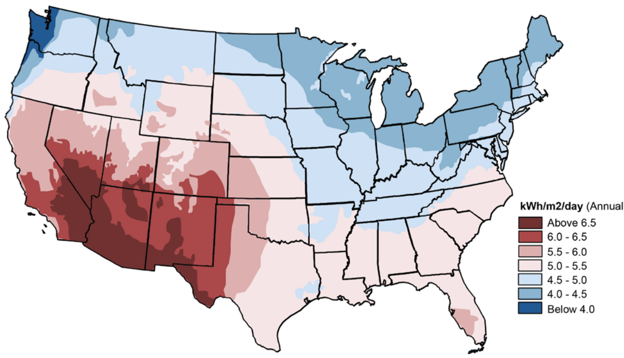
Photovoltaic Energy

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 convert sunlight to electricity. Only 0.9% of U.S. electricity is generated with solar technologies, in part because direct costs are high.[1]

Solar Resource and Potential

- On average, 1.05×10^5 terawatts (TW) of solar radiation reach the Earth's surface, while global electricity demand averages 2.4 TW.[3,4]
- Solar resource availability is well correlated with daily patterns of electricity consumption. However, the sun is not always shining; energy storage is necessary in order for solar energy to meet total electricity demand.[5]
- PVs can be installed where electricity is used to reduce stress on electricity distribution networks, especially during peak demand.[5]
- PV conversion efficiency is the percentage of incident solar energy that a PV converts to electricity. For production modules, conversion efficiency is 6% to 21%.[6]
- Assuming intermediate efficiency, PVs covering 0.6% of U.S. land area would generate enough electricity to meet national demand.[6]
- Residential PV systems require a modest amount of roof space to install. The average residential system in the U.S. is just over 5.0 kW and takes up approximately 500 square feet.[7]
- The U.S. Department of Energy's SunShot Initiative aims to reduce the price of solar energy by 75% from 2010 to 2020, which is projected to lead to 27% of U.S. electricity demand being met by solar technologies in 2050.[6]

Annual Average Solar Radiation[2]



PV Technology Types and Efficiencies[6,8]

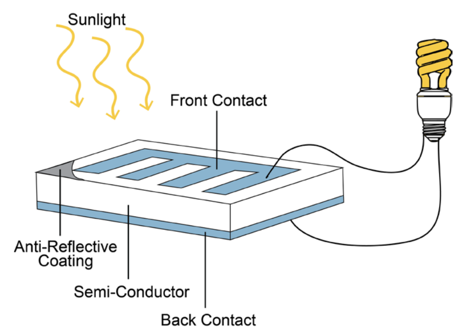
	PV Technology	Cell Conversion Efficiency	Module Conversion Efficiency
Crystalline	Monocrystalline Silicon (Si)	25.0%	14% - 16%
	Multicrystalline Si	21.3%	14% - 16%
	Gallium Arsenide (GaAs)	27.5 - 29.1%	N/A
Thin Film	Amorphous Si (a-Si)	13.6%	6% - 9%
	Cadmium Telluride (CdTe)	22.1%	9% - 12%
	CIS / CIGS	22.3%	8% - 14%

PV Technology and Impacts

PV Cells

- PV cells are made from semiconductor materials that produce electrons when photons strike the surface.[11]
- Most PV cells are square or rectangular, several inches on a side, and produce a few watts of direct current (DC) electricity.[12]
- PV cells also include electrical conductors called contacts, which allow for the flow of electrons, and surface coatings to reduce light reflection.[13]
- A variety of semiconductor materials can be used for PVs, including silicon, copper indium diselenide (CIS), and cadmium telluride (CdTe).[14] See table for common material types and their production efficiencies.
- Although PV conversion efficiency is an important metric, cost efficiency—the cost per watt of power—is more important for most power applications. Some very cost efficient cells do not have high conversion efficiencies.

PV Cell Diagram[9]



PV Modules and Balance of System (BOS)

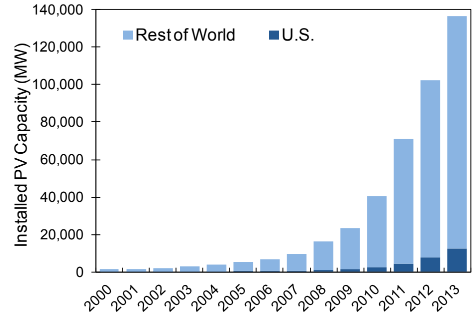
- PV modules typically comprise a rectangular grid of 60 to 72 cells, connected in several parallel circuits and laminated between a transparent front surface and a protective back surface. They usually have metal frames for strength and weigh 34 to 62 pounds.[14]
- A PV array is a group of modules, connected electrically and fastened to a rigid structure.[15]
- BOS components include any elements necessary in PV systems in addition to the actual PV panels, such as wires that connect modules in series, junction boxes to merge the circuits, mounting hardware, and power electronics that manage the PV array's output.[15]
- An inverter is a power electronic device that converts electricity generated by PV systems from DC to alternating current (AC).[15]
- A charge controller is another power electronic device, used to manage energy storage in batteries.[15]
- In contrast to a rack-mounted PV array, Building Integrated PV (BIPV) replaces building materials to improve PV aesthetics and costs.[16]
- Some PV arrays track the sun's daily movement to generate up to 46% more energy than fixed systems.[17]

2.2 kW Residential BIPV System[10]

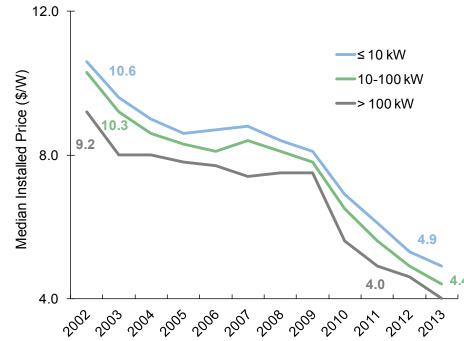
PV Installation, Manufacturing, and Cost

- Global cumulative capacity of PV systems grew 45-fold between 2005 and 2015, reaching more than 229 GW.[19]
- Global installed PV capacity grew 40% annually between 2000 and 2010.[20]
- Over 50 GW of newly installed PV capacity was added in 2015. The top three countries for new installations were China (15.2 GW), Japan (11.0 GW), and the U.S. (7.3 GW).[19]
- The US increased total PV capacity by 40%, totaling 25.6 GW.[21]
- PV module prices, a large part of total system cost, fell 68% from 2008 to 2013.[16]
- Global investment in the solar sector is the highest of renewable energies. In 2016, $114 billion was invested, down from $171 billion in 2015. For comparison, $113 billion was invested in wind, $7 billion was invested in biomass and $2 billion was invested in biofuels.[22]
- PV systems or components are manufactured in over 100 factories across 30 states.[14]
- Between 2000 and 2010, U.S. market share of PV production dropped from 30% to 7%.[23]
- PV energy costs range from 15¢ to 64¢/kWh in the U.S., depending on system size.[24] Retail electricity averages 10.3¢/kWh for all users and 12.6¢/kWh for residential.[1]

World Cumulative Installed PV Capacity[18]



Median Installed Price, Residential & Commercial PV Systems[16]



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 shows that amorphous silicon PVs generate 3 to 6 times more energy than are required to produce them.[25]
- Recycling multi-crystalline cells can reduce manufacturing energy 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 can reduce environmental impacts associated with fossil fuel electricity generation; for example, thermoelectric plants use an average of 19 gallons of water to produce one kWh of electricity.[29] U.S. air pollutant emissions were 684.9 kg CO_2/MWh, for the 2.64 x 10^9 MWh of electricity generated from fossil fuels in 2015.[1]

Solutions and Sustainable Actions

Policies Promoting Renewables

- PV energy costs are currently higher than conventional electricity; however, the price consumers pay for electricity does not cover externalities such as the cost of health effects from air pollution, environmental damage from resource extraction, or long-term nuclear waste storage. Policies that support PVs can address these externalities to make PV energy more cost-competitive.[30]
- Proposed carbon cap-and-trade policies would work in favor of PVs by increasing the cost of fossil fuel energy generation.[31]
- PV policy incentives include renewable portfolio standards (RPS), feed-in tariffs (FIT), capacity rebates, and net metering.[32]
  - An RPS requires electricity providers to obtain a minimum fraction of their energy from renewable resources by a certain date.
  - An FIT sets a minimum per kWh price that retail electricity providers must pay renewable electricity generators.
  - Capacity rebates are one-time, up-front payments for building renewable energy projects, based on installed capacity (in watts).
  - With net metering, PV owners get credit from the utility (up to their annual energy use) if their system supplies power to the grid.

What You Can Do

- Reduce the total amount of energy used in the first place by increasing your energy efficiency. Consider installing a PV system for your home or business, especially if your state offers capacity rebates or a net metering policy.
- "Green pricing" allows customers to pay a premium for electricity that supports investment in renewable technologies. In 2012, more than 850 utilities nationwide offered green pricing options.[33] Renewable Energy Certificates (RECs) also known as green tags or green certificates, can be purchased in addition to commodity electricity to "offset" electricity usage and help renewable energy become more competitive.[34]

A **watt** is a unit of power, or a rate of energy flow. 1 TW = 1,000 GW = 1,000,000 MW = 1,000,000,000 kW.
A **kilowatt-hour** is a unit of energy. 1 kWh is the electricity energy required to light a 100 watt light bulb for 10 hours.

1. U.S. Department of Energy (DOE), Energy Information Administration (EIA) (2017) Monthly Energy Review April 2017.
2. U.S. DOE, National Renewable Energy Lab (NREL) (2012) "Photovoltaic Solar Resource of the United States."
3. Goswami, Y. (2007) Energy: The Burning Issue. Refocus, 8(3): 22-25.
4. U.S. EIA (2017) International Energy Statistics.
5. America's Energy Future Panel on Electricity from Renewable Resources, National Research Council (2010) Electricity from Renewable Resources: Status, Prospects, and Impediments.
6. NREL (2012) SunShot Vision Study.
7. U.S. Environmental Protection Agency (EPA) (2011) Renewable Energy Ready Home: Solar Photovoltaic Specification, Checklist and Guide.
8. NREL (2016) "Best Research-Cell Efficiencies."
9. Adapted from NASA Science (2002) "How Do Photovoltaics Work?"
10. Photo courtesy of National Renewable Energy Laboratory, NREL-15610.
11. U.S. DOE, Energy Efficiency and Renewable Energy (EERE) (2013) "Energy Basics: Photovoltaic Cells."
12. U.S. DOE, EERE (2013) "Energy Basics: Photovoltaic Systems."
13. U.S. DOE, EERE (2013) "Energy Basics: Photovoltaic Electrical Contacts and Cell Coatings."
14. Platzer, M. (2015) U.S. Solar Photovoltaic Manufacturing: Industry Trends, Global Competition, Federal Support. Congressional Research Service.
15. U.S. DOE, EERE (2012) "Energy Basics: Flat-Plate Photovoltaic Balance of System."
16. Barbose, G., et al (2013) Tracking the Sun VI: An Historical Summary of the Installed Price of Photovoltaics in the United States from 1998 to 2012. Lawrence Berkeley National Laboratory, LBNL-6350E.2013.2017.
17. Mousazadeh, H., et al. (2009) A review of principle and sun-tracking methods for maximizing solar systems output. Renewable and Sustainable Energy Reviews, 13:1800-1818.
18. European Photovoltaic Industry Association (EPIA) (2014) Market Report 2013.
19. Solar Power Europe (2016) Global Market Outlook For Solar Power 2016-2020.
20. Dale, M. and S. Benson (2013) Energy Balance of the Global Photovoltaic Industry - Is the PV Industry a Net Energy Producer? Environmental Science & Technology, 47(7): 3482-3489.
21. Solar Energy Industries Association (2016) U.S. Solar Market Insight Report: 2015 Year in Review.
22. UNEP (2017) Global Trends in Renewable Energy Investment 2017.
23. NREL (2011) PV Manufacturing Cost Analysis: U.S. Competitiveness in a Global Industry.
24. Solarbuzz (2012) "Solar Electricity Prices: March 2012."
25. Pacca, S., et al. (2007) Parameters affecting life cycle performance of PV technologies and systems. Energy Policy, 35: 3316 – 3326.
26. Muller, A., et al. (2006) Life cycle analysis of solar module recycling process. Materials Research Society Symposium Proceedings, 895.
27. Kim, H., et al (2012) Life Cycle Greenhouse Gas Emissions of Thin-Film Photovoltaic Electricity Generation. Journal of Industrial Ecology, 16: S110-S121.
28. Whitaker, M., et al. (2012) Life Cycle Greenhouse Gas Emissions of Coal-Fired Electricity Generation. Journal of Industrial Ecology, 16: S53-S72.
29. Maupin, M., et al. (2014) Estimated use of water in the United States in 2010: U.S. Geological Survey.
30. Fthenakis, V. (2012) Sustainability metrics for extending thin-film photovoltaics to terawatt levels. Materials Research Society Bulletin, 37(4): 1-6.
31. Bird, L., et al. (2008) Implications of carbon cap-and-trade for U.S. voluntary renewable energy markets. Energy Policy, 36(6): 2063-2073.
32. U.S. DOE, EERE (2011) Solar Powering Your Community: A Guide for Local Governments.
33. U.S. DOE, EERE (2013) "The Green Power Network: Buying Green Power."
34. U.S. DOE, EERE (2012) "The Green Power Network: Green Power Markets: Renewable Energy Certificates."

Cite as: Center for Sustainable Systems, University of Michigan. 2017. "Photovoltaic Energy Factsheet." Pub. No. CSS07-08. **August 2017**