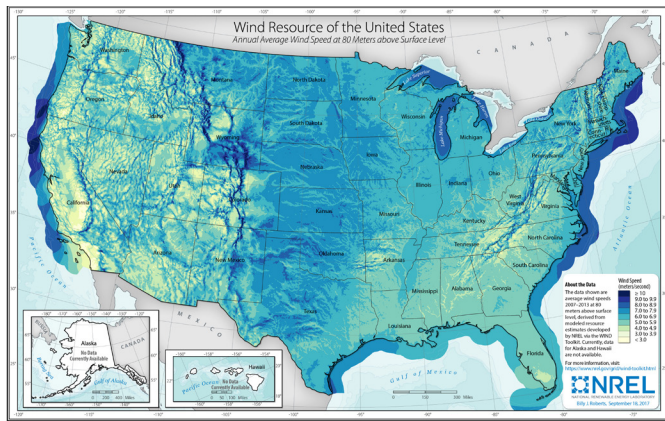


Wind Energy

Wind Resources and Potential

Approximately 2% of the solar energy striking the Earth's surface is converted into kinetic energy in wind.¹ Wind turbines convert the wind's kinetic energy to electricity without emissions¹, and can be built on land or offshore in large bodies of water like oceans and lakes². High wind speeds yield more energy because wind power is proportional to the cube of wind speed.⁴ Average annual wind speeds of 6.5m/s or greater at the height of 80m are generally considered commercially viable. New technologies are expanding the wind resources accessible for commercial projects.⁵ In 2023, wind energy generated 10% of U.S. electricity.⁶

U.S. Wind Resources (80m height)³



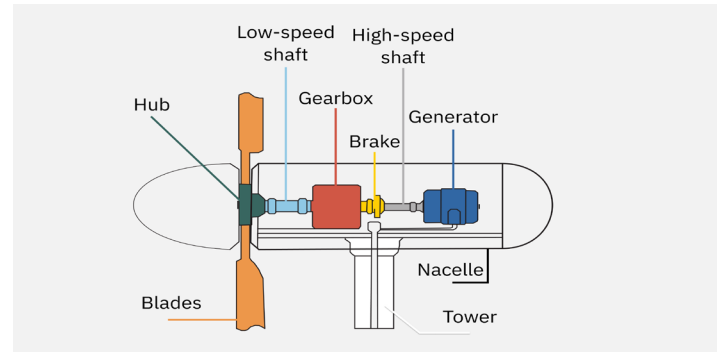
- Wind speeds are slower close to the Earth's surface and faster at higher altitudes. Average hub height is 98m for U.S. onshore wind turbines⁷, and 116.6m for global offshore turbines⁸.
- Global onshore and offshore wind generation potential at 90m turbine hub heights could provide 872,000 TWh of electricity annually.⁹ Total global electricity use in 2022 was 26,573 TWh.¹⁰ Continental U.S. wind potential of 43,000 TWh/yr⁹ greatly exceeds 2022 U.S. electricity use of 4,000 TWh⁶.
- Wind could provide 20% of U.S. electricity by 2030 and 35% by 2050.¹¹ Five of the eight Great Lakes states have offshore wind energy potentials that exceed their annual electricity demand (MI, WI, NY, OH, MN). Michigan's offshore resource could supply over 18 times its 2020 demand.¹²

Wind Technology and Impact

Horizontal Axis Wind Turbines

- Horizontal axis wind turbines (HAWT) are the predominant turbine design in use. The HAWT rotor comprises blades (usually three) symmetrically mounted to a hub. The rotor is connected via a shaft to a gearbox and generator. The nacelle houses these components atop a tower.¹³

Horizontal Axis Wind Turbine Diagram¹³



- HAWT come in a variety of sizes, ranging from 2.5m in diameter and 1 kW for residential applications to 100m+ in diameter and 10+ MW for offshore applications.
- The theoretical maximum efficiency of a turbine is ~59%, known as the Betz Limit. Most turbines extract ~50% of the energy from the wind that passes through the rotor area.¹¹
- The capacity factor of a wind turbine is its average power output divided by its maximum power capability.¹¹ Capacity factor of onshore wind turbines in the U.S. ranges from 9% to 53% and averages 37%.^{7,14}
- Curtailment is a reduction in the output of a generator from what it could otherwise produce, typically on an involuntary basis, due to supply-demand mismatch.¹⁵ U.S. wind power curtailment in 2022 averaged 5.3%, down from a peak of 11.1% in 2009, but up from a low of 2.1% in 2016.⁷
- Offshore winds are generally stronger than on land, and capacity factors are higher on average¹⁶ (expected to reach 60% by 2050 for new projects)¹⁷, but offshore wind farms are more expensive to build and maintain¹⁸.
- Offshore turbines are currently placed in depths up to 40-50m¹⁹, but floating offshore wind technologies could greatly expand generation, as 58% of the total technical wind resource in the U.S. lies in waters greater than 60m deep²⁰.

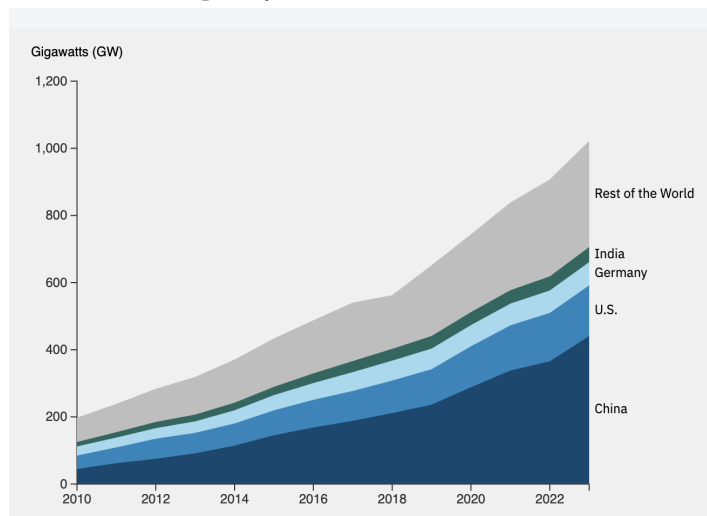
Installation, Manufacturing, and Cost

- Global wind capacity increased by 12% annually in the last decade, reaching 1,021 GW in 2023. China led wind energy development in 2023, both in terms of new and cumulative capacity, followed by the U.S. and Brazil.²¹
- Annual global onshore wind installations surpassed 100 GW for the first time in 2023, while the U.S. experienced a slowdown. 10.8 GW of offshore wind capacity was added worldwide, a 24% increase from 2022, bringing global offshore wind capacity to 75.2 GW. There are two commercial offshore wind projects in the U.S., totaling 42MW capacity.²¹
- U.S. wind capacity grew from 45 GW in 2010 to 147 GW in 2023, a 10% average annual increase.²²
- The U.S. average onshore wind turbine size was 3.2 MW in 2022, up 7% from 2021.⁷ Average capacity factor has increased from 31% for projects installed from 2004 to 2012

to 40% for projects built between 2013 and 2021.⁷

- Texas (40,151 MW), Iowa (12,783 MW), and Oklahoma (12,222 MW) are the leading states in installed wind capacity.⁷ Texas generated the most wind electricity of any U.S. state,²³ while Iowa generated 62.4% of its electricity from wind, the largest share of any state in 2022.⁷
- On a capacity-weighted average basis, wind project installed costs declined by 71% from \$4,804/kW in 1983 to \$1,370/kW in 2022.⁷ The average levelized cost of energy (LCOE) for land-based wind has fallen to \$32/MWh in 2022, down 60% since 2012.⁷
- Wind power purchase agreement (PPA) prices averaged 2.4¢/kWh in the U.S. in 2021-2022⁷, and surged to 6¢/kWh in 2023 in North America²⁴.
- The installed cost of a small turbine (<100 kW) averaged \$7,850/kW in 2022.²⁵
- Large wind projects (>20 MW) require ~85 acres of land area per MW of installed capacity, but 1% or less of this area is occupied by roads, foundations, or equipment; the remainder is available for other uses.¹¹
- In 2023, there were more than 120,000 full-time workers in the U.S. wind industry.²⁶
- For farmers, annual lease payments provide a stable income of around \$3,000/MW of turbine capacity.¹¹
- A 2013 study found energy return on investment (EROI) (energy delivered/energy invested) for wind power between 18 and 20.²⁷

Global Wind Capacity (GW)²¹



Environmental Impacts

- U.S. wind energy generation avoids an estimated 348 Mt of CO₂ emissions annually.²⁶ If 35% of U.S. electricity was wind-generated by 2050, electric sector would reduce GHG emissions by 23%, eliminate 510 Mt of CO₂ emissions annually, and decrease water use by 15%.¹¹

- Annual avian mortality from collisions with turbines is 0.2M, compared to 130M due to power lines and 300-1,000M from buildings. Careful siting can minimize mortality.¹¹
- Bat mortality due to wind turbines is less well studied. A large percentage of bat collisions occur in migratory species during summer and fall months.^{11, 28} The wind industry has been testing methods that potentially reduce bat mortality by over 50%.¹¹
- Noise levels at a distance of 350m from a typical wind farm is 35-45 dB. For comparison, a quiet bedroom is 35 dB and a 40 mph car 100m away is 55 dB.²⁹ As of 2013, several studies have conclusively determined that sound generated by wind turbines has no impact on human health.¹¹
- Over 2Mt of wind turbine blades are expected to be retired in the U.S. by 2050. The current cost of landfilling blades is relatively low. Development of design and materials, recycling technology, and waste management policies are needed to improve end-of-life performance of wind turbine blades.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 wind systems through 2032.³¹
- Residential customers can get a 30% tax credit on the costs of new, qualified clean energy equipment installed through 2032, including wind turbines.³²
- Customers can purchase renewable energy from producers or utilities through mechanisms such as unbundled renewable energy certificates (RECs), community choice aggregations (CCAs), and power purchase agreements (PPAs). In 2022, 9.6M customers procured 272 million MWh of renewable energy through the market, or 38% of the U.S. non-hydro renewable energy generation. 67% of market sales were from wind, while 33% were from solar.³³
- Renewable energy producers sell RECs in addition to the electricity they produce; for a few cents per kWh, customers can purchase RECs to “offset” their electricity use.³⁴
- CCA programs allow local governments to procure power on behalf of their residents, businesses, and municipal accounts from an alternative supplier while still receiving transmission and distribution service from their existing utility provider. CCAs are currently authorized in 10 states.³⁵
- Microsoft, Google, and T-Mobile were the top three corporate buyers of green power as of April 2024.³⁶
- Customers can self-supply renewable electricity by owning renewable electricity equipment (on- or off-site) and using the grid to connect them to their RE system.³⁷ Make your lifestyle more efficient to reduce the amount of energy you use.