Solar

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. Solar is unique in its ability to directly convert solar radiation into electricity, although some forms of solar also uses turbines. 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. Utility-scale solar is used to generate 2.3 percent of America's electricity. Rooftop and other localized solar installations also generate large amounts of electricity to power small pieces of infrastructure and minimize demand on the grid.

This policy brief will outline eight key factors that shape the current and future utilization of solar for American energy needs. To help build a comprehensive picture of solar'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 Solar

Solar power refers to the conversion of sunlight into energy using the photovoltaic effect in solar cells (PV) or by concentrating the sun's solar power to a single point using mirrors. PV cells convert sunlight directly into electrical power by receiving photons that displace electrons in the solar cell. Conductors in the cell form a circuit, allowing electrons to run through as electricity. Solar panels are the more common type of solar technology, and are composed of many photovoltaic cells that make up a panel, these are then installed either on rooftops or large scale arrays like solar farms. At utility scale, these generate the majority of power from solar, accounting for 88 billion kWh in 2020.

Concentrated solar power (CSP) converts sunlight into heat energy that turns a turbine connected to a generator. A combination of these two systems can be utilized in multiple different ways to maximize the amount of sunlight that can be captured. Concentrated solar power is less relied upon in the U.S., only generating 3 billion kWh in 2020, or 0.1 percent of the nation's energy mix.

While the sun has long sustained the planet through heat, agriculture, and even vitamin D production, electricity generation is relatively new. The discovery of the photovoltaic effect dates back to 1839, with the first solar panel being installed on a rooftop by 1883.[1] Then operating at only one percent efficiency, innovation has since made solar panels both prolific and reliable.

1. Density

The energy density for solar power depends on whether solar energy is captured by PV or CSP converters. While CSP captures the sun's heat and can be up to 70 percent efficient, PV uses photons to free electrons that can run through a circuit generating electricity and faces additional efficiency limitations.

The energy available from the sun at sea level averages out to about 6 kWh per square meter per day.[2,3,4,5] This clear-sky average means that different atmospheric conditions and different latitudes will greatly impact the available energy from the sun hitting the earth's surface. In addition to light being absorbed by the atmosphere, around 19 percent of the sun's light is not a suitable frequency to produce the photovoltaic effect.[6] Further, solar energy density is impacted by the efficiency of the solar cells, in most cases only being able to convert around 20 percent of the incoming solar energy into electricity. Finally, the capacity factor, or ratio of actual electricity to maximum generation capacity is very low for solar, given the need for daytime sunlight uninhibited by weather, obstructions, maintenance, and other factors. Photovoltaic arrays operate at capacity factors of 20 to 25 percent or below as of 2021.[7]

Accounting for inefficiencies, weather, interruptions, and other real world factors, the actual electricity generated is lower than the solar energy hitting the earth's surface. At utility scale, PV has a median power density of 5.84 watts per square meter, while CSP is estimated around 9.7 watts per square meter.[8,9,10]

To picture the energy density of solar power, consider how many solar panels it would take to power a modern house. The average U.S. household consumes 10,649 kWh of electricity per year. To run an average household on solar power alone for one year, it would take 208.16 square meters of solar panels at peak solar hours.

2. Cost

Technological advancement, private investments, and public assistance have driven the cost of solar energy down considerably in the past decade.[11] In 2017, the cost per kilowatt hour stood at 6 cents for utility scale PV solar power, having declined from a high of 28 cents/kWh in 2011.[12]

With innovation and investment remaining on trend, by 2026, solar costs will drop further. 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 plant type, and waste management and storage, we see lifecycle costs. Accordingly, the leveled cost of electricity and storage outlook for PV solar is between 3.13 and 4.51 cents per kWh.[13,14] Levelized cost of energy (LCOE) estimates for concentrated solar is currently approximately 18 cents/kWh.[15]

The average cost to fulfill a U.S. household's energy needs for one year utilizing only PV solar power would be approximately $406.79.

3. Availability and Reserves

An estimated 173,000 terawatts of solar radiation hits the earth continuously. That is on the order of over a quintillion kWh per year. Before viewing this inexhaustible and abundantly available resource as far more than our needed energy, consider that around 19 percent of solar radiation is unusable for photovoltaics, being of too low a frequency. Also consider that this massive amount of energy hitting the planet is not wasted, as the sun facilitates photosynthesis supporting both our food production and atmospheric oxygen, provides heat, and many other energy needs. But there is still enormous potential to capture and utilize the excess incoming radiation that would otherwise be reflected or absorbed by the earth or atmosphere.

Solar panel efficiency and capacity factors are technological limitations and more relevant for power generation and energy density. In terms of availability and reserves of the resource of solar energy, the supply is virtually infinite. The sun has a lifespan projected forward billions of years, and while some of its light is in unusable spectra, much of the remainder comprises the available reserves for power generation on earth's surface.

Due to Earth's rotation, curvature, local topography, and the climate of particular areas, sunlight reaches the Earth's surface unevenly. The availability of solar power largely depends on the location of solar panels on Earth's surface and local solar insolation. Placement closer to the equator achieves larger amounts of yearly sun than areas at higher latitudes, and the availability in any given location is limited to daytime hours as well as weather factors.[16,17]

The availability and reserves of resources needed to produce electricity from solar energy implicates material resources in addition to freely available solar radiation. Abundant quantities of aluminum, copper, glass, silicon, silver, steel, and other minerals are needed for solar cells, panels, and arrays.[18] This does not account for needed materials for power storage like lead, lithium, cadmium, and other batteries components. The availability of all these resources has expert analysis ranging from confidence in supply to skepticism about usage rates, depending on how fully the planet builds out renewable infrastructure, including wind and solar along with battery storage, electric vehicle fleets, and other projects utilizing high quantities of rare earth elements, precious metals, and other mining-intensive resources.[19,20]

4. Land Required

The total footprint of solar includes not only the arrays themselves at solar farms, but the land used for mining activity, material construction, transportation, energy storage, and waste disposal. Taking these into account greatly increases the land-use of solar, while other features of solar help to reduce its footprint. Rooftop installations provide concurrent land use, not requiring or disturbing new areas to capture radiation, but also reducing transmission infrastructure needed to route the electricity to consumers. For this analysis, only utility-scale solar installations are accounted for, and rooftop and lower capacity installations are omitted.

The land needed to generate electricity depends on the efficiency and capacity factor of the solar panel as well as its regional placement. As technology has advanced and improved PV efficiency, the land needs to produce 1,000kW has dropped from 7.3 acres (when averaged from 2013 to 2017) to 3.7 acres (averaged from 2018 to 2020).[21] The advancements in efficiency include ways to increase solar radiation captured by a single panel.[22] New textured and three-dimensional designs for solar panels can expand the surface area of a single solar panel by three to five times their current area, potentially increasing energy output per area.[23]

In the U.S., utility-scale solar is estimated to take up over 500,000 acres. In 2020, solar power produced 91 billion kWh of electricity, meaning its land-use intensity was around 182,000 kWh per acre.

To power the average U.S. household for one year with only utility-scale PV solar energy, it would require 0.06 acres (243 square meters).

5. Safety

Solar energy has among the lowest fatality rates of any energy source at 0.02 per terawatt hour (1 billion kWh) worldwide accounting for PV, solar-thermal, and CSP, while other estimates place rooftop solar at 0.44 deaths per terawatt hour.[24] Safety risks are still prevalent while installing, conducting maintenance, or modifying solar panels, especially on top of other infrastructure. The fatalities risks associated with solar include mining and transporting material, installations, and electrocution. Respiratory and pollution-related health fatalities are also calculated into the fatality rate for energy resources, but solar does not emit during its operation, keeping this category low. During the manufacturing process, however, workers may face risks associated with inhaling silicon dust or exposure to cleaning and other chemicals.

Solar panels cannot be switched off, and most solar panels, as long as they are absorbing sunlight, contain open-circuit voltage that can pose a threat to inexperienced maintenance workers or homeowners.[25] High-voltage shocks, solar heating of metal objects, and arc flashes due to the high amount of concentrated energy are the largest health risks from operational solar panels.[26,27] In the event of a malfunction or short circuit in the energy transfer system, there is a risk of fire caused by overheating of the solar panel or similar accidents.[28]

Overall, solar energy's safety record is exceptional and most risks to both consumers and producers are minimal. To power an average American household, the death rate would be 0.00000021. This would mean that over 4.6 million homes could be powered before a death is attributed to solar power.

6. Climate Impact

Solar panels produce no emissions from the energy production process. Like most other renewable energy sources, the carbon footprint of solar panels is largely made up of the manufacturing process behind its components, as well as the installation process. Similarly, renewable energy technology can create waste when the infrastructure or energy storage complements are decommissioned.

The manufacturing process for a PV system begins with quartz mining, obtaining metallurgy grade silicon for the panels, constructing the aluminum frame, and combining the panel circuitry with the newly constructed module.[29] The manufacturing process also contains several hazardous chemicals, including hydrochloric acid, sulfuric acid, nitric acid, hydrogen fluoride, 1,1,1-trichloroethane, and acetone, which are primarily used for cleaning.[30]

While all of this mining and industrial activity has a considerable footprint, the solar industry has become 50 percent more efficient in reducing their carbon footprint and handling hazardous chemicals over the past decade.[31] In order for solar panels to become carbon neutral, an average time of three years is needed to pay off the equivalent carbon for their production.[32]

For utility-scale power generation, the median lifecycle emissions are 48 grams of CO_2/kWh, while rooftop solar amounts to a median of 41 gCO_2/kWh.[33] The emissions range spans from as low as 18g to as high as 180g CO_2/kWh. For concentrated solar power, the median lifecycle emission is estimated to be 27g CO_2/kWh. These emissions come entirely from infrastructure and supply chain activities.

If the average U.S. household were run entirely on solar power from photovoltaic panels at utility scale, the annual emissions would be 511,152 grams CO_2 per year (1,126.9 pounds).

7. Long-Term Impact

The long-term impacts of solar panels usually stem from concerns at the stages of mining and manufacturing, but issues at the installation and operational stages may post just as much impact. Many of these relate to environmental issues, including land-uses, water consumption, and waste disposal.

Impacts to the surrounding environment also give cause for concern, as larger solar farms require lots of space to operate that can infringe on wildlife.[34] In particular, bird mortality is a concern of environmentalists.[35] In some cases, spatial demand could even result in deforestation or conversion of land from forest or agriculture to energy production. In fact, in South Korea, over 2.37 million trees were cleared for solar panel farms from 2017 to 2020.[36] Considering the global emphasis on renewable energy, long-term impacts of this nature may take place in more regions.

Large amounts of water are used in the manufacturing process to refine and clean material inputs and components. In some areas, to avoid efficiency losses from overheating, water is used to cool solar panels themselves. Additional groundwater usage by maintenance crews to ensure that panels and conductors are properly cleaned could put added strain on water supplies in arid areas where the sun could be most powerful.[37] This long-term water usage impact may particularly affect regions of the Southwest, where conditions are dry and solar concentrations are favorable.

Recycling solar panels also have a long-term impact on the scarcity of the rare earth elements that comprise them, if they are not recycled properly.[38] However, consistent research and development over the last decade has dropped the demand for new solar panel components by 62 percent. New materials that can be substituted for rare metals has allowed for greater conservation of rare earth elements and increased the production of panels worldwide.[39]

8. Limitations

The major limitations of solar panels come from their low energy efficiency, which in turn limits their ability to meet a substantial percent of the United States's energy demand. Most solar panels peak at around 20 percent efficiency. Another limiting factor tied to low efficiency is the need for large-scale deployment to compensate for low electricity generation per square meter.[40,41] As rooftop solar proliferates, this will utilize concurrent spaces and decrease the amount of utility-scale power needed from the grid more broadly.

The final limitation for solar power is energy storage. Solar currently lacks the ability to store energy from peak output for off-peak consumption demands.[42] Advances in energy storage and preventing energy decay can unlock solar's potential, on top of the continued improvements to solar panel's overall efficiency. Due to these limitations, solar power works best in combination with other energy sources to ensure a complement of base load, peaker plants, and other support.

Conclusion

While solar power has been in development since the 19th Century, it has only risen in prominence and reliability in the last decade. Still only accounting for around 2 percent of the U.S. energy mix, solar technology –including rooftop installations– greatly diminishes grid demand and adds to the energy portfolio being established for the remainder of the century. Overall, solar is not highly energy dense due to low efficiency and capacity factors, but it offers advantages in climate impact, cost, and safety record. While land-use concerns do exist, innovations are leading to more efficient panels with a smaller footprint, and rooftop installations may decrease single-use land requirements for solar.

Solar power has the potential to grow significantly as a portion of the U.S. and world energy mixes. Continued research, development, and investment in efficient energy storage solutions will only improve these outcomes. Trends indicate that solar costs will continue to fall in the coming years, but with insufficient energy storage capabilities, solar still faces significant challenges to becoming a reliable energy source at utility scale.

Citations and Notes

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