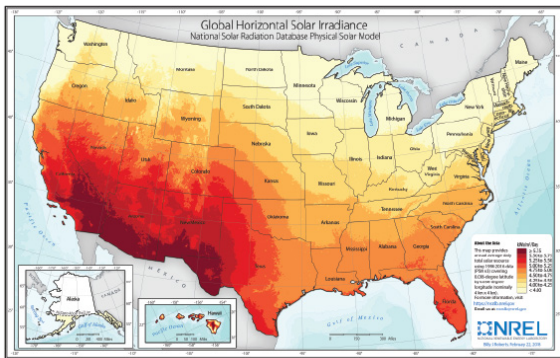


Solar PV Energy

Solar energy can be harnessed in two primary ways. First, photovoltaics (PVs) are semiconductors that generate electricity directly from sunlight. Second, solar thermal technologies utilize sunlight to heat water for domestic uses, warm building spaces, or heat fluids to drive electricity-generating turbines. Solar technologies generated 3.9% of U.S. electricity in 2023¹, with two-thirds from utility-scale solar².

Solar Resources and Potential

Annual Average Solar Radiation in the U.S.³



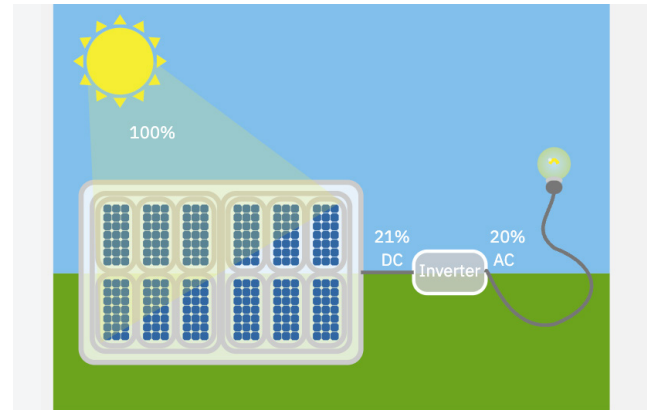
- On average, 173,000 TW of solar radiation continuously strike the Earth⁴, while global electricity demand averages 3.0 TW.⁵
- Electricity demand peaks at a different time than PV generation, leading to energy surpluses and deficits. Energy storage and demand management help to match PV generation with demand.⁶
- PV conversion efficiency is the percentage of solar energy that is converted to electricity.⁷ Though the average efficiency of solar panels available today is 21%⁸, some researchers have developed PV modules with efficiencies near 40%⁹. The highest recorded lab efficiency is achieved by hybrid four-junction (40.6%), and gallium arsenide (GaAs) III-V concentrating module (35.9%-38.9%).⁹
- Net energy ratio compares the life cycle energy output of an energy system to its life cycle primary energy input. One study showed that amorphous silicon PVs generate 3 to 6 times more energy than is required to produce them.¹⁰

PV Technology and Impacts

PV cells

- PV cells are made from semiconductor materials that free electrons when light strikes the surface, producing an electrical current. A variety of semiconductor materials can be used for PVs, including silicon, copper indium gallium diselenide (CIGS), cadmium telluride (CdTe), perovskites and even some organic compounds (OPV).¹¹ PV cells also include electrical contacts that allow electrons to flow to the load and surface coatings that reduce reflection.¹¹

PV Conversion Efficiency Diagram^{8, 12, 13}



- Most PV cells are small, rectangular, and produce a few watts of direct current (DC) electricity.¹¹

PV Modules and Balance of System (BOS)

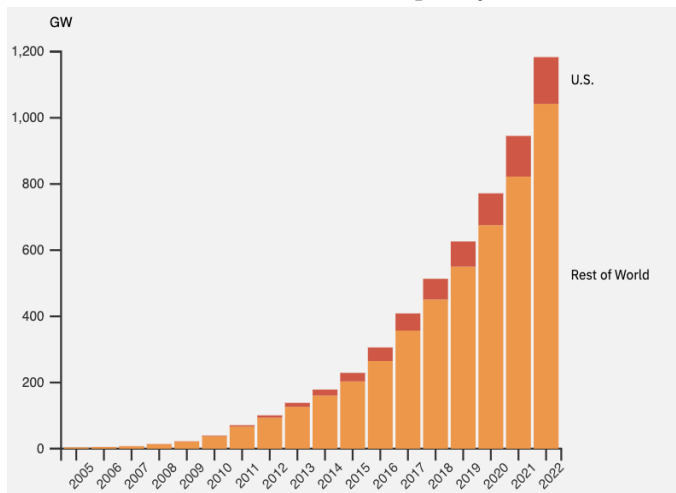
- PV modules typically comprise a rectangular grid of 60 to 72 cells, laminated between a transparent front surface and a structural back surface. They usually have metal frames and weigh 34 to 62 lbs.¹²
- A PV array is a group of modules, connected electrically and fastened to a rigid structure.¹³
- BOS components include any elements necessary in addition to the actual PV panels, such as wires that connect modules, junction boxes to merge the circuits, mounting hardware, and power electronics that manage the PV array's output.¹³
- An inverter is a power electronic device that converts electricity generated by PV systems from DC to alternating current (AC).¹³ Inverter loading ratio (ILR), or DC/AC ratio, is the ratio of DC module capacity to AC inverter capacity. Higher ILRs increase the utilization of the inverter, thereby decreasing the inverter costs per kWh of AC output.¹⁴
- A charge controller is a power electronic device used to manage energy storage in batteries, which themselves can be BOS components.¹³
- The dominant module technology in the current market is crystalline silicon (c-Si) both globally and in the U.S., with other commercialized technologies including cadmium telluride (CdTe), and copper indium-(gallium)-diselenide (CIGS and CIS) mainly as thin-film modules.¹⁵
- Cost efficiency—the cost per watt of power—is more important than conversion efficiency for most applications. In the U.S., c-Si modules had a minimum sustainable price (MSP) of \$0.25/W in 2020, while III-V technology had an MSP of \$77/W, keeping it in niche markets including space and terrestrial concentrator applications.¹⁵
- Bifacial PV modules can capture sunlight on both sides, increasing energy production up to 15% over single-sided modules.¹⁶ The global market share of bifacial PV modules was 12% in 2020 and is predicted to be 30% by 2030.¹⁷

- Tracking systems that can follow the sun through the day have become increasingly attractive for ground-mounted systems, despite upfront cost premiums. Trackers can increase energy production over fixed-tilt systems by 10-20% for single-axis trackers and 20-30% for dual axis trackers.¹⁶ In 2022, 94% of new capacity in the U.S. used tracking.¹⁸
- Building Integrated PV (BIPV), such as solar shingles, replaces building materials and improves PV aesthetics.¹⁹

PV Installation, Manufacturing, and Cost

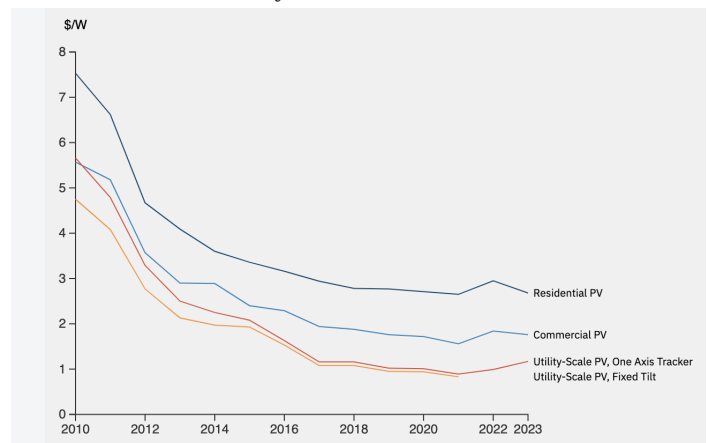
- In 2023, global PV power capacity grew by 447 GW and reached 1,624 GW. Top installers in 2023 were China (253 GW), the U.S. (32.4GW), and Brazil (15.4 GW).²¹

World Cumulative Installed PV Capacity (GW)¹⁶



- New PV installations grew by 87%, and accounted for 78% of the 576 GW of new renewable capacity added.²¹ Even with this growth, solar power accounted for 18.2% of renewable power production, and only 5.5% of global power production in 2023²¹, a rise from 4.5% in 2022.²²
- The U.S.'s average power purchase agreement (PPA) price fell by 88% from 2009 to 2019 at 2.2 ¢/kWh, and then rose slightly to 2.5 ¢/kWh in 2022.¹⁸
- In 2011, the U.S. DOE announced the SunShot Initiative with a 2030 goal of reducing the cost of utility-scale solar energy to \$0.03/kWh, cheaper than fossil-fuel electricity.²³
- Driven by lower capital costs and higher capacity factors,¹⁸ the average levelized cost of energy (LCOE) for utility-scale solar PV dropped by 85% since 2010, to \$0.036/kWh in 2021.²⁴
- However, significant disruptions in global supply chains over the past three years have resulted in a rise in LCOE,²² reaching \$0.061/kWh in 2024.²⁴
- In 2024, global investment in solar power is estimated to exceed \$500B, or 17% of total energy investment, surpassing all other generation sources combined.²⁵
- In December 2022, there were 263,883 solar workers in the U.S., a rise of nearly 9,000 jobs (3.5% growth) since 2021.²⁶

Median Installed PV System Price in the U.S. (\$/W)²⁰



Environmental Impacts

- Designing for end-of-life could improve the current 10% recycling rate of PV modules.²⁷
- Although pollutants and toxic substances are emitted during PV manufacturing, life cycle emissions are low. The life cycle GHG emissions of thin-film CdTe are roughly 14 g CO₂e/kWh²⁸, far below sources such as coal (1,001 g CO₂e/kWh)²⁹.
- PVs on average use far less water to generate electricity (26 gal/MWh), compared to non-renewable technologies such as coal (687 gal/MWh).³⁰

Solutions and Sustainable Actions

- The Inflation Reduction Act of 2022 provides a 30% Investment Tax Credit and a Production Tax Credit of 2.75 ¢/kWh (2023 value) for qualified solar systems through 2032.³¹
- Residential customers can get a 30% of tax credit on the costs of new, qualified clean energy equipment installed through 2032, including rooftop solar and solar water heaters.³²
- Check the [DSIRE database](#) or contact your state energy agency for more incentives on your solar installation.³³
- Those without access to roof space for PV panels can join community solar programs, which are local projects that share ownership and receive credit on their electricity bills.³⁴ As of April 2024, there are 37 community solar programs across 23 states.³⁵ See the "[Solar PV Energy Factsheet](#)" online for a community solar map.
- See the "[Wind Energy Factsheet](#)" for renewable energy mechanisms such as unbundled renewable energy certificates (RECs), community choice aggregation (CCAs), and power purchase agreements (PPAs). In 2022, 32% of market sales from these mechanisms were from solar.³⁶
- Solar REC (SREC) markets require electricity suppliers to purchase SRECs produced by in-state solar systems as part of their obligation under the state's Renewable Portfolio Standards.³⁷ CT, DE, DC, IL, MD, NJ, OH, and PA provide SREC programs as of 2024.³⁸