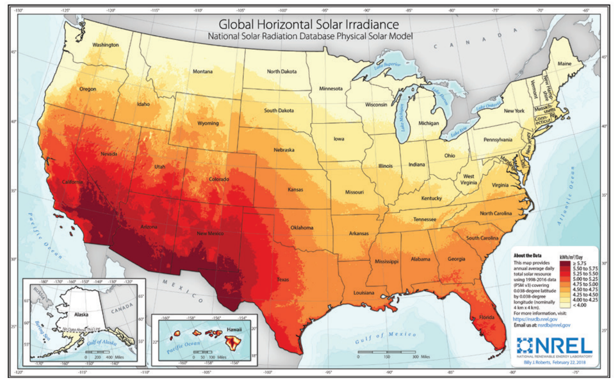
Photovoltaic Energy

Solar energy can be harnessed in two basic ways. First, solar thermal technologies utilize sunlight to heat water for domestic uses, warm building spaces, or heat fluids to drive electricity-generating turbines. Second, photovoltaics (PVs) are semiconductors that generate electrical current from sunlight. Only 2.3% of U.S. electricity was generated with solar technologies in 2020.[1]

Solar Resource and Potential

- On average, 1.73 x 10^5 terawatts (TW) of solar radiation continuously strike the Earth, while global electricity demand averages 2.7 TW.[3,4]
- Electricity demand peaks around mid-day, leading to energy surplus and deficits. Energy storage and demand forecasting will help to match PV generation with demand.[5]
- If co-located with load centers, solar PV can be used to reduce stress on electricity distribution networks, especially during peak demand.[6]
- PV conversion efficiency is the percentage of incident solar energy that is converted to electricity.[7]
- Though most commercial panels have efficiencies from 15% to 20%, researchers have developed PV cells with efficiencies approaching 50%.[8,9]
- Assuming intermediate efficiency, PV covering 0.6% of U.S. land area would generate enough electricity to meet national demand.[10]
- In 2011, the U.S. Department of Energy (DOE) announced the SunShot Initiative. Its aim was to reduce the cost of solar energy by 75%, making it cost competitive with other energy options. In 2017, DOE announced that the 2020 goal of utility-scale solar for $0.06/kWh had been achieved three years earlier than expected. The 2030 goal includes reducing utility-scale solar energy to $0.03/kWh, cheaper than electricity from fossil fuel energy resources.[11]

Annual Average Solar Radiation[2]



PV Technology Types and Efficiencies[9,12]

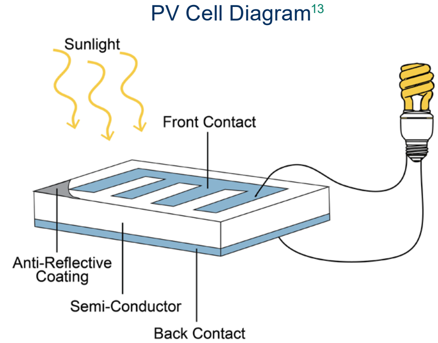
PV Technology		Cell Conversion Efficiency	Module Conversion Efficiency
Crystalline	Monocrystalline silicon (Si)	27.6%	24.4%
	Multicrystalline Si	23.3%	20.4%
	Multi-junction Gallium arsenide (GaAs)	47.1%	38.9%
Thin film	Cadmium telluride (CdTe)	22.1%	19.0%
	CIGS	23.4%	19.2%
Emerging	Perovskite	25.5%	17.9%
	Organic	18.2%	11.7%

PV Technology and Impacts

PV Cells

- PV cells are made from semiconductor materials that eject electrons when light strikes the surface, producing an electrical current.[15]
- Most PV cells are small, rectangular, and produce a few watts of direct current (DC) electricity.[16]
- PV cells also include electrical contacts that allow electrons to flow to the load and surface coatings that reduce light reflection.[15]
- 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).[15] Although PV conversion efficiency is an important metric, cost efficiency—the cost per watt of power—is more important for most applications.

PV Cell Diagram[13]



PV Modules and Balance of System (BOS)

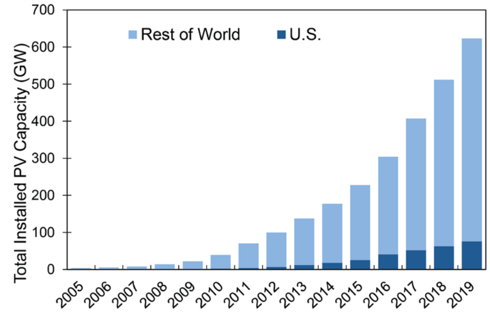
- PV modules typically comprise a rectangular grid of 60 to 72 cells, connected in several parallel circuits and laminated between a transparent front surface and a structural back surface. They usually have metal frames and weigh 34 to 62 pounds.[17]
- A PV array is a group of modules, connected electrically and fastened to a rigid structure.[18]
- 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.[18]
- An inverter is a power electronic device that converts electricity generated by PV systems from DC to alternating current (AC).[18]
- A charge controller is a power electronic device used to manage energy storage in batteries, which themselves can be BOS components.[18]
- In contrast to a rack-mounted PV array, Building Integrated PV (BIPV) replaces building materials and improves PV aesthetics.[19]
- Some ground-mount PV arrays employ a solar tracker. This technology can increase energy output by up to 100%.[20]

Residential PV System[14]

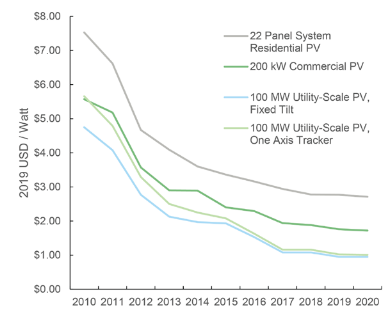
PV Installation, Manufacturing, and Cost

- In 2019, global PV power capacity grew by over 115 GW and reached 633.7 GW. Solar PV capacity has grown by nearly 400 times since 2000.[23]
- Top installers in 2019 were China (30.1 GW), the U.S. (13.3 GW), and India (8.8 GW).[23]
- New PV installations grew by 13% in 2019 and accounted for 48% of global power plant capacity additions. Even with this significant growth, solar power only accounts for 2.6% of global power generation.[23]
- The cost of solar power has dropped nearly 89% since 2009. Various contracts have been signed around the world with solar power prices as low as 1-2¢/kWh; this is much cheaper than conventional power sources.[23] In comparison, U.S. retail electricity averaged 10.66¢/kWh for all sectors and 13.20¢/kWh for residential consumers in 2019.[1]
- In 2019, global investment in solar power dropped to $131.1 billion. This is partially a result of declining capital costs of PV systems.[24]
- PV system/component manufacturing employed 34,000 people in the U.S. in 2018.[18]

World Cumulative Installed PV Capacity[21]



Median Installed Price, Residential, Commercial, and Utility-Scale PV Systems[22]



Energy Performance and Environmental Impacts

- Net energy ratio compares the life cycle energy output of a PV system to its life cycle primary energy input. One study showed that amorphous silicon PVs generate 3 to 6 times more energy than are required to produce them.[25]
- Reusing multi-crystalline cells can reduce manufacturing energy by over 50%.[26]
- Although pollutants and toxic substances are emitted during PV manufacturing, life cycle emissions are low. For example, the life cycle emissions of thin-film CdTe are roughly 14 g CO_2e per kWh delivered, far below electricity sources such as coal (1,001 g CO_2e/kWh).[27,28]
- PVs on average consume less water to generate electricity (26 gallons per MWh), compared to non-renewable technologies such as coal (687 gallons per MWh).[29]

Solutions, Sustainable Actions, and Future Technology

Policies Promoting Renewables

- Consumers that do not have roof space for PV panels can join community solar programs, which are local solar projects that community members can share and receive credit on their electricity bills.[30] Property assessed clean energy (PACE) programs allow property owners to finance the upfront costs of a solar installation through a voluntary assessment on annual property taxes.[31] Green banks and other lending institutions are being developed to specifically fund and support clean energy projects on local, regional, and national scales.[32]
- Carbon cap-and-trade policies would work in favor of PVs by increasing the cost of fossil fuel energy generation.[33]
- PV policy incentives include renewable portfolio standards (RPS), feed-in tariffs (FIT), capacity rebates, and net metering.
  - An RPS requires electricity providers to obtain a minimum fraction of energy from renewable resources.[34]
  - A FIT sets a minimum per kWh price that retail electricity providers must pay renewable electricity generators.[35]
  - Capacity rebates are one-time, up-front payments for building renewable energy projects, based on installed capacity (in watts).[35]
  - With net metering, PV owners get credit from the utility (up to their annual energy use) for energy returned to the grid.[35]

What You Can Do

- "Green pricing" allows customers to pay a premium for electricity that supports investment in renewable technologies. Renewable Energy Certificates (RECs) can be purchased to "offset" commodity electricity usage and help renewable energy become more competitive.[36]

Future Technology

- Emerging PV technologies include perovskites, bifacial PV modules and concentrator PV (CPV) technology. Perovskite solar cells have a high conversion efficiency (over 25%) and low production cost. Bifacial modules are able to collect light on both sides of the PV cells. CPV utilizes low-cost optics to concentrate light onto a small solar cell.[37,38, 39]
- Designing for end-of-life could improve the current 10% rate of PV module recycling.[40]

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