoltaic output**, meaning the solar resource is relatively constant between different months of the year.

Future Investment Potential

- Solar power generation can help developing countries expand the agricultural sector in areas of irrigation, cold storage, and food processing.
- Countries with high levels of solar radiation exposure are more optimally positioned. Ethiopia could cover its total energy demand with just 0.005% of its land dedicated to solar power.
- Some solar-focused programs are bringing large-scale businesses to developing countries, such as Tata Power Solar in India and M-KOPA Solar in Kenya. The African Development Bank approved a US$49.92 million fund to build a 30 MW solar PV plant.

Note: Solar Atlas does not provide data on solar PV potential in northern regions (northern Canada, Russia, and Europe).
Sources: World Bank, Solar Photovoltaic Power Potential by Country (2020); Unsustainable Magazine, Solar Power in Developing Countries (2023).
Credit: Hassan Riaz, Taicheng Jin, Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Scaling Solar” (14 August 2025).

Demand response can help mitigate daily power fluctuations by incentivizing users to time their consumption

Demand response financially incentivizes consumers

- Demand response programs try to **shift energy consumption** based on **energy availability**.
- Globally, the IEA projects that **500 GW of demand response availability** will be needed **by 2030**. At present, **only a fraction of that (<50 GW) is available**.
- Participation in these programs can be either **active or passive**:
  - **Active programs** require **explicit actions** by participating consumers and companies (e.g., turning off the AC).
  - When enrolled in a **passive program**, **consumer devices or commercial machines automatically respond** to signals sent by utilities (via a device like a smart thermostat).

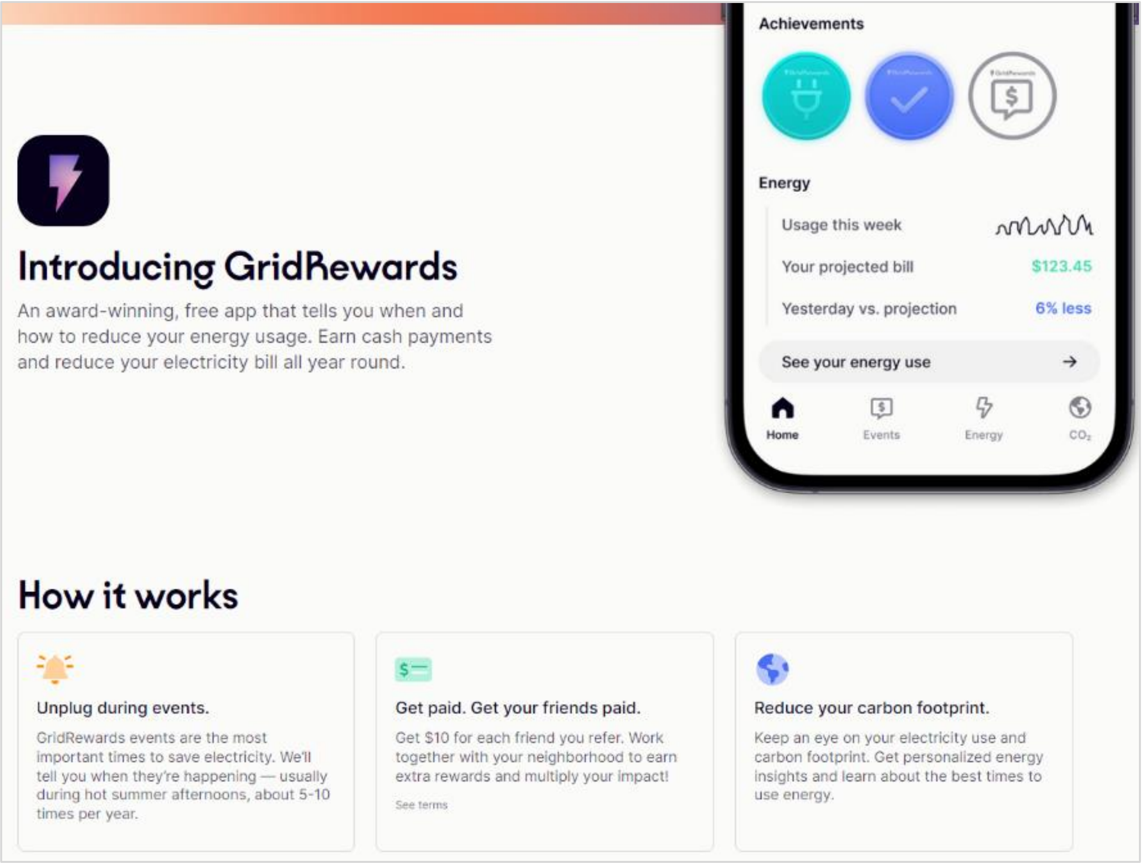
Price-based

Demand is managed through **dynamic electricity prices**, with **prices peaking** at times of **low availability** and **prices dropping** during **high availability**.

Incentive-based

Consumers **receive financial incentives** to **reduce their consumption** when energy availability is low.

NY state has an active demand response program

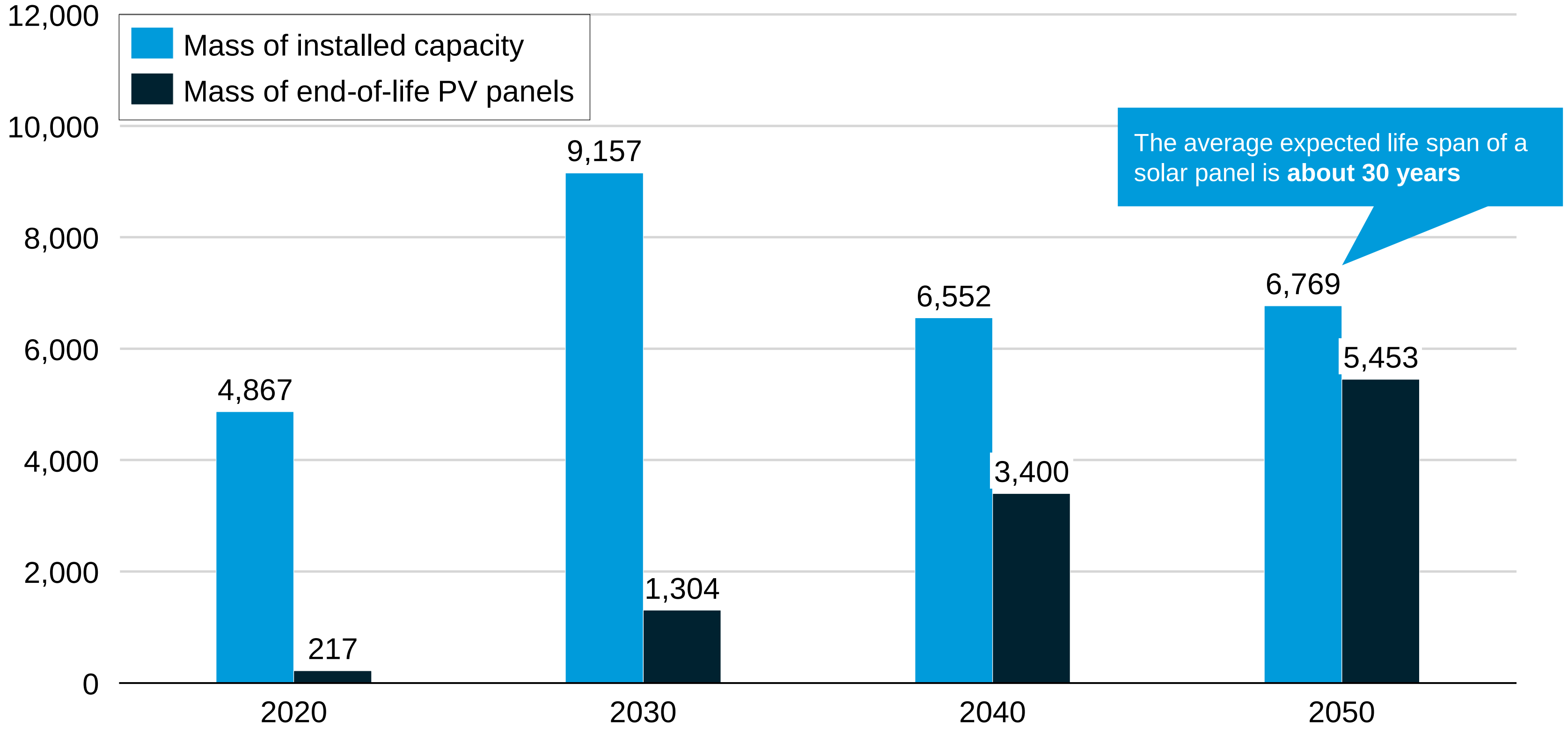


Sources: IEA, Demand Response (2025); Steele and Breitenstein, The History and Evolvement of Electrical Peak Load Control Systems in Europe and the U.S. (2010).
Credit: Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Scaling Solar” (14 August 2025).

By 2050, ~10 million tons of solar PV panels will retire; EU and China have announced recycling plans

Global annual amount of end-of-life PV panels will increase 25x by 2050

Annual installed and end-of-live PV panel mass (in millions of kg)



Observations

- Recycling solar PV panels has **two main benefits**:
  - **Environmental damage prevention**
  - **High-value material recovery**
- In the EU, **panel producers** are **directly responsible** for the **costs of collecting and recycling end-of-life panels** under the EU WEEE* directive.
  - Often producers team up to **centralize collection and recycling** (e.g., Germany).
- **US and China do not have national recycling programs.** However:
  - **China** announced the ambition to **establish a national recycling system** for end-of-life panels by 2025.
  - In the US, **California** and **Washington** have passed state laws addressing solar PV panel recycling.

(*) Waste Electrical and Electronic Equipment Directive.
Sources: IRENA, End-of-Life Management: Solar Photovoltaic Panels (2016); NREL, Solar Photovoltaic Module Recycling (2021); PV-Tech, China to Build Solar Recycling System by 2025 (2023); Solarwaste.eu, Waste from Electrical and Electronic Equipment (WEEE) (2025).
Credit: Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Scaling Solar” (14 August 2025).

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Appendix

Scenarios

ETS

The Economic Transition Scenario (ETS) reflects a world where policymakers pursue an energy transition relying only on **historical efficiency trends** and **economically competitive, commercially at-scale clean energy technologies**.

The ETS requires no further support for clean technologies beyond existing measures, although it does hinge on a level playing field that allows these solutions to access markets and compete with incumbent technologies.

NZS

The Net Zero Scenario (NZS) reveals the sheer scale and scope of the challenge of remaining within 1.75C of global warming and achieving the goals of the Paris Agreement.

Source: BNEF, New Energy Outlook 2025 (2025).
Credit: Isabel Hoyos, Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Balance of System components [ref. Slide 10]

BoS component	Description
Inverters	Solar panels produce direct current (DC) while power grids are alternating current (AC). Inverters convert the DC power generated by the panels to AC, making them the most crucial component of PV systems after solar panels.
Wiring	Connects the solar panels and other electrical parts of the PV system.
Switches	Used for safety reasons (can disconnect the panels from the grid in case of a power surge or emergency) and to direct the flow of power (e.g., either to the grid or to a battery).
Junction boxes	Metallic or plastic boxes used as meeting points for electrical connections.
Mounting systems	Provide support for the panels and fixes them in place.
Metering systems	Measure the amount of electricity flowing through them.
Batteries	*Optional item:* Store energy generated by the panels. Can provide power when the sun is not shining.
Charge controllers	*Optional item:* Devices that manage the electricity flow to and from batteries and protect them from overcharging.
Sensors	*Optional item:* More common in utility-scale projects. Help to keep track of environmental variables like panel temperature and solar irradiance. Used for monitoring and maintenance purposes

Sources: NREL, US Solar PV System Cost Benchmark (Q1 2023) (2023); SolarEdge, Balance of System and Energy Production Comparison (2024).
Credit: Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Scaling Solar” (14 August 2025).

Material components in crystalline silicon (c-Si) solar panels [ref. Slide 30]

Material	Main uses
Glass	Module cover
Aluminum	Module frame, mounting structure, connectors, back contact, inverters
Polymers	Back sheet of the solar module, encapsulation of solar cells
Silicon	Mono-Si or poly-Si wafers (core component of solar cells)
Copper	Cables, wires, ribbons, inverters
Silver	Electronic contacts, wiring across solar cells
Antimony	Added to glass to create solar-grade glass (reduces long-term impact of ultraviolet radiation on the solar performance of glass), added to encapsulant
Lead	Soldering paste and ribbon coating
Tin	Solder and ribbon coating

Note: Material composition percentages are averages.
Sources: IEA, Solar PV Global Supply Chains (2022); PV-Manufacturing.org, Photovoltaic Manufacturing and Technology (2025).
Credit: Isabel Hoyos, Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

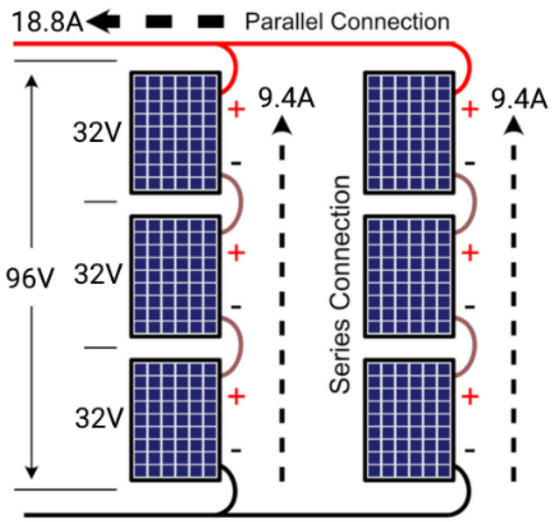
Glossary

AD/CVD	Antidumping and countervailing duties
APAC	Asia Pacific
ASEAN	Association of Southeast Asian Nations
BIPV	Building integrated PV
BoS	Balance of System
BSF	Back Surface Field
c-Si	Crystalline silicon
C&I	Commercial & industrial
CAGR	Compound annual growth rate
CapEx	Capital expenditures
CCS	Carbon capture and storage
CO_2	Carbon dioxide
CPV	Concentrator PV
CSP	Concentrated solar power
EMEA	Europe, Middle East, and Africa
EPC	Engineering, procurement, and construction
ESP	Energy service provider
EVA	Ethylene vinyl acetate
FiT	Feed-in tariff
FBR	Fluidized bed reactor
FPV	Floating PV
HJT	Silicon heterojunction cells
IRA	Inflation Reduction Act
IRR	Internal rate of returns
ITC	Investment tax credit
LID	Light-induced degradation
MOIC	Multiple on invested capital
mono-Si	Monocrystalline silicon
NPV	Net present value
OpEx	Operating expenses
O&M	Operating and maintenance
PAYG	Pay as you go
PERC	Passivated emitter and rear cell
Poly-Si	Polycrystalline silicon
PPA	Power purchase agreement
PTC	Production tax credit
PV	Photovoltaic
REC	Renewable energy credit
R&D	Research and development
RPS	Renewable portfolio standard
SG&A	Selling, general, and admin. expenses
SiO_2	Quartzite
SPV	Special purpose vehicle
TCO	Transparent conductive oxide
VIPV	Vehicle integrated PV
VOST	Value-of-solar tariffs

Units, calculations, and references

- One watt equates to one **joule** of energy per **second**
- In electrical systems, power (**watts**) is calculated by multiplying voltage (**volts**) by current (**amps**)

Kilowatt (kW)	1,000 (one thousand) watts
Megawatt (MW)	1,000,000 (one million) watts
Gigawatt (GW)	1,000,000,000 (one billion) watts
Terawatt (TW)	1,000,000,000,000 (one trillion) watts



Power from each panel = 32V x 9.4A = 300W

Power from each string = 96V x 9.4A = 900W
Power from each string = 3 x 300W = 900W

Power from whole array = 96V x 18.8A = 1800W
Power from whole array = 6 x 300W = 1800W

Source: Sunshineworks, Solar Calculation (2025).
Credit: Isabel Hoyos, Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

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