USDA Economic Research Service
U.S. DEPARTMENT OF AGRICULTURE

Economic Research Service

Economic
Research
Report
Number 330

May 2024

Utility-Scale Solar and Wind Development in Rural Areas: Land Cover Change (2009–20)

Karen Maguire, Sophia J. Tanner, Justin B. Winikoff,
and Ryan Williams

Economic Research Service
U.S. DEPARTMENT OF AGRICULTURE

Economic Research Service
www.ers.usda.gov

Recommended citation format for this publication:

Maguire, K., Tanner, S. J., Winikoff, J. B., and Williams, R., (2024). *Utility-scale solar and wind development in rural areas: Land cover change (2009–20)* (Report No. ERR-330). U.S. Department of Agriculture, Economic Research Service.

Use of commercial and trade names does not imply approval or constitute endorsement by USDA.

To ensure the quality of its research reports and satisfy governmentwide standards, ERS requires that all research reports with substantively new material be reviewed by qualified technical research peers. This technical peer review process, coordinated by ERS' Peer Review Coordinating Council, allows experts who possess the technical background, perspective, and expertise to provide an objective and meaningful assessment of the output's substantive content and clarity of communication during the publication's review.

In accordance with Federal civil rights law and U.S. Department of Agriculture (USDA) civil rights regulations and policies, the USDA, its Agencies, offices, and employees, and institutions participating in or administering USDA programs are prohibited from discriminating based on race, color, national origin, religion, sex, gender identity (including gender expression), sexual orientation, disability, age, marital status, family/parental status, income derived from a public assistance program, political beliefs, or reprisal or retaliation for prior civil rights activity, in any program or activity conducted or funded by USDA (not all bases apply to all programs). Remedies and complaint filing deadlines vary by program or incident.

Persons with disabilities who require alternative means of communication for program information (e.g., Braille, large print, audiotape, American Sign Language, etc.) should contact the responsible Agency or USDA's TARGET Center at (202) 720-2600 (voice and TTY) or contact USDA through the Federal Relay Service at (800) 877-8339. Additionally, program information may be made available in languages other than English.

To file a program discrimination complaint, complete the USDA Program Discrimination Complaint Form, AD-3027, found online at How to File a Program Discrimination Complaint and at any USDA office or write a letter addressed to USDA and provide in the letter all of the information requested in the form. To request a copy of the complaint form, call (866) 632-9992. Submit your completed form or letter to USDA by: (1) mail: U.S. Department of Agriculture, Office of the Assistant Secretary for Civil Rights, 1400 Independence Avenue, SW, Washington, D.C. 20250-9410; (2) fax: (202) 690-7442; or (3) email: program.intake@usda.gov.

USDA is an equal opportunity provider, employer, and lender.

Economic Research Service
U.S. DEPARTMENT OF AGRICULTURE

Economic Research Service

Economic Research Report Number 330

May 2024

Utility-Scale Solar and Wind Development in Rural Areas: Land Cover Change (2009–20)

Karen Maguire, Sophia J. Tanner, Justin B. Winikoff, and Ryan Williams

Abstract

This report examines land cover and land cover change associated with utility-scale solar and wind development in rural areas from 2009–20. Wind development has been expanding since the late 1990s and comprises a larger share of renewable capacity than solar as most utility-scale solar projects were installed after 2016. Due to decreasing costs and new or existing policies promoting renewable development, the pace of development is expected to increase. The amount of land cover directly affected by solar and wind is estimated to be small relative to the amount of farmland. Still, more than 90 percent of wind turbines and 70 percent of solar farms in rural areas were sited on agricultural land. There are large regional differences in the distribution of solar and wind development. Even in years when no development occurred, land cover changed more frequently on land used for solar than wind, suggesting that solar and wind were sited on different types of land. After installation, solar sites more commonly changed land cover than wind, including shifts away from agriculture. Wind sites maintained agricultural land cover. This suggests that wind is compatible with agriculture and that land-use competition exists between farmland and solar farms.

Keywords: solar energy, wind energy, rural areas, land cover, land use, agricultural land, wind turbines, energy, solar farms, wind farms, farmland

Acknowledgments

The authors thank economists Scott Callahan and Clayton Michaud, USDA, Economic Research Service (ERS), for conversations about land cover and major land uses in the United States; economist Steven Wallander, USDA, ERS, for discussions on the Cropland Data Layer and land cover change. The authors also appreciate feedback from economists Christopher Sichko, USDA, ERS, and Samantha Cohen, formerly USDA, ERS and spatial data work by geographer Opeyemi Zubair, USDA, ERS. Thanks also to Jeff Chaltas, Jana Goldman, and Adele Wilcoxen of USDA, ERS for editorial and design services.

About the Authors

Karen Maguire and Sophia Tanner are USDA, Economic Research Service research agricultural economists in the Conservation and Environment Branch in the Resources and Rural Economy Division; Justin Winikoff is a research agricultural economist in the Rural Economy Branch in the Resources and Rural Economy Division. Ryan Williams is a geographer with USDA, Natural Resources Conservation Service (NRCS), Farm Production and Conservation (FPAC).

Contents

USDA Economic Research Service
U.S. DEPARTMENT OF AGRICULTURE

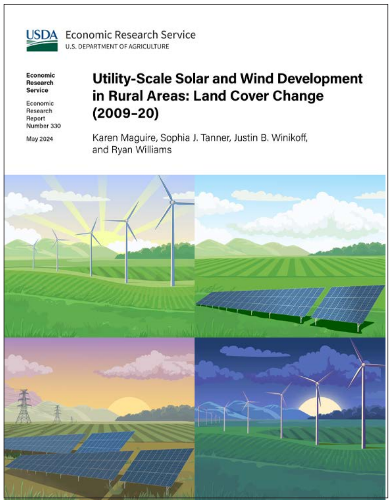
A report summary from the Economic Research Service *May 2024*

Utility-Scale Solar and Wind Development in Rural Areas: Land Cover Change (2009–20)

Karen Maguire, Sophia J. Tanner, Justin B. Winikoff, and Ryan Williams

What Is the Issue?

Federal policies to reduce greenhouse gas (GHG) emissions from electricity generation, including the Inflation Reduction Act of 2022, are projected to lead to growth in renewable energy capacity. Although the amount of land directly affected by a solar or wind farm is small (relative to the amount of farmland), large-scale, commercial solar and wind development leads to changes in the rural landscape. There are local community concerns regarding the effects of solar and wind development on agricultural land use, property values, and the environment. Local community resistance to renewable development can delay or prevent development in a particular area, increasing the costs of deploying solar and wind. Information on the types of land used for solar and wind development and land cover change associated with it may benefit stakeholders and reduce uncertainty for individuals and communities considering hosting solar or wind.


USDA Economic Research Service
U.S. DEPARTMENT OF AGRICULTURE

Economic Research Service

Economic Research Report Number 330

May 2024

Utility-Scale Solar and Wind Development in Rural Areas: Land Cover Change (2009–20)

Karen Maguire, Sophia J. Tanner, Justin B. Winikoff, and Ryan Williams

What Did the Study Find?

This study examines land cover surrounding rural solar and wind installation sites from 2009–20. It explores regional patterns in the distribution of land cover and estimates the amount of land directly affected by development. Finally, the report examines land cover changes associated with solar and wind projects.

- In rural areas, in 2020, the footprint, or land area directly affected by solar or wind farms, is small relative to the approximately 897 million acres of land in farms. The estimated footprint for solar and wind farms was 336,000 acres and 88,000 acres, respectively.

Land cover prior to solar and wind farm development:

- Most solar farms were installed on land that was in cropland (43 percent) or pasture-rangeland (21 percent) prior to development.
- Wind turbines were predominantly installed on land that was classified as cropland (56 percent) and pasture-rangeland (36 percent).

- Solar projects were more commonly installed on nonagricultural land (17 percent) than wind turbines (3 percent).
- In the Midwest, 66 percent of solar farm sites were characterized as cropland prior to installation. In the Plains and the West, most solar sites were pasture-rangeland (60 percent and 51 percent, respectively).
- In the Midwest, 93 percent of wind turbine sites were classified as cropland prior to installation. In the Plains, 45 percent of turbine sites were pasture-rangeland, and in the West, 65 percent.

Average annual rate of land cover change on land used for a solar or wind installation site:

- On average, 16 percent of all solar sites experienced a year-to-year land cover change. For turbine sites, the share was 4 percent.
- The average annual rate of land cover change was largely unchanged after solar and wind development.

Land cover change in proximity to a solar or wind development, from 3 years before to 3 years after installation:

- Land cover changed at 26 percent of solar sites but only 5 percent of wind sites. Fifteen percent of solar sites shifted out of agriculture after installation; for wind, it was less than 1 percent.
- Typically, solar sites that were categorized as cropland prior to installation remained in the same land cover category after installation (82 percent). For wind turbines, the share was 99 percent.
- Seventy-three percent of solar sites and 92 percent of wind turbine sites that were categorized as pasture-range prior to development maintained the same land cover category after development.
- For sites categorized as continuous cropland prior to installation, a higher share of solar sites (36 percent) was fallow (uncultivated) in at least 1 of the 3 years after installation, compared to wind (7 percent).

How Was the Study Conducted?

This study used data from Federal sources to examine land cover and land cover change associated with solar and wind development from 2009–20 in rural areas of the contiguous United States. Data on solar projects were collected from the U.S. Department of Energy, Energy Information Administration (EIA) Form 860 (EIA-860) and for wind projects, from the U.S. Wind Turbine Database (USWTDB) (Hoen et al., 2018; EIA-860, 2021). The USDA Agricultural Resource Management Survey (ARMS) III farm production expenditure regions delineate five geographic regions for analysis (USDA, National Agricultural Statistics Service (NASS), 2022a). Information from the Major Uses of Land in the United States, 2012 is used to describe land cover (Bigelow & Borchers, 2017). Rural areas are defined using the 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census Bureau, 2010 and 2019). Land cover and land cover change were measured using the USDA National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) from 2009–20 (USDA, NASS, 2009–20).

Utility-Scale Solar and Wind Development in Rural Areas: Land Cover Change (2009–20)

Introduction

Achieving a reduction in greenhouse gas (GHG) emissions from the electricity sector requires a significant expansion of utility-scale solar and wind development (Denholm et al., 2022; Gagnon et al., 2022). Although solar and wind capacity has been expanding since the mid-2000s, there is limited information on regional differences in the distribution of solar and wind developments across agricultural and nonagricultural lands in rural areas. To understand the effects of renewable development on the rural landscape, it is important to consider the type of land used, the amount of land cover change that is associated with development, how land cover changed, and to explore the differences in land cover and land cover change between solar and wind projects.

Widespread expansion of utility-scale renewable energy development in the United States began with growth in the wind energy sector in the 1990s, followed by solar in the mid-2000s. In 2020, wind-generated electricity was the second largest source of renewable energy after hydropower, comprising 8.4 percent of total electricity generation. Solar power was third with 2.3 percent (U.S. Energy Information Administration (EIA), 2021b). Utility-scale solar and wind projects were located predominantly in rural areas and often on lands used for crop production or animal grazing. As of 2020, 99.8 percent of utility-scale wind turbines and 74 percent of utility-scale solar installations were in rural areas (U.S. Census Bureau, 2019; Hoen et al., 2018; EIA 860, 2021a).[1] Although there is less solar than wind capacity, solar is growing at a faster rate and is expected to comprise nearly three-quarters of the growth in renewable generation beginning in 2025 (EIA, 2021a). Further, policies, including the Inflation Reduction Act (IRA) of 2022, are expected to lead to a more rapid expansion of solar and wind development (Gagnon et al., 2022). Despite the growth in solar and wind projects, the cumulative amount of land in rural areas that is directly affected by the development is small relative to the amount of farmland. Still, rural landscape changes and the socioeconomic effects in local communities from nearby solar and wind development may be substantial in some areas.

Renewable electricity generation from solar and wind leads to reduced GHG emissions compared to traditional fossil fuel generation and does not produce air pollution, providing local, national, and global environmental benefits (Cullen, 2013; Novan, 2015; Callaway et al., 2018). Due to differences in the land area directly affected by solar and wind developments, there are expected to be marked differences in the effects of solar and wind on land cover. Typically, a wind farm is spread over a much larger land area than a solar farm. Wind turbines must be spaced apart to maximize wind flow. However, estimates suggest that 96–99 percent of the land in a wind farm does not contain any permanent physical structures (Harrison-Atlas et al., 2022). The direct land cover impact of a wind farm is limited to the relatively small area on which service roads, turbine pads, and other infrastructure are constructed (Denholm et al., 2009). Alternative land uses, such as farming or ranching, are typically maintained on the land within the wind farm (Harrison-Atlas et al., 2022). In solar projects, spacing between panels is limited, and the land cover in the area beneath the solar panels is removed prior to development, leaving bare soil on which the solar panels are constructed (Horowitz et al., 2020; Graham et al., 2021). While solar farms tend to be smaller than wind farms, the direct land cover impact of a solar farm (the area beneath solar panels and other infrastructure) typically extends throughout a larger portion of the solar farm (Ardani et al., 2021; Ong et al., 2013; Denholm et al., 2009).

---

[1] In this report, rural areas are defined using the U.S. Census 2019 urban-rural boundaries. The U.S. Census defines urbanized areas with populations of 50,000 or more and urban clusters with populations of 2,500 to 50,000. Other areas with less population density are designated as rural (U.S. Census Bureau, 2019 and 2021). For more information on the calculation of the share of solar and wind development in rural areas, see the Spatial Data and Methodology section on page 12.

Land Cover and Land Use

The terms land cover and land use often denote similar land surface conditions and, in some cases, can be used interchangeably, but they have slightly different meanings. Land cover refers to the physical characteristics that exist on the surface of the land in an area (e.g., cropland, grassland, forest, developed). Land use refers to the dominant purpose for which the land is employed (e.g., corn production, grazing, harvesting wood, urban area).

This report explores how land cover at solar and wind sites varies across rural areas in the contiguous United States, how it differs between utility-scale solar and wind project locations prior to development, and the land cover changes associated with solar and wind developments over the period 2009–20. The analyses focus on the types of agricultural land used for solar and wind projects and the associated land cover changes. The findings inform evaluations of the landscape changes and associated local socioeconomic effects of utility-scale solar and wind development in rural areas.

What Is Utility-Scale?

Utility-scale systems have a capacity of 1 megawatt (MW) or more and provide electricity primarily to the electric grid for offsite use (EIA, 2022a). Utility-scale solar or wind developments are often referred to as farms or projects. Each solar panel or wind turbine has an associated capacity or generating capacity, which is the maximum amount of electricity that can be generated in a specific period. For example, a 2-MW wind turbine can generate a maximum of 2 MW of electricity if there are suitable conditions, e.g., wind speeds. The total capacity of a solar or wind farm is the sum of the capacities of the solar panels or wind turbines that comprise the development.

Some large-scale solar projects, designed to provide electricity primarily offsite, may also be described as community solar. Community solar projects typically have less than 5 MW of capacity and are subscriber-based, with customers often paying a fee to receive solar-generated electricity (Heeter et al., 2020). Community solar encompasses a variety of business and nonprofit models, and the distinction between community solar and utility-scale projects is often not clear. This analysis includes all solar projects 1 MW or greater installed in rural areas through 2020, as reported to the U.S. Energy Information Administration (EIA).

Utility-scale systems are contrasted with small-scale systems (e.g., rooftop solar), which typically have capacities of 0.1 MW or less. Small-scale systems generate electricity primarily for use on-site, although in some cases excess electricity may be sent back to the grid for a credit or payment from the consumer's electric utility. In the United States, wind-generated electricity is almost entirely produced using utility-scale systems. Solar-generated electricity is commonly produced in both utility-scale and small-scale systems.

Background

Figure 1
ARMS III farm production expenditure regions, 2022

ARMS III = Agricultural Resource Management Survey - Phase III.

Note: The USDA Agricultural Resource Management Survey – Phase III (ARMS III) doesn't include Alaska and Hawaii. The States in each ARMS III production expenditure region are: Atlantic (Connecticut, Delaware, District of Columbia, Kentucky, Maine, Maryland, Massachusetts, New Hampshire, New York, North Carolina, Pennsylvania, Rhode Island, Tennessee, Vermont, Virginia, West Virginia); South (Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, South Carolina); Midwest (Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, Wisconsin); Plains (Kansas, Nebraska, North Dakota, Oklahoma, South Dakota, Texas); and West (Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, Wyoming).

Source: USDA, Economic Research Service using information from the USDA, National Agricultural Statistics Service (NASS) ARMS III Farm Production Expenditure Regions Map (USDA, NASS, 2022a).

Solar Development

Although some utility-scale solar projects existed as early as the 1980s, solar capacity was still less than 0.5 gigawatts (GW) in 2007.[2] [3] For comparison, at that time, the total capacity of the electric power sector was more than 1,000 GW (EIA 860, 2021a; EIA, 2022b). Solar capacity began experiencing sustained growth in 2007, but the majority of utility-scale solar development occurred after 2016 due in part to the declining

---

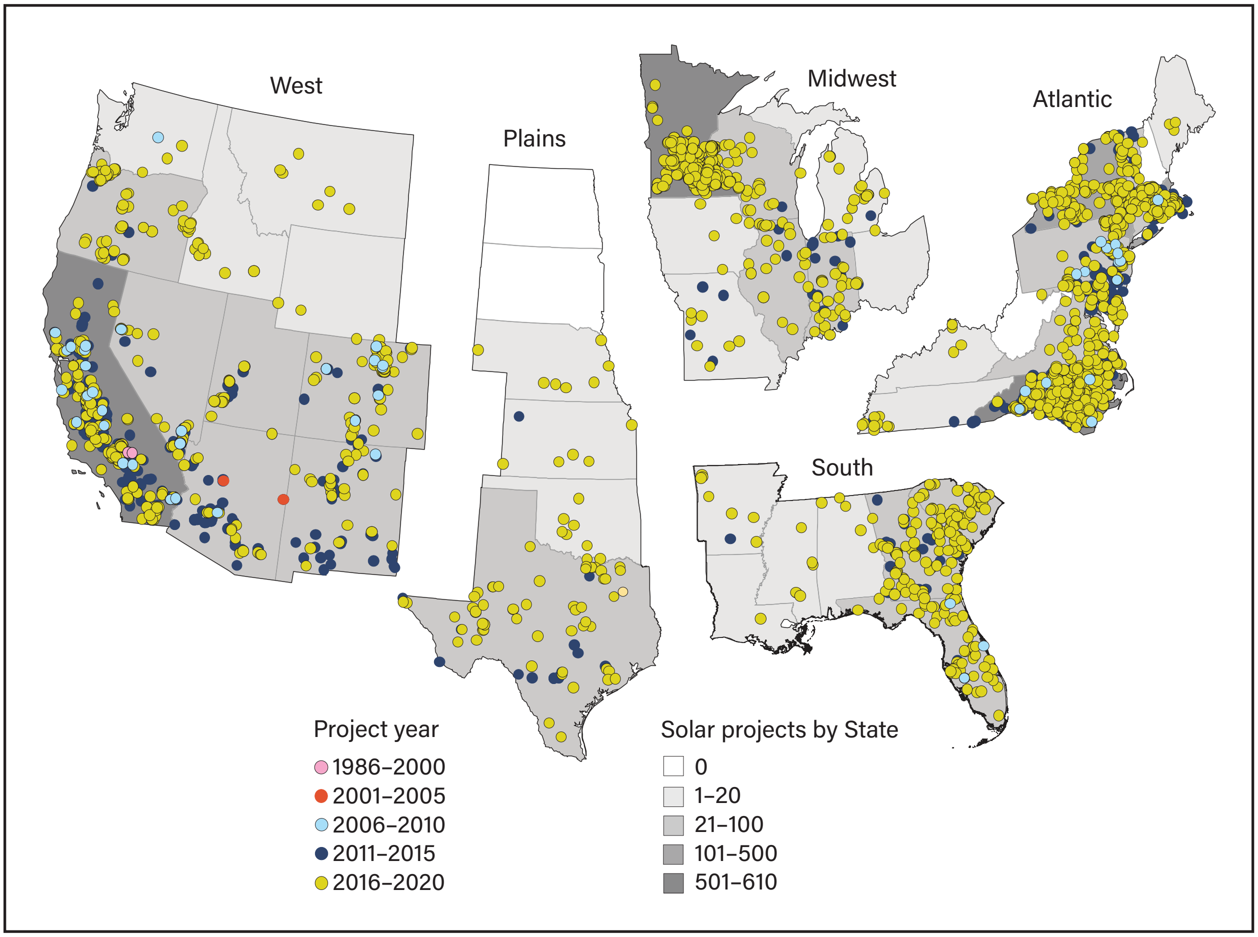
[2] Figure 1 depicts the Agricultural Resource Management Survey (ARMS) III farm production expenditure regions and the States that are included in each region.

[3] 1 terawatt (TW) is equal to 1,000 gigawatts (GWs), 1 GW is equal to 1,000 megawatts (MWs), and 1 MW is equal to 1,000 kilowatts (kWs).

costs of solar panels. Between 2016 and 2020, utility-scale solar capacity in rural areas increased from 21 to 45 GW, and the number of solar projects increased from 2,316 to 3,364 (EIA, 2021a) (figure 2).[4] [5]

Figure 2

Utility-scale solar projects in rural areas of the United States, 2020



Total number of solar projects = 3,364

Note: The USDA Agricultural Resource Management Survey – Phase III (ARMS III) doesn't include Alaska and Hawaii. This study examines solar projects in rural areas of the contiguous United States. The figure includes five regions representing each of the ARMS III production expenditure regions. One point represents the location of a solar project, and the color corresponds with the year in which the project started. Due to scale, some points may overlap with others. States are shaded in grayscale to indicate the total number of statewide solar projects in 2020.

Source: USDA, Economic Research Service using data from U.S. Energy Information Administration (EIA) Form 860 (EIA, 2021a); USDA, NASS ARMS III Production Expenditure Regions Map (USDA, NASS, 2022a); and 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census Bureau, 2019).

Through 2020, solar development was concentrated on the coasts and more prominent in the Atlantic and West regions (figure 2). The frequency of solar in the West was due to the large number of solar farms in California, which has policies that promote renewable energy development (EIA, 2022c). This includes the Cap-and-Trade Program for GHG emissions, which was implemented in 2012 for electric utilities (California

---

[4] Solar data from the EIA Form 860 includes an observation for each solar generator, which is a group of solar panels sited together (EIA-, 2021a). Groups of utility-scale solar panels are commonly referred to as solar projects or solar farms. This report uses the terms solar project or solar farm when referring to an observation from the EIA Form 860 data. See appendix A for a discussion of how the EIA Form 860 data was developed for this study.

[5] Solar data from the EIA Form 860 record the first year that a solar farm begins generating electricity (EIA-860, 2021a). Since construction for a solar farm is typically completed within months, this analysis assumes that the project year is the same as the year the solar farm begins generating electricity.

Air Resources Board [CARB], 2012). In the Atlantic region, North Carolina and Massachusetts had a large share of solar installations and policies incentivizing solar projects. Also, in the Midwest, Minnesota has a relatively large share of solar projects and policies promoting renewable energy development (NC Clean Energy Technology Center, 2023).

Despite the concentration of solar projects on the coasts, there is a significant amount of solar potential (the solar resources available for electricity generation) across much of the United States.[6] According to research from the National Renewable Energy Laboratory (NREL), the contiguous United States has an estimated 96 terawatts (TW) of solar capacity potential (NREL, 2021).[7] This far exceeds the current capacity of the U.S. electric power system, which was approximately 1.2 TW in 2020 (EIA, 2022b).

Denholm et al. (2022) estimated the amount of renewable capacity that would be required for the United States to achieve net-zero GHG emissions from electricity generation by 2035 under different scenarios. They estimate that between 0.3 and 1.5 TW of solar capacity would be required.[8] This is much less than the available solar potential but also much more than the current installed solar capacity (48 gigawatts (GW) in 2020) (EIA, 2022b). Further, to achieve the required capacity by 2035, Denholm et al. (2022) estimated that 25 to 120 GW of solar capacity would need to be added annually for the next 10 years with an average annual rate of 40 megawatts (MW). For comparison, in 2020, solar capacity increased by 10.5 GW, and the average annual capacity addition was 4 GW from 2009 to 2020 (EIA, 2022b). Therefore, the estimated average annual rate of solar capacity additions required to achieve net-zero GHG emissions by 2035 in the Denholm (2022) study, 40 MW, is 10 times the average annual rate during the sample period (2009–20).

The expansion of solar farms through 2020 has led to local community concerns about the effects of solar development on rural landscapes and land use competition between solar developments and farmland (Hoffacker et al., 2017; Rand & Hoen, 2017; Weselek et al., 2019; Katkar et al., 2021; Bessette & Mills, 2021; Pascaris et al., 2021; Susskind, 2022). An increase in solar development may increase concerns from local communities about land use competition and landscape changes in rural areas. Ardani et al. (2021) estimated the solar capacity requirements under various scenarios to achieve a 95-percent reduction in carbon dioxide (CO_2) emissions in the electricity sector by 2035 and a 100-percent reduction by 2050. The study estimated that the maximum amount of solar capacity required was 0.38 TW in 2035 and 0.67 TW in 2050 (Ardani et al., 2021). Assuming that solar capacity requires 7.5 acres per MW of land area, they estimated that the amount of land required for solar capacity under the modeled scenarios would be less than 10 percent of "previously disturbed" land (Ardani et al., 2021, p. 19). Potentially suitable disturbed lands included developed land (ground areas, not rooftops), quarries or gravel pits, Superfund sites, landfills, abandoned mine lands, and brownfield areas, among others (Ardani et al., 2021; Moore-O'Leary et al., 2017). Assuming that the maximum projected 1.5 TW of solar capacity required under the scenarios modeled in the Denholm et al. (2022) study also requires approximately 7.5 acres per MW, the estimated amount of land required in the Denholm et al. (2022) study would also be far less than the estimated amount of suitable previously disturbed land.[9] There are limitations on the feasible locations of solar farms, however, including the topography of the land and the proximity to electricity transmission lines. Other researchers have also evaluated

---

[6] NREL has developed estimates of available solar and wind resources, also called technical potential, or potential, for areas across the contiguous United States at a fine geographic scale (NREL 2021). The potential is the estimated capacity or generation that is feasible under a specific set of assumptions, including technology used and topographic, environmental, and land-use constraints (NREL, 2022a).

[7] The estimated solar potential is from NREL's Photovoltaic (PV) Reference Access Siting Regime scenario of solar supply curves released in 2021 (NREL, 2022a).

[8] The scenario outcomes in Denholm et al. (2022) vary based on different assumptions regarding technology development and adoption, including battery storage technology, electricity infrastructure, land use, costs, and other factors (Denholm et al., 2022).

[9] The Ardani et al. (2021) study includes estimates only for the land area directly affected by solar farms. The authors of that study did not consider land area for other electricity generation structures, including battery storage and transmission lines.

the feasibility of siting utility-scale solar on nonagricultural lands for particular States, such as California and New York, and estimated that there is sufficient available land (Hoffacker et al., 2017; Katkar et al., 2021).

In addition, solar power is frequently deployed in small-scale systems, which are typically constructed on existing structures, such as rooftop solar panels. Therefore, these systems are not expected to directly affect land cover or lead to concerns regarding land use competition. In 2021, 96 percent of the solar photovoltaic (PV) systems in the United States were residential rooftop systems (U.S. Department of Energy [DOE], 2021).[10] Further, there is an estimated 1.1 TW of rooftop solar PV potential (Gagnon et al., 2016).[11] [12] There are also a significant number of small-scale solar systems that are used by agricultural producers, such as rooftop solar and solar panels for powering electric fences. Hitaj and Suttles (2016) found that 36,331 (1.7 percent) U.S. farms had on-farm solar panels in 2012.

Still, utility-scale solar comprised 73 percent of total solar capacity in 2020, and 74 percent of utility-scale solar farms and 93 percent of utility-scale solar capacity were in rural areas.[13] Further, the ideal land for large-scale solar capacity is flat with good sunlight, much like the ideal land for crop production (Hernandez et al., 2015; Adeh et al., 2019). Also, during the installation of solar panels, the existing land cover is typically removed underneath and between the solar panels, leaving bare soil (Denholm et al., 2009; Mills, 2015; Horowitz et al., 2020; Graham et al., 2021).

Despite additional small-scale potential and utility-scale solar potential on nonagricultural lands, concerns remain regarding land use competition between solar farms and agricultural land. Partially in response to these concerns, an alternative technological system, agrivoltaics, has been developed (Sekiyama & Nagashima, 2019; Weselek et al., 2019; Pascaris et al., 2021; Dohlman et al., 2024). Agrivoltaics is the colocation of solar panels and agricultural production. It is designed to allow an alternative land use (e.g., crop production or livestock grazing) beneath solar panels. As of 2022, however, utility-scale agrivoltaics sites were typically smaller than traditional utility-scale systems and were largely limited to those sites with pollinator-friendly habitats planted beneath the panels after installation. There were some sites that included sheep grazing and a small number of agrivoltaics sites growing specialty crops beneath solar panels, but the feasibility of growing crops, particularly field crops, in agrivoltaics systems has not been established (NREL, 2022b; Dohlman et al., 2024).

Wind Development

After the early adoption of wind turbines in California in the 1980s, wind capacity across the United States grew dramatically, from 2.4 GW in 1990 to 119 GW at the end of 2020. From 2009 to 2020, wind capacity more than tripled from 35 to 119 GW (EIA, 2022b). There was significant growth in wind power beginning in the mid-2000s—the number of turbines in rural areas in 2020 (64,985 turbines) was more than 6 times the number in 2006 (10,651 turbines).[14] As of 2020, wind turbines were most prominent in the

---

[10] There are two types of solar panels: solar thermal and solar photovoltaic (PV). Solar thermal has been in use longer, but solar PV is the predominant system for utility-scale generation. Solar PV has dominated solar thermal use since 2011, comprising 98 percent of solar generation in 2020.

[11] 1 MW of rooftop PV capacity is equivalent to 1 MW of utility-scale PV capacity (Cole et al., 2016).

[12] The Denholm et al. (2022) projections of utility-scale solar capacity required to achieve net-zero GHG emissions by 2035 include 190 GWs of small-scale rooftop systems. The study does not project small-scale solar capacity but indicates that there is additional small-scale capacity potential.

[13] The share of utility-scale solar capacity was calculated by USDA's ERS using information from the U.S. EIA's Electric Power Annual 2020 Report, table 4.3. In 2020, there was a total of 76 GWs of net summer capacity. Of this total, 48 GWs was utility-scale capacity (EIA, 2021c). See table 1 on page 9 for more information on calculating the share of solar development and solar capacity in rural areas.

[14] This does not include turbines that have been decommissioned, of which there are approximately 10,000. Many of these turbines were smaller and installed in the 1980s in California.

Plains, followed by the West and the Midwest (figure 3).[15] The regional distribution of wind development has been determined in part by State-level energy policy, but it is most directly influenced by wind potential (Hitaj, 2013; Maguire & Munasib, 2016).[16] Onshore utility-scale wind potential is concentrated in areas with consistent, high wind speeds, such the Plains and the Midwest. Some areas in the West region also have significant wind potential, including the front range of Montana, Wyoming, Colorado, and New Mexico, while much of the Southeastern United States lacks sufficient wind potential for utility-scale development (NREL, 2017).[17] The distribution of wind turbines aligns closely with the distribution of onshore wind potential in the contiguous United States.

The Inflation Reduction Act: Solar and Wind Development

The Inflation Reduction Act (IRA) of 2022 includes an approximate $370 billion investment in energy programs, with the intent of lowering energy costs, increasing energy employment, securing critical minerals, and spurring private investment in clean energy solutions (The White House, 2023). Many of the programs and tax provisions in the IRA target increasing investment in renewable energy sources such as solar and wind power. Researchers project that IRA funding will lead to additional growth in solar and wind capacity (Gagnon et al., 2022).

The IRA extended production and investment tax credits for solar and wind power to reduce the upfront costs of building large clean energy projects. The act also includes $40 billion in loan guarantees for clean energy funding through the U.S. Department of Energy. An additional $27 billion was allocated to the Environmental Protection Agency's Greenhouse Gas Reduction Fund with the intent of spurring clean energy investments through a competitive grant program (The White House, 2023).

Several programs administered by the USDA are funded through the IRA. USDA's Rural Development (RD) agency is slated to receive $1 billion for its Rural Utilities Service (RUS) loans for renewable energy infrastructure. The Rural Energy for America Program (REAP) is slated to receive more than $2 billion to help fund energy efficiency and renewable energy programs, including funding for agricultural producers and rural small businesses investing in renewable energy. An additional $9.7 billion may be available for RUS to offer financial assistance to rural electric cooperatives for projects that include renewable energy development (USDA, Rural Development [RD], 2023). IRA funding provides support for the USDA's climate-smart agriculture and forestry (CSAF) strategy. One of the goals of the program is to invest in renewable energy infrastructure in rural communities by building on existing programs administered by USDA's RD (USDA, 2021).

---

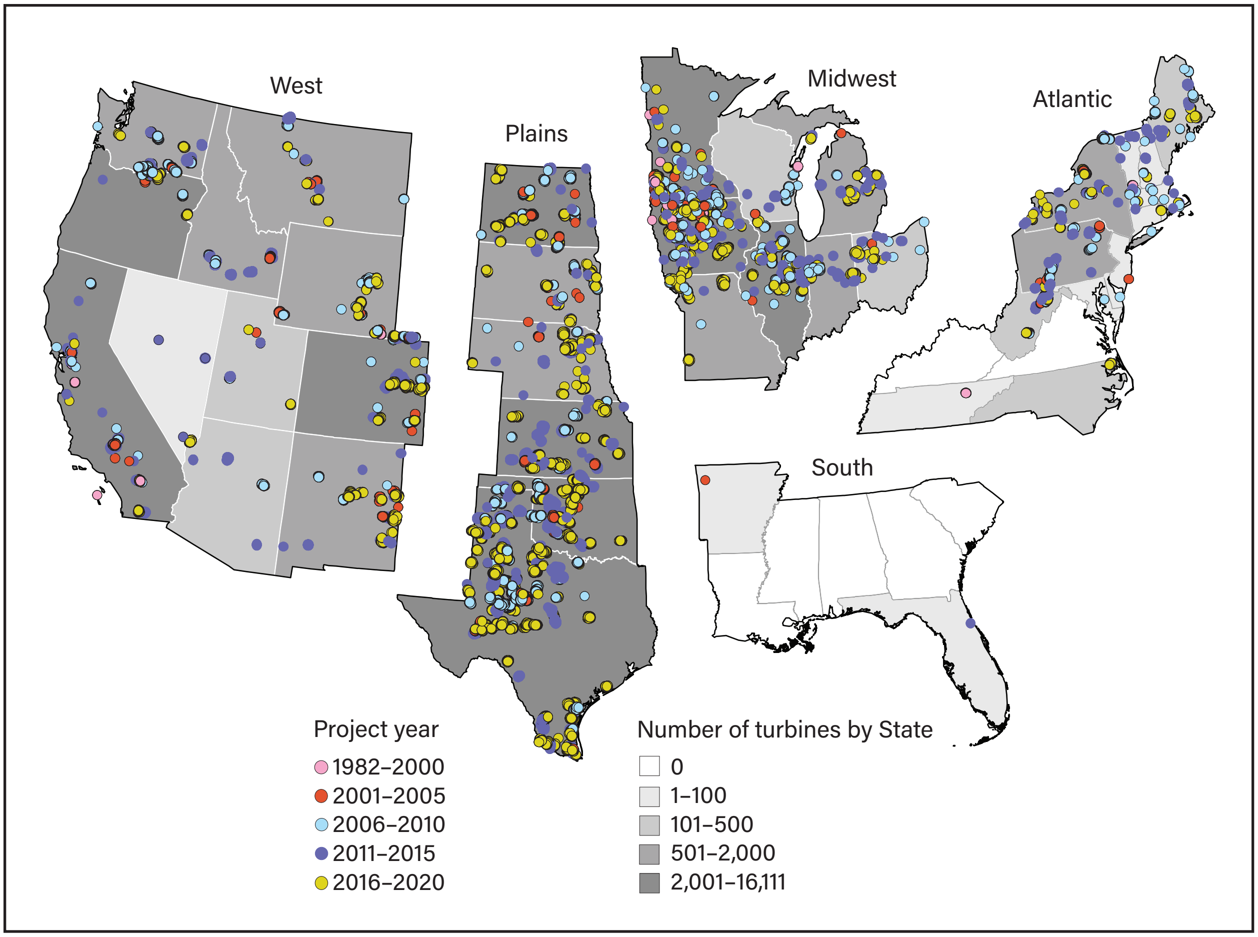
[15] Over this period, there was only one turbine in the South.

[16] Other factors that influence the location of solar and wind farms within regions include their proximity to transmission lines and local zoning restrictions.

[17] Wind speeds at approximately 100-meter heights are relevant for modern utility-scale turbines (Wiser & Bolinger, 2018). As technology changes, the height of wind turbines and the distribution of wind potential across the Nation may also change (Lantz et al., 2019).

Figure 3

Utility-scale wind turbines in rural areas of the United States, 2020



Total number of wind turbines = 64,985.

Note: The USDA Agricultural Resource Management Survey – Phase III (ARMS III) doesn't include Alaska and Hawaii. This study examines wind turbines in rural areas of the contiguous United States. The figure includes five regions representing each of the ARMS III production expenditure regions. One point represents the location of a wind turbine, and the color corresponds with the year in which the project started. Due to scale, some points may overlap with others. States are shaded in grayscale to indicate the total number of statewide wind turbines in 2020.

Source: USDA, Economic Research Service using data from Hoen et al. (2018); USDA, NASS ARMS III Production Expenditure Regions Map (USDA, NASS, 2022a); and 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing TIGER/Line Shapefiles (U.S. Census Bureau, 2019).

In addition to the differences in the distribution of solar and wind potential, the total estimated onshore wind potential (7.8 TW) is much smaller than solar (96 TW) (NREL, 2020, 2021).[18] Still, like solar, the amount of wind potential far outweighs the maximum estimated amount of wind capacity required in the Denholm et al. (2022) study to achieve net-zero GHG emissions from electricity generation by 2035, which is at most 1.6 TW. Still, although wind capacity far exceeded solar capacity in 2020 (119 GW compared with 48 GW), the Denholm et al. (2022) study estimates that more than 60 GW of wind capacity will need to be added annually on average for 10 years.[19] For comparison, between 2009–20 the average annual increase in wind capacity was 7.6 GW, and the maximum was 14.4 GW in 2020 (EIA, 2022b). Therefore, the estimated average annual rate of wind capacity additions required to achieve net-zero GHG emissions in the electricity sector by 2035 in the Denholm et al. (2022) study is nearly eight times the rate during the sample period.

---

[18] The estimated wind potential is from NREL's Reference Access Land-Based Wind scenario of wind supply curves released in 2020 (NREL, 2020).

[19] The Denholm et al. (2022) study considers offshore wind but focuses on onshore wind because the U.S. offshore wind industry was early in its development, with only 42 MW of capacity in 2020 (Denholm et al., 2022, p.26).

However, although wind turbines can affect rural landscapes, including through noise and view disturbance, growth in wind development is not expected to have the same land use effects as solar. As noted above, the direct land use impact of a wind farm is small, and farmers and ranchers typically farm or ranch around wind turbines, allowing for the use of land for agricultural production and wind energy generation. The ease with which the turbine pad can be farmed around may vary. For example, it may be difficult to plant crops if the turbine is too close to a fence (Mills, 2015). These siting considerations can often be addressed during installation to reduce the cost associated with adjusting farming around the base of the turbine. Generally, wind turbines are located with agricultural production, and wind projects have not led to the same concerns about land use competition as solar installations (Denholm et al., 2009; Mills, 2015; Pascaris et al., 2021).

Footprint of Solar and Wind Development on Rural Lands

Researchers often refer to the footprint of a solar or wind farm, but the definition can be inconsistent. Footprint can refer to the entire land area used for a solar or wind farm or to only the land area directly affected by permanent physical structures such as solar panels, wind turbine pads, or roads. For this study, footprint refers to the land area that is directly affected by the development of solar or wind farms.

Modern solar panels typically have a capacity of less than 1 kilowatt (kW), and in utility-scale projects, there are multiple panels sited closely together.[20] The footprint includes the solar panels, spacing between rows, and a buffer around the panels, and is typically estimated for each solar farm, not each solar panel (Denholm et al., 2022). For a solar farm, the estimated footprint per MW of capacity is 7.5 acres (Ardani et al., 2021).[21] In a wind farm, estimates indicate that 96–99 percent of the land area will not be directly affected by wind turbines because they are spaced widely apart to accommodate the turbine blades (Harrison-Atlas et al., 2022). Therefore, the footprint of a wind farm is typically estimated for each turbine site. A typical turbine site includes a turbine pad on which the turbine is located, a permanent clearing area around the turbine, and a service road providing access to the turbine. For a wind farm, the estimated footprint per MW is 0.74 acres (Denholm et al., 2009).[22]

To provide context for the study of land cover and land cover change, it is important to consider the aggregate footprint of solar farms and wind turbines across all rural areas. Estimates of the cumulative footprint include the total land area directly affected by solar farms or wind farms in rural areas based on the capacity of the projects in 2020 (table 1).

Table 1

Cumulative footprint of solar farms and wind turbines in rural areas, 2020

	Footprint (Acres per MW)	Total capacity in rural areas (MW)	Total rural footprint (Acres)
Solar farms	7.50	44,812	336,090
Wind turbines	0.74	118,762	87,884
Total		163,574	423,974

MW = megawatt.

---

[20] In rural areas of the contiguous United States through 2020, the maximum capacity of a solar project was 300 MW, and the minimum capacity was 0.1 MW. The median size was 3 MW. Calculated by USDA, ERS using the EIA Form 860 data and U.S. Census designated rural areas (U.S. Census Bureau, 2019; EIA 860, 2021).

[21] Ong et al. (2013) estimated that a solar installation required between 5.5 and 9.4 acres per MW.

[22] Denholm et al. (2009) found that the permanent direct impact of a wind project ranged from 0.15 to 5.9 acres per MW. Eighty percent of the projects studied had a permanent direct impact of less than 1 acre per MW. This study uses the average impact area which was 0.74 acre per MW.

Note: The footprint estimates are for solar and wind sites in rural areas of the contiguous United States. The estimated footprint of a wind turbine is 0.74 acres per MW of capacity (Denholm et al., 2009). The estimated footprint of a solar farm is 7.5 acres per MW (Ardani et al., 2021). For solar, 74 percent of solar farms and 93 percent of solar capacity were in rural areas. For wind, the share was consistent; 99.8 percent of wind turbines and wind capacity were in rural areas.

Source: Calculations by USDA, Economic Research Service using spatial data on the location of solar projects and wind turbines and data on the total capacity of solar projects and wind turbines in 2020 (EIA 860, 2021a; Hoen et al. 2018), spatial data defining the boundaries for rural areas of the contiguous United States from the 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing TIGER/Line Shapefiles (U.S. Census Bureau 2019), the estimated footprint of a solar farm (Ardani et al., 2021), and the estimated footprint of a wind turbine (Denholm et al. 2009).

The estimated footprint of solar farms was approximately 336,000 acres; the footprint of wind farms was approximately 88,000 acres. For comparison, there were approximately 897 million acres of land in farms in 2020, so the estimated footprint of solar and wind was approximately 0.05 percent of farmland acres (USDA, NASS, 2022b).[23] Nearly 80 percent of the estimated footprint in rural areas was from solar projects, which provided 27 percent of the capacity. This footprint does not capture additional physical structures, including transmission lines, which are required to transport the generated electricity. For example, Denholm et al. (2022), in scenarios targeting net-zero GHG emissions in the electricity sector by 2035, estimated that the land required for large-scale transmission lines (those greater than or equal to 500 kilovolts (kV)) would be 2.6 to 3.5 times greater than the land required for onshore wind turbines. Additionally, cumulative estimates of solar and wind farm footprints do not capture the potential local landscape and socioeconomic effects of a shift in land cover associated with solar or wind development.

Given the importance of addressing climate change, it is not surprising that researchers have found broad support for solar and wind development (Carlisle et al., 2015; Rand & Hoen, 2017; Couse et al., 2021; Susskind, 2022). Still, there is evidence of local community resistance and local opposition to renewable development that can delay or possibly prevent development in an area, increasing the costs of deploying solar and wind capacity (Bessette & Mills, 2021; Rand & Hoen, 2017). Lopez et al. (2022a) found that there were at least 1,800 local zoning restrictions for wind development as of 2021, including setback requirements to mitigate development that is immediately adjacent to another property or household (Lopez et al., 2022a).[24] Further, Lopez et al. (2022b) found approximately 800 restrictions related to solar development, including limits to the number of agricultural acres in a county that can be developed into solar (Lopez et al., 2022b). Additionally, there is evidence that restrictions have increased, have been getting stricter over time, and are more likely to be imposed in areas that have experienced prior renewable energy development (Nilson & Stedman, 2022; Winikoff, 2022; Rand & Hoen, 2017). Researchers have found that local opposition increases as the scale of the project increases, particularly for solar, and decreases in areas with fewer natural amenities, larger farms, and more absentee owners (Bessette & Mills, 2021; Couse et al., 2021; Nilson & Stedman, 2022; Rand & Hoen, 2017). Additionally, opposition increases in areas where community residents perceive that the energy development will result in uncompensated losses that were unfairly imposed on them (Nilson & Stedman, 2022; Parkins et al., 2022; Mills et al., 2019; Rand & Hoen, 2017).

In addition to research on local community concerns regarding solar or wind development, studies found both local socioeconomic benefits and costs from renewable energy development. The benefits include leasing income for landowners who host solar or wind development. Additionally, research on wind development found that it may provide other local positive economic benefits, including lower property taxes and increased employment and school spending (Brown et al., 2012; Kahn, 2013; Brunner et al., 2021; Solar Energy Industries Association [SEIA], 2021; Wiser et al., 2021). Conversely, there may be costs imposed on local residents, including changes to the rural landscape—particularly conversion of farmland to solar farms—noise

---

[23] In 2020, there were 82 million acres of agricultural land planted in soybeans and 89 million acres in corn (USDA, FSA, 2021).

[24] The Lopez et al. (2022a and 2022b) datasets include only county- and some State-level restrictions. Other local restrictions, by municipalities for example, are not included.

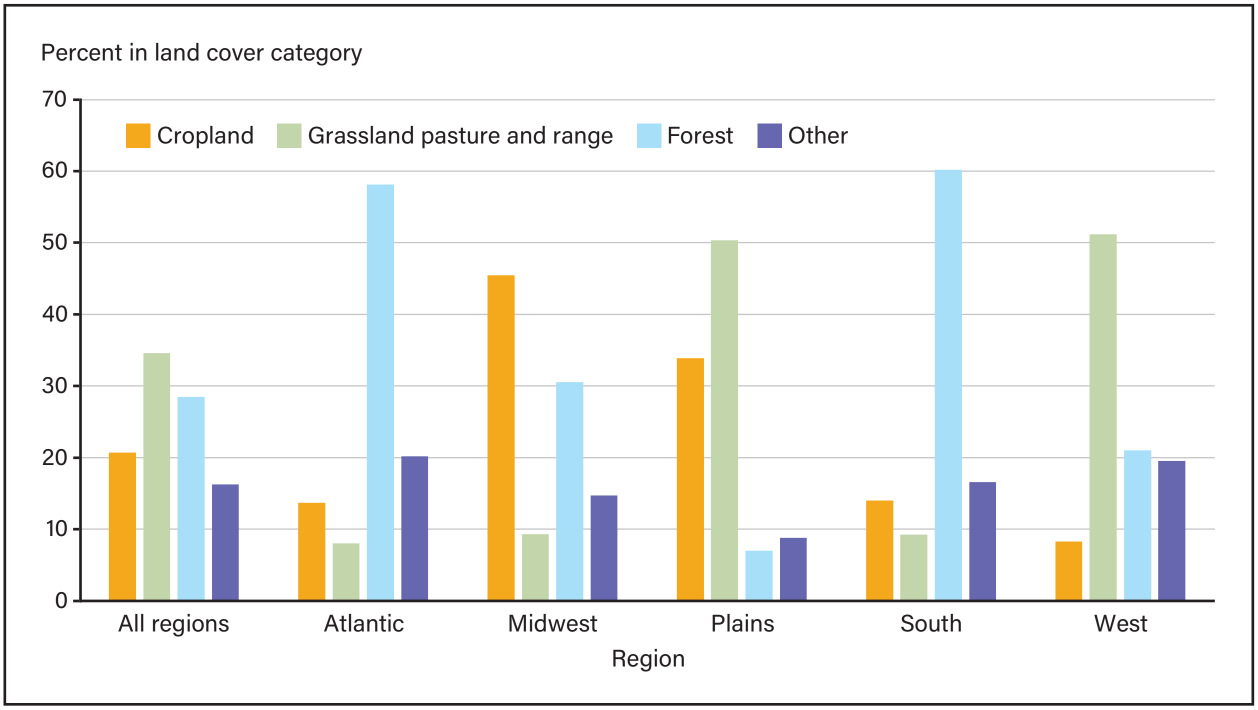
and altered views from wind turbines, environmental effects such as loss of wildlife and wildlife habitat, and a reduction of property values (Heintzelman & Tuttle, 2012; Hoen et al., 2013; Carlisle et al., 2015; Gibbons, 2015; Mills, 2015; Heintzelman et al., 2017; Rand & Hoen, 2017; Weselek et al., 2019; Sampson et al., 2020; Couse, 2021; Pascaris et al., 2021; Crawford et al., 2022; Nilson & Stedman, 2022; O'Shaughnessy et al., 2022). Information on the type of land used for solar and wind projects and the land cover change associated with them can reduce the uncertainty associated with development and assist stakeholders in evaluating the local socioeconomic effects.

Regional Land Cover

The USDA Major Uses of Land (MLU) series of reports uses data from the USDA's Census of Agriculture (COA) to estimate land cover across the contiguous United States (Bigelow & Borchers, 2017). The most recent MLU report was released in 2017 and uses data from the 2012 COA (Bigelow & Borchers, 2017). In this study, the authors examine the regional distribution of land cover, land cover is categorized into four land cover categories (cropland, grassland pasture and range, forest, and other) for the contiguous United States and each of the five USDA ARMS III farm production expenditure regions (figure 4). Across all regions, the most common land cover types were grassland pasture and range (35 percent), followed by forest (29 percent) and cropland (21 percent), but there was significant regional variation.

Figure 4

Share of land cover by category and region, 2012



Note: Within each region, the land cover categories sum to 100 percent. The other category includes the USDA, ERS Major Uses of Land categories of special-use areas, urban areas, and miscellaneous other land (marshes, deserts, and residential areas).

Source: USDA, Economic Research Service (ERS) using data from the USDA, ERS Major Uses of Land in the United States, 2012 report (Bigelow & Borchers, 2017) and the USDA, National Agricultural Statistics Service (NASS) ARMS III Production Expenditure Regions Map (USDA, NASS, 2022a).

The Atlantic and South regions were dominated by forest (58 and 60 percent of the land, respectively), the Plains and West regions by grassland pasture and range, (50 and 51 percent, respectively), and the Midwest by cropland (45 percent). Given the differences in the regional distribution of solar and wind (shown in figures 2 and 3), it is expected that there were differences in the types of land cover on which they were sited. In particular, solar installations were most prominent in the Atlantic and the West, which are dominated by forest and grassland pasture and range, respectively. Also, solar installations were distributed across all regions, so it is expected that land cover at solar sites varied. Wind development occurred primarily in the Midwest and Plains regions, which include a significant amount of cropland and grassland pasture and range.

Spatial Data and Methodology

This report combined data from several Federal sources to construct measures of land cover at each rural solar farm and wind turbine site from 2009 to 2020. The solar data from U.S. Energy Information Administration (EIA) Form 860 (EIA-860) include detailed information on each solar project, including the location, project year, and project capacity for all utility-scale solar projects. The wind data from the U.S. Wind Turbine Database (USWTDB) contain detailed information for each utility-scale wind turbine, including location, project year, and capacity (Hoen et al., 2018; EIA, 2021).[25] [26] Rural areas were defined as any land outside of U.S. Census-designated urban areas in the contiguous United States (U.S. Census Bureau, 2010 and 2019).[27] The Census updates boundaries of urban areas annually, but the urban boundary changes had limited effects on the rural designation for wind or solar installations.[28] Because the analysis focuses on development in current rural areas, solar and wind projects were classified as rural based on the 2019 urban boundaries. Through 2020, 3,364 (74 percent) of all solar projects and 44,812 MW (93 percent) of solar project capacity were in rural areas, whereas 64,985 (99.8 percent) of all wind turbines and 118,762 MW (99.8 percent) of all wind turbine capacity were in rural areas.[29]

Estimates of land cover at solar and wind sites were constructed using the USDA, National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (USDA, NASS, 2009–20).[30] Although solar and wind development precede this period, annual 30-meter resolution data on land cover from the CDL were available beginning in 2009.[31] Spatial analyses were used to determine the dominant land cover category within a 150-meter radius buffer at each solar project and wind turbine location in each year between 2009 and 2020. The dominant land cover category is defined as the land cover category that occurs with the highest frequency among all 30-meter cells within the buffer.[32]

---

[25] U.S. Wind Turbine Database (ver. 4.3, January 14, 2022).

[26] A detailed description of how the USWTDB and EIA-860 solar data were used is in appendix A.

[27] Urban areas include both urbanized areas with populations of 50,000 or more and urban clusters with populations of 2,500 to 50,000 (U.S. Census, 2021).

[28] Using the 2019 urban boundaries, 1,206 solar projects and 165 wind turbines were in urban areas, compared with 989 solar projects and 150 wind turbines using the 2009 boundaries.

[29] There were 65,147 turbines and 119 MW of wind capacity recorded in the USWTDB in the contiguous United States in 2020 and 4,570 solar projects and 48 MW of solar capacity in the EIA-860 data (Hoen et al., 2018; EIA, 2021). Appendix B compares land cover for all solar and wind installations (urban and rural areas) to the sample that includes only rural installations.

[30] Appendix C, table C.1 includes a complete list of the CDL land cover classes included in the report.

[31] USDA's NASS CDL spatial data is now available at 30-meter resolution for 2008 as well.

[32] In the limited number of cases where there was no single dominant land cover (i.e., there was a tie), the land cover at the installation location was used instead. Land cover at the installation location was used for 1.9 percent of solar observations and 0.37 percent of wind observations.

The 150-meter buffer is equivalent to approximately 17.5 acres at each installation site. Based on the estimated footprint of a wind turbine, the buffer is expected to encompass the turbine site and adjacent land cover. A typical utility-scale wind turbine has approximately 2 MW in capacity and an estimated footprint of 1.5 acres (Denholm et al., 2009).[33] For a solar farm, the estimated footprint is 7.5 MW per acre. Based on the capacities of the solar farms in the sample, the 150-meter buffer is large enough to encompass the entire footprint of approximately 44 percent of solar farms in the sample. However, this estimate is calculated under the assumption that the recorded solar farm location is in the center of the installation. There is expected to be some variation in the recorded location relative to the center of the solar farm and the shape of the installations within the buffer.[34] This will lead to variation in how much buffer land is covered with solar panels. It is expected that the buffer commonly captures the footprint of the solar panels and some proximate land cover. To evaluate how the size of the buffer influenced the land cover findings from this study, alternative buffer sizes of 300 meters (70 acres) for solar farms and 75 meters (4.4 acres) for wind turbines are considered (appendix D).

Measuring Land Cover

The study uses both a broad and detailed categorization of land cover. The broad categorization groups land cover at each site into five categories: **cropland**, **pasture-range**, **forest**, **developed**, and **other**. The cropland category includes field crops, specialty crops, and fallow/idle cropland.[35] This broad categorization of land cover provides a conservative measure of agricultural land cover change, which is more likely to include only meaningful changes in land cover rather than normal shifts within a land cover category such as crop rotations. This categorization also takes advantage of the strengths of the CDL, which is most accurate in identifying dominant commodity crops and differences between cropped and noncropped land (Boryan, 2011; Lark et al., 2021).[36]

In this report, pasture and rangeland are included as a single noncropped agricultural land cover category. In some cases, pasture is considered agricultural land because it is typically hayed in some years, but rangeland is excluded because it is used exclusively for grazing and not actively managed (Boryan et al., 2011; Claassen et al., 2011). Alternatively, in the most recent USDA Major Land Uses report noncropped agricultural land is categorized as grassland pasture and range (Bigelow & Borchers, 2017).[37] For the analysis of land cover change, we use the latter definition with a single Pasture-Range category that includes grassland/pasture and shrubland.[38]

---

[33] Through 2020, the median size of turbines in rural areas of the contiguous United States was 2 MW, 88 percent of turbines were from 1 to 3 MWs in size, and the maximum capacity was 4.8 MW as calculated by USDA's ERS using the USWTDB and U.S. Census-designated rural areas data (U.S. Census Bureau, 2019; Hoen et al., 2018).

[34] The instructions for Form EIA-860 state that the latitude and longitude of the plant should be recorded at a "central point within the plant's property such as a generator" (EIA, 2023).

[35] Initially, the authors separately examined specialty crops (defined as fruits, nuts, and vegetables, including nursery crops) and field crops (all other crops, including grains, oilseeds, legumes, fiber crops, and hay) (USDA, Agricultural Marketing Service, 2022). These crops were subsequently combined into one category because a small fraction of development occurred on land used in specialty crop production: 1.8 percent of solar projects and 0.3 percent of wind turbines.

[36] Appendix E presents more information on the accuracy of the CDL in measuring land cover and land cover change.

[37] This derives from the USDA's Census of Agriculture (COA), which does not distinguish between pasture and rangeland. The COA delineates three categories of managed and unmanaged agricultural land: permanent pasture and rangeland, woodland pasture, and pasture or grazing land (including rotational pasture) (USDA, 2017).

[38] The CDL defines two major categories of noncropped agricultural land: grassland/pasture and shrubland. They were aggregated into one category to minimize misidentification of land cover change (e.g., from pasture to shrubland) that is due to potential miscategorization in the CDL. The CDL is designed primarily to identify detailed crop-specific land cover on croplands and is not as rigorous in its ability to distinguish land covers dominated by grasses and shrubs (Boryan et al., 2011; Lark et al., 2021).

Land Cover and Land Cover Change

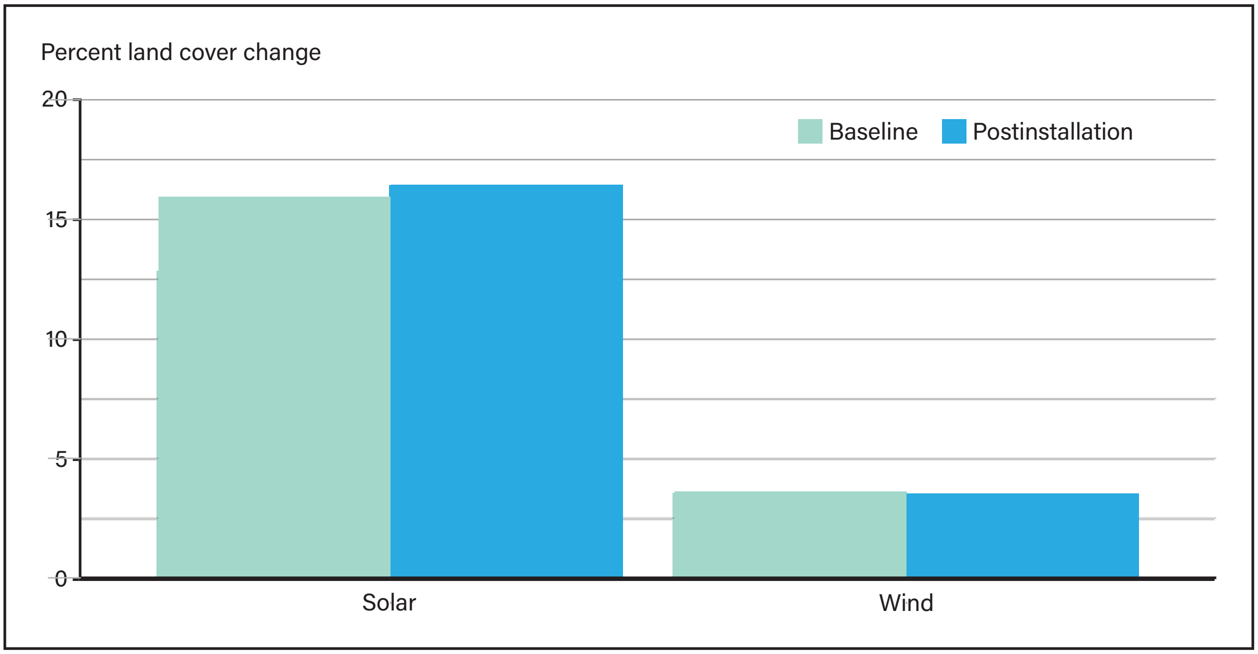
Annual Land Cover Change

To provide context for the examination of land cover change associated with a solar or wind installation, it is important to consider the typical rate of land cover change at locations that experienced solar or wind development during the sample period. These locations are referred to as solar or wind lands. The dominant land cover within each buffer for solar and wind lands was categorized as **cropland**, **pasture-range**, **forest**, **developed**, or **other** for each year from 2009 to 2020. The baseline rate of land cover change is the average annual share of land cover change on solar or wind lands. The average annual measure is the share of all solar or wind lands that experienced a land cover change from the previous year averaged across all years of the sample period. On average, in any given year, 15.9 percent of solar lands changed land cover from the previous year, and 3.6 percent of wind lands changed land cover from the previous year (figure 5).[39]

To evaluate the influence of solar or wind development on land cover change, we constructed the average annual postinstallation rate of change. The annual rate of land cover change after installation was calculated as the share of solar or wind lands on which a development occurred in the previous year that experienced a land cover change. For example, roughly 5 percent of the wind turbines installed in 2009 experienced a change in land cover between 2009 and 2010. The postinstallation rate is the annual rate of land cover change after installation averaged across all years of the sample period. The difference between the baseline rate and the postinstallation rate provides a measure of the influence of solar or wind installations on the rate of land cover change.

Figure 5

Average annual land cover change: Solar lands and wind lands, 2010–20



Note: There were 46,139 turbines and 3,332 solar projects installed in rural areas of the contiguous United States from 2009 to 2020. Annual land cover change is measured as a change in the dominant land cover category (cropland, pasture-range, forest, developed, or other) from the previous year within a 150-meter buffer at each site.

Source: USDA, Economic Research Service using data from the U.S. Energy Information Administration Form 860 (EIA, 2021a); Hoen et al. (2018); USDA, National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (USDA, NASS, 2009–20); and 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census Bureau, 2019).

---

[39] For comparison, in appendix F the authors examine annual land cover change using a land cover measure developed by Clarke and Melendez (2019).

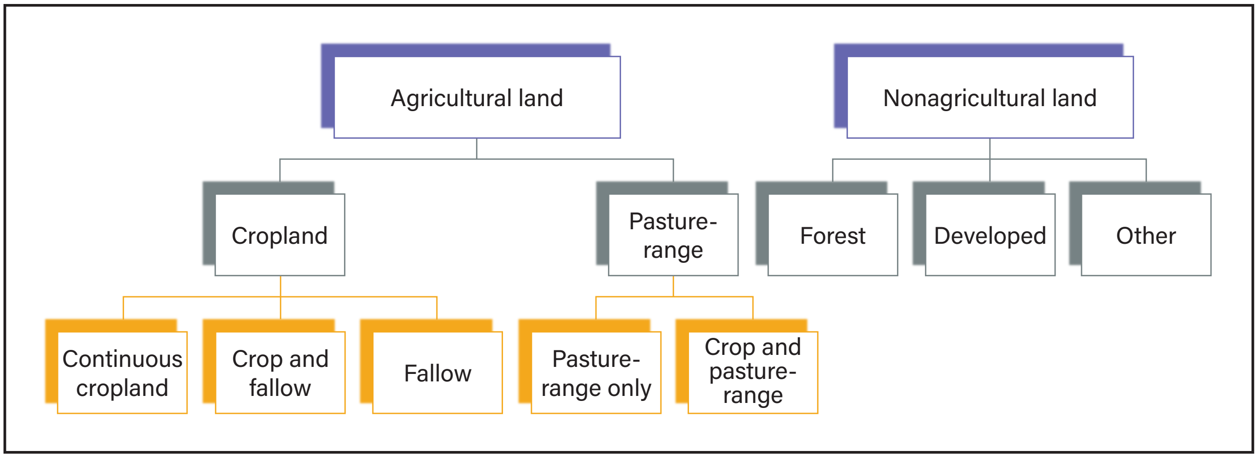
After a solar installation, the rate of land cover change was about 0.5 percentage points higher than the baseline rate (16.4 percent compared with 15.9 percent). For wind lands, the baseline rate was significantly lower than solar lands and was largely unchanged when the analysis included only lands that had experienced wind development (roughly 3.5 percent). Although this study is unable to identify the factors that led to the higher rate of land cover change on solar lands than wind lands, it suggests that they are distinct from one another. Differences in the regional distribution of solar and wind lands and the regional distribution of land cover were likely a factor.

Land Cover and Land Cover Change: From 3 Years Before to 3 Years After Development

To provide a more indepth examination of land cover and land cover change, the following sections use a 3-year measure of land cover: Three years before installation of a solar or wind development and 3 years after installation.[40] Land cover is categorized using the five broad land cover categories for agricultural and nonagricultural land (second level of figure 6). For a more detailed analysis of agricultural land, there is a second categorization (third level of figure 6) that includes additional categories for **cropland** and **pasture-range**. Specifically, there are three cropland categories: **continuous cropland, crop and fallow**, and **fallow**, and two pasture-range categories: **pasture-range only** and **crop and pasture-range**. Nonagricultural land cover categories are **forest**, **developed**, and **other**. A solar or wind project is included in a category only if the dominant land cover in the buffer remained in that category during the entire 3-year period; otherwise, it is categorized as other.[41] For example, in the analysis of land cover in the 3 years prior to installation, sites categorized as fallow were fallow in each of the 3 years before the project year. The detailed categorization allows us to explore differences in land cover on cropland between solar and wind sites. For example, there is potentially a difference in land cover at an installation that was categorized as crop and fallow, which was likely in rotation, and fallow, which was out of production for at least 3 years. Further, including the additional category of crop and pasture-range captures sites that rotated between cropland and pasture-range in a 3-year period.

Figure 6

Agricultural and nonagricultural land cover categories



Source: Land cover categories developed by USDA, Economic Research Service based on land cover classes from USDA, National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (USDA, NASS, 2009–20).

---

[40] Appendix G examines the dominant land cover category at each installation in the project year, including detailed crop-specific categories. Results are consistent with those in the preferred approach using land cover in the 3 years prior to development.

[41] The results were similar when categorizing land using 5 or 8 years before the project, but with an increase in the share of lands categorized as other as the number of years increased.

This report uses multiple years and detailed categories to balance the goal of measuring meaningful land cover shifts with a high degree of detail for agricultural land types while minimizing measurement of extraneous land use changes (e.g., crop rotations). The data do not, however, enable an examination of why land was used for a particular purpose. For example, if the land remained fallow prior to installation, the study cannot identify whether an installation occurred on lands that were left fallow in preparation for development or if the lands were left fallow for another reason.

Finally, the other category includes the CDL land cover classes of barren, wetlands, open water, woody wetlands, herbaceous wetlands, and sites that transitioned between any of the land cover categories within the 3-year period (e.g., cropland and developed).[42] The other category is a small part of the sample. In the 3 years prior to installation, other comprised 13 percent of the solar sample and only 1 percent of the wind sample. Of the observations categorized as other, 15 percent of solar and 33 percent of wind were in a category that was excluded from the analysis (e.g., barren land or water). The remainder were observations that transitioned between land cover categories in the 3-year period. Because the share that transitioned between categories was small and the land cover categorization for these groups is unclear, they are categorized as other, providing a more accurate but less detailed land cover categorization.

Land Cover Before Solar or Wind Installations

To examine land cover in the 3 years before a project, the sample is restricted to installations between 2012 and 2020. This reduces the number of observations to 3,180 solar and 34,076 wind projects, 95 and 74 percent of the full sample (2009–20), respectively. [43] [44] Using this sample, the 3-year land cover categories were constructed using the dominant land cover category in the buffer at each solar or wind project in the 3 years prior to an installation.

Figure 7 shows the distribution of land cover prior to solar projects both nationally and by region, and the share of solar projects in each category is in the table below. Overall, solar development occurred predominantly on agricultural land.[45] Forty-three percent of solar projects were on land categorized as **cropland (continuous cropland, crop and fallow,** or **fallow)** prior to installation. Of these projects, 34 percent were on continuous cropland, 7 percent on crop and fallow, and 2 percent on fallow. An additional 7 percent of solar lands were categorized as **crop and pasture-range** prior to installation. Further, 21 percent of solar installations were on land categorized as **pasture-range only**. The shares were low for nonagricultural land, as 11 percent of solar lands were categorized as forest and 6 percent were categorized as **developed** prior to installation.

There is significant regional variation in land cover prior to installation at solar sites. Installations occur mostly on pasture-range only in the West (51 percent) and in the Plains (60 percent), whereas in the Midwest, the development was most common on continuous cropland (66 percent). The Atlantic had the highest share of installations in forest (23 percent), but the majority were in continuous cropland (37 percent). Sites in the South were the most diverse of all regions, with 35 percent categorized as continuous cropland or crop and fallow, 17 percent as forest, 14 percent as pasture-range only, and 21 percent categorized as other. The variation is explained in part by the regional land cover distribution discussed previously (figure 4). However, solar sites were most commonly located on land categorized as continuous cropland in the Atlantic, the Midwest, and the South, but cropland was the dominant land cover category only in the Midwest. Further, the share

---

[42] Overall, the CDL data provided a robust measure of land cover, but there was some apparent misidentification (e.g., land cover transitioning from cropland to forest and back to cropland), which were relegated to the Other category.

[43] See appendix H, tables H.1 and H.2, for a comparison of the distribution of land cover categories across samples, e.g., solar or wind lands (2009–2017) and solar or wind lands (2012–2020).

[44] Between 2009 and 2020, there were 3,332 solar projects and 46,139 wind turbines installed. A small number of observations had missing or invalid dominant land cover categories for 1 or more years and were excluded from individual analyses.

[45] Results from a robustness check using 300-meter buffers are in appendix D, table D.1.a, and are consistent with those using the 150-meter buffer.

of solar lands categorized as cropland (continuous cropland, crop and fallow, and fallow) prior to installation was higher than expected based on the share of cropland in each region. In the Midwest, 45 percent of the land was in cropland, but 66 percent of the solar lands were categorized as cropland prior to installation. In the Atlantic and South, less than 15 percent of the land was in cropland, but 43 percent of the solar lands in the Atlantic and 37 percent in the South were categorized as cropland prior to installation (figures 4 and 7). This finding supports the argument in research literature that land suited for crop production is also well-suited for solar development (Hernandez et al., 2015; Adeh et al., 2019).

Almost half of all turbines were located on land that was categorized as continuous cropland (46 percent) or crop and fallow (9 percent) in the 3 years before installation (figure 8).[46] Although few solar installations were on land that was categorized as fallow for the 3 years before installation (1.6 percent), the share of wind turbines was near zero (0.1 percent). Wind turbines were commonly installed on pasture-range as well. In the 3 years prior to a wind installation, 36 percent of turbine locations were categorized as pasture-range only. Wind turbines were rarely sited on nonagricultural land; the share of wind lands categorized as forest or developed prior to installation was less than 5 percent.

The findings in this study are largely consistent with previous work examining land cover associated with wind development. For example, Xiarchos and Sandborn (2017) found a similar distribution of land cover, but they found that in 2014 (in the project year), the highest share of wind turbines were located on land in pasture and rangeland, followed by cropland.[47] Harrison-Atlas et al. (2022), using a buffer around each wind farm rather than each turbine and land cover data from the National Land Cover Database (NLCD), also found that wind farms were most commonly located on land that was in cultivated crops followed by pasture and rangeland.

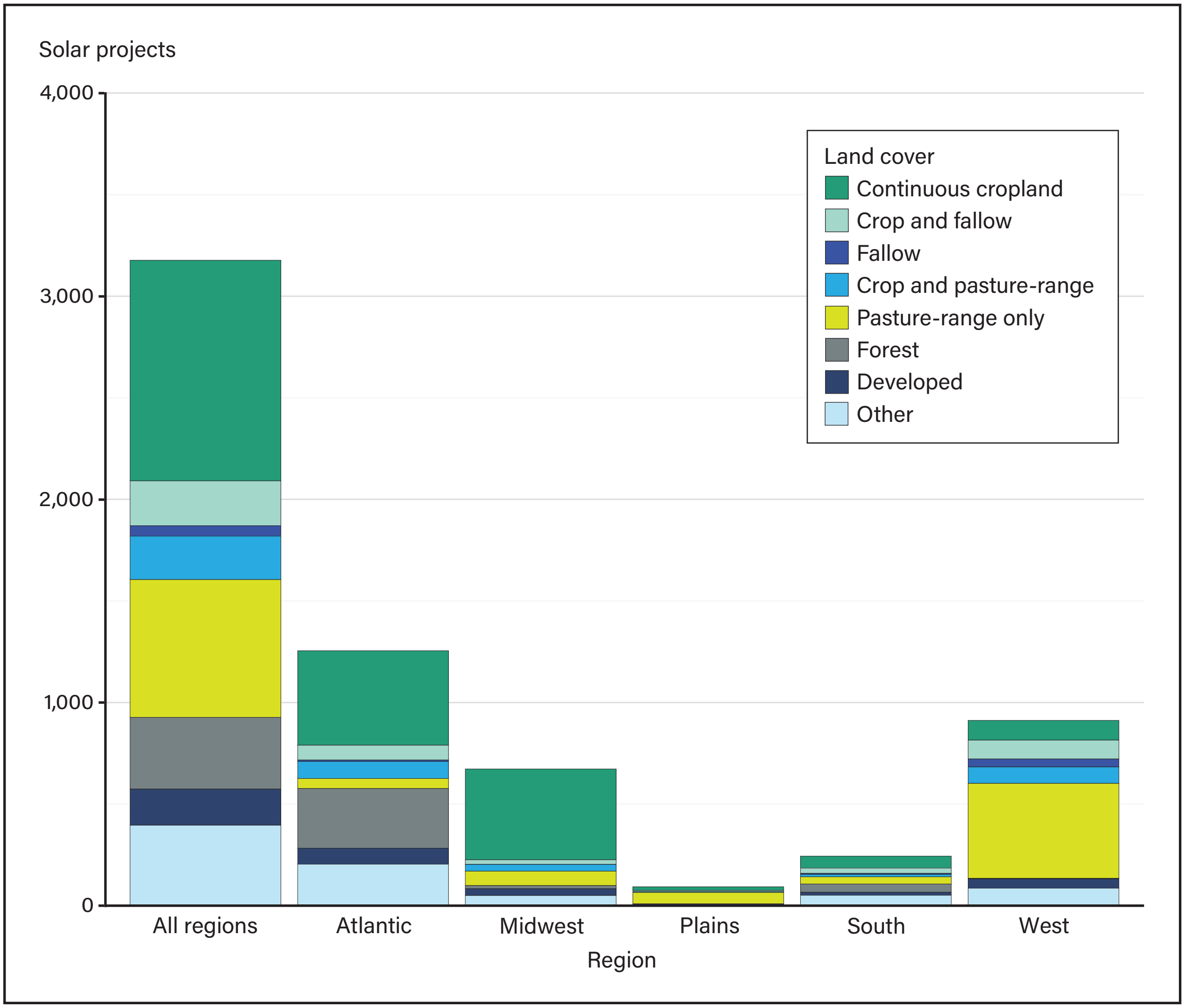
---

[46] Results from a robustness check using 75-meter buffers are in appendix D, table D.1.b, and are consistent with those using the 150-meter buffer.

[47] Appendix G, table G.2, includes an analysis of land cover in the project year.

Figure 7

Share of solar projects by land cover category and region prior to an installation, 2012–20



Land cover category	All regions	Atlantic	Midwest	Plains	South	West
			(percentage)			
Continuous cropland	34.2	37.1	66.4	19.4	24.2	10.6
Crop and fallow	7.0	5.8	3.4	6.5	10.7	10.2
Fallow	1.6	0.6	0	0	2.1	4.3
Crop and pasture-range	6.7	6.7	4.9	4.3	4.9	8.9
Pasture-range only	21.3	3.9	10.6	60.2	14.3	51.2
Forest	11.1	23.4	2.2	0	16.8	0.3
Developed	5.6	6.3	5.1	4.3	6.2	5.0
Other	12.5	16.3	7.4	5.4	20.9	9.4
Total[1]	3,177	1,255	673	93	244	912

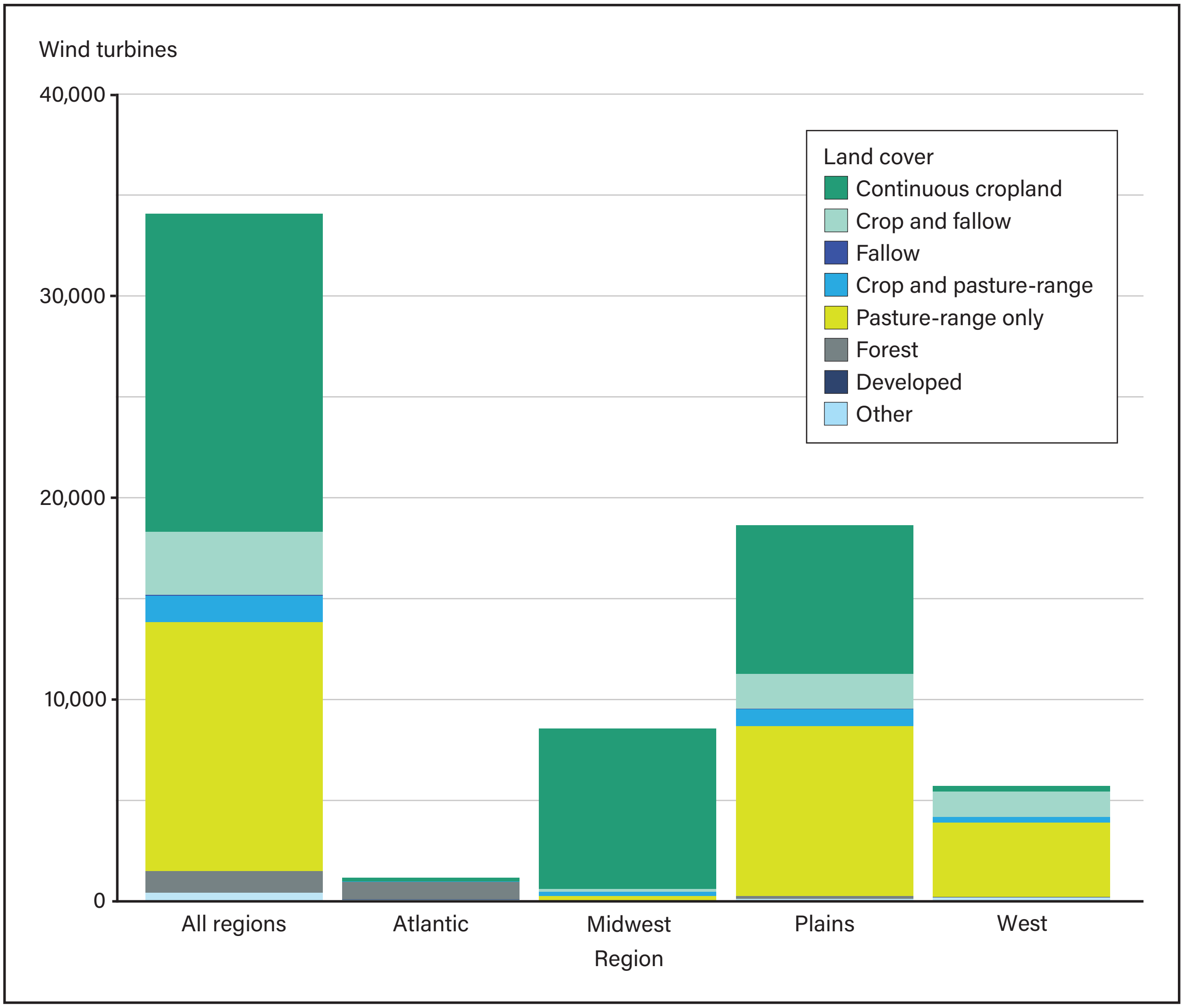
Note: The vertical axis in the figure is the number of installations; the total for all regions is in the first column, and the remaining columns show the land cover by region. Land cover is measured by determining the dominant land cover category in each year in the 3 years prior to installation within a 150-meter buffer for each site. The other category includes the Cropland Data Layer (CDL) land cover classes of barren, wetlands, open water, woody wetlands, herbaceous wetlands, and sites that shifted between land cover categories in the 3-year period prior to installation.

[1] The national total excludes three observations with missing land cover in one or more of the 3 years before the project year.

Source: USDA, Economic Research Service using data from U.S. Energy Information Administration (EIA) Form 860 (EIA, 2021a); USDA, National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (USDA, NASS, 2009–20); USDA, NASS Agricultural Resource Management Survey – Phase III (ARMS III) Production Expenditure Regions Map (USDA, NASS, 2022a); and 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census Bureau, 2019).

Figure 8

Share of wind turbines by land cover category and region prior to an installation, 2012–2020



Land cover category	All regions	Atlantic	Midwest (percentage)	Plains	West
Continuous cropland	46.3	15.9	92.8	39.6	4.6
Crop and fallow	9.2	0	1.7	9.2	22.0
Fallow	0.1	0	0	0.1	0.3
Crop and pasture-range	3.9	1.3	2.3	4.6	4.7
Pasture-range only	36.2	0.7	2.7	45.2	64.5
Forest	3.1	75.2	0.2	0.7	0.4
Developed	<0.1	0.1	<0.1	<0.1	0.1
Other	1.2	6.9	0.3	0.6	3.4
Total[1]	34,073	1,167	8,559	18,643	5,703

Note: The vertical axis in the figure is the number of installations; the total for all regions is in the first column, and the remaining columns show the land cover by region. Land cover is measured by determining the dominant land cover category in each year in the 3 years prior to installation within a 150-meter buffer for each site. The other category includes the Cropland Data Layer (CDL) land cover classes of barren, wetlands, open water, woody wetlands, herbaceous wetlands, and sites that shifted between land cover categories in the 3-year period prior to installation. There is only one turbine in the South, and as it is on developed land, it is not shown in the figure or table, but it is included in the total for all regions.

[1] The total for all regions excludes three observations with missing land cover in one or more of the 3 years before the project year.

Source: USDA, Economic Research Service using data from Hoen et al. (2018); USDA National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (USDA, NASS, 2009–20); USDA, NASS Agricultural Resource Management Survey – Phase III (ARMS III) Production Expenditure Regions Map (USDA, NASS, 2022a); and 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census Bureau, 2019).

Like solar, the land cover prior to wind development was influenced by regional differences in the distribution of land cover (figure 8). In the West and Plains, where approximately 50 percent of the land is in grassland pasture and range, 65 percent and 45 percent of turbines were installed on land categorized as pasture-range only (figures 4 and 8). In the Midwest, although cropland comprised 45 percent of land cover, 93 percent of turbines were located on continuous cropland, supporting previous findings that wind turbines can be located with crop production (Denholm et al., 2009; Mills, 2015).

In the forest-dominant Atlantic region, 75 percent of turbines were sited on land classified as forest. However, only a small share of turbines was in the Atlantic (3 percent), and fewer than 1,000 turbines were on land categorized as forest prior to development. Finally, there is only one turbine located in the South, and it is on land classified as developed. As noted earlier, this is due to the limited wind potential in the region.

Land Cover Changes Associated With Solar and Wind Development

To examine land cover change from 3 years before to 3 years after a solar or wind installation, the sample is limited to those locations for which the land cover in the 3 years before and after development can be identified. Therefore, the sample excludes solar farms or wind turbines where installation occurred prior to 2012 or after 2017. The sample includes 1,861 solar installations and 20,784 wind turbines (56 and 51 percent of the full sample, respectively).

Land cover change was more common on solar lands than wind lands after an installation. There was a land cover change on 26 percent of solar lands and 5 percent of wind lands after installation (table 2). This finding contrasts with the previous result (figure 5) that showed only a slight increase in land cover change after development. Importantly the analysis in table 2 considers a longer period before and after development, allowing for a more robust measure of land cover change. Additionally, a higher share of solar lands than wind lands that were in agriculture (**cropland** and **pasture-range**) left agriculture after installation (15 percent and less than 1 percent, respectively). The findings are salient to discussions of the local land use effects of solar development, particularly considering community concerns regarding the loss of farmland to solar development.

Table 2

Land cover and land cover change on solar and wind lands, 2012–17

	Solar			Wind		
	Count before installation	Land cover change (percentage)	Left agriculture (percentage)	Count before installation	Land cover change (percentage)	Left agriculture (percentage)
Land cover category	(1)	(2)	(3)	(1)	(2)	(3)
Cropland	717	18.3	14.4	11,208	1.5	0.3
Pasture-range	605	26.6	14.9	8,352	8.1	0.8
Forest	173	18.5	N/A	867	5.1	N/A
Developed	117	22.2	N/A	10	20.0	N/A
Other	249	51.4	N/A	347	32.9	N/A
All	1,861	25.7	14.6	20,784	4.8	0.5

N/A = Not applicable.

Note: The first column in each panel includes the number of sites in each broad land cover category in the 3 years before installation. The second column includes the share that changed land cover in the 3 years after installation. For the agricultural land cover categories, the third column includes the share that shifted out of agriculture. The sample includes solar and wind sites in rural areas of the contiguous United States. Land cover is measured by determining the dominant land cover category in each year in the 3 years prior to and after installation within a 150-meter buffer for each site. The other category includes the CDL land cover classes of barren, wetlands, open water, woody wetlands, herbaceous wetlands, and sites that shifted between land cover categories in the 3-year period prior to or after installation.

Source: USDA, Economic Research Service using data from the U.S. Energy Information Administration (EIA) Form 860 (EIA, 2021a); Hoen et al. (2018); USDA, National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (USDA, NASS, 2009–20); and 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/ Line Shapefiles (U.S. Census Bureau, 2019).

For each of the five broad land cover categories, solar lands consistently experienced land cover change at a higher rate than wind lands following installation. On solar lands, 18 percent of sites categorized as cropland and 27 percent of sites classified as pasture-range prior to installation, changed land cover categories after a solar installation. The larger estimated footprint of solar farms as compared to wind turbines within the buffer may account for the increased land cover change on solar lands. The median size of a solar farm was 3 MW compared to 2 MW for a wind turbine, and the estimated solar footprint is 10 times the wind footprint per MW. It is also important to note that solar lands had a higher share of annual land cover change than wind lands even when no development occurred (figure 5), suggesting that the type of land on which solar and wind developed may have differed. On wind lands, only 2 percent of cropland and 8 percent of pasture-range sites changed land cover categories after a wind turbine installation. Further, a higher share of solar lands shifted out of agriculture; 14 percent of solar lands in cropland and 15 percent in pasture-range left agriculture, compared with less than 1 percent for wind lands. This suggests that wind development was compatible with crop and livestock production. Solar lands also had a higher share of land cover change than wind lands after an installation on nonagricultural land, particularly for sites in the **forest** and **developed** land cover categories. This finding is distinct from the previous finding (figure 5), which showed only a 0.5 percent increase in land cover change on solar lands in the year after development.

The fact that a high share of land (approximately 85 percent of sites in cropland and pasture-range) in proximity to solar farms remained in agricultural land cover may be somewhat unexpected. The land cover under and between solar panels is removed during the construction of a typical utility-scale solar installation. Although vegetative cover may be planted beneath the panels after installation in some cases, there were a limited number of agrivoltaics sites with crop production during the sample period. This suggests that there was some crop production in proximity to solar farms. Further, the high share of land that stayed in pasture-range after a solar installation suggests that it was possible that livestock grazing continued near solar developments.

Given the relatively low number of solar projects on land categorized as developed, the findings suggest that there may be opportunities for additional solar development on nonagricultural land, but there may be other factors, including proximity to transmission lines and topography of the land, that limited the suitability of developed land for hosting solar farms. Further, locating solar on nonagricultural land may mitigate concerns regarding land use competition with farmland, but it would also eliminate the local economic benefits from solar development, including leasing income for agricultural producers.

Distribution of Land Cover After Solar or Wind Installations

Tables 3 and 4 show the distribution of land cover before and after installation on solar and wind lands using the detailed land cover categories. In each table, the categories listed along the top row are the land cover category before installation, and those in the leftmost column are the land cover category after installation. For example, the first cell in the table includes the share of land that was in **continuous cropland** prior to installation and that remained in continuous cropland after installation.

After solar installations, solar lands categorized as continuous cropland most commonly remained in the same category (49 percent) (table 3).[48] However, just 30 percent of solar lands were categorized as continuous cropland prior to installation, so 14 percent of solar lands started and remained in the category. For continuous cropland locations that experienced land cover change, they most commonly shifted into **crop and fallow** (28 percent) or other (13 percent). Smaller shares shifted into **fallow** (6 percent), **crop and pasture-range** (4 percent), or **pasture-range only** (less than 1 percent). Although the share of sites in continuous cropland declined after installation (from 30 percent to 19 percent), these findings suggest that crop production occurred on land near solar farms.

---

[48] Results from a robustness check using 300-meter buffers are in appendix D, table D.2.a, and are consistent with those using the 150-meter buffer.

Table 3

Share of land cover change associated with solar installations (3 years before and after), 2012–17

	Land cover category	Continuous cropland	Crop and fallow	Fallow	Crop and pasture-range	Pasture-range only	Developed	Forest	Other
Land cover category after installation	Continuous cropland	48.5	23.1	9.4	17.6	0	4.3	0	3.2
	Crop and fallow	27.6	30	34.4	13.6	0.5	0	0	2
	Fallow	5.8	27.7	40.6	7.4	0.2	0	0	1.2
	Crop and pasture-range	4	0.8	0	13.6	2.3	0	0.6	5.6
	Pasture-range only	0.9	0	0	25.6	85.1	0	0.6	14.5
	Developed	0	0	0	0.6	0	77.8	0	12.5
	Forest	0.2	0	0	2.8	0	0.9	81.5	12.5
	Other	13.2	18.5	15.6	18.8	11.9	17.1	17.3	48.6
	Share 3 years before installation	29.8	7.0	1.7	9.5	23.1	6.3	9.3	13.4
	Share 3 years after installation	18.6	12.6	5.3	3.9	24.3	6.6	9.6	19.2

Total number of solar projects = 1,861.

Note: The categories along the top row of the table represent the land cover in the 3 years prior to installation, and the categories along the first column of the table represent the land cover category in the 3 years after installation. The sample includes solar sites in rural areas of the contiguous United States. Land cover is measured by determining the dominant land cover category in each year in the 3 years prior to and after installation within a 150-meter buffer for each site. The other category includes the CDL land cover classes of barren, wetlands, open water, woody wetlands, herbaceous wetlands, and sites that shifted between land cover categories in the 3-year period prior to or after installation.

Source: USDA, Economic Research Service using data from U.S. Energy Information Administration (EIA) Form 860 (EIA, 2021a); USDA, National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (USDA, NASS, 2009–20); and 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census Bureau, 2019).

Solar lands categorized as crop and fallow commonly transitioned to fallow (28 percent) or continuous cropland (23 percent) and had less persistence in land cover than sites categorized as continuous cropland. Only 30 percent of crop and fallow sites maintained the same land cover category after installation. This, not unexpectedly, indicates that there was an overlap in the detailed cropland categories. This was likely due, at least in part, to sites where cropland was left fallow in some years as part of a rotation.

In addition to continuous cropland, a relatively high percentage of solar projects were sited on land in pasture-range only (23 percent), and the sites typically maintained the same land cover (85 percent). Like the crop and fallow category, a relatively small share (14 percent of locations in crop and pasture-range) remained in crop and pasture-range, and 26 percent shifted to pasture-range only. A relatively large share of solar lands (19 percent of crop and pasture-range and 12 percent of pasture-range only) shifted into other.

Locations categorized as nonagricultural land infrequently shifted into agricultural land. For example, 4 percent of land categorized as **developed** shifted into continuous cropland, and the remainder that changed categories shifted into other. Notably, only 6.3 percent of solar lands were classified as developed before installation, so less than 1 percent of solar lands that were in developed were categorized as continuous cropland after installation. Given that it is such a small share, and that the measurement of land cover is imperfect, this may reflect an imprecise measure of land cover rather than a shift from developed land to agricultural land. Finally, when sites categorized as **forest** changed land cover categories, they predominantly shifted into **other**.

Table 4 shows the findings for wind are largely consistent with the previous results from figure 5 and table 2; there is little land cover change after a wind turbine installation.[49] For land categorized as continuous cropland, 92 percent remained in the same category after a wind installation. For wind, 44 percent of wind lands were on continuous cropland prior to installation. This indicates that approximately 40 percent of all wind land started in and remained in continuous cropland.

Table 4

Share of land cover change associated with wind turbine installations (3 years before and after), 2012–17

	Land cover category	Continuous cropland	Crop and fallow	Fallow	Crop and pasture-range	Pasture-range only	Developed	Forest	Other
Land cover category after installation	**Continuous cropland**	92.0	23.1	7.1	38.9	0.6	0	0.1	9.2
	Crop and fallow	6.8	73.6	64.3	12.6	0.3	0	0	1.7
	Fallow	0.1	0.6	14.3	0.7	<0.1	0	0	0
	Crop and pasture-range	0.7	2.3	14.3	25.2	2.4	0	0	0.9
	Pasture-range only	0.1	0	0	21.4	95.9	0	0.5	12.7
	Developed	0	0	0	0	0	80	0	0.9
	Forest	0	0	0	0	0	0	94.9	7.5
	Other	0.3	0.3	0	1.3	0.8	20	4.5	67.2
	Share 3 years before installation	44	9.9	0.1	4.9	35.2	0	4.2	1.7
	Share 3 years after installation	45.1	11	0.1	2.7	35.1	0.1	4.1	1.8

Total number of wind turbines = 20,784.

Note: The categories along the top row of the table represent the land cover in the 3 years prior to installation, whereas the categories along the first column of the table represent the land cover in the 3 years after installation. The sample includes wind sites in rural areas of the contiguous United States. Land cover is measured by determining the dominant land cover category in each year in the 3 years prior to and after installation within a 150-meter buffer for each site. The other category includes the Cropland Data Layer (CDL) land cover classes of barren, wetlands, open water, woody wetlands, herbaceous wetlands, and sites that shifted between land cover categories in the 3-year period prior to or after installation.

---

[49] Results from a robustness check using 75-meter buffers are in appendix D, table D.2.b, and are consistent with those using the 150-meter buffer.

Source: USDA, Economic Research Service using data from Hoen et al. (2018); USDA, National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (USDA, NASS, 2009–20); and 2019 U.S. Department of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census Bureau, 2019).

The high rate of persistence found for wind lands classified as continuous cropland holds for those categorized as pasture-range only (96 percent), but there is far less persistence for wind lands classified as fallow (14 percent) and crop and pasture-range (25 percent). Still, the shifts in land cover for these land cover categories were almost entirely into other agricultural land types, supporting the finding that wind development is compatible with agricultural production.

The share of land cover categorized as **other** was markedly different between solar and wind lands. Thirteen percent of solar lands were categorized as other prior to installation, compared to 1.7 percent for wind. Solar lands more commonly shifted into the other category. For solar lands categorized as cropland prior to installation, 13 percent of sites in continuous cropland, 19 percent of sites in crop and fallow, and 16 percent of sites in fallow shifted into the other category after installation. For wind, the share of sites in each cropland category that moved to the other category after installation was less than 1 percent. The same pattern held for other categories of agricultural land. On solar lands, for sites that were in the crop and pasture-range and pasture-range only categories prior to installation, 19 percent and 12 percent were categorized as other after installation. For wind lands, the shares were less than 2 percent. Sites categorized as other were primarily sites that did not have a consistent land cover category over the 3-year period. This study is unable to discern the reason for the difference in the share of sites categorized as other between solar and wind lands, and several factors may play a role in the finding, including regional differences in the distribution of solar and wind lands. Further, for the nonagricultural categories of developed and forest, 17 percent in each category shifted to other after installation on solar lands. This result supports the previous finding that solar lands are different from wind lands and that solar farm developments were more commonly associated with land cover change than wind turbine installations.[50]

To further investigate differences in solar and wind lands, this report examined the share of fallow land for solar and wind lands. Prior to installation, the share of land that was categorized as fallow was higher for solar lands (1.7 percent) than wind lands (0.1 percent), but it was a small share of land overall. About 22.6 percent of solar lands that were in one of the cropland categories (crop and fallow, and fallow) were fallow for at least 1 year prior to installation, compared with 18.4 percent for wind lands. Further, for solar land in one of the cropland categories (continuous cropland, crop and fallow, and fallow) prior to installation, the share that was fallow for at least 1 year after an installation was more than double the pre-installation level, 49 percent. For wind lands in one of the cropland categories prior to installation, the share that was fallow for at least 1 year following a wind installation was 19.8 percent—just 1 percent more than the pre-installation level.

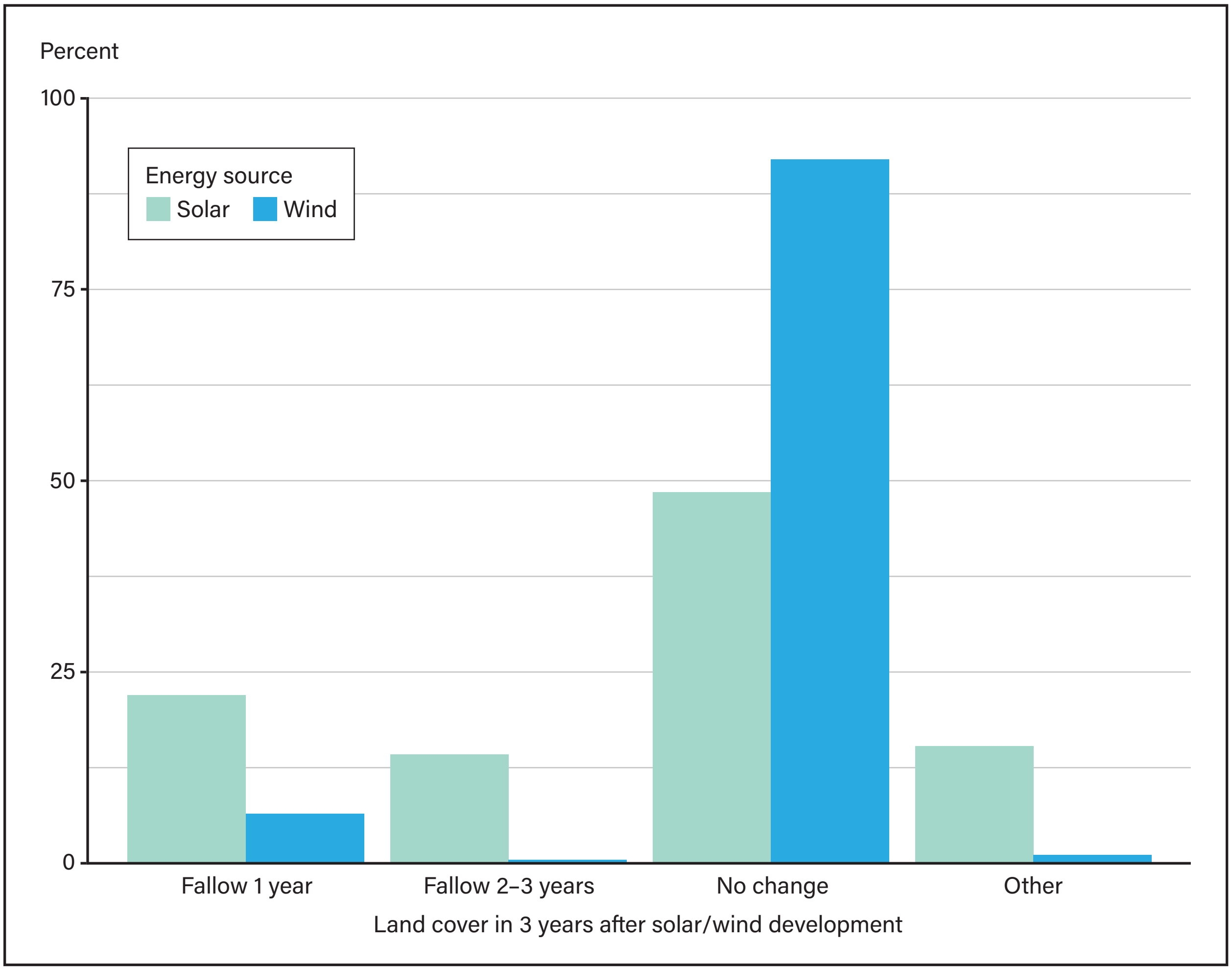
Figure 9 includes sites that were in continuous cropland prior to installation. It includes the distribution of land cover after installation, focusing on the number of years in which the location was fallow. For solar, 48 percent of land remained in continuous cropland; for wind, 92 percent remained in that category. Of the remainder, 22 percent of solar sites were fallow in 1 of the 3 years after installation, compared with 6 percent for wind. Another 14 percent of the solar sites were fallow for 2 or 3 years following a solar installation, compared with less than 1 percent for wind. Overall, for solar lands in continuous cropland prior to installation, 36 percent of sites were fallow in at least 1 year after installation, while for wind lands, it was 7 percent. These findings do not indicate, however, whether the number of years the land was categorized as fallow after the installation was due to the installation or if it was due to other factors, such as differences in the regional distribution of solar farms and wind turbines or resource issues, such as water constraints, that limited the feasibility of cropping the land.

---

[50] See appendix I for additional analysis of land cover change using data from the National Land Cover Database (NLCD).

Figure 9

Sites in continuous cropland: Fallow years after a solar or wind installation, 2012–17



The sample includes 555 solar sites and 9,144 wind turbine sites.

Note: The no change category includes all sites that remained in continuous cropland in the 3 years after installation. The other category includes all sites that did not remain in continuous cropland or crop and fallow after installation. Land cover is measured by determining the dominant land cover category in each year in the 3 years prior to and after an installation within a 150-meter buffer for each site.

Source: USDA, Economic Research Service using data from the U.S. Energy Information Administration (EIA) Form 860 (EIA, 2021a); Hoen et al. (2018); USDA, National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (USDA, NASS, 2009–20); and 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/ Line Shapefiles (U.S. Census Bureau 2019).

Conclusion

Reducing greenhouse gas emissions from the electricity sector will require a significant expansion of renewable electricity generation. Along with existing policies, funding from the Bipartisan Infrastructure Law of 2021 and the Inflation Reduction Act of 2022 is expected to significantly increase the pace of development of utility-scale solar and wind projects (Denholm et al., 2022). The estimated cumulative footprint in 2020 was 424,000 acres (far less than 1 percent of the amount of land in farms); approximately 80 percent of the estimated footprint and 27 percent of the electricity capacity were from solar. The footprint includes only the land area directly affected by solar and wind development and does not include additional structures such as transmission lines. A significant expansion of utility-scale solar and wind projects will have local landscape effects in rural areas. These projects also have local socioeconomic effects in rural communities, providing benefits such as leasing revenue and tax revenue but also imposing costs such as changes to the local landscape, farmland conversion following solar development, noise and altered views from wind turbines, environmental effects, and potential reductions in property values. Although wind turbines have other effects on the rural landscape, their smaller footprints make them compatible with crop and livestock production. Due to the larger footprint of solar farms and the compatibility of solar farms with the same type of land used for farming (flat with lots of sun), there have been concerns regarding land use competition between solar farms and agriculture.

Local community resistance regarding land use change can delay or even prevent renewable development (Lopez et al. 2022a and 2022b; Bessette & Mills, 2021; Rand & Hoen, 2017). The findings from this report provide information for stakeholders that may reduce the uncertainty about the types of land, particularly agricultural land, that were affected by solar or wind development, how the development was distributed across the country, and the share and type of land cover change that was associated with solar or wind projects.

During the sample period 2009–20, almost three-quarters of solar projects and more than 90 percent of solar capacity were located in rural areas; more than 70 percent of these projects were on agricultural land. Wind turbines were almost entirely located in rural areas, with approximately 95 percent of these on agricultural land. In rural areas, the largest share of solar farms and wind turbines were sited on land that was categorized as cropland in the 3 years prior to development, though this share was higher for wind turbines than solar farms (approximately 56 percent of turbines compared to 43 percent of solar farms).

Through 2020, solar farms were more common along the east and west coasts and across the southern United States, particularly in the Atlantic region, due in part to State policies promoting solar development. Wind turbines were more common in the Plains and the Midwest, where there is high wind potential. The distribution of solar and wind development across land cover types only partially reflects the distribution of land cover in these regions. Although less than half of all Midwest land cover was cropland, almost 70 percent of solar projects and 90 percent of wind turbines in this region were installed on sites that were categorized as cropland in the 3 years prior to development. Despite relatively small shares of cropland in the Atlantic and the South, solar was most commonly located on land that was classified as cropland prior to development in these regions as well.

Land at solar farm installation sites more commonly experienced a change in land cover category than land at wind turbine installation sites. On average, land cover changed annually at 16 percent of solar sites, regardless of whether a solar project was developed at the site in the previous year. This was more than three times the rate at which land cover changed at turbine sites, suggesting the two energy sources were installed on different types of land.

From 3 years before to 3 years after an installation, approximately one-quarter of solar sites shifted land cover categories, five times more than the share of wind sites. Of these, 15 percent of solar sites categorized as cropland or **pasture-range** prior to installation left agriculture. For wind, the share was near zero. Despite concerns that solar development is replacing farmland, the findings indicate that agricultural land in proximity to solar farms often remains in the same land cover category.

For locations that were characterized as cropland prior to installation, approximately 20 percent of solar farms and wind turbines were located on sites that were classified as fallow in at least 1 of the 3 years prior to development. The share of cropland sites with at least 1 fallow year after installation was more than double for solar projects but increased only slightly for wind turbine locations. Further, five times more solar sites than wind turbine sites (36 percent compared to 7 percent) that were classified as **continuous cropland** in the 3 years prior to development were left fallow for at least 1 of the 3 years after installation. However, the findings do not indicate the reason for the higher share of solar sites with fallow years after installation. The increased share could be due to other factors, including differences in the type of land used for solar or wind development or resource constraints, e.g., insufficient water for irrigation.

The amount of renewable generation necessary to achieve net zero GHG emissions in the electricity sector requires a significant increase in solar and wind capacity. The land cover effects of this expansion in rural areas will depend on several factors, including the share of solar capacity that is deployed in small-scale versus large-scale systems. There will likely be significant variation in the effects of utility-scale solar and wind development on the rural landscape by region and energy type.

References

Adeh, E. H., Good, S. P., Calaf, M., & Higgins, C. W. (2019). Solar PV power potential is greatest over croplands. *Scientific Reports*, 9(1), 11442.

Alemu, W. G., Henebry, G. M., & Melesse, A. M. (2020). Land cover and land use change in the U.S. prairie pothole region using the USDA Cropland Data Layer. *Land,* 9(5), 166.

American Wind Energy Association. (2018). U.S. wind industry annual market report: Year ending 2017. *American Wind Energy Association*.

Ardani, K., Denholm, P., Mai, T., Margolis, R., O'Shaughnessy, E., Silverman, & T., Zuboy, J. (2021). *Solar futures study*. U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE).

Bessette, D. L., & Mills, S. B. (2021). Farmers vs. lakers: Agriculture, amenity, and community in predicting opposition to United States wind energy development. *Energy Research & Social Science*, 72, 101873.

Bigelow, D. P., & Borchers, A. (2017). *Major uses of land in the United States, 2012* (Report No. EIB-178). U.S. Department of Agriculture, Economic Research Service.

Boryan, C., Yang, Z., Mueller, R., & Craig, M. (2011). Monitoring U.S. agriculture: The U.S. Department of Agriculture, National Agricultural Statistics Service, Cropland Data Layer program. *Geocarto International*, 26(5), 341–358.

Brown, J. P., Pender, J., Wiser, R., Lantz, E., & Hoen, B. (2012). Ex post analysis of economic impacts from wind power development in U.S. counties. *Energy Economics* 34(6), 1743–1754.

Brunner, E., Hoen, B., & Hyman, J. (2022). School district revenue shocks, resource allocations, and student achievement: Evidence from the universe of U.S. wind energy installations. *Journal of Public Economics*, 206, 104586.

California Air Resources Board. (2012). *Cap-and-trade program, program overview: How does the program work?*

Callaway, D. S., Fowlie, M., & McCormick, G. (2018). Location, location, location: The variable value of renewable energy and demand-side efficiency resources. *Journal of the Association of Environmental and Resource Economists*, 5(1), 39–75.

Carlisle J. E., Kane, S. L., Solan, D., Bowman, M., & Joe, J.C. (2015). Public attitudes regarding large-scale solar energy development in the U.S. *Renewable and Sustainable Energy Reviews*, 48, 835–47.

Chen, T. (2020). *Three essays on environmental economics: Externalities and policy implications*. (Doctoral dissertation, University of Illinois at Urbana-Champaign).

Claassen, R., Carriazo, F., Cooper, J. C., Hellerstein, D., & Ueda, K. (2011). *Grassland to cropland conversion in the northern Plains: The role of crop insurance, commodity, and disaster programs* (Report No. ERR-120). U.S. Department of Agriculture, Economic Research Service. June 2011.

Clarke, P., & Melendez, R. (2019). *National neighborhood data archive (NaNDA): Land cover by census tract, United States, 2001–2016*. Ann Arbor, MI: Inter-University Consortium for Political and Social Research (distributor), September 11, 2019.

Cole, W., Lewis, H., Sigrin, B., & Margolis, R. (2016). Interactions of rooftop PV deployment with the capacity expansion of the bulk power system. *Applied Energy*, 168, 473–481.

Copenhaver, K., Hamada, Y., Mueller, S., & Dunn, J. B. (2021). Examining the characteristics of the Cropland Data Layer in the context of estimating land cover change. ISPRS *International Journal of Geo-Information*, 10(5), 281.

Cousse, J. (2021). Still in love with solar energy? Installation size, affect, and the social acceptance of renewable energy technologies. *Renewable and Sustainable Energy Reviews*, 145, 111107.

Crawford, J., Bessette, D., & Mills, S. B. (2022). Rallying the anti-crowd: Organized opposition, democratic deficit, and a potential social gap in large-scale solar energy. *Energy Research & Social Science*, 90, 102597.

Cullen, J. (2013). Measuring the environmental benefits of wind-generated electricity. *American Economic Journal: Economic Policy*, 5(4), 107–133.

Denholm, P., Hand, M., Jackson, M., & Ong, S. (2009). *Land-use requirements of modern wind power plants in the United States* (NREL/TP-6A2-45834). National Renewable Energy Laboratory. August 2009.

Denholm, P., Brown, P., Cole, W., Mai, T., Sergi, B., Brown, M., Jadun, P., Ho, J., Mayernik, J., McMillan, C., & Sreenath, R. (2022). *Examining supply-side options to achieve 100% clean electricity by 2035* (NREL/TP-6A40-81644). National Renewable Energy Laboratory.

Dewitz, J., & U.S. Geological Survey. (2021). *National Land Cover Database (NLCD) 2019 products* (Version 2.0, June 2021).

Dohlman, E., Maguire, K., Davis, W.V., Husby, M., Bovay, J., Weber, C. & Lee, Y. (2024). *Trends, Insights, and Future Prospects for Production in Controlled Environment Agriculture and Agrivoltaics Systems* (Report No. EIB-264). U.S. Department of Agriculture, Economics Research Service.

Gagnon, P., Margolis, R., Melius, J., Phillips, C., & Elmore, R. (2016). *Rooftop solar photovoltaic technical potential in the United States: A detailed assessment* (NREL/TP-6A20-65298). National Renewable Energy Laboratory.

Gagnon, P., Brown, M., Steinberg, D., Brown, P., Awara, S., Carag, V., Cohen, S., Cole, W., Ho, J., Inskeep, S., Lee, N., Mai, T., Mowers, M., Murphy, C., & Sergi, B. (2022). *2022 standard scenarios Report: A U.S. electricity sector outlook* (NREL/TP-6A40-84327). National Renewable Energy Laboratory.

Gibbons, S. (2015). Gone with the wind: Valuing the visual impacts of wind turbines through house prices. *Journal of Environmental Economics and Management*, 72, 177–196.

Graham, M., Ates, S., Melathopoulos, A. P., Moldenke, A. R., DeBano, S. J., Best, L. R., & Higgins, C. W. (2021). Partial shading by solar panels delays bloom, increases floral abundance during the late-season for pollinators in a dryland, agrivoltaic ecosystem. *Scientific Reports*, 11, 7452.

Harrison-Atlas, D., Lopez, A., & Lantz, E. (2022). Dynamic land use implications of rapidly expanding and evolving wind power deployment. *Environmental Research Letters,* 17, 044064.

Heeter, J., Xu, K., & Fekete, E. (2020). *Community solar 101: National Renewable Energy Laboratory* (NREL/PR-6A20-75982). National Renewable Energy Laboratory.

Heintzelman, M. D., & Tuttle, C. M. (2012). Values in the wind: A hedonic analysis of wind power facilities. *Land Economics*, 88(3), 571–588.

Heintzelman, M. D., Vyn, R. J., & Guth, S. (2017). Understanding the amenity impacts of wind development on an international border. *Ecological Economics,* 137, 195–206.

Hernandez, R. R., Hoffacker, M. K., Field, C. B. (2015). Efficient use of land to meet sustainable energy needs. *Nature Climate Change*, 5, 353–358.

Hitaj, C. (2013). Wind power development in the United States. *Journal of Environmental Economics and Management*, 65(3), 394-410.

Hitaj, C., & Suttles, S. (2016). *Trends in U.S. agriculture's consumption and production of energy: Renewable power, shale energy, and cellulosic biomass* (Report No. EIB-159). U.S. Department of Agriculture, Economic Research Service. August 2016.

Hoen, B., Brown, J. P., Jackson, T., Wiser, R., Thayer, M., & Cappers, P. (2013). *A spatial hedonic analysis of the effects of wind energy facilities on surrounding property values in the United States* (LBNL-6362E). Lawrence Berkeley National Laboratory. August 2013.

Hoen, B. D., Diffendorfer, J. E., Rand, J. T., Kramer, L. A., Garrity, C. P., & Hunt, H. E. (2018). *United States wind turbine database v4.3 (January 14, 2022)*: U.S. Geological Survey, American Clean Power Association, and Lawrence Berkeley National Laboratory.

Hoffacker, M. K., Allen, M. F., & Hernandez, R. R. (2017). Land-sparing opportunities for solar energy development in agricultural landscapes: A case study of the Great Central Valley, CA, United States. *Environmental Science and Technology*, 51(24), 14472–14482.

Horowitz, K., Ramasamy, V., Macknick, J., & Margolis, R. (2020). *Capital costs for dual-use photovoltaic installations: 2020 benchmark for ground-mounted PV systems with pollinator-friendly vegetation, grazing, and crops* (NREL/TP-6A20-77811). National Renewable Energy Laboratory. December 2020.

Hyder, Z. (2022). What is a solar farm? Costs, land needs & more. *Solar Reviews*. May 19, 2022.

Kahn, M. E. (2013). Local non-market quality of life dynamics in new wind farms communities. *Energy Policy*, 59, 800–807.

Katkar, V. V., Sward, J. A., Worsley, A., & Zhang, K. M. (2021). Strategic land use analysis for solar development in New York State. *Renewable Energy*, 173, 861–875.

Klingebiel, A. A., & Montgomery, P. H. (1961). *Land-capability classification. Agricultural handbook No. 210.* U.S. Department of Agriculture, Soil Conservation Service. September 1961.

Lantz, E., Roberts, O., Nunemaker, J., DeMeo, E., Dykes, K., & Scott, G. (2019). Increasing wind turbine tower heights: Opportunities and challenges (NREL/TP-5000-73629). National Renewable Energy Laboratory.

Lark, T. J., Schelly, I. H., & Gibbs, H. K. (2021). Accuracy, bias, and improvements in mapping crops and cropland across the United States using the USDA Cropland Data Layer. *Remote Sensing*, 13(5), 968.

Lopez, A., Levine, A., Carey, J., & Mangan, C. (2022a). *U.S. wind siting regulation and zoning ordinances.* National Renewable Energy Laboratory.

Lopez, A., Levine, A., Carey, J., & Mangan, C. (2022b). *U.S. solar siting regulation and zoning ordinances.* National Renewable Energy Laboratory.

Maguire, K., & Munasib, A. (2016). The disparate influence of state renewable portfolio standards on renewable electricity generation capacity. *Land Economics*, 92(3), 468–490.

Mills, S.B. (2015). *Preserving agriculture through wind energy development: A study of the social, economic, and land use effects of windfarms on rural landowners and their communities.* (Doctoral dissertation, University of Michigan).

Mills, S. B., Bessette, D., & Smith, H. (2019). Exploring landowners' post-construction changes in perceptions of wind energy in Michigan *Land Use Policy*, 82, 754–762.

MLRC: Multi-Resolution Land Characteristics Consortium. (2022). NLCD land cover (CONUS) all years.

Moore-O'Leary, R. R., Hernandez, D. S., Johnston, S. R., Abella, K. E., Tanner, A. C., Swanson, J., Kreitler, R., & Lovich, J. E. (2017). Sustainability of utility-scale solar energy – Critical ecological concepts. *Frontiers in Ecology and the Environment*, 15(7), 385–394.

National Renewable Energy Laboratory. (2017). *Wind resources maps and data*.

National Renewable Energy Laboratory. (2020). *Geospatial data science: Wind supply curves: Reference access land-based wind 2020 data*.

National Renewable Energy Laboratory. (2021). *Geospatial data science: Solar supply curves: PV reference access siting regime.*

National Renewable Energy Laboratory. (2022a). *Geospatial data science: Renewable energy technical potential.*

National Renewable Energy Laboratory. (2022b) *InSPIRE: Agrivoltaics map*. October 6, 2022.

NC Clean Energy Technology Center. (2022). *Database of state incentives for renewables and efficiency.* North Carolina State University. (Retrieved August 16, 2022).

Nilson, R. S., & Stedman, R. C. (2022). Are big and small solar separate things?: The importance of scale in public support for solar energy development in Upstate New York. *Energy Research & Social Science*, 86: 102449.

Novan, K. (2015). Valuing the wind: Renewable energy policies and air pollution avoided. *American Economic Journal: Economic Policy*, 7(3), 291–326.

Ong, S., Campbell, C., Denholm, P., Margolis, R., & Heath, G. (2013). *Land use requirements for solar power plants in the United States* (NREL/TP-6A20-56290). National Renewable Energy Laboratory. June 2013.

O'Shaughnessy, E., Wiser, R., Hoen, B., Rand, J., & Elmallah, S. (2022). Drivers and energy justice implications of renewable energy project siting in the United States. *Journal of Environmental Policy & Planning*, 25(3), 258–272.

Parkins, J. R., Anders, S., Meyerhoff, J., & Holowach, M. (2022). Landowner acceptance of wind turbines on their land: Insights from a factorial survey experiment. *Land Economics*, 98(4), 674–689.

Pascaris, A. S., Schelly, C., Burnham, L., & Pearce, J. M. (2021). Integrating solar energy with agriculture: Industry perspectives on the market, community, and socio-political dimensions of agrivoltaics. *Energy Research and Social Science*, 75, 102023.

Rand, J., & Hoen, B. (2017). Thirty years of North American wind energy acceptance research: What have we learned? *Energy Research and Social Science*, 29, 135–148.

Sampson, G. S., Perry, E. D., & Tayler, M. R. (2020). The on-farm and near-farm effects of wind turbines on agricultural land values. *Journal of Agricultural and Resource Economics*, 45(3), 410–427.

Sekiyama, T., & Nagashima, A. (2019). Solar sharing for both food and clean energy production: Performance of agrivoltaic systems for corn, a typical shade-intolerant crop. *Environments*, 6(6), 65.

Solar Energy Industry Association. (2021). *11th annual national solar jobs census 2020. SEIA report.* May 2021.

Susskind, L., Chun, J., Gant, A., Hodgkins, C., Cohen, J., & Lohmar, S. (2022). Sources of opposition to renewable energy projects in the United States. *Energy Policy*, 165, 112922.

The White House. 2023. *Building a clean energy economy: A guidebook to the Inflation Reduction Act's investments in clean energy and climate action*. January 2023 (Version 2).

U.S. Census Bureau. (2010). *Census: Census urban and rural classification and urban area criteria.* (Last updated October 28, 2021).

U.S. Census Bureau. (2012). *2010 TIGER/line shapefiles: Census tracts.* (Last updated March 26, 2012).

U.S. Census Bureau. (2019). *2019 TIGER/line shapefiles: Urban areas.* (Last updated August 9, 2019).

U.S. Census Bureau. (2022). *2010 census tallies of census tracts, block groups and blocks.* (Last updated July 18, 2022).

U.S. Department of Agriculture. (2021). *Climate-smart agriculture and forestry strategy: 90-day progress report.* May 2021.

U.S. Department of Agriculture, Agricultural Marketing Service. (2012). *USDA definition of specialty crop.* (Retrieved September 1, 2022).

U.S. Department of Agriculture, Economic Research Service. (2015). *County typology codes.*

U.S. Department of Agriculture, Economic Research Service. (2022). *Farming and farm income.*

U.S. Department of Agriculture, Farm Service Agency. (2021). *Crop acreage data.*

U.S. Department of Agriculture, National Agricultural Statistics Service (2017). *Cropland data layer – national download, 2009.*

U.S. Department of Agriculture, National Agricultural Statistics Service. (2011). *Cropland data layer – national download, 2010.*

U.S. Department of Agriculture, National Agricultural Statistics Service (2012). *Cropland data layer – national download, 2011.*

U.S. Department of Agriculture, National Agricultural Statistics Service (2013). *Cropland data layer – national download, 2012.*

U.S. Department of Agriculture, National Agricultural Statistics Service (2014). *Cropland data layer – national download, 2013.*

U.S. Department of Agriculture, National Agricultural Statistics Service (2015). *Cropland data layer – national download, 2014*

U.S. Department of Agriculture, National Agricultural Statistics Service (2016). *Cropland data layer – national download, 2015.*

U.S. Department of Agriculture, National Agricultural Statistics Service (2017). *Cropland data layer – national download, 2016.*

U.S. Department of Agriculture, National Agricultural Statistics Service (2018). *Cropland data layer – national download, 2017.*

U.S. Department of Agriculture, National Agricultural Statistics Service (2019). *Cropland data layer – national download, 2018.*

U.S. Department of Agriculture, National Agricultural Statistics Service (2020). *Cropland data layer – national download, 2019.*

U.S. Department of Agriculture, National Agricultural Statistics Service (2022). *Cropland data layer – national download, 2020.*

U.S. Department of Agriculture, National Agricultural Statistics Service. (2020). *CropScape and cropland data layer – metadata: Colorado 2019.*

U.S. Department of Agriculture, National Agricultural Statistics Service. (2022a). *Charts and maps: ARMS Phase III production expenditure regions.* July 2022.

U.S. Department of Agriculture, National Agricultural Statistics Service. (2022b). *Farms and land in farms: 2021 summary*. February 2022.

U.S. Department of Agriculture, Natural Resources Conservation Service. (2001). *Definition: Land capability classes and subclasses.*

U.S. Department of Agriculture, Natural Resources Conservation Service. (2015). *Gridded Soil Survey Geographic (gSSURGO) Database for the United States of America and the territories, commonwealths, and island nations served by the USDA-NRCS.*

U.S. Department of Agriculture, Rural Development. (2023). *Inflation Reduction Act funding for rural development.* August 4, 2023.

U.S. Department of Energy. (2022). *InSPIRE: Agrivoltaics map.* October 6, 2022.

U.S. Department of Energy, Energy Information Administration. (n.d.). *Glossary*: *electricity*.

U.S. Department of Energy, Energy Information Administration. (2021a). *Form EIA-860.*

U.S. Department of Energy, Energy Information Administration. (2021b). *Annual energy outlook 2021. AEO2021*. February 2021.

U.S. Department of Energy, Energy Information Administration. (2021c). *Electric power annual 2020.* October 2021.

U.S. Department of Energy, Energy Information Administration. (2022a). *What is U.S. electricity generation by source?* February 2022. (retrieved August 19, 2022).

U.S. Department of Energy, Energy Information Administration. (2022b). *Electricity: Historical state data: Existing nameplate and net summer capacity by energy source, producer type and state (EIA-860), 1990–2021.*

U.S. Department of Energy, Energy Information Administration. (2022c). *Renewable energy explained: Portfolio standards.* November 30, 2022.

U.S. Department of Energy, Energy Information Administration. (2023). *Form EIA-860: Instructions Annual Electric Generator Report*.

Weselek, A., Ehmann, A., Zikeli, S., Lewandowski, I., Schindele, S., & Högy, P. (2019). Agrophotovoltaic systems: Applications, challenges, and opportunities. A review. *Agronomy for Sustainable Development*, 39(4), 35.

Winikoff, J. B., 2022. Learning by regulating: The evolution of wind energy zoning laws. *Journal of Law and Economics*, 65(S1), S223–S262.

Wiser, R. H., & Bolinger, M. (2018). *2017 wind technologies market report.* U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy.

Wiser, R. H., Bolinger, M., Hoen, B., Millstein, D., Rand, J., Barbose, G. L., Gorman, N. R., Gorman, W., Jeong, S., Mills, A. D., & Paulos, B. (2021). *Land-based wind market report: 2021 edition*. National Renewable Energy Laboratory. October 2021.

Xiarchos, I. M., & Sandborn, A. (2017). *Wind energy land distribution in the United States of America.* U.S. Department of Agriculture, Office of the Chief Economist. July 2017.

Appendix A: Characteristics and Implementation of the Solar and Wind Data

The location and characteristics of utility-scale solar and wind projects are from the U.S. Energy Information Administration (EIA) Form 860 (EIA-860) solar generators and plants data and U.S. Wind Turbine Database (USWTDB) through 2020 (EIA, 2021a; Hoen et al., 2018). The USWTDB includes the project year, turbine capacity, and the location of each turbine. The USWTDB defines utility-scale turbines as those that feed into the power grid rather than directly to a home or business. Modern utility-scale turbines typically have approximately 2 megawatts (MW) of capacity. Through 2020, the median size for turbines in rural areas of the contiguous United States was 2 MW, and 88 percent of turbines were between 1 and 3 MW in size.[51]

The EIA collects information on the location, capacity, name, and other characteristics for all utility-scale generators and the plants associated with them. The EIA defines a utility-scale plant as one that has a minimum capacity of 1 MW. According to the EIA, a generator is a piece of equipment that produces electricity, and a plant is a facility that contains generators or a generating facility (EIA, n.d.). Plants can consist of a single generator or multiple generators at a single location (EIA, 2023). The EIA collects location data for each plant rather than each generator, so multiple generators may have an identical location. Despite this, land cover at each utility-scale solar project is estimated at each generator rather than at each plant. There are three reasons for this:

- Based on the data, it is difficult to identify whether generators or plants are solar farms or portions of solar farms. Sometimes, in a particular location, there are several plants with similar names, each with one generator, while in other cases, there is one plant with multiple generators in a specific location.
- Based on the amount of capacity recorded for solar generators, firms are reporting information for solar farms (multiple panels sited together) as generators. Over the sample period, solar generators ranged in capacity from 0.1 MW to 300 MW, while an individual solar panel has a capacity of less than 1 kW (EIA, 2021a).
- Solar panels in proximity to each other will likely be associated with a similar, if not identical, dominant land cover category. To ensure that land cover is evaluated for all utility-scale solar farms, land cover for each generator is examined.

---

[51] Calculated by USDA's ERS using the USWTDB and U.S. Census 2019 urban-rural boundaries (U.S. Census Bureau, 2019; Hoen et al., 2018).

Appendix B: Comparison of Rural Sample Versus All Observations

Compared to all solar projects in the contiguous United States over the sample period 2009–20, the dominant land cover category in the project year was more commonly agricultural land for installations in rural areas. The largest difference was for the share of solar projects sited on land in **field crops**—35 percent of rural solar installations were in field crops compared to 28 percent for all solar projects (Table B.1). Further, the share of the rural solar sample on **developed** land was 8 percent, compared to all solar installations at 23 percent. Unsurprisingly, many of the solar installations in urban areas were on developed land. For wind, nearly all wind turbines (99.8 percent) were in rural areas, so the distribution of land cover across categories is similar between the rural sample and the sample that includes all wind turbines.

Table B.1

Land cover by category for rural sample and all observations, 2009–20

	Solar			Wind		
Land cover category	**Count (all)**	**Percent (all)**	**Percent (rural)**	**Count (all)**	**Percent (all)**	**Percent (rural)**
Cropland						
Field crops	1,268	28.2	34.9	23,800	51.4	51.6
Specialty crops	64	1.4	1.8	114	0.3	0.3
Fallow/idle cropland	350	7.8	10.0	2,035	4.4	4.4
Pasture-range						
Grassland/pasture	541	12.0	14.0	10,833	23.4	23.5
Shrubland	511	11.4	14.2	7,110	15.4	15.4
Other land types						
Forest	577	12.8	13.4	1,987	4.3	4.3
Developed	1,009	22.5	7.9	111	0.2	0.1
Other	175	3.9	3.9	275	0.6	0.6
Total[1]	4,495		3,330	46,265		46,138

Note: All observations include all solar or wind sites in the contiguous United States. The rural sample includes all solar or wind sites in rural areas of the contiguous United States. Land cover is measured by determining the dominant land cover category in the project year within a 150-meter buffer for each site. The other category includes the Cropland Data Layer (CDL) land cover classes of barren, wetlands, open water, woody wetlands, and herbaceous wetlands.

[1] Excludes two solar projects (both rural) and eight wind turbines (one rural) that are missing land cover in the project year.

Source: USDA Economic Research Service using data from the U.S. Energy Information Administration (EIA) Form 860 (EIA-860, 2021a); Hoen et al. (2018); USDA, National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (USDA, NASS, 2009–20); and 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census Bureau, 2019).

Appendix C: Cropland Data Layer Land Cover Classes and Associated Land Cover Categories

Table C.1

Cropland Data Layer land cover classes and associated land cover category

Agricultural					
CDL code	**CDL class name**	**Category**	**CDL code**	**CDL class name**	**Category**
1	Corn	Cropland (Field crops)	45	Sugarcane	Cropland (Field crops)
2	Cotton		46	Sweet potatoes	
3	Rice		58	Clover/wildflowers	
4	Sorghum		59	Sod/grass seed	
5	Soybeans		60	Switchgrass	
6	Sunflower		224	Vetch	
10	Peanuts		225	Dbl crop winwht/corn	
I11	Tobacco		226	Dbl crop oats/corn	
12	Sweet corn		235	Dbl crop barley/sorghum	
13	Pop or orn (ornamental) corn		236	Dbl crop winwht/sorghum	
21	Barley		238	Dbl crop winwht/cotton	
22	Durum wheat		240	Dbl crop soybeans/oats	
23	Spring wheat		241	Dbl crop corn/soybeans	
24	Winter wheat		254	Dbl crop barley/soybeans	
25	Other small grains		47	Misc vegs & fruits	Specialty crops
26	Dbl crop winwht/soybeans		48	Watermelons	
27	Rye		49	Onions	
28	Oats		50	Cucumbers	
29	Millet		51	Chick peas	
30	Speltz		52	Lentils	
31	Canola		53	Peas	
32	Flaxseed		54	Tomatoes	
33	Safflower		57	Herbs	
34	Rape seed		66	Cherries	
35	Mustard		67	Peaches	
36	Alfalfa		68	Apples	
37	Other hay/non-alfalfa		69	Grapes	
38	Camelina		70	Christmas trees	
39	Buckwheat		71	Other tree crops	
41	Sugarbeets		72	Citrus	
42	Dry beans		74	Pecans	
43	Potatoes		75	Almonds	
44	Other crops		76	Walnuts	

CDL code	CDL class name	Category
204	Pistachios	Specialty crops
205	Triticale	
206	Carrots	
207	Asparagus	
208	Garlic	
209	Cantaloupes	
210	Prunes	
211	Olives	
212	Oranges	
213	Honeydew melons	
214	Broccoli	
217	Pomegranates	
219	Greens	
220	Plums	
221	Strawberries	
222	Squash	
227	Lettuce	
229	Pumpkins	
242	Blueberries	
243	Cabbage	
246	Radishes	
250	Cranberries	
61	Fallow/idle cropland	Fallow
176	Grassland/pasture	Pasture-range
152	Shrubland	Pasture-range

Nonagricultural		
CDL code	**CDL class name**	**Category**
63	Forest	Forest
141	Deciduous forest	
142	Evergreen forest	
143	Mixed forest	
121	Developed/open space	Developed
122	Developed/low intensity	
123	Developed/ medium intensity	
124	Developed/high intensity	
87	Wetlands	Other
111	Open water	
190	Woody wetlands	
195	Herbaceous wetlands	
131	Barren	

CDL = Cropland Data Layer, Dbl Crop = Double cropped, WinWht = Winter wheat, Speltz = Spelt, Chick peas = Chickpeas

Source: USDA, National Agricultural Statistics Service (NASS) CDL (USDA, NASS, 2009–20).

Appendix D: Robustness Checks Using Alternative Buffers

Land Cover Before Solar or Wind Installations

Table D.1.a

Solar lands prior to an installation by region and land cover category using a 300-meter buffer, 2012–20

	Percent land cover					
Land cover category	**All regions**	**Atlantic**	**Midwest**	**Plains**	**South**	**West**
Continuous cropland	33.4	33.8	67.5	20.4	22.1	12.0
Crop and fallow	5.6	4.5	1.9	4.3	10.3	8.7
Fallow	1.6	0.4	0	0	1.6	4.6
Crop and pasture-range	6.6	5.8	5.8	4.3	4.5	9.2
Pasture-range only	22.0	3.7	11.9	66.7	13.5	52.5
Developed	4.0	3.4	3.4	0	2.9	6.0
Forest	14.8	30.8	3.3	0	23.0	0.4
Other	12.0	17.5	6.2	4.3	22.1	6.6
Total[1]	3,177	1,255	673	93	244	912

Note: Land cover is measured by determining the dominant land cover category in each year in the 3 years prior to installation within a 300-meter buffer for each site. The other category includes the Cropland Data Layer (CDL) land cover classes of barren, wetlands, open water, woody wetlands, herbaceous wetlands, and sites that shifted between land cover categories in the 3-year period prior to development.

[1] The national total excludes three observations with missing land cover in 1 or more of the 3 years before the project.

Source: USDA, Economic Research Service using data from U.S. Energy Information Administration (EIA) Form 860 (EIA, 2021a); USDA, National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (USDA, NASS, 2009–20); USDA, NASS Agricultural Resource Management Survey – Phase III (ARMS III) Production Expenditure Regions Map (USDA, NASS, 2022a); and 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census Bureau, 2019).

Table D.1.b

Wind lands prior to an installation by region and land cover category using a 75-meter buffer, 2012–20

	Percent land cover				
Land cover category	**All regions**	**Atlantic**	**Midwest**	**Plains**	**West**
Continuous cropland	45.4	17.4	90.2	39.1	4.7
Crop and fallow	10.2	0.1	4.4	9.9	22.0
Fallow	0.1	0	0	0.2	0.3
Crop and pasture-range	4.6	1.4	2.4	5.0	7.0
Pasture-range only	35.1	0.8	2.3	44.1	62.0
Developed	<0.1	0.2	0.1	<0.1	<0.1
Forest	2.8	71.0	0.1	0.6	0.2
Other	1.7	9.2	0.5	1.2	3.7
Total[1]	34,075	1,167	8,559	18,645	5,703

Note: Land cover is measured by determining the dominant land cover category in each year in the 3 years prior to installation within a 75-meter buffer for each site. The other category includes the Cropland Data Layer (CDL) land cover classes of barren, wetlands, open water, woody wetlands, herbaceous wetlands, and sites that shifted between land cover categories in the 3-year period prior to development.

[1] The national total excludes one observation with missing land cover in one or more of the 3 years before the project.

Source: USDA, Economic Research Service using data from Hoen et al. (2018); USDA, National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (USDA, NASS, 2009–20); USDA, NASS Agricultural Resource Management Survey – Phase III (ARMS III) Production Expenditure Regions Map (USDA, NASS, 2022a); and 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census Bureau, 2019).

Land Cover Change from 3 Years Before to 3 Years After Development

Table D.2.a

Share of land cover change associated with solar installations (3 years before and after) using a 300-meter buffer, 2012–17

	Land cover category	Continuous cropland	Crop and fallow	Fallow	Crop and pasture-range	Pasture-range only	Developed	Forest	Other
Land cover category after installation	**Continuous cropland**	59.2	21.7	2.9	18.7	0.2	1.1	0	4.3
	Crop and fallow	22.1	31.1	32.4	13.9	0.5	0	0	3.0
	Fallow	4.7	28.3	50	7.8	0.2	0	0	1.3
	Crop and pasture-range	3.1	0.9	0	15.7	2.3	0	0	1.7
	Pasture-range only	0.2	0	0	29.5	87.7	0	0.4	12.6
	Developed	0	0	2.9	0	0.2	87.6	0	8.2
	Forest	0.7	0	0	0	0.5	1.1	90.0	10.8
	Other	10.0	17.9	11.8	14.5	8.4	10.1	9.6	58.0
	Share 3 years before installation	29.9	5.7	1.8	9.0	23.8	4.8	12.4	12.5
	Share 3 years after installation	21.3	10.7	4.9	3.1	25.8	5.4	12.9	16.5

Number of solar installations = 1,861.

Note: The sample includes solar sites in rural areas of the contiguous United States. The categories along the top row of the table represent the land cover in the 3 years prior to installation, and the categories along the first column of the table represent the land cover category in the 3 years after installation. Land cover is measured by determining the dominant land cover category in each year in the 3 years prior to and after an installation within a 300-meter buffer for each site. The other category includes the Cropland Data Layer (CDL) land cover classes of barren, wetlands, open water, woody wetlands, herbaceous wetlands, and sites that shifted between land cover categories in the 3-year period prior to or after an installation.

Source: USDA, Economic Research Service using data from U.S. Energy Information Administration (EIA) Form 860 (EIA, 2021a); USDA, National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (USDA, NASS, 2009–20); and 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census Bureau, 2019).

Table D.2.b

Share of land cover change associated with wind turbines (3 years before and after) using a 75-meter buffer, 2012–17

	Land cover category	Continuous cropland	Crop and fallow	Fallow	Crop and pasture-range	Pasture-range only	Developed	Forest	Other
Land cover category after installation	**Continuous cropland**	91.0	24.7	17.7	32.7	0.6	0	0	7.8
	Crop and fallow	7.6	71.9	47.1	13.3	0.2	0	0	2.8
	Fallow	0	0.7	17.7	2.3	0	0	0	1.2
	Crop and pasture-range	0.9	2.6	17.7	24.1	5.2	0	0	4.0
	Pasture-range only	0.1	0	0	25.5	91	0	0.5	18.8
	Developed	0	0	0	0	0	78.6	0	2.4
	Forest	0	0	0	0	0	0	87.1	6.8
	Other	0.4	0.1	0	2.1	3.0	21.4	12.4	56.1
	Share 3 years before installation	43.6	10.4	0.1	5.8	33.8	0.1	3.9	2.4
	Share 3 years after installation	44.5	11.7	0.3	3.9	32.7	0.1	3.6	3.2

Number of wind turbines = 20,784.

Note: The sample includes wind sites in rural areas of the contiguous United States. The categories along the top row of the table represent the land cover in the 3 years prior to installation, and the categories along the first column of the table represent the land cover in the 3 years after installation. Land cover is measured by determining the dominant land cover category in each year in the 3 years prior to and after an installation within a 75-meter buffer for each site. The other category includes the Cropland Data Layer (CDL) land cover classes of barren, wetlands, open water, woody wetlands, herbaceous wetlands, and sites that shifted between land cover categories in the 3-year period prior to or after an installation.

Source: USDA, Economic Research Service using data from Hoen et al. (2018); USDA, National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (USDA, NASS, 2009–20); USDA, NASS Agricultural Resource Management Survey – Phase III (ARMS III) Production Expenditure Regions Map (USDA, NASS, 2022a); and 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census Bureau, 2019).

Appendix E: Measuring Land Cover Change with the USDA, National Agricultural Statistics Service Cropland Data Layer

To measure land cover, this study used the USDA, National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL). The CDL is a georeferenced 30-meter resolution land cover map of the contiguous United States (Boryan et al., 2011; USDA, NASS, 2009–20). The purpose of the CDL is to estimate the planted acreages of each State's major commodity crops for the Agricultural Statistics Board and to produce georeferenced, crop-specific spatial data (USDA, NASS, 2019). In addition to geospatial data on cropland, the CDL also classifies nonagricultural land cover throughout the United States into categories such as shrubland, forest, and developed (Lark et al., 2021; Boryan et al., 2011). Data from the USDA's Farm Service Agency (FSA) on crop acreage is used to verify the CDL in agricultural areas, and the National Land Cover Database (NLCD) is used to verify the accuracy of the CDL for nonagricultural areas (Boryan et al., 2011). The NLCD is also a 30-meter resolution raster spatial dataset for the contiguous United States. It is released approximately every 3 years and designed to estimate both agricultural and nonagricultural land cover, but it includes only one category for all crops, cultivated cropland. The CDL provides richer detail for agricultural lands and allows for the construction of more detailed categorizations of agricultural land. Additionally, because the CDL is annual, it provides greater temporal detail to estimate land cover before and after each solar and wind development.

Researchers have evaluated the accuracy of the CDL for measuring land cover and land cover change (Copenhaver et al., 2021; Lark et al., 2021; Alemu et al., 2020; Boryan et al., 2011). Initial evaluations by USDA's NASS researchers in 2009 found that the CDL was generally between 85 and 95 percent accurate in identifying major crops categories (Boryan et al., 2011). A recent study developed aggregated State-level measures of crop acres using the USDA Census of Agriculture (COA), the USDA National Resources Inventory (NRI), and the CDL (Copenhaver et al., 2021). The authors of that study found that changes in aggregated State-level measures of acres by crop between COA years (2007, 2012, and 2017) differed between the COA and CDL, and the NRI and CDL. They concluded that these differences—often a larger change in the number of acres by crop in the CDL as compared with the other two datasets—were indicative of inaccuracies in the CDL. However, one would expect the COA, NRI, and CDL estimates to differ due to differences in factors such as data collection technology, statistical methodology used to construct the estimates, and the purpose of the data collection. For example, the CDL is designed to provide estimates of planted acres for the dominant commodity crops in each State, while the COA provides estimates of harvested acres. Despite differences in the State-level measures of changes in crop acres between the COA and CDL, and the NRI and CDL, only the CDL can be used for analysis of land cover and land cover change at a fine geographic scale.

Using the 2012 CDL, Lark et al. (2021) found that the CDL land cover classification for major field crops, corn, and soybeans had high accuracy rates (generally greater than 90 percent). The rates for major commodity crops were significantly higher than for specialty crops or noncropped land, primarily grassland or shrubland categories. In addition, the CDL demonstrated high accuracy when distinguishing between aggregate cropped and noncropped categories. Overall, the CDL provides an accurate measure of land cover and land cover change, particularly for major commodity crops and when aggregated into cropped and noncropped categories (Lark et al., 2021). Further, unlike the COA or NRI data, the CDL provides a measure of land cover at a specific location (at a 30-meter resolution), providing a powerful tool to measure land cover and land cover change for locations in field crops and locations that shifted between cropped and noncropped land.

To address concerns about overstating the rate of land cover change (e.g., categorizing crops in rotation as land cover change), this study classified land cover in two ways: a broader, five-category classification and a second that includes more detailed categories for agricultural land cover (figure 6). Further, because of the potential inaccuracy of land cover at each 30-meter pixel, the analyses examined the dominant land cover category within a buffer. Finally, land cover was categorized using 3-year periods during which the dominant land cover category had to remain consistent for inclusion in a particular category. If multiple dominant land cover categories were identified for a particular location during the 3-year period, the land cover was categorized as other.

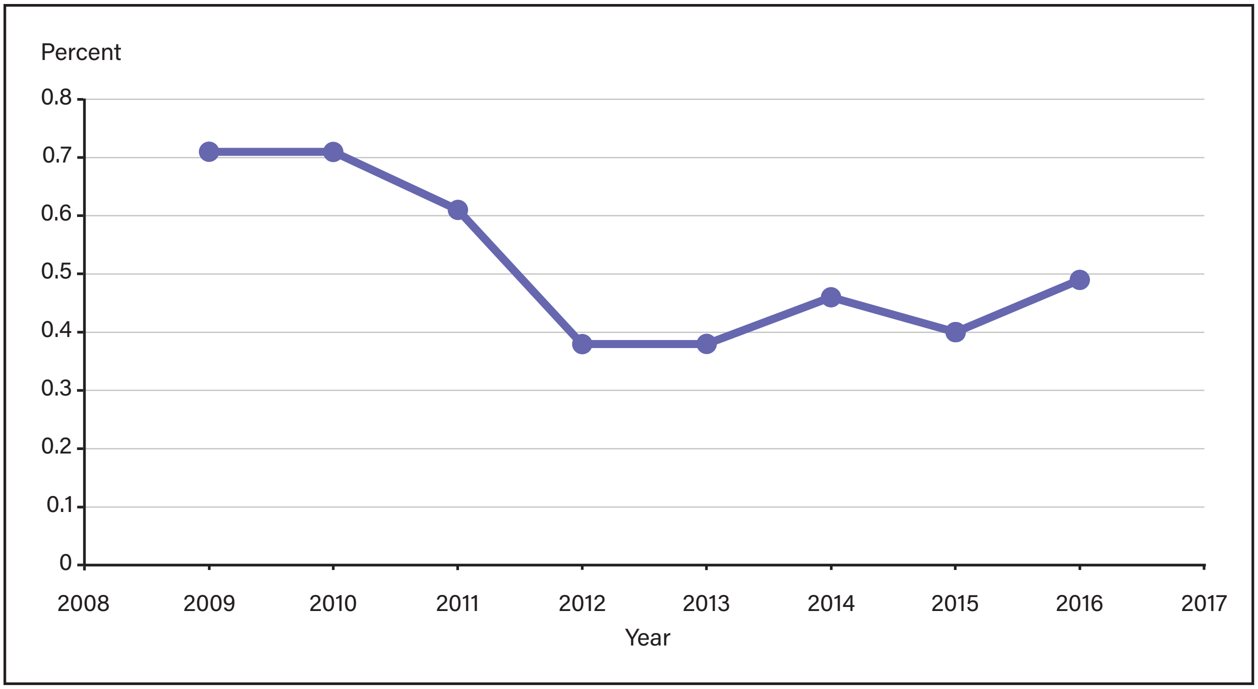
Appendix F: Annual Land Cover Change by Census Tract

The National Land Cover Database (NLCD) informs the Cropland Data Layer's (CDL) land cover categorization of noncropped lands. (See appendix E for more information on the CDL and NLCD.) While the CDL provides annual measures of land cover and includes detailed information on types of cultivated crops, the NLCD is produced approximately every 3 years and includes only one category for cropland, cultivated crops. Clarke and Melendez (2019) constructed an annualized NLCD dataset with land cover at the U.S Department of Commerce, Bureau of the Census tract level from 2001–2016. The data were used to develop a measure of the typical annual rate of land cover change in rural areas. The findings do not allow for direct comparison with the measures of land cover change on solar or wind lands, which were constructed at a much finer geographic scale (150-meter buffers). Instead, census tracts provide a broad assessment of land cover change nationally. This analysis used 26,148 tracts that intersected with rural areas (U.S. Census, 2022, 2019, and 2012). [52] [53]

The dominant land cover category (**cropland**, **pasture-range, forest**, **developed**, or **other**) in each census tract was identified each year from 2009 to 2016. Overall, year-to-year changes in the dominant land cover category at the tract level are very low, less than 1 percent of tracts per year (figure F.1).

Figure F.1

Annual land cover change in rural census tracts, 2009–16



Note: The sample includes census tracts in the contiguous United States that intersected with rural areas.

Source: USDA, Economic Research Service using annualized National Land Cover Database (NLCD) data at the census tract level (Clarke & Melendez, 2019), Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census Bureau, 2019).

---

[52] Rural areas were defined using the 2019 U.S. census rural-urban boundaries. The rural census tracts used in this analysis include those in the 2010 census tract spatial boundaries data that intersected with rural areas (U.S. Census, 2012 and 2019).

[53] Four rural census tracts were excluded from the analysis because annualized NLCD land cover data were not available.

Appendix G: Land Cover in the Project Year: Solar and Wind Development

The dominant land cover category was constructed using the CDL within a 150-meter buffer at each solar or wind development in rural areas of the contiguous United States in its project year. Land cover is categorized using five broad categories: **cropland**, **pasture-range**, **forest**, **developed**, and **other**, as well as CDL land cover classes for select crops (tables G.1 and G.2). Pasture-range is further subdivided into CDL land cover classes grassland/pasture and shrubland (tables G.1 and G.2).

The two largest land cover categories for solar projects were cropland (47 percent) and pasture-range (28 percent). Forest (13 percent) and developed (8 percent) land cover was much less common. Despite the wide distribution of solar farms across regions, a small share of solar farms was constructed on nonagricultural land. This result supports findings in previous literature indicating that cropland and solar farms share an ideal land cover type (Hernandez et al., 2015; Grout & Ifft, 2018; Adeh et al., 2019).

The most prevalent crops on solar sites were soybeans (14 percent) and corn (9 percent), while 10 percent of solar farms were installed on fallow/idle cropland. This may be driven by the large number of solar installations in Minnesota, which has significant corn and soybean production. Additionally, more than 160 million acres were in corn and soybean production in 2020, so land use for corn or soybeans is widespread. Less than 5 percent of solar farms were on any other individual crop type.

Because the land beneath a solar farm is typically cleared prior to development, replacing the previous land use, there could be significant effects to local agricultural land use from solar installations. The cumulative footprint of solar farms in 2020 was small and is projected to remain small relative to the total acres in agricultural land cover, but changes in land cover and in the rural landscape may have local socioeconomic effects.

Table G.1

Solar projects by land cover type in the project year, 2009–20

Land cover type	Number	Percent
Cropland (total)	**1,552**	**46.6**
Soybeans	450	13.5
Fallow/idle cropland	332	10.0
Corn	304	9.1
Other hay/non-alfalfa	153	4.6
Winter wheat	51	1.5
Alfalfa	51	1.5
Cotton	43	1.3
All other crops	168	5.0
Pasture-range (total)	**938**	**28.2**
Grassland/pasture	466	14.0
Shrubland	472	14.2
Forest	445	**13.4**
Developed	264	**7.9**
Other	131	**3.9**
Total[1]	3,330	

Note: The sample includes solar sites in rural areas of the contiguous United States. Land cover is measured using the dominant land cover category in the project year within a 150-meter buffer for each wind turbine site. The other category includes the Cropland Data Layer (CDL) land cover classes of barren, wetlands, open water, woody wetlands, and herbaceous wetlands.

[1] Excludes two observations with missing land cover in the project year.

Source: USDA, Economic Research Service using data from the U.S. Energy Information Administration (EIA) Form 860 (EIA, 2021a); USDA, National Agricultural Statistics Service Cropland Data Layer (CDL) (USDA, NASS, 2009–20); and 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census Bureau, 2019).

Approximately 95 percent of wind development occurred on agricultural land, consistent with the regional distribution of wind turbines across the Midwest and Plains (table G.2). By contrast, only 75 percent of solar development was on agricultural land (table G.1). Further, more than half (56 percent) of wind turbines were located on cropland, including 4 percent on fallow/idle cropland. Solar was less commonly installed on cropland than wind and more commonly located on fallow/idle cropland. Like solar, major crops grown on land in which turbines were located were corn (15 percent), soybeans (14 percent), and winter wheat (11 percent). These findings are consistent with earlier estimates in the literature (Xiarchos & Sandborn, 2017). Additionally, 39 percent of turbines were installed on pasture-range. This is largely consistent with previous literature (Harrison-Atlas et al., 2022; Xiarchos & Sandborn, 2017), but Xiarchos and Sandborn (2017) found a higher share of turbines were sited on rangeland than cropland in 2014. Few turbines were on forest (4 percent), developed, or other land cover types (less than 1 percent each).

Table G.2

Wind turbines by land cover type in the project year, 2009–20

Land cover type	Number	Percent
Cropland (total)	**25,939**	**56.2**
Corn	6,920	15.0
Soybeans	6,281	13.6
Winter wheat	4,894	10.6
Fallow/idle cropland	2,035	4.4
Cotton	1,945	4.2
Sorghum	1,339	2.9
Spring wheat	616	1.3
All other crops	1,909	4.1
Pasture-range (total)	**17,927**	**38.9**
Grassland/pasture	10,822	23.5
Shrubland	7,105	15.4
Forest	**1,969**	**4.3**
Developed	**34**	**0.1**
Other	**269**	**0.6**
Total[1]	**46,138**	

Note: The sample includes wind sites in rural areas of the contiguous United States. Land cover is measured using the dominant land cover category in the project year within a 150-meter buffer for each wind turbine site. The other category includes the Cropland Data Layer (CDL) land cover classes of barren, wetlands, open water, woody wetlands, and herbaceous wetlands.

[1] Excludes one observation with missing land cover in the project year.

Source: USDA, Economic Research Service using data from Hoen et al. (2018); USDA, National Agricultural Statistics Service Cropland Data Layer (CDL) (USDA, NASS, 2009–20); and 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census Bureau, 2019).

From these static snapshots of land cover in the project year, it is not possible to discern associated land cover change. Several dynamic factors could affect the assessment of the types of land cover associated with solar or wind developments in the project year. For example, field crops such as corn and soybeans are typically grown in rotation with other crops or with periods where the land is left fallow, and pastures can transition between haying and grazing from year to year. Additionally, land can shift in or out of agricultural land over time, irrespective of whether renewable development has occurred. In the preferred analyses, land cover is categorized using 3-year periods.

Appendix H: Comparison of Land Cover Categories Across All Rural Samples

The distribution of land cover categories in the project year is similar across the different sample periods for solar or wind sites in rural areas of the contiguous United States (tables H.1, H.2). There are small differences in the share in each land cover category between samples for solar sites. The share of solar lands categorized as developed is slightly higher in the change sample (2012–2017) (9 percent) than in the before sample (2012–2020), 7 percent. Additionally, the amount of land categorized as cropland is slightly lower, 45 percent in the change sample and 47 percent in the before sample. The share in pasture-range is slightly higher, with 31 percent in the change sample and 28 percent in the full sample. The differences suggest that solar was slightly more commonly located on developed or pasture-range than on cropland in the later part of the sample when compared with earlier years. Still, because the changes are small and the relative distribution remains the same (cropland is the most common, followed by pasture-range, forest, developed, and other), comparisons between groups are appropriate.

Table H.1

Rural solar projects by land cover in the project year across samples

	2009–2020 (full sample)	**2012–2020** (before)	**2012–2017** (change)	**2009–2017** (after)
Cropland	46.6	47.3	44.6	43.7
Pasture-range	28.2	27.6	30.8	31.5
Forest	13.4	13.8	12.0	11.4
Developed	7.9	7.4	8.9	9.6
Other	3.9	3.9	3.7	3.8
Total[1]	3,330	3,178	1,862	2,014

Note: The samples include solar sites in rural areas of the contiguous United States. Land cover is measured using the dominant land cover category in the project year within a 150-meter buffer for each solar site. The Other category includes the Cropland Data Layer (CDL) land cover classes of barren, wetlands, open water, woody wetlands, and herbaceous wetlands.

[1] Full sample total excludes two observations with missing land cover in the project year.

Source: USDA, Economic Research Service using data from the U.S. Energy Information Administration (EIA) Form 860 (EIA, 2021a); USDA, National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (USDA, NASS, 2009–20); and 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census Bureau 2019).

The distribution of land cover in the project year for wind installations is largely consistent across all samples. Differences in the wind turbine sites included in each sample are not expected to influence the findings.

Table H.2

Rural wind projects by land cover in the project year across samples

	2009–2020 (full sample)	**2012–2020** (before)	**2012–2017** (change)	**2009–2017** (after)
Cropland	56.2	58.1	57.5	55.1
Pasture-range	38.9	37.9	37.1	38.7
Forest	4.3	3.3	4.4	5.4
Developed	0.1	0.1	0.1	0.1
Other	0.6	0.6	0.9	0.8
Total[1]	46,138	34,075	20,786	32,849

Note: The samples include wind sites in rural areas of the contiguous United States. Land cover is measured using the dominant land cover category in the project year within a 150-meter buffer for each wind turbine site. The other category includes the Cropland Data Layer (CDL) land cover classes of barren, wetlands, open water, woody wetlands, and herbaceous wetlands.

[1] Full sample total excludes one observation with missing land cover in the project year.

Source: USDA, Economic Research Service using data from Hoen et al. (2018); USDA, National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (USDA. NASS, 2009–20); and 2019 U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census Bureau, 2019).

Appendix I: Land Cover Change on Solar and Wind Lands Using the National Land Cover Database

For robustness, the National Land Cover Database (NLCD) is used to measure land cover change for solar and wind lands (Dewitz & U.S. Geological Survey (USGS, 2021)). The NLCD is updated approximately every 3 years and does not categorize land cover using the detailed crop categories that are included in the Cropland Data Layer (CDL). (See appendix E for more information on the CDL and NLCD.) Despite its limited detail on cultivated croplands, the NLCD provides a robust alternative measure of land cover. The land cover change was measured using the dominant land cover category within a 150-meter buffer at each solar and wind location in rural areas of the contiguous United States. The dominant land cover before and after installation is defined using the closest year prior to and after the solar or wind installation.

The distribution of land cover before solar development and the share that shifted between land cover categories after development was broadly consistent with the main results for the **cropland**, **pasture-range**, and **forest** categories (tables 5 and I.1). When using the NLCD to classify land cover prior to a solar installation, 4 percent of solar sites are in **other**, compared with 13 percent when using the CDL (table 3). Further, the share in **developed** prior to installation is larger here (11 percent) than in the CDL analysis (6 percent). The smaller share of solar sites classified as other is likely because the main analyses use 3 years of the CDL to categorize land cover before an installation, and sites that transitioned between agricultural and nonagricultural categories during those years were classified as other. The NLCD categorization uses only 1 year of data, so, by construction, no observations transitioned between categories. Only sites in barren, wetlands, open water, woody wetlands, and herbaceous wetlands prior to installation were categorized as other.

In the NLCD analysis, a higher share of land is categorized as developed prior to and after installation compared to the CDL analysis (table 3). Using the CDL, the share of solar sites in developed increased slightly, from 6.3 percent before installation to 6.6 percent after installation. This small increase includes 0.8 percent of solar lands that shifted into developed as well as 78 percent of solar sites in developed that remained in the same category (table 3).[54] In the NLCD analysis, approximately one-third of solar lands were categorized as developed after installation, an increase of over 20 percentage points from the share prior to installation (table I.1). The increase was largely due to the high persistence of land in developed and shifts from agricultural land into developed. Twenty-four percent of solar land categorized as cropland and over 30 percent of solar land categorized as pasture-range prior to installation shifted into developed. In the CDL analysis, agricultural land that shifted out of agriculture instead shifted into other. This is noteworthy because of concerns regarding land use competition between solar development and farmland.

---

[54] The share that moved into developed includes 12.5 percent of sites that were in categorized as other, and 0.6 percent that were classified as crop and pasture-range prior to installation (table 3).

Table I.1

Land cover change associated with solar installations using NLCD, 2012–18

		Land cover category before installation				
	Land cover category	**Cropland**	**Pasture-range**	**Forest**	**Developed**	**Other**
Land cover category after installation	**Cropland**	75.1	0.9	0.5	0.8	1.1
	Pasture-range	1.3	67.1	20.8	0	1.1
	Forest	0.1	0.9	64.5	0	1.1
	Developed	23.5	30.7	13.7	99.2	6.5
	Other	0.1	0.4	0.5	0	90.2
	Share before	42.7	33.7	8.7	10.9	4.1
	Share after	32.5	25.0	6.0	32.6	3.9

NLCD = National Land Cover Database. Total number of solar projects = 2,255.

Note: The sample includes solar sites in rural areas of the contiguous United States. The land cover before an installation is the dominant land cover category within a 150-meter buffer for each site calculated using the most recent available year of the NLCD prior to installation. The land cover category after an installation is the dominant land cover category within a 150-meter buffer for each site in the next available year after installation. The other category includes the NLCD land cover classes of barren land, open water, woody wetlands, and emergent herbaceous wetlands. The pasture-range category includes the NLCD land cover classes of grass, pasture hay, and shrub.

Source: USDA, Economic Research Service using data from the NLCD (2011, 2013, 2016, 2019) (Dewitz & U.S. Geological Survey (USGS), 2021); 2019 U.S. Energy Information Administration (EIA) Form 860 (EIA, 2021a); and U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census, 2019).

For wind lands, the NLCD land cover change findings (table I.2) were consistent with the CDL analysis (table 2). In the NLCD analysis, wind turbines were largely sited on agricultural land, and there was limited land cover change after a wind development across all land cover categories (table I.2).

Table I.2

Land cover change associated with wind turbine installations using NLCD, 2012–18

		Land cover category before installation				
	Land cover category	**Cropland**	**Pasture-range**	**Forest**	**Developed**	**Other**
Land cover category after installation	**Cropland**	99.9	0.9	0.1	0	0
	Pasture-range	0.1	98.8	6.2	0	0.6
	Forest	0	0.2	93.7	0	1.2
	Developed	0	0	0	100.0	0
	Other	0	0	0	0	98.3
	Share before	57.4	38.1	3.7	0	0.7
	Share after	57.7	37.9	3.6	0.1	0.7

NLCD = National Land Cover Database. Total number of wind turbines = 23,827.

Note: The sample includes wind turbines in rural areas of the contiguous United States. The land cover before an installation is the dominant land cover category within a 150-meter buffer for each site calculated using the most recent available year of the NLCD prior to installation. The land cover category after an installation is the dominant land cover category within a 150-meter buffer for each site in the next available year after installation. The other category includes the NLCD land cover classes of barren land, open water, woody wetlands, and emergent herbaceous wetlands. The pasture-range category includes the NLCD land cover classes of grass, pasture hay, and shrub.

Source: USDA, Economic Research Service using data from the NLCD (2011, 2013, 2016, 2019) (Dewitz & U.S. Geological Survey (USGS), 2021); 2019 U.S. Energy Information Administration (EIA) Form 860 (EIA, 2021a); and U.S. Department of Commerce, Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line Shapefiles (U.S. Census, 2019).