Land Use Requirements of Solar and Wind Power Generation: Understanding a Decade of Academic Research

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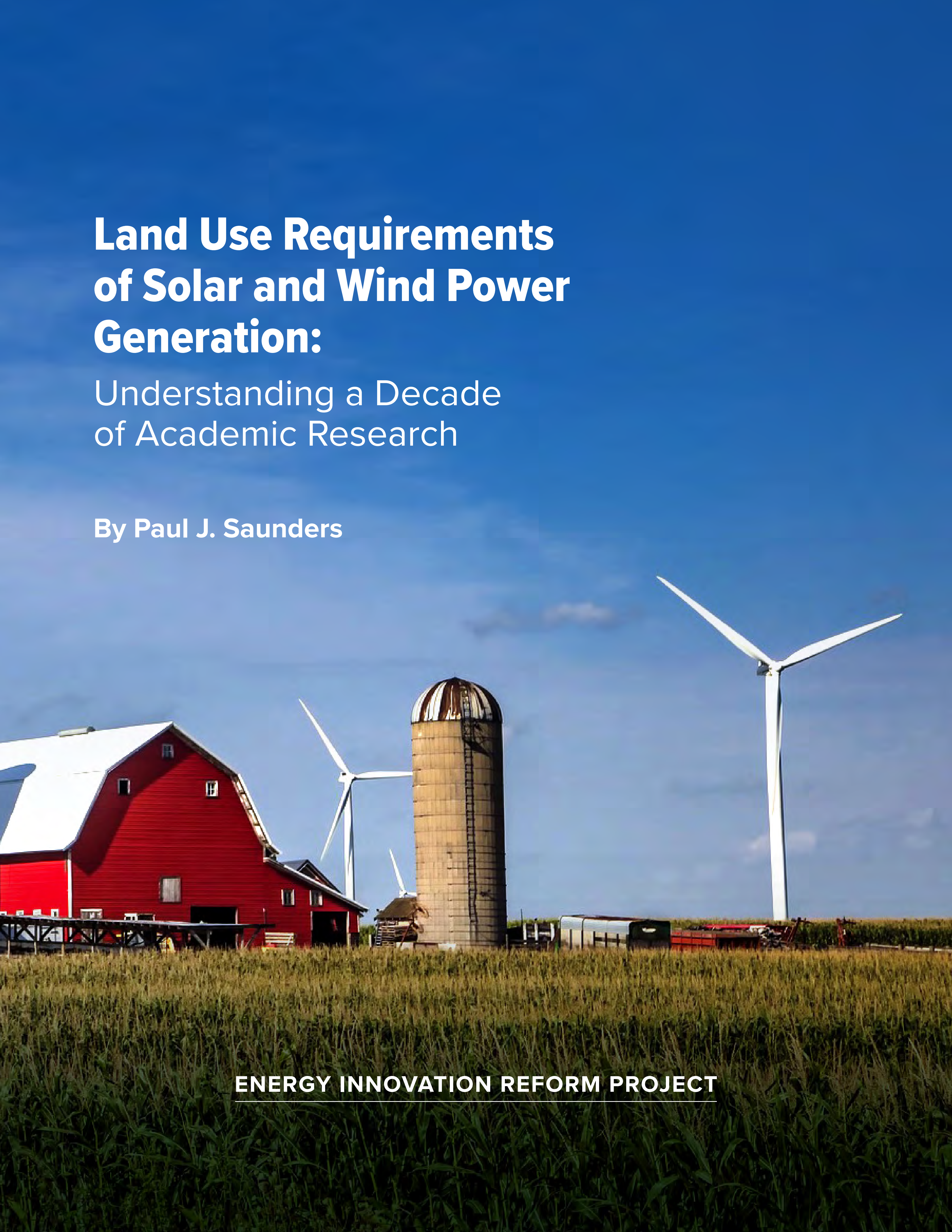
Energy Innovation Reform Project



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Energy Innovation Reform Project is a non-partisan non-profit organization dedicated to promoting policies that advance innovation in energy technologies and practices to improve the affordability, reliability, safety, and security of American energy supplies and our energy economy. EIRP was founded in Washington, DC in 2013. Its work combines policy reports, scholarly research, and economic modeling with creative efforts to bridge partisan differences over energy policy.

Contents

Acronyms

CSP	concentrating solar power
DOE	Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ERGI	Energy Resource Governance Initiative
EU	European Union
LCOE	levelized cost of electricity
MW	megawatt
MWh	megawatt-hour
NREL	National Renewable Energy Laboratory
OPEC	Organization of the Petroleum Exporting Countries
PV	photovoltaic
TW	terawatt
TWh	terawatt-hour
UNFCCC	United Nations Framework Convention on Climate Change
USGS	U.S. Geological Survey
W	watt
WWS	wind, water, and solar energy

Executive Summary

Solar and wind power technologies have improved significantly in the last decade, and their market share has expanded rapidly. Driven by both economics and policy, these trends are expected to continue, if not accelerate. While the economic and greenhouse gas emissions implications of these technologies have been much discussed, their land use impacts have received relatively little national attention.

This report seeks to contribute to public understanding of the land use issues related to solar and wind power in the United States. Toward that end, it reviews over 100 academic studies and U.S. government reports that address land use impacts of solar and wind power and presents key findings in an accessible format. The report draws upon research published during the 10-year period from 2009 to 2019.

Five central findings emerge from this literature review:

1. *There is no consensus on definitions and assumptions used in solar and wind land use analyses.* Quantitative analyses are hampered by challenges in collecting real-world data, as well as the absence of common definitions of terms and metrics. Assumptions about key factors such as projected electricity demand and technological performance vary widely, driving divergent conclusions.
2. *The potential space impacts of solar and wind facilities depend on many factors and can vary widely.* Geography, technology, and policy influence the nature and extent of the space impacts of solar and wind projects. Some locations have more favorable resources; some projects employ more land-intensive technologies. Conservation considerations, as well as the nature of public or private ownership, can also influence land use impacts.
3. *Solar and wind are likely to affect significantly more land than other electricity sources.* Fossil fuels and nuclear generation are vastly more power-dense than renewables; natural gas, for example, is roughly 80 times more power dense than solar power and 200 times as dense as wind. Even taking fuel extraction and life-cycle considerations into account does not change this fundamental picture.
4. *Solar and wind facilities are associated with significant quality impacts.* Despite their environmental appeal, renewable development—particularly wind power—does impact environmental quality in a variety of ways, including landscape fragmentation, bird and bat deaths, temperature changes, visibility and noise, and other environmental damage.
5. *Developing a 100% renewable energy system would be challenging from a land use policy perspective.* The land use impacts of renewable energies will depend greatly on the scale of our ambitions for the role that these resources play in the energy system. A power system that relies exclusively on wind, water, and solar generation will necessarily have much greater land use impacts than one that also uses more power-dense fuels; electrifying other sectors of the economy would increase demand, requiring a still-larger system. Studies suggest that there may be enough land to physically accommodate an all-renewable energy system—but

> the scale of the physical footprint could be daunting: according to one study, an all-solar energy system in the European Union (EU) would require 45% of the combined land area of the 27 EU countries. The same study found that an all-solar energy system in the United States would require over five times the total land area currently occupied by all settlements and infrastructure in America (Capellan-Perez, de Castro, and Arto 2017).

This report and its findings are not intended to encourage or discourage decisions to pursue new solar or wind generation projects. Rather, the goal is to provide clear research-based information to policymakers and citizens who must balance competing interests, values, and rights in making the best electricity choices for their communities.

This is particularly important in that land use debates surrounding electricity generation—among other forms of development—can cause political friction between urban and rural areas. Urban areas typically have higher electricity demand in smaller geographic regions that are less amenable to utility-scale solar and wind projects. Though some urban residents may perceive rural land as available for development, rural residents may have different perspectives and priorities for the land that surrounds them.

This report seeks to facilitate informed and civil debate on these important energy policy questions among all those interested in developing solar and wind power.

1. Purpose, Scope, and Methods

The dramatic expansion in America's solar and wind power generation over the last decade, in part a consequence of sharp decreases in costs of new solar and wind projects, has won increasing attention from experts, activists, officials, media, and consumers. Advocates, politicians, and others have proposed considerable further growth in renewable energy generation, primarily as a means to reduce the power sector's greenhouse gas emissions, especially carbon dioxide emissions from coal-fired power plants. The role that solar and wind energy could play in reducing emissions has become a topic of extensive public discussion, but less attention has been paid to other impacts of these technologies. Notably, solar and wind generation have a significant impact on land use—a topic that is often central to state and local policy and political debates surrounding solar and wind project development.

In America's federal system, land use decisions typically reside at the state level, the local level, or both, in accordance with state constitutions. As is the case with many other types of development, conflicting interests and values surrounding land use decisions for solar and wind facilities can create divisions within and between local governments, or between local and state governments. Informed and civil debate is the best means to address these controversies and to develop effective policies that stand over time.

In an effort to contribute to public debate on the continuing expansion of solar and wind generation in the United States, this report assesses academic and U.S. government research on the land use impacts of utility-scale solar and wind power projects and distills their findings in an accessible format. As land use is its principal focus, the report concentrates on onshore rather than offshore projects. Its underlying intent is to provide clear research-based information that may be helpful to state and local policymakers, stakeholders, citizens, and others interested in renewable energy policy.

This report is not an academic-style literature review. Rather, it aims to make academic findings accessible to a broad, nonacademic audience without a background in solar and wind energy, power markets, or mathematical modeling and other sophisticated quantitative research methods. It does not identify every academic study of wind and solar land use; instead, it presents broad conclusions from representative academic works after a thorough (though not exhaustive) review of journal articles and U.S. government reports addressing the land use impacts of wind and solar energy. The report draws upon review of over 100 academic studies produced during the last 10 years (2009–2019) as well as Department of Energy (DOE) reports. The reports were identified using Google Scholar and other academic search tools. Two external scholars reviewed this report—and offered valuable comments—prior to publication. The author alone is responsible for the report's contents, including any errors.

This report does not advise state or local policymakers whether to support or oppose solar and wind energy projects in their jurisdictions or elsewhere. Such decisions should naturally result from consideration of each jurisdiction's circumstances and each project's prospects for contributing to the energy, environmental, economic, social, and other goals established through that jurisdiction's political processes. Rather than offering advice, this report presents broad conclusions from academic research, explains key concepts and areas of uncertainty, and outlines real-world tradeoffs in order to help elected and career officials, citizens, and others engaged in energy and electricity policy make informed decisions.

This report begins with a brief review of key terms and concepts that appear throughout the text (section 2). Following this is an overview of America's electricity sector, which describes the way the United States generates electricity and the growing role of solar power, wind power, and natural gas–fired generation (section 3). The next section describes some of the policies and proposals that have supported expanding solar and wind generation and that could substantially increase their contribution to U.S. electricity supplies in the future (section 4). The longest section of the report then presents five broad findings from academic and government research related to the land use impacts of solar and wind power (section 5). Citations in the text are to the References; the full list of studies reviewed follows in the Appendix.

2. Key Terms and Concepts

This report divides land use impacts into three broad categories: **space impacts**, **time impacts**, and **quality impacts**.[1]

Space impacts refer to the land area that a given project directly occupies, including the land used for solar panels and wind turbine towers as well as access roads, service buildings, and other infrastructure. This land is also described as cleared or disturbed. *Total footprint* includes the space impacts as well as the land area between individual rows of solar panels or wind turbines that constitute a specific solar or wind facility.

Time impacts refer to the time period during which space impacts endure. They can be *permanent*, meaning that the space impacts last for the lifetime of the facility (and possibly longer), or *temporary*, meaning that the space impacts occur only during a portion of the facility's lifetime—often during the construction and decommissioning phases—beyond which the land can be used for other purposes or restored to its original condition or purpose. Unless otherwise stated, the space and quality impacts in this report are permanent.

Quality impacts refer to effects on natural or environmental systems (e.g., wildlife facing landscape fragmentation due to new access roads or other infrastructure, birds killed by wind turbines) and/or on human health or enjoyment of the land (e.g., landscape views, persistent noise). Academic sources often refer to these quality impacts as *indirect impacts*.

Land use efficiency describes the power per unit of land area (often measured in watts per square meter [W/m^2]) and is equivalent to *power density*; a higher value reflects a greater ability to generate power over a given area and therefore a smaller land requirement to generate a fixed rate of electricity. Conversely, **land use intensity** describes the land required per unit of power (often measured in square meters per megawatt [m^2/MW] of installed capacity or square meters per megawatt-hour [m^2/MWh] of electric generation). Here, a higher value reflects lower power production in a given area and therefore larger land area to generate a fixed amount of electricity. A technology with high land use efficiency (and thus high power density) has low land use intensity.

The land use efficiency (or intensity) of a given technology is a function of its **capacity basis** and **generation basis**. Capacity basis describes the nominal (nameplate) generating capacity of the electricity source at a point in time and indicates the maximum electricity generation possible from the facility if continually influenced by optimum conditions (e.g., summer sun at noon for a solar facility, constant fast winds for a wind facility). Generation basis describes what the facility actually generates over a defined period of time. The ratio of the generation basis to the capacity basis is the

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[1] This categorization of impacts draws heavily upon Paul Denholm et al. (2009).

capacity factor; in addition to being influenced by the consistency and intensity of sun and wind,[2] the capacity factor for solar panels and wind turbines will vary based on spacing, maintenance, technical characteristics, and other conditions that increase or decrease their operating efficiency.[3]

Levelized cost of electricity, or **LCOE**, is a statistic used to compare the costs of various types of electricity generation by dividing a power plant's lifetime costs by its lifetime electricity production. While LCOE can be a useful yardstick, it measures costs without valuing other generation attributes, such as the firm (consistent) power provided by nuclear and fossil fuel–fired plants, the relative flexibility of natural gas generation, or the zero-emission power provided by solar, wind, hydroelectric, and nuclear installations.[4] LCOE likewise does not include externalized costs, such as the costs of greenhouse gas emissions or other environmental or health impacts or the costs, of inherently intermittent solar and wind power for the overall electricity system.

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[2] Wind turbines require a certain threshold wind speed to begin generating electricity and will shut off at high speeds, making consistency especially important. The Department of Energy states that turbine controllers will start the equipment at wind speeds of 8 to 16 mph and shut it off at 55 mph. See Department of Energy, "The Inside of a Wind Turbine," https://www.energy.gov/eere/wind/inside-wind-turbine.

[3] According to the Energy Information Administration, in 2019 the average capacity factors of U.S. solar and wind power facilities were 24.5% and 34.8%, respectively. For comparison, the respective averages for nuclear, natural gas, coal, and hydropower were 93.5%, 56.8%, 47.5%, and 39.1%. See DOE (2020b).

[4] While generating solar, wind, hydroelectric, or nuclear power does not produce meaningful greenhouse gas emissions, building solar panels, wind turbines, hydroelectric dams, and nuclear reactors currently does produce emissions and is likely to do so for quite some time. These life-cycle emissions have been a topic of extensive study.

3. America's Evolving Electricity Sector: An Overview

America's utility-scale solar-powered electricity generation increased nearly 74 times between 2008 and 2018, a remarkable figure.[5] Utility-scale wind generation increased by only five times during that period, but it began from a much higher starting point than solar power; thus this fivefold increase pushed wind turbines past hydroelectric dams and made wind America's leading source of renewable generation in 2019 (EIA 2020d). Nevertheless, wind and solar still comprised only 7.3% and 1.8%, respectively, of U.S. utility-scale electricity generation in 2019, contributing to a total of 17.5% for all renewables (including hydroelectric power, biomass, and geothermal power) (EIA 2020b). Natural gas provided 38.4% of generation, coal 23.5%, and nuclear 19.7%, with various additional sources producing the minimal remainder (EIA 2020b).

Falling costs to build solar and wind generation have been the principal driver of their growing use. The investment firm Lazard (2019) reports that the levelized costs of crystalline solar photovoltaic (PV) and wind energy fell 89% and 70% respectively between 2009 and 2019. This means that if a solar PV project built in 2009 had a cost of $100 million over its lifetime, the same project would have a lifetime cost of just $11 million 10 years later—a truly remarkable improvement.

While Lazard (2019, 3) noted that federal tax credits remain an "important component" of LCOE calculations for renewable energy in the United States today,[6] the manufacturing efficiency increases that pushed costs downward have led developers in southern Europe (where sunshine is plentiful) to begin building solar facilities in some locations without subsidies or tax credits (Chediak and Eckhouse 2019).[7]

Photo credit: Steven Baltakatei Sandoval

The Chehalis Generation Facility, a natural gas power plant near Chehalis, Washington. Natural gas provided almost two-fifths of America's electricity in 2019.

In the United States, the substantial declines in the LCOE of solar PV and wind generation have made building utility-scale facilities for these two technologies increasingly attractive to investors, who are not responsible for their intermittency-related external costs. Wind power has been especially appealing, as LCOE values (including tax credits) can reach as little as $11 per MWh—increasingly competitive

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[5] Energy Information Administration, "Table 3.1.A. Net Generation by Energy Source: Total (All Sectors), 2008–2018," https://www.eia.gov/electricity/annual/html/epa_03_01_a.html.

[6] See Lazard (2019, 7) for solar and wind LCOE decreases relative to other electricity generation and Lazard (2019, 3) for the impact of the Investment Tax Credit (for solar power) and the Production Tax Credit (for wind power) on LCOE calculations.

[7] Spain, Italy, and Portugal are cited as leaders in unsubsidized solar projects.

with existing power plants on an LCOE basis (Lazard 2019, 6).[8] These declines in LCOE are important because they can encourage power plant developers to shut down other facilities before the end of their anticipated lives and replace them with wind or solar projects.

In fact, in 2019, U.S. operators retired almost 14,000 MW in coal-fired generation capacity while simultaneously building 9,100 MW in new wind capacity, 5,300 MW in new solar PV capacity, and 8,300 MW in new natural gas–fired capacity (EIA 2020c).[9] Some of these coal-fired plants had likely reached the end of their useful lives.

Like coal plants, nuclear plants are facing considerable financial stress from relatively inexpensive solar, wind, and natural gas. Costly regulatory requirements and higher fixed operating and maintenance expenses add to nuclear power's financial woes (Knickmeyer 2019). Between 2013 and 2020, 10 nuclear reactors closed prematurely, and another 5 are slated to shut down early between 2020 and 2025. In total, the 15 reactors avoided 57.9 million metric tons of carbon dioxide emissions per year, over 3% of total U.S. greenhouse gas emissions from the power sector in 2018 and more than Bolivia's total greenhouse gas emissions from all sources (Desai and McCallum 2020).[10]

Photo credit: Tony Fisher (Flickr)

New York's Indian Point Unit 2 nuclear power plant closed on April 30, 2020.

Relatively low project cost is not the only reason that solar, wind, and natural gas electric generation are growing simultaneously. Solar and wind power inherently depend on sunshine and wind speed and cannot generate the continuous ("firm") electric power that fossil fuel–fired power stations and nuclear plants deliver. As a result, building additional solar and/or wind generation requires simultaneously developing "peaker" natural gas power plants[11] or some other means to provide electricity when renewable resources are unavailable. Replacing a given quantity of firm capacity will thus require a larger amount of intermittent solar or wind capacity complemented with this peaker power.

By 2013, the combination of increasing domestic natural gas production[12] and relatively low prices[13] made natural gas turbines the preferred source of peaking power (EIA 2013). But according to projections in a 2018 study by GTM Research and Wood Mackenzie, decreases in the cost of utility-

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[8] According to Lazard's (2019) analysis, prior to the COVID-19 pandemic the LCOE of new subsidized onshore wind (including Production Tax Credits) ranged between $11/MWh and $45/MWh, compared to $26–41/MWh for existing coal plants and $27–31/MWh for existing nuclear plants. The LCOE of unsubsidized onshore wind varied from $28/MWh to $54/MWh.

[9] EIA (2020c) reported that "access to abundant natural gas supply from the Marcellus and Utica shale plays in Pennsylvania and Ohio" drove the increases in gas-fired generating capacity.

[10] The nuclear plants avoided 57.9 million metric tons of carbon dioxide emissions; the electricity sector produced 27% of America's 6,677 metric tons of carbon dioxide equivalent emissions in 2018. For power sector emissions, see Environmental Protection Agency, "Inventory of U.S Greenhouse Gas Emissions and Sinks," https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks. For emissions by country, including Bolivia, see Ge and Friedrich (2020).

[11] Peaker power plants derive their name from their role in producing power at times of peak demand; their principal characteristic is the ability to adjust output up (or down) rapidly in order to follow changes in demand. This makes peaker power plants well-suited to balancing the variable supply from solar and wind facilities.

[12] Energy Information Administration, "U.S. Natural Gas Gross Withdrawals," https://www.eia.gov/dnav/ng/hist/n9010us2A.htm.

[13] Energy Information Administration, "U.S. Natural Gas Electric Power Price," https://www.eia.gov/dnav/ng/hist/n3045us3a.htm.

scale battery storage could mean that batteries directly compete with natural gas–fired peaker plants by 2022.[14] Still, current battery storage technologies are suitable only in meeting intra-day variations in electricity supply and demand (EESI 2019), as opposed to the weekly, monthly, and seasonal variations that occur in systems with high percentages of solar and wind generation. This longer-term variability in supply and demand calls for either additional firm generation, new long-term electricity storage technologies, or overbuilding solar or wind capacity sufficient to ensure that even low generation periods can meet electricity demand.

In August 2020, rolling blackouts in California provoked debate about the integration of variable solar and wind power into the state's broader electricity system (Kahn and Bermel 2020). At this writing, California's electricity regulators are investigating the blackouts to produce a public report (Kramer 2020).

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[14] The unnamed study is cited in Newberry (2018).

4. Policies and Proposals to Promote Solar and Wind Generation

Federal and state policies are important drivers of expanding solar and wind generation in the United States and in turn force generation- and transmission-related land use decisions at the state and local level. Looking ahead, proposals to accelerate solar and wind power deployment will increase the scope and urgency of land use policy in communities across the United States. In this context, it is useful to review policies and proposals that promote these two renewable technologies.

Solar and wind power began to gain political momentum in the 1970s. Physicist Amory Lovins produced one of the most forceful early calls for heavy reliance on solar and wind energy, the 1976 *Foreign Affairs* article "Energy Strategy: The Road Not Taken?" Writing in the wake of the 1973 OPEC oil embargo, which dramatically increased U.S. energy prices, Lovins urged a turn away from what he termed a "hard" energy strategy based on "hard" technologies (such as coal, oil and gas, and nuclear fission). Instead, he recommended a "soft" approach based on "flexible, resilient, sustainable and benign" technologies. (Lovins, 77) Lovins argued that the "soft" technologies would "rely on renewable energy flows that are always there whether we use them or not, such as sun and wind and vegetation." According to Lovins, an evangelist for the small and simple, this approach would ensure that "energy supply is an aggregate of very many individually modest contributions" and that these resources are "relatively low-technology—which does not mean unsophisticated, but rather, easy to understand and use without esoteric skills" (Lovins, 78).

Lovins aimed less to reduce greenhouse gas emissions than to minimize broader human impacts on the global environment by reshaping human society. Nevertheless, efforts to promote solar and wind power accelerated following the 1992 United Nations Framework Convention on Climate Change (UNFCCC), a global agreement that acknowledged the problem of increasing temperatures and called upon its signatories to achieve "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference in the climate system" (UN 1992, article 2). President George H. W. Bush signed the UNFCCC at the Earth Summit in Rio de Janeiro; the U.S. Senate ratified it in October 1992.

Promoting solar and wind power as emissions-free energy has since become a core objective of many environmental advocacy groups seeking to combat climate change. For example, the Sierra Club's "Ready for 100" campaign calls for "affordable, community-based, and 100% clean, renewable sources of energy" and notes that "solar panels and wind turbines were some of the few climate solutions that a majority of people—regardless of geography or political affiliation—could get behind."[15] The advocacy organization 350.org similarly backs policies that "quickly transition to 100% renewable energy" and "increase the share of solar, wind and hydro energy dramatically."[16]

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[15] Sierra Club, "What Is Ready for 100?" https://www.sierraclub.org/ready-for-100/about-our-program.

[16] 350.org, "Climate Science Basics," https://350.org/science/.

A body of academic research has provided a foundation for policy proposals seeking to transform the U.S. electricity sector, and the entire U.S. energy system, to one powered largely or even solely by wind, water, and solar energy (WWS). This research has at times provoked debate no less intense than the political disputes surrounding U.S. energy and environmental policy.

Among the academic works pressing for a transition to a WWS-only energy system, the research of Stanford University professor Mark Z. Jacobson and multiple collaborators is perhaps the best known, due both to its influence and the controversy it has generated. Jacobson's foundational work on this topic, with Professor Mark A. Delucchi of the University of California–Davis, was an ambitious two-part 2011 article, "Providing All Global Energy with Wind, Water, and Solar Power" (Jacobson and Delucchi 2011; Delucchi and Jacobson 2011). Because solar and wind power are variable, this approach relies significantly on hydroelectric power to balance their availability, a topic Jacobson and colleagues explored in further detail in a U.S.-focused paper (Jacobson et al. 2015). That work prompted a critique cosigned by 21 scholars who alleged "significant shortcomings" in Jacobson's study: they asserted that it "used invalid modeling tools, contained modeling errors, and made implausible and inadequately supported assumptions" (Clack et al. 2017, 6722).

Notwithstanding the work of those who advocate for WWS-only energy systems, few academic researchers argue that the United States can reliably and affordably replace its current electric power generation fleet exclusively with solar and wind power. A 2018 review of 40 studies of pathways to "deep decarbonization" (defined as an 80–100% reduction in carbon dioxide emissions) found that the most affordable pathways "include a substantial share of firm low-carbon generation in their lowest cost resource portfolio" in addition to variable solar and wind (Jenkins, Luke, and Thernstrom 2018, 2508). The review points out that this firm low-carbon generation requires resources in addition to geothermal energy and existing hydropower, since those two resources are "severely constrained in most models due to available sites suitable for expansion."

While neither the federal government nor any state governments have committed to electricity systems based solely on wind, water, and solar power, deployment of solar and wind generation has been significantly assisted by legislation, regulation, and policies at both levels. In America, three main efforts are among the most visible: federally funded research to develop and improve solar and wind power technologies and to assess their role and impacts (supported overwhelmingly through the DOE), federal tax credits to support solar and wind projects (primarily through the Investment Tax Credit for solar projects and the Production Tax Credit for wind), and widespread state and local programs to encourage solar and wind energy. A variety of proposed federal policies would further expand solar and wind power.

Federal research on solar and wind power

At the federal level, DOE's Office of Science and Office of Energy Efficiency and Renewable Energy (EERE) are responsible for basic and applied research, respectively.[17] The EERE also oversees the National Renewable Energy Laboratory (NREL) in Golden, Colorado, though other national laboratories also conduct research on solar and wind power. In addition to its scientific research, NREL publishes technical studies concerning solar and wind energy, including reports that compare their land use requirements to nuclear- and fossil fuel–generated electricity. These include NREL's 2009 study *Land-*

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[17] The Office of Science describes itself as "the nation's largest supporter of basic research in the physical sciences, the steward of 10 of the Nation's national laboratories, and the lead federal agency supporting fundamental research for energy production and security." Department of Energy, "About the Office of Science," https://www.energy.gov/science/about-office-science. The mission of the Office of Energy Efficiency and Renewable Energy is "to create and sustain American leadership in the transition to a global clean energy economy." Department of Energy, "About the Office of Energy Efficiency and Renewable Energy," https://www.energy.gov/eere/about-office-energy-efficiency-and-renewable-energy.

The National Renewable Energy Laboratory in Golden, Colorado.

Use Requirements of Modern Wind Power Plants in the United States (Denholm et al. 2009) and its 2013 report *Land-Use Requirements for Solar Power Plants in the United States* (Ong et al. 2013). The U.S. Congress appropriated $7 billion to the Office of Science and $2.8 billion to EERE for the 2020 fiscal year; these amounts include all programmatic and management expenses for these offices, not only those related to solar and wind energy.[18]

Federal policies promoting solar and wind power

The federal government promotes solar and wind power in a variety of ways, most visibly through tax credits that encourage their development. The U.S. Congress Joint Committee on Taxation projects that the solar Investment Tax Credit will cost a total of $20.8 billion during 2019–2023, while the wind Production Tax Credit will cost a total of $17.9 billion (Joint Committee on Taxation 2019). Although the solar Investment Tax Credit for individuals will expire at the end of 2021, commercial entities currently enjoy a permanent 10% tax credit on their investments.[19]

The Production Tax Credit provides between 1 cent and 1.9 cents per kilowatt-hour to wind power generators for 10 years, with the amount based on the date when construction began, and is currently slated to expire at the end of 2020.[20] The federal government also offers a wind Investment Tax Credit, which provides a credit of 12–18% for large turbines and 22–30% for small turbines (DOE 2020a). DOE suggests that the wind Investment Tax Credit is most appropriate for offshore wind (large turbines) and distributed generation (small turbines). This credit is likewise slated to expire at the end of 2020.[21]

State policies promoting solar and wind power

Regulatory standards requiring increasing shares of low or zero-emission electricity are a common instrument to spur development of solar and wind power. A large majority of America's states, districts,

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[18] Congress.gov, "H.R. 1865 – Further Consolidated Appropriations Act, 2020," https://www.congress.gov/bill/116th-congress/house-bill/1865/text?q=%7B%22search%22%3A%5B%22energy+department+appropriate%22%5D%7D&r=5&s=9.

[19] Solar Energies Industry Association, "Solar Investment Tax Credit (ITC)," https://www.seia.org/initiatives/solar-investment-tax-credit-itc.

[20] Construction must begin before December 31, 2020. See Department of Energy, "Production Tax Credit and Investment Tax Credit for Wind," https://windexchange.energy.gov/projects/tax-credits#:~:text=The%20Production%20Tax%20Credit%20(PTC,generation%20for%20utility%2Dscale%20wind.

[21] Construction must begin before December 31, 2020. *Ibid.*

and territories have thus far established clean and/or renewable energy standards in various forms; those jurisdictions include 37 U.S. states and the District of Columbia.[22] Eight states—California, New York, Virginia, Hawaii, Maine, Nevada, New Mexico, and Washington—have committed to 100% clean energy goals.[23]

Legislative and regulatory definitions of renewable and clean energy are complex and diverse; they necessarily respond to local circumstances, including available resources, costs, public preferences, and politics.

In California, for example, the California Energy Commission has published a 112-page guidebook explaining eligibility under the state's Renewables Portfolio Standard. It defines "renewable" as "a power source other than . . . nuclear energy" and not derived from "the operation of a hydropower facility greater than 30 megawatts or the combustion of fossil fuels, unless cogeneration technology . . . is employed in the production of such power"[24] (California Energy Commission 2017, 85). Notably, some environmentalists have opposed classifying large hydropower projects as renewable; they fear that counting the projects toward the state's renewables target would reduce pressure to build solar and wind facilities, and they have concerns about large dams' environmental impacts (Roth 2019) and greenhouse gas emissions (Weiser 2016). Also significant is California's inclusion of biomass, which some have dismissed as "renewable" but not "clean," in that combustion of wood pellets or other biomass fuels can depend on fossil fuels (for producing fertilizers and planting/harvesting/transporting the biomass crops) while also producing significant greenhouse gas emissions.[25]

Federal policy proposals

At the federal level, the best-known proposal to expand solar and wind generation is the Green New Deal,[26] released formally in February 2019 by newly elected Rep. Alexandria Ocasio-Cortez (D-NY) and Sen. Edward Markey (D-MA) (Kurtzleben 2019). Though an earlier Green New Deal proposal from Jill Stein, the 2012 Green Party presidential candidate, explicitly sought to eliminate fossil fuels and nuclear power (Schroder 2019), the 2019 Green New Deal resolution calls for "meeting 100 percent of the power demand in the United States through clean, renewable, and zero-emission energy sources."[27] As stated, this goal could in principle include nuclear energy and fossil fuel generation with carbon capture and other emissions controls. Still, after the resolution's introduction, over 600 climate and environmental advocacy groups

Photo credit: Senate Democrats (Flickr)

Rep. Alexandra Ocasio-Cortez (center) and Sen. Edward Markey (right) present the Green New Deal.

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[22] See Database of State Incentives for Renewables & Efficiency, https://programs.dsireusa.org/system/program?type=38&. See also Clean Air Task Force (2020).

[23] Sierra Club, "Check Out Where We Are Ready For 100%," https://www.sierraclub.org/ready-for-100/map?show=committed.

[24] Cogeneration technology refers to combined heat and power plants, which simultaneously generate electricity and produce heat, with the heat typically used for industrial processes or district heating.

[25] Progressive filmmaker Michael Moore's documentary *Planet of the Humans* is a recent visible example of this criticism of biomass energy. See https://planetofthehumans.com/.

[26] H. Res. 109, "Recognizing the Duty of the Federal Government to Create a Green New Deal," https://www.congress.gov/116/bills/hres109/BILLS-116hres109ih.pdf.

[27] H. Res. 109, "Recognizing the Duty of the Federal Government to Create a Green New Deal," 7, https://www.congress.gov/116/bills/hres109/BILLS-116hres109ih.pdf.

signaled their strong opposition to nuclear energy and fossil fuels (including with carbon capture) in an open letter (Meyer 2019). Shortly after the 2018 midterm election, Rep. Ocasio-Cortez declared her support for “100% renewable energy,”[28] though the Green New Deal resolution took the more moderate position described here.

While endorsing a technology-neutral approach, the Democratic Party’s 2020 Platform calls for installing 500 million solar panels and 60,000 wind turbines within five years (Demconvention.com 2020, 51),[29] which would require building hundreds of new large solar farms (Bryce 2020)[30] and doubling the number of wind turbines in America.[31]

Due to their declining costs, solar and wind power appear likely to remain attractive in many parts of the United States and will be the focus of ongoing land use debates and decisions across the country. New federal and state policies could intensify solar and wind development and the land use questions surrounding such an expansion. With this in mind, this report next presents its findings from a review of academic literature and governments reports.

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[28] On Twitter, Rep. Ocasio-Cortez wrote that she supported reinstating a House of Representatives select committee to address climate change and supported activists calling for the committee to have a “mandate to draft a Green New Deal for 100% renewable energy.” @ AOC, November 13, 2018, 12:08 p.m., https://twitter.com/AOC/status/1062391746036948993. The activists had occupied House Speaker Nancy Pelosi’s office.

[29] The 2020 Democratic Party Platform explicitly endorses using “all zero-carbon technologies, including hydroelectric power, geothermal, existing and advanced nuclear, and carbon capture and storage.”

[30] Bryce notes that one of America’s largest solar projects has 1.7 million solar panels; installing 500 million solar panels would require 294 facilities of this size.

[31] U.S. Geological Survey (USGS), “How Many Turbines Are Contained in the U.S. Wind Turbine Database?” https://www.usgs.gov/faqs/how-many-turbines-are-contained-us-wind-turbine-database?qt-news_science_products=0#qt-news_science_products. The USGS Wind Turbine Database included 58,000 utility-scale wind turbines as of January 2019. According to USGS, America has added an average of 3,000 utility-scale wind turbines per year since 2005; adding 60,000 in five years would require building 12,000 wind turbines per year, at four times the 15-year average rate. USGS, “How Many Wind Turbines.”

5. Impact of Solar and Wind Power on Land Use: Key Research Findings

As described above, this report draws upon a careful review of over 100 academic studies and government reports published over a 10-year period. The studies vary in geographic scope from the global to the local-community level and consist mainly of national and subnational studies focused on the United States and Europe. The following principal conclusions emerged from that review:

1. There is no consensus on definitions and assumptions used in solar and wind land use analyses.
2. The potential space impacts of solar and wind facilities depend on many factors and can vary widely.
3. Solar and wind are likely to affect significantly more land than other electricity sources.
4. Solar and wind facilities are associated with significant quality impacts.
5. Developing a 100% renewable energy system would be challenging from a land use policy perspective.

The following sections report these conclusions in detail, with reference to many but not all of the reviewed studies. One underlying challenge across studies is that some data are public, while other data are private. For example, in a confidential interview, one researcher told us that scholars must typically sign nondisclosure agreements with utilities or other operators to obtain detailed generation statistics. As a result, modeling and other quantitative assessments often rely upon capacity figures that do not fully reflect real-world conditions.

Based on our research, no generation data from an operational solar or wind facility has ever been made publicly available at a finer temporal resolution than the one-month sums reported by the U.S. Energy Information Administration (EIA) or than the hourly but regional aggregates in California[32] and Texas.[33] Thus any calculations, modeling, and other quantitative assessments at the scale of a solar or wind facility are at best based on these monthly averages; while better than capacity-based estimates, this work does not fully reflect the intermittency of solar and wind generation.

Finding 1: There is no consensus on definitions and assumptions used in solar and wind land use analyses.

Complex quantitative analysis like that in many studies of land use in solar and wind projects requires precise definitions as well as many assumptions. In practice, researchers use varying definitions

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[32] California ISO provides grid information for each generation source at five-minute intervals. See California ISO, "Managing Oversupply," http://www.caiso.com/informed/Pages/ManagingOversupply.aspx, accessed September 20, 2020.

[33] Texas ERCOT provides grid information reports on solar and wind output. See ERCOT, "Generation," http://www.ercot.com/gridinfo/generation, accessed September 20, 2020.

and assumptions that influence findings and at times limit comparisons among studies without common definitions and assumptions. The text below illustrates some of the important definitions and assumptions encountered during this project.

Varying definitions

Varying definitions frustrate direct comparisons between solar, wind, and other electricity sources. One of the most profound definitional issues is deciding whether land is "used" or not. Most obviously, wind turbines within a given facility are widely distributed across a large area and are often sited on land used for other purposes, such as agriculture. Defining the total footprint as used may overstate a wind project's space impact, while using a narrower definition—such as the land occupied by wind turbine pads, access roads, and transmission lines—may understate or ignore quality impacts throughout the total footprint area. Some estimates suggest that 3–5% of the total footprint in wind projects is cleared land, which provides some perspective on the gap between space impact and total footprint for wind projects (McDonald et al. 2009).[34]

In practice, there are many ways to define a wind project's total footprint, including using the boundaries of the project site (the most expansive) or mathematically defined buffer areas around clusters of turbines (less expansive, but varying, based on the distribution of turbines at the project site and the mathematical method used) (Denholm et al. 2009).[35]

Regarding wind sites, a 2009 NREL study found that individual wind turbines accounted for only 10% of permanent space impacts, with access roads comprising nearly 80% and the balance used for substations, transmission, and other purposes (Denholm et al. 2009). Hence counting only wind turbine concrete pads would substantially underestimate the cleared land at a wind site.

The dominance of access roads among wind facilities' space impacts produces significant habitat fragmentation (described below in the discussion of quality impacts). Wind turbines may have other quality impacts throughout the total footprint area. Deciding how to define a wind project's land use is thus complex and subjective.

Even for solar, nuclear, and fossil fuel facilities, where researchers more comfortably rely on total footprint data, a project's land area can include significant "undisturbed" land, such as land set aside for potential expansion or the buffers between the facility and inhabited areas. Nuclear and fossil fuel plants can incorporate lakes or reservoirs used for cooling that may remain available for other uses (Smil 2016).

Another key question is whether to count land used outside the boundaries of a generating facility and, if so, whether to include only the land required for operating activities (for example, the land for transmission lines or access roads) or to assess land use for the full life cycle of a generating facility, including activities before and after its operational life. These life-cycle calculations could include land used for various purposes: 1) to extract and process fuels like coal, oil, natural gas, and uranium, 2) to extract and process the materials necessary to build generating plants, solar panels, wind turbines, and other equipment, 3) to manufacture this generating equipment, 4) to deliver fuels and materials to factories or generating plants, 5) to transmit electricity from the generating site to consumers, and 6) to dispose of waste. Academics have not developed widely accepted approaches to many of these issues.

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[34] McDonald et al. (2009) notes for comparison that roughly 5% of the total footprint is cleared for geothermal, natural gas, and oil wells at extraction sites. Fossil fuel power plants are more compact.

[35] Denholm et al. (2009) illustrates three possible approaches to shaping the buffer areas.

When considering land use at the state or local levels, it is important to recognize that many if not most life-cycle space impacts may take place in other jurisdictions, or (in the case of mines, factories, and roads built for other purposes) may have already occurred before decisions regarding construction of a new generation project. Thus a decision to pursue one or another type of electricity generation in a state or locality may not generate broader life-cycle space impacts within that jurisdiction other than those associated with transportation and transmission to and from a project site. In many situations, fuels and machinery will arrive from another jurisdiction and waste will go elsewhere (if not stored on-site, with no additional space impacts). For example, Bloomberg Green reports that just three landfills in the United States accept wind turbine blades, which are currently quite difficult to recycle or reuse (Martin 2020).

Still, ignoring land use requirements in other jurisdictions is sometimes impossible. Transmission-related land use decisions made outside the state or locality that is considering a new generating facility can in some cases determine the project's success or failure. State and local officials, stakeholders, and citizens are in the best position to assess which life-cycle land use considerations may be relevant in their jurisdictions.

Varied assumptions

A further challenge to understanding land use implications for solar and wind energy (as well as other forms of power generation) is that academic studies include varying assumptions, both quantitative and qualitative.

Future electricity demand is a core assumption in most studies that forecast solar and wind generation and related land uses. The EIA produces widely used forecasts of electricity generation and renewable electricity generation in its *Annual Energy Outlook*.[36] However, the EIA assumes only small additions to overall U.S. electricity demand in the coming decades (EIA 2020a), despite the possibility that use of electric vehicles and the electrification of buildings and industrial processes will significantly increase electricity demand.[37] The *Annual Energy Outlook* is conservative in forecasting electric vehicle adoption and the electrification of other sectors of the economy, such as the industrial sector, where firms need heat as well as power and often build their own fossil-fuel combined heat and power plants. In contrast, academic studies modeling pathways to 100% WWS energy systems or other high-renewable scenarios assume much higher electricity demand to meet these and other needs, and the land use consequences of those scenarios would necessarily be proportionately greater.

Many academic assessments of the land use requirements associated with solar and wind power rely upon installed capacity rather than actual generation; those based on real-world generation typically use historical generation to predict future generation. This approach can understate solar and wind potential if actual generation figures include older facilities that are less efficient than newer and potential future technologies. It can also overstate solar and wind potential if project developers select the best sites first and must then build facilities in decreasingly desirable locations as solar and wind expand (Shum 2017).

To understand the types of assumptions that can drive outcomes in academic research, consider the critiques of Mark Jacobson's effort to demonstrate that the United States could cost-effectively transition to a 100% WWS energy system. According to Jacobson's critics, such assumptions included "replacement of our current aviation system with yet-to-be developed hydrogen-powered planes"; "the availability of multiweek energy storage systems that are not yet proven at scale . . . at a capacity twice that of the entire United States' generating and storage capacity today"; and "underground

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[36] The 2020 edition is available at https://www.eia.gov/outlooks/aeo/.

[37] See NREL's multi-part *Electrification Futures Study* (Jadun et al. 2017).

thermal energy storage (UTES) systems deployed in nearly every community to provide services for every home, business, office building, hospital, school, and factory in the United States" (Clack et al. 2017, 6723). Jacobson's study also assumed considerable expansions of hydroelectric capacity, the production and use of hydrogen, transmission expansion and a nationally integrated grid, and cost-free time shifting of electricity demand to respond to variable supplies (Clack et al. 2017).

The point here is not to find fault in Jacobson's work, but rather to show that scholarly assumptions vary widely and are often contested. Proposed energy systems based on differing assumptions often differ significantly in their land use requirements.

Finding 2: The potential space impacts of solar and wind facilities depend on many factors and can vary widely.

All solar and wind energy projects are not created equal; many factors shape the space impacts of real-world solar and wind developments, including geography, technology, and policy.

Geography

Geography is among the most influential forces that shape solar and wind projects. Geography determines the availability of the sunlight and moving air masses upon which project development decisions, and eventual power generation, depend. NREL provides extensive online resources and tools to evaluate solar irradiance (energy received from the sun) and wind speeds in the United States.[38] In the contiguous United States, the highest solar irradiance is in the Southwest, while the lowest is in the states along the U.S. border with Canada. The fastest onshore wind speeds (at 100 m above ground level) are in a band extending north to south from North Dakota and Minnesota through Kansas and Oklahoma to west Texas. The lowest wind speeds are in the West, the Northeast, the Mid-Atlantic, and the Southeast. Offshore wind speeds are highest off the Pacific coast of southern Oregon and northern California, off the Atlantic coast between Maine and New York City, and in Lake Superior near the center of Michigan's Upper Peninsula. Solar or wind facilities in regions with less suitable sunlight or wind will have lower power densities and thus higher land use requirements than equivalent facilities in sunnier or windier locations.

Land ownership can also influence land use efficiency. In a study of 160 utility-scale solar energy projects in California, researchers found that installations on privately owned land had considerably higher capacity-based land use efficiency than those on public land: 36.8 W/m^2 (plus or minus 2.7 W/m^2) compared to 25.4 W/m^2 (plus or minus 3.5 W/m^2) (Hernandez, Hoffacker, and Field 2014). They proposed three possible reasons for this difference: 1) private landowners have stronger economic incentives to minimize land use, 2) public projects could be older, using less efficient technologies, and 3) the geography of public lands might require more space—e.g., if those lands are farther from existing transmission lines and need additional land for transmission.

Technology

Technology choices are also important in shaping the space impacts of solar and wind developments. Today, utility-scale solar power facilities typically use either solar PV systems, in which solar panels directly transform the sun's energy into direct current electricity, or concentrating solar power (CSP)

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[38] For example, see the Federal Energy Management Program Screening Map at https://www.nrel.gov/gis/solar.html, which provides detailed information on solar and wind resources as well as resources suitable for other forms of renewable energy, including hydroelectric, geothermal, wave power, and biomass.

A fixed-tilt solar array, with spacing between rows.

systems, in which large arrays of mirrors collect and concentrate the sun's energy to produce heat to spin a turbine or carry out industrial processes. In either case, solar collectors that tilt and track the sun—constantly ensuring that the sun's rays are perpendicular to the surface of the panel—gather more energy than fixed-tilt systems, which are angled based on latitude but do not track the sun.

According to a 2013 NREL study of land use by solar power projects in the United States, fixed-tilt solar PV systems require an average of 13% less land than single-axis tracking systems on a capacity basis, but use an average of 15% more land based on actual generation output per unit land area (Ong et al. 2013). These differences reflect the fact that fixed-tilt solar PV systems can be more tightly packed than single-axis tracking systems, but they operate less efficiently because they do not track the sun's movement across the sky; according to the NREL study, single-axis tracking can increase generation by 12–25% compared to fixed-tilt systems. The NREL assessment also finds that CSP facilities are broadly comparable with large (over 20 MW capacity) utility-scale PV installations in their land use requirements.

With respect to wind power, height above ground is an important factor, although rotors, blades, controls, and the turbine's drivetrain also contribute to efficiency and power output (DOE 2008). For example, in large portions of the United States, increasing the height of a wind turbine hub from 80 m to 110 m above ground increases the annual average wind speed between 0.5 and 1.0 meters per second (m/s). Raising the hub from 80 m to 160 m increases the annual average wind speed between 1.0 and 1.5 m/s (Lantz et al. 2019).

Higher average wind speeds also allow for larger turbines that generate more electricity and operate more consistently, with a higher capacity factor, and potentially at lower cost (Lantz et al. 2019).[39] Just as increasing solar irradiance on solar panels boosts their output and reduces their space impacts, increasing the speed of the wind driving a turbine increases a wind project's land use efficiency and decreases its land use intensity.

In addition to the choice among specific solar or wind technologies, the choice between solar and wind also has important land use consequences. Most obvious is the difference in spacing between individual solar panels and wind turbines: solar panels are typically in densely packed rows, with necessary space for cleaning and other maintenance between them, while wind turbines must be

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[39] Wind turbines generate electricity only when they operate above a threshold wind speed; higher average wind speeds can help to keep the wind above that threshold more frequently and regularly.

much farther apart to avoid “turbine-to-turbine” and “turbine-to-atmosphere” interference (Miller and Keith 2018b). The side-to-side spacing between wind turbines is typically around four times the rotor diameter, and the front-to-back spacing is about 10 times the diameter (Trainor, McDonald, and Fargione 2016). As a result, when solar and wind projects are compared based on their total footprint they are found to have very different average power densities: a 2018 study found the average power density of 1,047 solar power plants to be 5.7 W/m^2, as opposed to an average of just 0.9 W/m^2 for 430 wind projects (Miller and Keith 2018b).[40]

Policy

Policy is also important in determining space impacts of wind and solar facilities. For example: policy determines whether buffer areas around solar and wind installations are larger or smaller, and hence affects the overall land area needed for a given project. Perhaps most significantly, policies can increase or decrease the amount and quality of suitable land available for solar and wind development.

In a major study assessing the intersection between conservation policy and clean energy policy in California and 10 other western states, The Nature Conservancy found that California’s land protections could affect the balance among solar, wind, and battery storage, and would likely increase the costs of California’s 100% zero-carbon policy (Wu et al. 2019, 2). The study noted that conservation-driven siting constraints would likely force wind power projects to develop sites with lower wind speeds (and thus lower land use efficiency) while simultaneously requiring additional battery storage. California could mitigate these impacts by importing zero-carbon electricity from one or more of the 10 western states included in the study, although this approach “requires significantly more transmission infrastructure and can have greater land use impacts under scenarios with lower levels of environmental protections” (Wu et al. 2019, 2).

Finding 3: Solar and wind are likely to affect significantly more land than other electricity sources.

Despite the challenges that data, definitions, and assumptions impose in making comparisons, academic research demonstrates persuasively that solar and wind generation affect more land than fossil fuel or nuclear generation. A 2018 study by two scholars at Leiden University looked at 54 peer-reviewed studies and government reports assessing average power density of electricity generation in the United States (Zalk and Behrens 2018). The study found natural gas generation to have the highest average power density, followed closely by nuclear, oil, and coal and distantly by solar, geothermal, wind, hydro, and biomass.

Figure 1 is adapted from this study to show the median power densities for each technology; see the original study (Zalk and Behrens 2018) for a more detailed chart that includes power density ranges for each technology and the number of studies upon which each median relies. Figure 1 presents values for fossil fuel and nuclear generation and renewable generation, with the caveat that wind values are derived from total footprint. Two charts are presented, rather than one, due to the considerable gap in power densities between the two groups of technologies.

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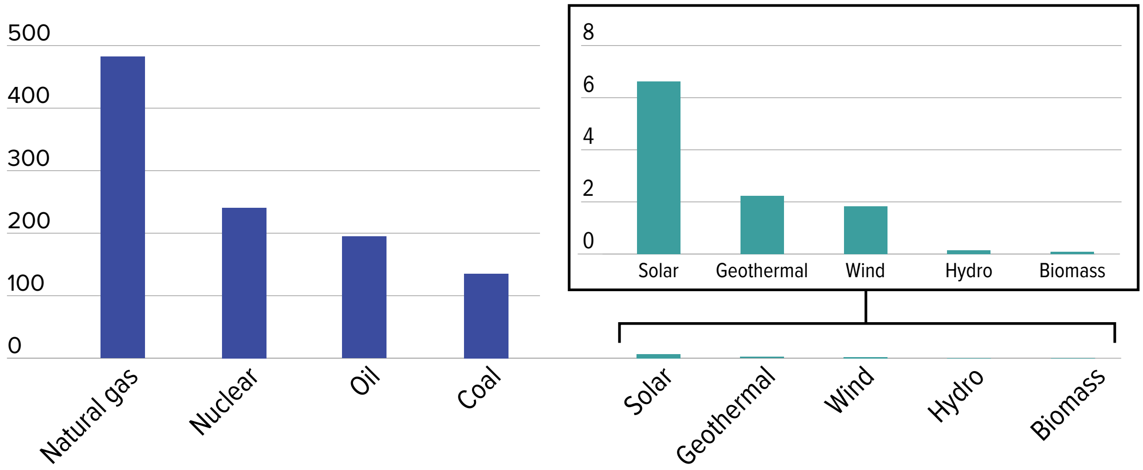
[40] The wind figure was corrected to the value cited above in Miller and Keith (2019).

Figure 1. Median Power Densities of Fossil-Fuel and Nuclear Generation & Renewable Electricity Generation (W/m²)



Source: Adapted from Zalk and Behrens 2018.

Figure 1 illustrates that the median power density of natural gas generation is roughly 80 times that of solar generation and well over 200 times that of wind electricity. Hydroelectric dams tend to have low power densities because of the large areas flooded to create reservoirs. Biomass facilities tend to have low power densities because biomass fuels require growing crops on land; their power density is thus constrained by solar irradiance and reduced further by efficiency losses in converting crops to fuel to power.

Fossil fuel and nuclear generation facilities require mined or extracted fuels, unlike solar, wind, geothermal, and hydro. Nonetheless, even accounting for the land use impacts of mined or extracted fuels, researchers found that land use intensities of renewable generation are greater than those of fossil fuel and nuclear generation.

In its Third National Climate Assessment, the U.S. Global Change Research Program[41] reported projections of the land use intensity of several modes of electricity generation in 2030 (Melillo, Richmond, and Yohe 2014, 266). These projections, drawn from a study by Nature Conservancy scientist Robert McDonald and colleagues and using an Energy Information Administration model,[42] are shown in figure 2. The estimates incorporate both the footprint of the power plant and land affected by energy extraction—that is, the land required for coal mines, oil and gas wells, and uranium mines, as well as the land needed for biomass crops. Figure 2 excludes the values for biodiesel and ethanol, as these are principally transportation fuels. The numbers reflect square kilometers per terawatt-hour (km²/TWh) per year; one terawatt-hour is 1,000 gigawatt-hours, 1 million megawatt-hours, or 1 billion kilowatt-hours.

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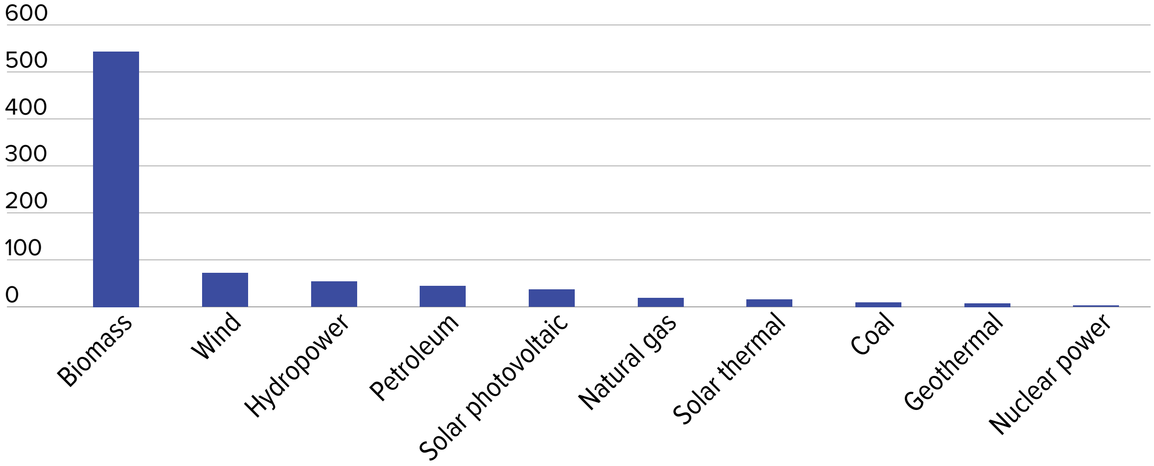
[41] The U.S. Global Change Research Program is a congressionally mandated collaboration among 13 federal agencies that "conduct or use research" on climate change. U.S. Global Change Research Program, "About USGCRP," https://www.globalchange.gov/about.

[42] The report states that its chart is adapted from McDonald et al. (2009). In the original source, these figures are reported as midpoints between high and low estimates, with margins of error.

Figure 2. Projected Land Use Intensity of Electricity Generation in 2030 (km²/TWh/year)



Source: Melillo, Richmond, and Yohe 2014, based on McDonald et al. 2009.

While this report is not concerned with biomass power, figure 2 illustrates the extreme land use requirements if America were to cultivate biomass for electricity on a large scale. The 4,178 TWh of electricity generated by U.S. utility-scale facilities in 2018[43] would require almost 2.3 million km² of land from a total U.S. land area of 9.5 million km² for a 100% biomass electricity system.[44]

Setting biomass aside, figure 2 shows clearly the disparities in land use intensity between coal and nuclear power on the one hand, and solar PV and wind on the other, even when incorporating the land required to obtain fossil fuels and uranium. The figure also suggests that should the United States continue to replace coal-fired power and nuclear plants with natural gas, wind, and solar electricity, the space and quality impacts of our national electricity systems could increase substantially.

Moreover, while these land use intensity statistics include land to extract fuels, they do not incorporate the land required to extract metals and minerals for construction of the generating facilities. Stanford's Mark Jacobson and a colleague have estimated the number of plants or devices necessary for a 100% WWS energy system in the United States, based on projected total U.S. energy demand in 2030. Assuming that solar and wind provide 90% of that energy, hydropower provides 4%, and the remainder is from wave, tidal, and geothermal power, they estimate that the United States would require 590,000 wind turbines (each with 5 MW capacity), 110,000 wave devices, 830 geothermal plants, 140 hydroelectric plants (of which 70% are already in place), 7,600 tidal turbines, 265 million rooftop solar PV systems, 6,200 solar PV plants, and 7,600 solar CSP plants (Jacobson and Delucchi 2011).

For perspective on the resources necessary to construct the generation facilities proposed in the Jacobson study, tables 1 and 2 show the materials requirements (excluding fuel) for electricity-generating technologies, as published in the Department of Energy's 2015 *Quadrennial Technology Review* (DOE 2015, 390). Table 1 shows materials requirements for coal, natural gas combined cycle, and nuclear pressurized water reactors, while table 2 shows requirements for silicon solar PV, wind, and hydro, which DOE reports as including materials for upstream energy collection. Values are reported in tons per terawatt-hour and are based on generation rather than capacity.

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[43] Energy Information Administration, "Table 3.1.A. Net Generation by Energy Source: Total (All Sectors), 2008–018," https://www.eia.gov/electricity/annual/html/epa_03_01_a.html.

[44] For total U.S. land area, see Pole (2020). Land use of 2.27 million km² results from multiplying 4,178 TWh/year by 543.4 km²/TWh/year.

Table 1. Generator-only Materials Requirements: Fossil Fuel and Nuclear (tons/TWh)

Materials	Coal	Natural gas	Nuclear
Aluminum	3	1	0
Cement	0	0	0
Concrete	870	400	760
Copper	1	0	0
Glass	0	0	0
Iron	1	1	4
Lead	0	0	0
Plastic	0	0	0
Silicon	0	0	0
Steel	310	170	310

Source: DOE 2015.

Table 2. Generator and Upstream Energy Collection Materials Requirements: Renewables (tons/TWh)

Materials	Hydroelectric	Wind	Solar photovoltaic
Aluminum	0	35	680
Cement	0	0	3,700
Concrete	14,000	8,000	350
Copper	1	23	850
Glass	0	92	2,700
Iron	0	120	0
Lead	0	0	0
Plastic	0	190	210
Silicon	0	0	57
Steel	67	1,800	7,900

Source: DOE 2015.

Anyone comparing the two tables must be struck by the much greater materials requirements of renewables. Beyond the enormous quantities of concrete required to build hydroelectric dams, there are the substantial amounts of concrete and steel consumed in wind projects, and the cement, steel, and glass required for solar PV facilities—requirements that contribute to life-cycle space and quality impacts. The chemical process used to make cement, which is the main ingredient in concrete, produces about 8% of global carbon dioxide emissions (Lehne and Preston 2018). Steel manufacturing is responsible for 7% to 9% of carbon dioxide emissions from fossil fuels (World Steel Association 2020); over the 41 years from 1970 to 2011, fossil fuels produced about 78% of global carbon dioxide emissions.[45] The container and flat glass industries together emit more carbon dioxide than Portugal (Springer and Hasanbeigi 2017), although their share of overall global emissions is a small fraction of a percent.[46]

Research on power density, land use efficiency, and land use intensity demonstrates persuasively that the space and quality impacts of solar and wind power will typically affect more land than nuclear or

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[45] Environmental Protection Agency, "Global Greenhouse Gas Emissions Data," https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data.

[46] World Bank, "CO2 Emissions (kt)," https://data.worldbank.org/indicator/EN.ATM.CO2E.KT.

fossil fuel projects, even when including fuel extraction. Moreover, solar and wind have significant life-cycle land use impacts.

Finding 4: Solar and wind facilities are associated with significant quality impacts.

In addition to their space impacts, solar and wind generation each have demonstrable quality impacts. These can be especially significant for wind power, as widely spaced turbines impact quality in a wider area than densely packed solar PV panels. As in the case of fossil fuel and nuclear generation, these quality impacts also include environmental consequences that extend beyond site boundaries. Solar and wind power quality impacts may include the following:

- Landscape fragmentation
- Bird and bat deaths
- Temperature changes
- Visibility and noise
- Environmental damage, especially from mining and processing of rare earth elements

While many of these quality impacts can be mitigated, and some are modest in comparison with impacts from other energy or non-energy human activity, all merit attention in considering land use decisions for solar and wind projects.

Landscape fragmentation

Academic research finds that both solar and wind projects can contribute to landscape fragmentation, in which structures, roads, and other plant elements limit the area where wildlife can move freely; as noted earlier, roads can account for 80% of cleared land in wind power projects. Both a study of large-scale solar power plants (Turney and Fthenakis 2011) and a review of articles assessing biodiversity and ecosystem impacts of oil, natural gas, and wind energy (Jones, Pejchar, and Kiesecker 2015) find the fragmentation impacts of solar and wind similar to those of fossil energy.[47] Scholars view habitat loss and fragmentation as "the leading threats to biological diversity," though there are steps that project developers can take to mitigate damage (Hernandez et al. 2014, 770).

Importantly, an NREL report on wind power land use makes clear that fragmentation can vary substantially based on siting; for example, wind turbines located in agricultural regions "should have significantly less impact" due to fragmentation "than turbines located in forested area" (Denholm et al. 2009, 6–7). Likewise, biodiversity, biomass density, and cloud cover are more important considerations in forested areas compared to more open land uses, such as farmland, desert, or desert shrubland (Turney and Fthenakis 2011).

Bird and bat deaths

Bird and bat deaths are a frequent topic in public debates on solar and especially wind power.[48] According to the U.S. Fish and Wildlife Service, wind turbines kill 140,000 to 500,000 birds per year,

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[47] Turney and Fthenakis (2011) compare solar to "traditional power," which presumably includes fossil fuels, while Jones, Pejchar, and Kiesecker (2015) suggest that hydro and coal have fewer fragmentation impacts than wind, oil, and gas.

[48] For example, see Hudson (2020).

a number that could increase to 1.4 million per year with growth in the number of wind turbines.[49] However, the Fish and Wildlife Service also reports much higher levels of bird deaths due to other factors: collisions with building glass kill between 365 million and 988 million birds per year,[50] collisions with vehicles kill 89 million to 340 million birds per year,[51] and collisions with electric utility lines kill between 8 million and 57 million birds per year.[52]

Some researchers have expressed concern that studies of wind turbine bird and bat fatalities could understate actual deaths because scavengers may be removing carcasses before they are counted, and they argue that even relatively small numbers of deaths could have disproportionate consequences for rare or long-lived species with low reproduction rates (Tabassum-Abbasi, Abbasi, and Abbasi 2014). Nevertheless, it is clear that wind turbines play a modest role in bird fatalities compared to other human activity, although the impacts are not trivial. It is possible that these harms could be reduced; a recent study in Norway suggests that painting one wind turbine blade on each tower black could prevent up to 70% of bird collisions (May et al. 2020).

Solar facilities kill birds both through collision and through burning or singeing above concentrating solar mirrors. A 2016 study suggests 37,800 to 138,600 such fatalities per year in the United States (Walston et al. 2016).

Temperature changes

Both solar PV and wind energy can affect temperatures. Shade from solar panels does not appear to significantly influence nearby air temperatures (due to convection currents), but the panels can reduce temperatures of crops beneath them during the day and raise temperatures at night, in turn reducing day-night temperature variation (Marrou et al. 2013). This can be beneficial for agriculture.

Many studies have shown that wind turbines can increase surface air temperatures. A study that reports observations from 28 U.S. wind farms concludes that the turbine-atmosphere interactions mix warmer air from aloft with cooler air closer to the surface (Miller and Keith 2018a). During daylight hours with sunlight heating the ground, natural air currents mix the lower atmosphere, but in the absence of sunlight at night, atmospheric mixing near the surface is much weaker, and wind turbines' warming effects are much more pronounced. This day-night contrast in the warming effect of wind turbines has also been observed using publicly available high-resolution NASA satellite data (Miller 2020).

Using a climate model to estimate the effects of generating all present-day U.S. electricity demand from wind, researchers found that reliance on wind alone could theoretically increase annual average continental U.S. surface temperatures by 0.24° Celsius (or 0.43° Fahrenheit), with much more of this warming occurring at night (Miller and Keith 2018a).

Visibility and noise

Because visibility and noise directly affect human experience, they can be the most controversial aspects of solar and particularly wind power development. As a result, researchers have sought to

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[49] Fish & Wildlife Service, "Wind Turbines," https://www.fws.gov/birds/bird-enthusiasts/threats-to-birds/collisions/wind-turbines.php#:~:text=The%20most%20comprehensive%20and%20statistically,and%20500%2C000%20birds%20per%20year.

[50] Fish & Wildlife Service, "Buildings & Glass," https://www.fws.gov//birds/bird-enthusiasts/threats-to-birds/collisions/buildings-and-glass.php.

[51] Fish & Wildlife Service, "Road Vehicles," https://www.fws.gov/birds/bird-enthusiasts/threats-to-birds/collisions/road-vehicles.php.

[52] Fish & Wildlife Service, "Electric Utility Lines," https://www.fws.gov/birds/bird-enthusiasts/threats-to-birds/collisions/electric-utility-lines.php.

develop models to measure the visual impact of solar facilities (Sanchez-Pantoja, Vidal, and Pastor 2018) and wind facilities (Rodrigues, Montanes, and Fueyo 2010).

Such efforts typically seek to understand how to ensure public acceptance of solar and wind projects; as one study states, "an overwhelmingly large majority perceives wind energy as highly benign and desirable but most who favor wind energy do not favor wind turbines to be located near them" (Tabassum-Abbasi, Abbasi, and Abbasi 2014, 273). The authors of that study state further, "many prefer not to have wind turbines wherever they happen to go often enough." The authors note that as turbines become taller—to generate more electricity more efficiently—their "dominance on landscapes" increases too.

Other scholars have stressed that siting renewable facilities in rural areas "involves particularly sensitive linked issues such as land occupancy for food production, as well as the conservation of nature and the preservation of landscapes" (Poggi, Firmino, and Amado 2018, 631). Many studies also report annoyance from "shadow flicker" caused by light passing through spinning turbine blades (Freiberg et al. 2019).

Noise, which is a factor only with wind turbines, is a separate matter. Wind turbines produce two distinct types of noise, mechanical sounds (from the turbine's gear box and generator) and aerodynamic sounds (from the movement of its blades through the air). While engineers have successfully addressed much of the mechanical noise (Wang and Wang 2015), aerodynamic noise remains disturbing to some, in part because the sounds are rhythmic rather than consistent (Tabassum-Abbasi, Abbasi, and Abbasi 2014).

A 2019 review of 84 academic articles on human health impacts from wind turbines reports mixed results, demonstrating no stress effects but varied findings on sleep disturbance, quality of life, and mental health (Freiberg et al. 2019). The number of turbines and their distance can influence noise impacts.

Environmental

Table 2 demonstrates that solar and wind facilities and manufacturing are resource intensive, requiring considerable quantities of commodities like cement, concrete, glass, and steel, all of which have associated environmental costs. Solar panel and wind turbine manufacturing also require smaller but significant amounts of toxic chemicals and rare earth minerals. Cadmium, a key component in cadmium telluride thin film solar cells, was banned by the European Union until a 2010 EU measure that allowed its use in solar panels (Aman et al. 2015). As a result of this and other toxic components, solar panels require safe handling at the end of their life cycles; recycling currently costs more than landfill disposal and returns materials less valuable than those used to manufacture the panels (Shaibani 2020).

Wind turbines require rare earth minerals such as neodymium and dysprosium for high-strength magnets. Although rare earths are not uncommon, they are in low concentrations within other ores, "resulting in energy intensive and environmentally taxing mining, extractions, and refining processes" (Zaimes et al. 2015).

In 2019, China produced about 85% of rare earth oxides and about 90% of rare earth metals, alloys, and permanent magnets.[53] To the extent that federal policymakers seek to avoid U.S. dependence on China for the materials required to expand domestic wind turbine deployment, they will need to turn to domestic mining and processing or rely on other nations for these materials, or both. Several bills

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[53] China Power, "Does China Pose a Threat to Global Rare Earth Supply Chains?," China Power Project, Center for Strategic and International Studies, https://chinapower.csis.org/china-rare-earths/#:~:text=As%20of%202019%2C%20China%20still,of%20major%20rare%20earth%20importers.

in the U.S. Congress seek to promote domestic mining and processing.[54] In 2019, the U.S. Department of State launched the Energy Resource Governance Initiative (ERGI). Noting that "increasing demand for renewable energy, electric vehicles, and battery storage will create unprecedented demand for energy resource minerals," the State Department created ERGI "to promote sound mining sector governance and resilient energy mineral supply chains" (DOS 2019). Governments participating in ERGI include Argentina, Australia, Botswana, Brazil, Democratic Republic of the Congo, Namibia, Peru, the Philippines, and Zambia (Reuters 2019).

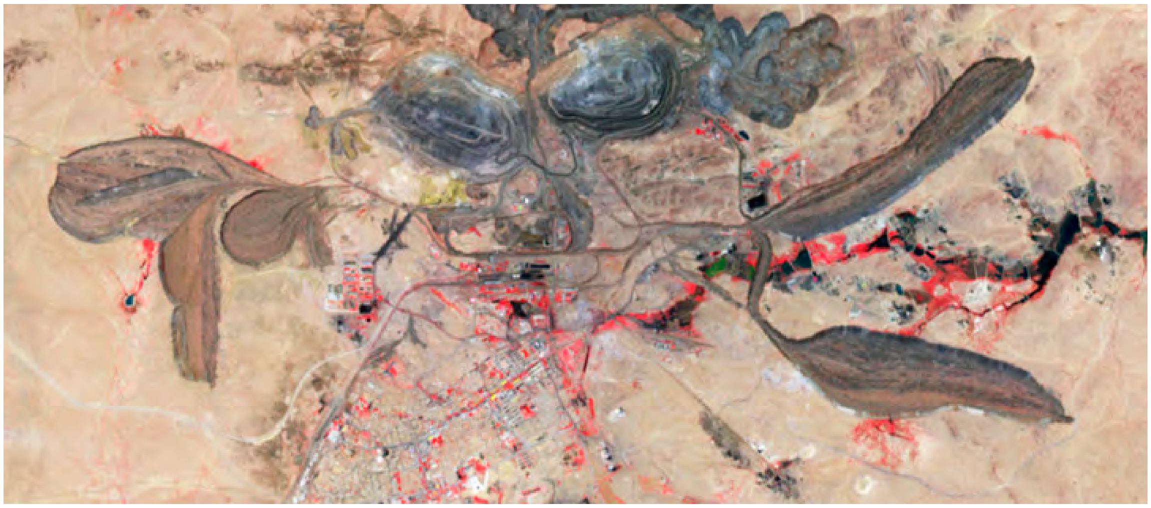

Photo credit: NASA Earth Observatory

China's Bayan Obo rare earth mine, in 2006. When NASA's Terra satellite collected this false-color image, the mine supplied about half of the world's rare earths. The light brown color represents grasslands, rocks in the roughly circular open mine pits (top center) are black, and vegetation is red. The irregular and oblong dark brown areas (left and right sides) are tailings.

Finding 5: Developing a 100% renewable energy system would be challenging from a land use policy perspective.

Recognizing the land use requirements of solar and wind electricity generation, many scholars have sought to determine whether sufficient land is available to meet global, national, or state-level electricity demand relying heavily or exclusively on wind, water, and solar electricity sources.

Jacobson's and Delucchi's 2011 global study, referenced above, concludes that a 100% WWS energy system would require less than 2% of global land area, including spacing between wind turbines that could be available for agriculture or other uses (Jacobson and Delucchi 2011; Delucchi and Jacobson 2011). The study assumes that 50% of global wind capacity would be offshore and that 30% of global solar capacity would be rooftop-based. It states that the rooftop solar power would require no additional land or transmission; for wind transmission, it counts only the footprint of transmission towers rather than including rights-of-way below transmission lines between towers. The study also assumes that access roads will likely already exist in agricultural areas and that additional access roads "would not increase the footprint requirements of wind farms more than a small amount" (Jacobson and Delucchi 2011a, 1161).

On a smaller scale, a Canadian researcher found that utility-scale solar PV systems could meet all of Ontario's mid-day electricity demand, including the demand associated with a completely

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[54] See the U.S. Congress legislative database at www.congress.gov.

electrified light-duty vehicle fleet, with 0.5%–8.5% of the province's agricultural land (Calvert 2018).[55] The variation between the low and high estimates—a factor of 17—illustrates the impact of panel efficiencies and spacing.

Given the potential land use impacts of solar and wind power, other scholars question the feasibility of systems that rely on them alone. For example, a team of Spanish researchers assessed the viability of a 100% solar energy system for 27 European Union (EU) member states[56] and 13 non-EU countries (including the United States); the 40 countries together accounted for 65% of global population and 90% of global gross domestic product (Capellan-Perez, de Castro, and Arto 2017). Incorporating assessments of solar power's seasonal variation, the actual land use of existing solar facilities, and the degradation of solar PV cells over time, they found that a 100% solar energy system in the EU would require about 45% of the EU's total land area. Six countries, including Belgium, Denmark, and the United Kingdom, would not have sufficient land area to supply their final energy demand with solar power alone. While the United States has considerably greater land area, even in America a fully solar energy system would require over five times the total land occupied by all built-up areas (settlements and infrastructure) in the country at that time.

The authors conclude that the land use challenges associated with solar PV are greatest in "northern latitudes with high population densities and high electricity consumption per capita" (774). They argue that their work could help to explain why expanding solar PV generation has increasingly led to siting projects in "agricultural areas and biodiversity hotspots" (770) and suggest reconsidering the view of solar power as an unlimited resource.

In a 2018 analysis seeking to model a full-solar economy for the 48 contiguous U.S. states, three researchers at Purdue University sought to take into account the end-use efficiency of energy conversion, the intermittency of solar power, actual solar farm output, and land availability (Li, Miskin, and Agrawal 2018). In assessing land availability, the authors exclude agricultural land—croplands, pastures, and ranges—as well as forests and "special-use land" such as national and state parks, which they report comprise in aggregate 93.2% of total land. The authors find that in 16 states, solar PV would require over 50% of "miscellaneous" and urban land.[57] The assumption that America's 770 million acres of pastures and rangeland is wholly unavailable may prove conservative: over half of this land is privately owned, and thus available in many cases for any legal uses that owners consider appropriate; the remaining land is publicly owned, and thus available for any uses that federal, state, and local officials and their constituents consider appropriate.[58]

Limiting space impacts with multiple land uses

Researchers have explored a variety of means to limit the space impacts of solar and wind projects. Most of these rely upon finding multiple simultaneous uses for land—especially integrating generating facilities with agriculture, developing rooftop solar power, or using land considered "degraded," a

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[55] Calvert analyzes 95 existing projects to calculate land use intensity and assumes that rooftop systems provide 20% of mid-day demand.

[56] The study took place prior to the United Kingdom's withdrawal from the European Union.

[57] Li, Miskin, and Agrawal (2018) state that miscellaneous land includes "marshes, deserts, and other barren land generally of low value for agricultural purposes."

[58] U.S. Forest Service, "About Rangeland Management," https://www.fs.fed.us/rangeland-management/aboutus/index.shtml. According to the Forest Service, over half of rangeland is privately held, while 43% is federally managed. State and local governments oversee the balance. America's 770 million acres of rangeland amounts to roughly one-third of total U.S. land area of 2.3 billion acres. See U.S. Department of Agriculture, Economic Research Service, "Major Land Uses," https://www.ers.usda.gov/topics/farm-economy/land-use-land-value-tenure/major-land-uses/.

term without a commonly accepted definition[59] that in this context often refers to contaminated or formerly contaminated land. This report does not separately explore rooftop solar installations, which are typically not utility-scale projects and which generally provide distributed power, i.e., power to the site at which they are located. In 2018, utility-scale solar projects comprised almost 60% of new solar capacity in the United States (Bolinger, Seel, and Robson 2019). Likewise, although some have urged adopting new policies to facilitate community-based distributed energy (Moroni, Antoniucci, and Bisello 2016), we do not assess small wind turbines sited at the distribution level.

Many scholars and activists consider degraded land to be an attractive siting option for solar and wind projects. For example, researcher Jacqueline Waite (2017) found that three of four U.S. regions (West, Midwest, and Mid-Atlantic) had sufficient degraded land to meet existing policy mandates for solar and wind even if only 10% of the capacity available on degraded land could be developed.

The U.S. Environmental Protection Agency (EPA) has sought to encourage the development of solar and wind projects on degraded land, particularly at abandoned mine sites and Superfund sites.[60] EPA's RE-Powering America's Land Initiative has been a key vehicle for federal efforts to encourage renewable power projects on these lands.[61] Some research has suggested that in addition to using degraded land productively, such projects can also contribute to restoring the land's ecology (Hernandez et al. 2019).

Degraded lands in the United States have a total area roughly double that of California, which some researchers estimate could produce 38.6% of America's 2015 electricity demand if fully utilized for solar photovoltaic power (Hernandez et al. 2019). In practice, of course, it is unlikely that all such land will be economically attractive to develop. As Waite (2017) noted, factors such as slope and shading can reduce solar potential and necessitate new transmission, while clean-up status and requirements (including liability) can affect project costs.

Solar and wind energy present different opportunities and pose different challenges when facilities are sited on agricultural land. Solar power and agriculture rely upon the same fundamental process—transforming sunlight into energy, whether as electricity or chemical energy stored in plants for people or animals to consume (or for processing into fuels or other agricultural products outside the energy sector, such as textiles). As a result, excluding arid regions that are unsuitable for crops, the same land is often desirable for both agriculture and solar power. According to a study

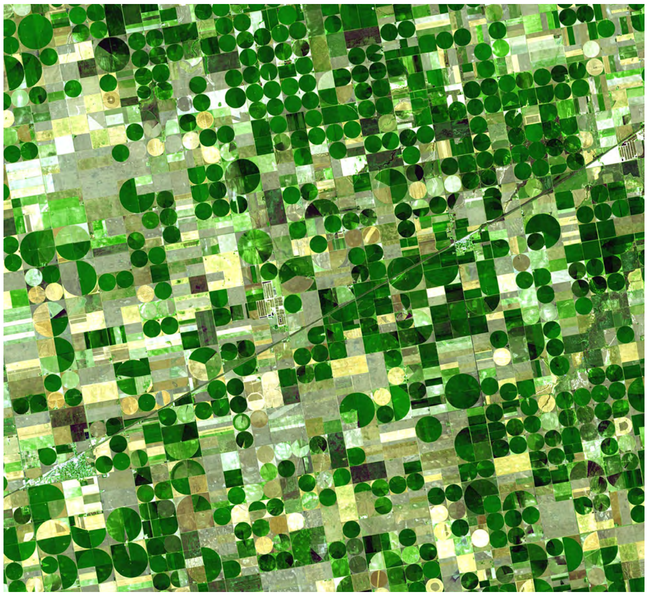
Photo credit: NASA Earth Observatory

A 2001 satellite image of farms in southwestern Kansas illustrates the green circles that center-pivot irrigation systems produce. The unirrigated areas outside the circles are potentially available for solar PV installation.

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[59] World Resources Institute, "What is Degraded Land?" https://www.wri.org/faq/what-degraded-land#:~:text=Degraded%20land%20is%20land%20that,definition%20of%20%E2%80%9Cdegraded%20land%E2%80%9D.

[60] Environmental Protection Agency, "Abandoned Mine Lands: Revitalization and Reuse," https://www.epa.gov/superfund/abandoned-mine-lands-revitalization-and-reuse#energy.

[61] Environmental Protection Agency, "RE-Powering America's Land," https://www.bia.gov/sites/bia.gov/files/assets/as-ia/ieed/ieed/pdf/idc1-021630.pdf.

by Adeh et al. (2019, 3), the efficiencies of solar facilities and agriculture are both highest in locations with "plentiful insolation [sunshine], light winds, moderate temperatures, and low humidity." The study also found that while officials and developers often prioritize barren land for solar installations, there is greater power potential globally in croplands, grasslands, and permanent wetlands.

Nevertheless, some researchers have argued against using agricultural land for solar development. The authors of an assessment of solar and wind projects in Portugal concluded that "ground-mounted solar power plants present a type of dense physical land occupation and should only be permitted in areas which are not farmable and with no natural scenic value" (Poggi, Firmino, and Amado 2018, 636). This perspective illustrates the fact that land use decisions are not strictly utilitarian but reflect competition between various social priorities.

Other scholars have tried to reconcile the tension between agriculture and solar project development and to evaluate potential synergies. Because agriculture is a major form of land use, comprising about 37% of global land area,[62] using agricultural lands for solar generation could add dramatically to the area available for such facilities. University of California–Davis scholar Rebecca Hernandez and co-authors propose a framework of 16 so-called techno-ecological synergies between solar energy, agriculture, and a wide range of other land uses (Hernandez et al. 2019).[63] The authors' agricultural proposals include siting solar power systems in the uncultivated spaces between center pivot irrigation systems[64] and integrating crops and solar energy with "agrivoltaic" systems that could include shade-tolerant crops beneath solar panels, tall crops under elevated PV systems, or greater spacing between solar panels to reduce shading.

Still other scholars have proposed redesigning solar systems with new materials to create partially transparent solar panels that would simultaneously generate electricity and allow light and energy to reach crops below (Miskin et al. 2019). Researchers who found that five pollinator-dependent crops account for over 90% of the agriculture within 1.5 km of existing utility-scale solar facilities have argued that such facilities could serve as habitats for bees and other pollinators (Walston et al. 2018).

Notwithstanding these and other useful findings and various creative proposals to integrate solar power with agriculture, the vast majority of academic studies seek to assess what is theoretically possible rather than what is economically viable, much less what might be economically attractive to utilities and to landowners.

High-voltage transmission towers have relatively small footprints, though the land area beneath transmission lines is considerably greater. In assessing transmission land use, some scholars count only the footprints of the towers, while others calculate the area of the rights-of-way along the route.

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[62] World Bank, "Agricultural Land (% of land area)," https://data.worldbank.org/indicator/AG.LND.AGRI.ZS.

[63] These synergies also include the use of degraded land, described above.

[64] Center pivot irrigation systems distribute water through a linear sprayer, one end of which is anchored. Seen from above, they produce irrigated circles, leaving corner areas unirrigated and unused. For a brief explanation of their design and history, see Anderson (2018).

Transmission

While this report does not separately assess academic studies or government reports projecting solar and wind power transmission requirements, there is broad consensus that transitioning to an electricity system heavily reliant on variable solar and wind power will require a substantial increase in transmission capacity and placement to balance supply with demand and to handle the system's additional electricity consumption.[65] This requirement in turn imposes additional space, time, and quality impacts.

For example, one study of Europe's electricity grid demonstrated that the ideal electric grid in a 100% renewable electricity system would require over 11 times the existing cross-border transmission, although roughly six times the existing cross-border connections would provide 98% of the benefits available in the ideal system (Rodriguez et al. 2014).

Similarly, a model of a 100% renewable U.S. grid developed by some of the same scholars projected that it would require 9,225 miles in additional links among existing regional systems, with the greatest transmission capacity required between the expanded grid's MISO and PJM electricity interconnections to southeastern states (Becker et al. 2014).[66] Neither study assesses the transmission that would be required to connect new generating facilities to the grid or to connect the grid to consumers.

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[65] For example, see Milligan et al. (2012). See also Jenkins, Luke, and Thernstrom (2018).

[66] For a map illustrating the structure of the U.S. electric grid, see Federal Energy Regulatory Commission, "RTOs and ISOs," https://www.ferc.gov/industries-data/electric/power-sales-and-markets/rtos-and-isos. The study's distance calculation is from midpoint to midpoint within regions and is thus illustrative rather than exact.

Conclusion

Solar panels, wind turbines, and other electricity generation facilities will be a part of the landscape until there is no longer a desire for the power they produce. Today, this desire is growing and is increasing the land use requirements of solar and wind power.

The fundamental land use challenge for solar and wind is that they have low power densities relative to other means of generating electricity, including nuclear and fossil fuels. As a result, solar and wind generation facilities typically require a larger geographic footprint than nuclear or fossil fuel plants to produce a given amount of power. These land use requirements are in turn significant because no matter what the project—a generating facility or transmission line, factory, shopping center, housing development, highway, pipeline, school, or park—land use decisions can be among the most contentious political issues in local communities.

Like many other political controversies, land use decisions incorporate competing interests (often largely economic), values (conservation, landscapes, development and jobs, clean energy), spatial and distributional justice (who experiences negative space and quality impacts, how benefits are allocated), and rights (liberty, property, expression). Differences in each of these areas' land use decisions can contribute to political friction between more urban communities, where land is perceived to be less available, and more rural communities, where land is perceived to be more available. The fact that urban and rural areas can have radically different electricity needs may exacerbate this friction. Incorporating findings from academic research into land use policy debates and decisions could help to address this challenge.

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Appendix: Studies Reveiwed

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