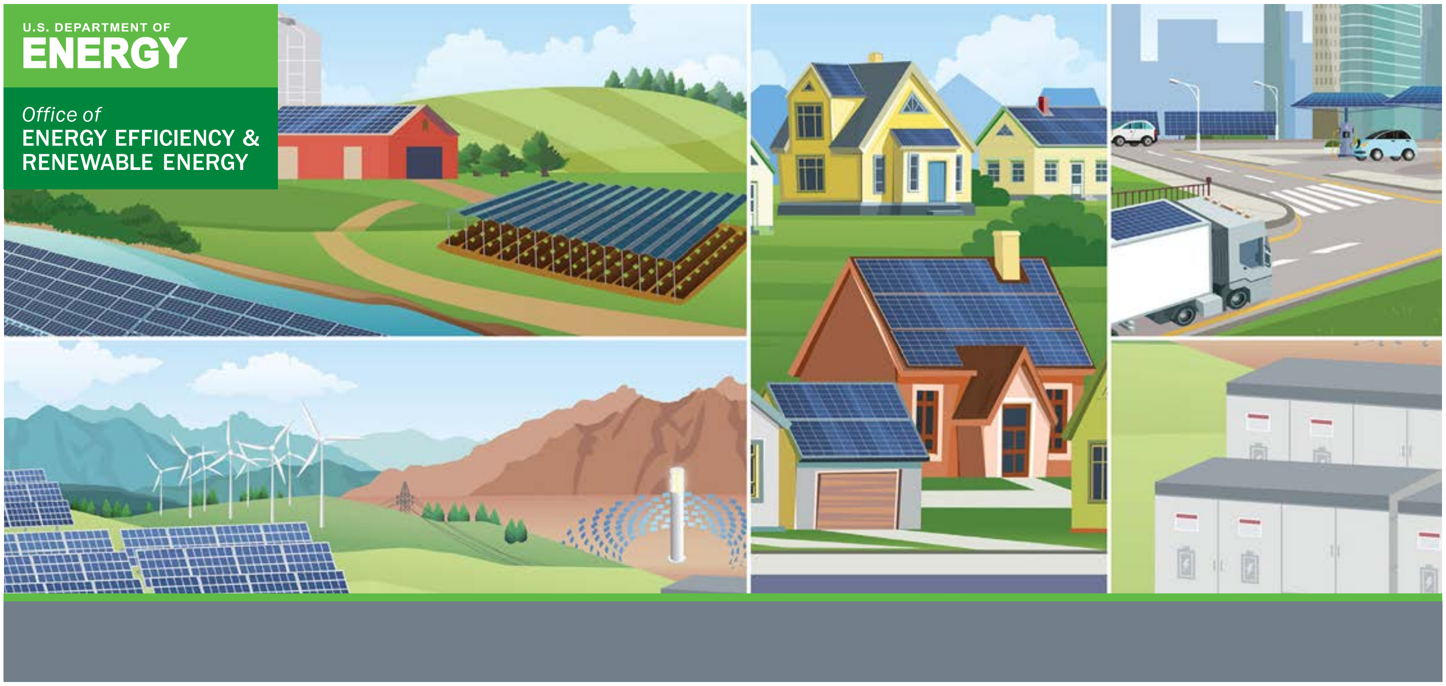
U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY



The Solar Futures Study

The Solar Futures Study explores potential pathways for solar energy to drive deep decarbonization of the U.S. electric grid by 2035, and envisions how further electrification could decarbonize the broader U.S. energy system by 2050.

The study was produced by the U.S. Department of Energy's Solar Energy Technologies Office and the National Renewable Energy Laboratory (NREL). The study draws on NREL's decades of solar analysis expertise and was reviewed by an external panel of more than 70 experts.

Scope of the Report

The study focuses on three future scenarios, two of which assume the U.S. electric grid becomes 95% decarbonized by 2035 and 100% decarbonized by 2050. To achieve these levels of decarbonization, solar would need to account for 45% of electricity generation in 2050 with other zero-carbon energy sources—especially wind energy—supplying the rest.

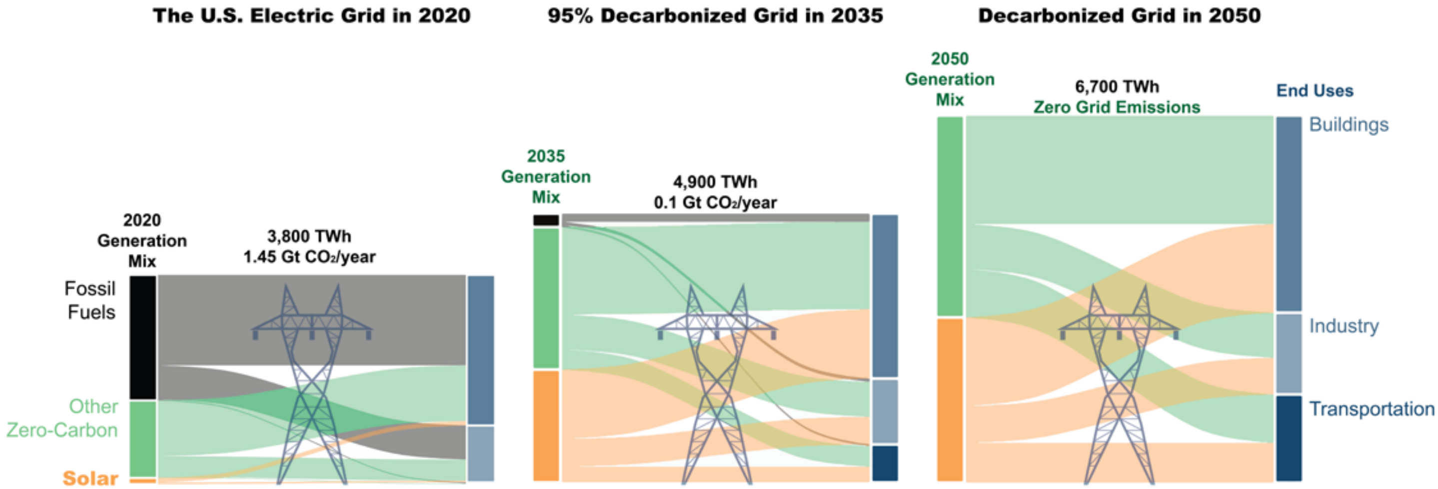
In addition to detailed analysis of solar energy adoption and carbon emissions reductions in these scenarios, the Solar Futures Study also considers key factors, including:

- Integrating solar onto the electric grid
- Ensuring an equitable solar future
- Synergies between solar and storage
- Necessary technological advancements
- Supply chain and environmental considerations
- Solar use in buildings, transportation, and industry

Key Findings

(Based on the core scenario with the greatest amount of decarbonization by 2050)

- Solar will grow from 3% of the U.S. electricity supply today to 40% by 2035 and 45% by 2050. In 2050, this would be supplied by about 1600 gigawatts AC (GW_{AC}) of solar capacity.
- Solar will provide 30% of building energy, 14% of transportation energy, and 8% of industrial energy by 2050, through electrification of these sectors.
- To achieve 95% grid decarbonization by 2035, the United States must install 30 GW_{AC} of solar each year between now and 2025 and ramp up to 60 GW_{AC} per year from 2025–2030. The United States installed about 15 GW_{AC} of solar capacity in 2020.
- Through technology advances, a 95% decarbonized grid can be achieved with no impact on 2035 electricity prices.
- The net incremental cost in 2050 of a 100% decarbonized grid, plus further electrification of buildings and transportation, will be about $210 billion, compared to a reference scenario. Avoided climate damages and improved air quality will result in net overall savings of $1.7 trillion.
- At the levels of growth envisioned in the Solar Futures Study, the solar industry could employ 500,000–1,500,000 people by 2035.



Grid mixes and energy flows in 2020, 2035, and 2050, as envisioned in the Solar Futures Study. Newly electrified loads from buildings, transportation, and industrial sectors mean that the electric grid will deliver more energy in 2035 and 2050. This energy will come almost entirely from solar and other zero-carbon sources.

Three Scenarios

The study uses a suite of detailed power sector models to develop and evaluate three core scenarios:

- Reference – a business-as-usual future that includes existing state and federal clean energy policies but lacks a comprehensive effort to decarbonize the grid.
- Decarbonization (Decarb) – a future in which policies drive a 95% reduction (from 2005 levels) in the grid's carbon dioxide emissions by 2035 and a 100% reduction by 2050.
- Decarbonization with Electrification (Decarb+E) – a future similar to the Decarb scenario that also includes large-scale electrification of energy end uses, like buildings and transportation.

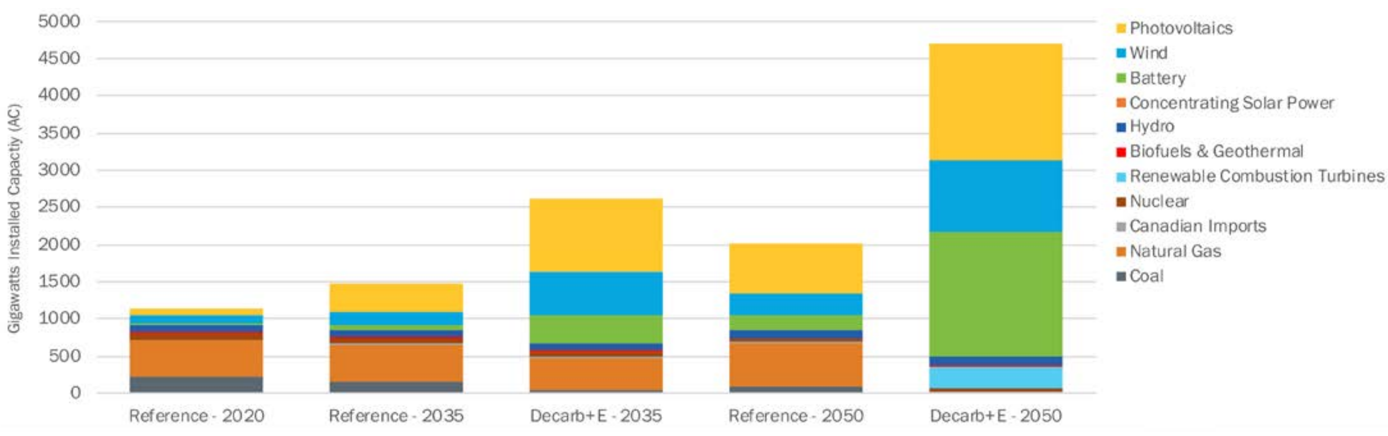
This fact sheet focuses on the Decarb+E scenario, as it envisions the greatest reduction in emissions in the U.S. energy system by 2050. Unless otherwise noted, all details in this fact sheet are based on the Decarb+E scenario.

Grid Integration

The Solar Futures how the large-scale addition of solar, wind, and other renewables impact the reliability and resilience of the grid. Energy storage, long distance transmission, flexible renewable generators, and strategic solar and wind curtailment are all important tools in this transition. Modeling demonstrates that grid performance of can be maintained as the grid decarbonizes.

Energy storage enables high levels of decarbonization. Storage with ≤12 hours of capacity will expand by up to 70-fold. This will allow renewable energy to be stored when it is less useful and released when needed. However, other technologies must also be used to ensure energy is always available when needed—known as firm capacity—when the grid approaches full decarbonization.

Demand flexibility plays a critical role by providing firm capacity and reducing the cost of decarbonization. Demand flexibility will shift some electric demand to times when more energy is available to better utilize solar generation. Demand flexibility reduces decarbonization costs by about 10% in the study.



Generation capacity on the U.S. electric grid under the study's three scenarios over time. Solar, wind, energy storage, and renewably fueled combustion turbines (CTs) all play a key role in decarbonization.

Costs and Benefits

The *Solar Futures Study* considers the economic, environmental, and health impacts of each scenario and finds that the decarbonization scenarios offer broad benefits.

By 2035, solar can facilitate deep decarbonization of the U.S. electric grid without increasing projected 2035 electricity prices. 95% decarbonization can be achieved in 2035 without increasing electricity prices for consumers, because decarbonization and electrification costs are fully offset by savings from technological improvements and enhanced demand flexibility.

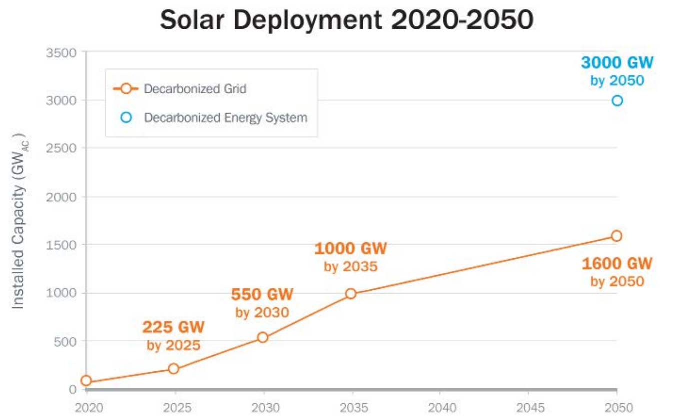
By 2050, the benefits of achieving the Solar Futures Study's decarbonization scenarios far outweigh additional costs incurred. Because the final stages of decarbonization are most expensive, power system costs will be about 25% higher in 2050, compared to the reference scenario. However, this also reflects the costs of serving electrified loads previously powered through direct fuel combustion. Avoided climate damages and improved air quality will more than offset those additional costs, resulting in net savings of $1.7 trillion.

The solar-driven clean energy transition will yield broad economic benefits in the form of jobs and workforce development. The solar industry already employs around 230,000 people in the United States, and with the level of growth envisioned in the Solar Futures Study, it could employ 500,000–1,500,000 people by 2035.

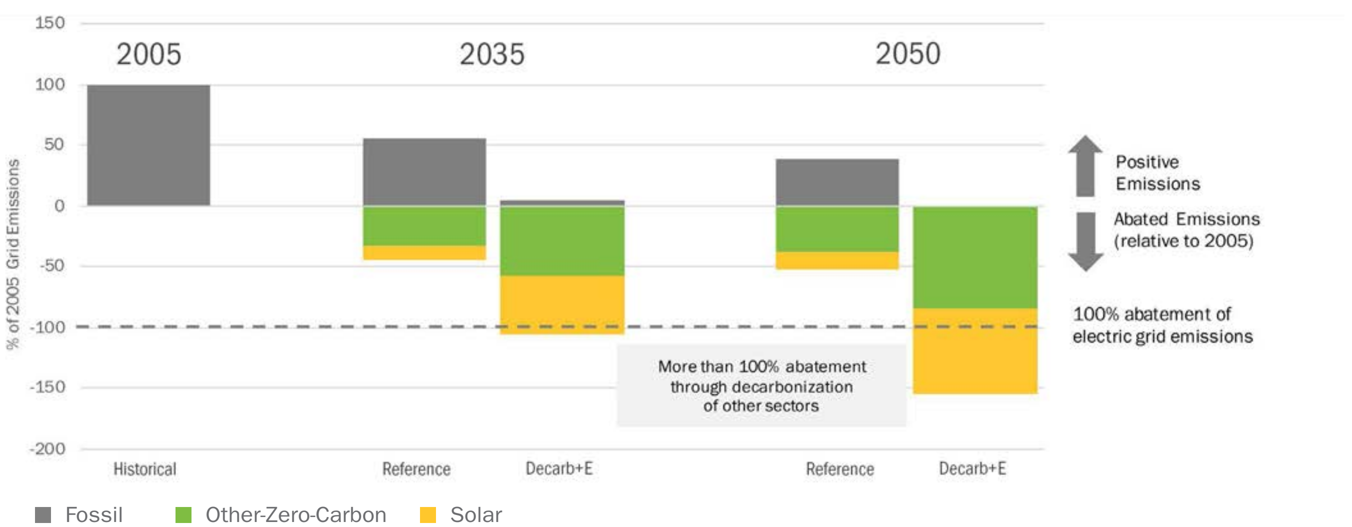
Equity

Challenges must be addressed to ensure that solar costs and benefits are distributed equitably. Low- and medium-income communities and communities of color have been disproportionately harmed by the fossil-fuel-based energy system. The clean energy transition presents opportunities to mitigate these energy justice problems by implementing measures focused on equity. This study explores the distribution of public and private benefits, the distribution of costs, procedural justice in energy-related decision making, the need for a just workforce transition, and potential negative externalities related to the siting of solar projects, energy infrastructure, and the disposal of solar materials.

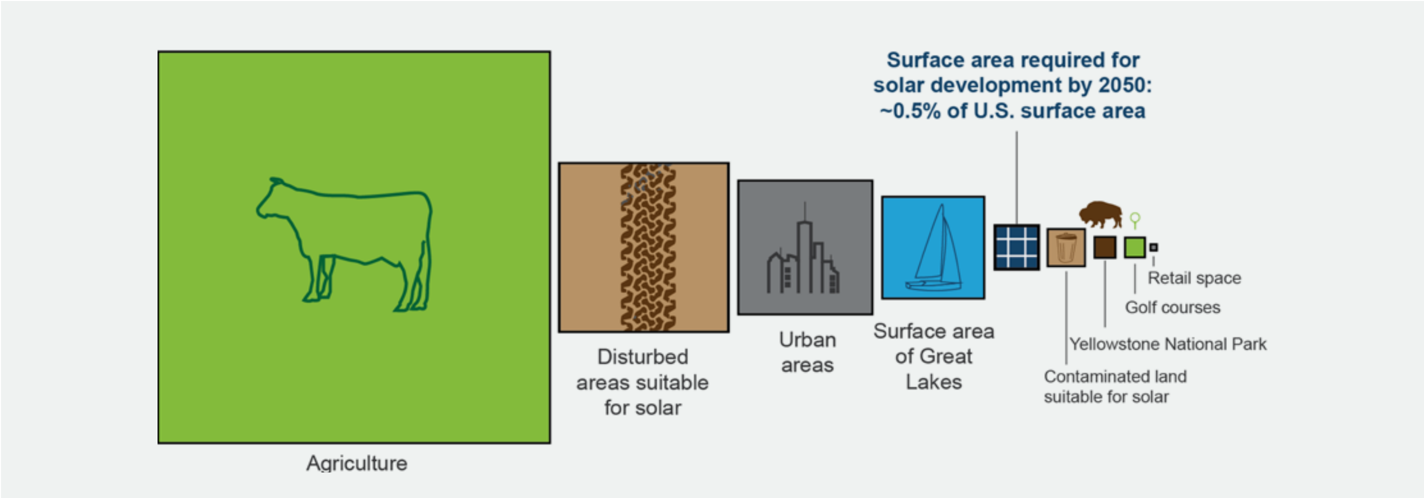
More research is needed to ensure a just transition. Research must identify effective restorative measures, maximize the benefits of the clean energy transition, and mitigate potential future harms. Further work is needed to understand and account for the intangible costs and benefits of clean energy (e.g., the value of community empowerment).



A large expansion in the amount of installed solar energy (shown here in gigawatts AC) plays a key role in decarbonization. Preliminary modeling of an additional scenario, beyond Decarb+E, in which the entire U.S. energy system is 100% decarbonized, would require about 3000 gigawatts of solar deployment.



By replacing significant direct fossil fuel use in the buildings, transportation, and industrial sectors, the Decarb+E scenario abates more than 150% of the electric grid's 2005 carbon emissions.



The level of solar deployment envisioned in the study would require less space than many other current land uses. This calculation does not account for siting of solar on rooftops, bodies of water, or over farm fields.

Environmental and Supply Chain Considerations

Availability of materials will likely not limit solar growth, especially with materials recycling. Technology breakthroughs and more participation in recycling and the circular economy will maximize the use of recoverable materials. This will yield benefits in energy and materials security, improved social and environmental outcomes, and new opportunities for jobs and domestic manufacturing.

Developing U.S. solar manufacturing could mitigate supply chain challenges, but lax labor standards and regulations abroad create cost-competitiveness challenges.

Although land acquisition poses challenges, land availability does not constrain solar deployment. In 2050, ground-based solar technologies will require a maximum land area equivalent to 0.5% of the contiguous U.S. surface area. This requirement could be met using less than 10% of potentially suitable disturbed lands, thus avoiding conflicts with high-value lands in current use.

Installing PV systems on waterbodies, in farming or grazing areas, and in ways that enhance pollinator habitats can enhance solar energy production while providing benefits such as lower water evaporation rates and higher agricultural yields.

Power sector water withdrawals will decline by about 90% by 2050. The water savings result from the low water use of solar and other clean energy generation technologies, compared with fossil fuel and nuclear generators.

Solar Use by End Sector

Solar can help decarbonize the buildings, transportation, and industrial sectors. Electrification of fuel-based end uses will enable solar electricity to power about 30% of all building end uses, 14% of transportation end uses, and 8% of industrial end uses by 2050. Solar fuel production could further power some end uses in each sector.

Of the end uses examined, buildings are the most predisposed to further electrification in the near term. Rooftop solar can increase the value of batteries and load automation systems. Distributed batteries and load automation can increase the grid value of solar.

Managed and coordinated electric vehicle charging could unlock key synergies between electrified transportation and abundant, low-cost solar.

Solar can immediately help to decarbonize the 14% of industrial loads that are already electrified, but further progress will require technology innovation. ■

Learn More

Download the Full Report: www.energy.gov/eere/solar/solar-futures-study

Download the Supporting Reports: www.nrel.gov/analysis/solar-futures.html

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For more information, visit: energy.gov/eere/solar/

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