Wind

An Overview of Critical Factors for Energy Resources

Introduction

America generates energy from a number of sources. At its most basic level, each source turns a turbine to generate electricity. That power is then fed into the electrical grid to be distributed to homes and businesses. America consumes 4 trillion kilowatt hours (kWh) of electricity per year. The energy mix to generate this electricity is a blend of public policy and private action. Wind is used to generate 8.4 percent of America's electricity as of 2020.

This policy brief will outline eight key factors that shape the current and future utilization of wind for American energy needs. To help build a comprehensive picture of wind's energy outlook, this brief will examine its energy density, costs to generate energy, availability and reserves, land needed, overall safety record, climate impact, long-term impact, and potential limitations of the energy source.

Basics of Wind

Wind power has long been utilized as an energy source for small farms, water collection, and other agricultural processes. Wind's potential to supply large amounts of energy in environments that normally would be barren, like deserts, tundras, and large mountain ranges, make wind an extremely adaptable energy source. Wind turbines work by harnessing wind power to turn three propellers connected to a central rotor, which in turn spins a generator creating electricity.[1]

Wind power is an indirect form of solar energy, as wind is caused by a combination of three factors: uneven heating of the atmosphere by the sun, irregularities of the Earth's surface, and the rotation of the planet.[2] Wind can be modified by bodies of water and different types of vegetation, meaning differences in wind over bodies of water and terrain can both be utilized using vertical-axis turbines and horizontal-axis turbines.[3] The difference between the two turbines is that vertical-axis turbines do not need to be adjusted to face the direction of the wind.[4]

As technology to harness wind power has improved, so has wind's share of the U.S. and global energy mix. This has been further advanced by utilizing offshore wind farms. By tapping into offshore wind, several land-use concerns are mitigated and access to strong ocean wind is guaranteed. Limitations of wind and other renewable sources include intermittency and lower capacity factors to harness the full natural resources potential. Combined with a lack of large scale power storage technology, wind has not been viewed as viable for providing base load power, but relegated to supporting the overall energy mix. Innovations in technology and greater deployment of turbines may soon change some of that calculus.

1. Density

Wind power density depends on wind's speed, volume, and density, and is measured in watts per square meter (W/m^2). While the wind's characteristics are one factor, the turbine blade design and ability to capture the energy also impacts its power output. Currently, wind turbines are able to capture and convert between 30 percent and 50 percent of the wind's energy into electricity.

Wind power is divided between classes based on wind speeds ranging from 0 to 26 mph.[5,6] Energy density for wind power falls into a range for each of seven classes:

Classes at 10m (33ft)	Classes at 50m (164ft)
Class 1 = (0 W/m^2 - 100 W/m^2)	Class 1 = (0 W/m^2 - 200 W/m^2)
Class 2 = (100 W/m^2 - 150 W/m^2)	Class 2 = (200 W/m^2 - 300 W/m^2)
Class 3 = (150 W/m^2 - 200 W/m^2)	Class 3 = (300 W/m^2 - 400 W/m^2)
Class 4 = (200 W/m^2 - 250 W/m^2)	Class 4 = (400 W/m^2 - 500 W/m^2)
Class 5 = (250 W/m^2 - 300 W/m^2)	Class 5 =(500 W/m^2 - 600 W/m^2)
Class 6 = (300 W/m^2 - 400 W/m^2)	Class 6 = (600 W/m^2 - 800 W/m^2)
Class 7 = (400 W/m^2 - 1000 W/m^2)	Class 7 = (800 W/m^2 - 2000 W/m^2)

The average horizontal-axis wind turbine has a capacity of 1,500 kW, which operating at 33 percent capacity[7] would generate 4.824 million kWh per year.[8] In 2020, the 67,000 turbines across the U.S. generated 338 billion kWh, or 5,044,776 kWh per turbine on average.

To picture the energy density of wind power, consider how many wind turbines it would take to power a modern house. The average U.S. household consumes 10,649 kWh of electricity per year.[9] To run an average household on wind alone for one year would use 0.002 wind turbines.

2. Cost

Renewable resources have intuitively low operating costs due to no fuel inputs. Wind energy is generally the lowest cost energy on the market.[10] However, the actual cost of installing a commercial scale wind turbine ranges from $3 to $4 million.[11] The costs related to wind turbine installation and up front costs have decreased every year since 2015 and are projected to continue on a downward trend.[12] Currently, 75 to 80 percent of capital costs involve the actual construction and installation of wind turbines.[13]

Factoring in capital costs, fixed operations and maintenance (O&M) costs, variable costs that include O&M, financing costs, an assumed utilization rate for each turbine type, and waste management and storage, the total cost comes in higher. Accordingly, the leveled cost of electricity and storage outlook for onshore wind is projected to be 3.15 cents per kWh, while the outlook for offshore wind is 11.50 cents per kWh.[14,15]

To power the average U.S. household for one year solely wind energy would cost $335.44 with onshore and $1,224.64 from offshore.

3. Availability and Reserves

Wind turbines harness natural air movement, a resource that is renewable and continuously supplied by changing weather patterns and natural processes. It is both plentiful and easy to access, with wind power having the potential to serve as an energy source both on land and offshore. Projections estimate that wind power will be a viable and competitive source of energy in all 50 U.S. states by 2050, with coastal states having the potential to capture higher amounts of energy with additional offshore wind turbines.[16]

Overall, wind turbines are best located where air speeds stay at or above 9 mph or 4 m/s.[17] Turbines generally must stand hundreds of feet in the air to capture consistent high-speed wind supply. Higher elevations increase the amount of direct wind that can be utilized for electricity generation, giving mountainous states potential advantages.[18] Alternatively, plains are advantageous as there are no mountains to disrupt wind.

Domestic wind supply for electricity generating purposes is measured in wind potential energy. For the potential wind energy within only the U.S. mainland at 80 meters and 100 meters height, total annual capacity is almost 10,500 GW and over 12,000 GW, respectively.[19,20] This combined capacity of 22,500 GW represents over 81 trillion kWh of annual electricity potential, or 20 times domestic energy demand.

Offshore, wind potential in 2018 represented 8.086 trillion kWh; more than twice U.S. electricity demand in the same year.[21] In fact, more than the annual energy demand for the nation could be achieved from maximizing turbine locations offshore limited to within 60km from shore and no more than 60m deep water. The U.S. wind power technical potential for maximizing all offshore potential to include greater distance from shore and ocean depth is 46.727 trillion kWh per year, or 11 times the total national energy demand.[22,23]

While wind is a renewable source, it is not always blowing in any given region or time with consistency. The same advantage – that weather organically creates this energy resources – can be a disadvantage when it is unavailable. But fortunately, there are no reserves to exhaust and the domestic and global supply is essentially infinite. While wind is the energy resource in question, turbines do require material mined from the earth. Steel, fiberglass, resin, plastic, iron, copper, aluminum, and concrete are needed for construction. These are widely used and available, and can even be recycled in many circumstances from turbines themselves and other industrial uses.

4. Land Required

Wind turbines have minimal spatial requirements to function effectively in large groups. For large-scale wind turbine farms, each wind turbine needs at least seven rotor diameters of space between one another.[24] This means in practice that a 262-foot rotor diameter would need to be a third of a mile away from other wind turbines, so as not to create turbulence for other turbines and limit other wind turbines efficiency.[25] Large wind turbine farms also require connectivity to power lines and other transmission infrastructure to integrate with the grid.[26] As wind power tends to be generated in more remote areas or offshore, additional power lines may need to be constructed, increasing its footprint.

Because much of the footprint is due to spacing between towers, this allows turbines to be installed on land that can be utilized in other ways. The Great Plains of the United States, which comprises largely flat, midwestern states primarily used for agriculture, currently hosts the majority of domestic wind farms.[27] Farms may continue to operate as normal, with wind turbines spaced out on the property and minimal impact to livestock or crops.[28] Although regular service and maintenance does require service roads between towers.

The total infrastructure footprint of wind power must account for the mining and construction of materials, concrete tower pads, land used for wind farms, and waste disposal and storage. Transmission infrastructure to carry electricity from generation source to end users is not counted here, but adds a greater land-use requirement.[29] In 2018, land intensity for then-installed capacity was estimated at 10 MW per square mile.[30] With capacity surpassing 67,000 turbines in 2020 and accounting for its total footprint, wind in the U.S. currently requires an estimated 6.7 million acres.[31] The relatively small footprint of actual turbine towers means that a tower-only footprint (subtracting tower spacing) is only 70,000 acres.[32] With wind generating 338 billion kWh of electricity in the U.S. in 2020, this means total land use of 50,447.76 kWh/acre.[33]

In order to power an average U.S. household for a year on wind energy alone, the total acreage required would be 0.211 acres (or 854 square meters).

5. Safety

The safety record for wind turbines is generally high, and technological advancements have driven down catastrophic failures to fewer than 40 incidents across the then 40,000 installed turbines in the U.S. as of 2014.[34] The main safety concerns from the infrastructure itself are catastrophic failures in the form of a tower collapse, as well as blade throws, fire, and weather-included ice shedding. Other casualty risks arise at the mining, construction, and maintenance phases, where workers face varied risks from industrial factors to fatal falls.

Complete tower collapses are rare, tallying as few as 227 worldwide since the 1980s;[35] although four of the seven structural failures in 2019 occurred in the U.S.[36,37,38] Total accidents are difficult to calculate, as many are unreported or minor, but at least 3,033 have been confirmed, with industry trackers estimating this is likely only "the tip of the iceberg" accounting for, in some cases, fewer than one percent of the actual total wind turbine incidents worldwide since 1980.[39] Among the accidents, only 220 fatalities were counted. The most common issues are blade throws and fires. A smaller, but legitimate concern is ice accumulation on turbine blades, which can occur in freezing conditions and lead to ice shedding that falls hundreds of feet. This issue can be mitigated by delaying the startup times for every turbine and ensuring that no one is below the turbine when ice breaks off of the blades.[40] Any severe ice buildup causes most wind turbines to shut down until conditions improve.

The worldwide fatality rate from wind power stands between 0.04 and 0.15 deaths per terawatt hour (1 billion kWh).[41,42] The majority of deaths comes from falls during maintenance activities, while others may be attributed to collapses, blade throws, fires, ice throws, and transportation either to turbine sites for construction and maintenance or during the transport of large blade components by highways.[43]

The annual fatality rate for powering a single U.S. household would be an estimated 0.000001. This would mean a million homes would be powered before a death is attributed to wind.

6. Climate Impact

Wind turbines do not emit carbon dioxide or other emissions while in operation. However, the materials that go into wind turbines and the processes used to get the raw materials for wind turbines do produce carbon and other emissions.[44] Wind turbines are primarily a front-loaded carbon emission energy source. On a lifecycle basis, the median emissions from wind power comes in at 11 grams CO_2/kWh for onshore and 12 grams CO_2/kWh offshore.[45] The estimated range for lifecycle emissions is between 7 grams to 56 grams CO_2/kWh.[46]

The steel, aluminum, and resins that hold the turbine together are the three largest contributors to wind turbines construction carbon footprint. Broken down by component: "the steel tower accounts for 30 percent of the carbon impact, the concrete foundation accounts for 17 percent, and the carbon fiber and fiberglass make up 12 percent."[47] However, wind turbines have the ability to offset their own emissions generated from construction within three to eight months of operation.[48,49] Wind power projects also require roads to access the site, trucks to transport materials, and cranes and construction material to excavate foundations and build the turbine towers on site, adding to the carbon footprint.[50]

Overall, the carbon footprint of wind turbines are most concentrated in the mining and refining of materials needed for the turbines and not the energy production. Aside from atmospheric emissions, wind turbines can create a waste problem with very large and difficult to recycle blade materials. These have most commonly been discarded in landfills. Innovations in recycling wind turbines for future reuse is currently under development to limit the amount of waste generated from replacing wind turbine components.[51]

In terms of wildlife impact, wind turbines do pose a threat to birds. Environmental studies have shown that over 500,000 birds from over 200 species are killed by wind turbine collisions annually, alongside nearly 900,000 bats.[52,53] Moreover, mandated wind capacity growth in the U.S. will increase the turbine count as much as sixfold, leading to statistical projections of 1.4 million bird deaths each year and many more bats.[54] However, this can be contextualized as a lower figure than deaths caused by building collisions, which can be estimated to be as much as

1,500 times greater.[55] Additional context points to cats killing high numbers of birds, which tend to be small birds with higher rates of reproduction, rather than larger, longer-lived, slower to reproduce, migratory, or endangered bird species potentially threatened by turbines.

Offshore, the record may be more mixed. While birds may still fatally impact with turbine blades at sea, marine life may realize benefits from offshore installations.[56,57] In some cases, evidence suggests turbine bases can serve as artificial reefs, a boon to fish and mussels. They could, however, also host harmful algae or invasive species, especially in tropical waters or water warmed as the climate shifts.[58]

For an average American household's annual energy needs to be fulfilled with wind power, the emissions generated from wind turbines would be 117,139 grams of CO_2 (258 pounds).

7. Long-Term Impact

The long-term impact of wind turbines mainly deals with retiring worn out blades and continuing to maintain turbines across the country. Wind turbines must be retired after erosion from weather and general wear and tear.[59] This is usually on a 20-year timescale.[60] Maintenance and upgrades at roughly six-month intervals can marginally extend the lifespan, but can also impose economic and environmental costs.

Most turbine blades have ultimately been sent to landfills, although some alternatives have arisen in recent years.[61] Virtually all of the turbines installed in the 1990s are now past their lifespan and set for retirement, with the U.S. decommissioning roughly 8,000 blades each year;[62] and over the next 20 years, over 720,000 tons of blade waste will need to be dealt with.[63] This massive material waste problem implicates land use, environmental concerns, and costs.

Given the resilient blade material, it can be difficult to cut down, recycle, or dispose of, and processes to do so require high energy usage and even diamond-wire saws. Where recycling is possible, as with 85 percent of the turbines 8,000 parts, the infrastructure can be highly sustainable. Innovations in blade recycling include using the full or partial blade as structural material in buildings, bus stops, or playgrounds, and grinding it down to be used for other applications.[64,65,66] Some projects have even sought to avoid landfills by sending blade refuse to coal mine reclamation sites.[67] Emerging technology able to pull metals out of renewable energy products like wind turbines and solar panels have been tested and are currently being utilized to maximize the recycling process.[68] Other technology, like bird detection is also being developed that has the potential to further limit wind turbines long-term impact on birds and other flying species.[69]

Finally, the longterm and regular presence on cropland as maintenance crews continue to need access to wind turbine farms remains an impact. These semipermanent roads and easements can limit or interfere with agricultural activity, continue to utilize swaths of land, and serve fuel-consuming vehicles putting out emissions and disrupting dirt on unpaved roads.

8. Limitations

Wind energy does have several limitations that necessitate either mitigation or accounting for when deploying turbines to generate energy. These include technical issues centered on maximizing energy efficiency as well as storing that energy. Political and economic costs may be another limitation.

First, the spacing requirement for groups of turbines leads to large-scale wind farms quickly taking up large amounts of space. This would potentially increase the cost of monitoring and repairing turbines, require additional roads, and increase transmission infrastructure.[70] The spacing is necessitated by the Betz limit, which also caps the theoretical maximum efficiency a wind turbine will be able to achieve. Based on groupings, distances, turbine design, air density and speed, and interaction with the wind, the rule states that wind turbines will peak at 59.3 percent.[71]

Second, wind is an inconsistent renewable resource, meaning that energy captured from wind gusts must be stored for times when the wind does not blow.[72] Innovations in storage are still not easily scaleable. This prevents wind from being able to supply base load power - or the constant level of demand across the grid - and further, wind cannot be dialed up or scaled back easily like fossil fuel plants. This means wind will need to either have far greater capacity or high storage volume alongside a smarter grid, or else remain a supplementary source of power in the energy mix.

A final limitation implicates politics. Wind turbines have a high upfront investment, which could deter some investors from committing capital without tax credits and public benefits. Factoring in the disposal and waste management side, wind can be an economically and logistical challenging investment. Politically, many people support wind, but not near them due to noise and visual impact industrializing the landscape.[73] Tax treatment and political support/opposition will likely change over time.

Conclusion

Wind has true and growing potential to be a major source of energy for the United States. While its energy density and intermittency limit its output, wind is incredibly low cost and widely accessible with a relatively small footprint. Land can be used concurrently, and the safety and climate record stand out even among other renewables. While transmission infrastructure may add to costs and land use, the grid is a separate policy and engineering challenge to address.

The major hurdle to wind energy lies with capacity and storage. For this reason, innovation is the gatekeeper to widespread reliance on wind power. From more efficient turbine designs to power storage and even recycling of turbine materials, innovative technologies and techniques are needed to cement wind's place as a U.S. and global renewable energy mainstay.

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