POTENTIAL PLACEMENT OF UTILITY-SCALE SOLAR INSTALLATIONS ON AGRICULTURAL LANDS IN THE U.S. TO 2040

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As the country transitions to renewable energy, solar energy installations will be deployed on millions of U.S. acres over the next few decades. To better understand the potential impacts and opportunities of rapid solar expansion on U.S. farmlands and ranchlands, American Farmland Trust developed a spatially explicit national level solar model to predict future solar siting on agricultural lands to 2040 and inform solar siting policies and practices. Driven by a conservative estimate of solar demand, AFT's national model deploys utility-scale solar projects on roughly 2.5 million acres across the lower 48 states based on historical use patterns and other siting factors.

About 83% of new solar projects are installed on farmland and ranchlands, with almost 50% placed on the most productive, versatile, and resilient land. To meet the national goal of eliminating greenhouse gas emissions from the power sector by 2050, solar could be deployed on over 7 million acres by 2040. As the total acreages for solar scale up, the results of modeling just 2.5 million acres of solar show the likelihood of a much larger impact on farmland and ranchland that will vary by state and region with the potential for much higher conversion in some areas.

Here we report the results of AFT's modeling in the context of a multitude of research efforts underway that observe and seek to minimize potential impacts of utility solar installations on farmland and ranchlands. AFT's modeling attempts to project and display this conversion at the national level. However, given the wide range of predictions for how much solar could be installed, there is a pressing need for better datasets, analyses, and mapping to help improve the impact predictions. At the local level, improved analyses can better inform issues of farm viability, soil health, and intergenerational transition. A better understanding of possible future impacts will also provide local, state, and federal policymakers with needed information to manage this land use change. AFT's Smart Solar^{SM} principles will help farmers, ranchers, and communities accomplish decarbonization without jeopardizing future food security and agricultural viability.

This work was undertaken as part of American Farmland Trust's Farms Under Threat Initiative. We extend our heartfelt appreciation to USDA's Natural Resources Conservation Service (NRCS) which provided financial assistance for this work through the AFT-NRCS Contribution Agreements 68-3A75-14-214 and 68-3A75-18-005. AFT's solar model was developed by Scott Beck while he was part of our Land Use Protection Research Division. This overview report benefited greatly from the input of many AFT staff (including AFT's solar team and Ryan Murphy, and Shradha Shrestha from AFT's Land Use and Protection Research team) and our USDA NRCS colleagues. We are very grateful for their willingness to share their time and expertise.

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Contents

Introduction

Energy consumption in the U.S. will increase in coming decades. Meeting this demand will require conversion of farmland and ranchland, regardless of what types of energy sources are used. But to rapidly reduce greenhouse gas emissions and limit the impacts of future droughts, floods, and extreme heat—including on agricultural production and food security—the U.S. must quickly transition to renewable energy. This critical transition to carbon-free energy will include the installation of significantly more large-scale utility solar projects, potentially transforming over 7 million acres by 2040 (U.S. DOE 2021). These large-scale utility solar installations represent a significant change in land use that is already affecting agricultural resources (Katkar et al. 2021; Berryhill 2021; Walston et al. 2021). Most farmland and ranchland is flat with good sun exposure, characteristics that are also important for solar installations.

Although the loss of farmland to renewable energy projects may seem insignificant when viewed in the context of 920 million acres of agricultural land in the lower 48 states, in some states and in particular communities, the impacts will be outsized. Many Eastern states are projected to build enough solar to take up 1.5 to 6% of their undeveloped land, with the majority expected on farmland (U.S. DOE 2021). These are statewide totals – the concentrations in communities with good siting and transmission opportunities will be substantially higher. For example, one county in the Mohawk Valley of New York with high concentrations of farming could lose almost 35% of its active farmland (4,000 acres) to proposed solar projects (Levy et al. 2022). This type of concentration will likely increase land prices, decrease land availability, and undermine the viability of farm support services – straining the economic viability of the farms that remain (Schultz et al. 2021).

To better understand the potential impacts and opportunities of rapid solar expansion on U.S. farmland and ranchlands, and to inform solar siting policies and practices; AFT developed a national, spatially explicit solar model to predict future solar siting on agricultural lands to 2040. The model projects deployment of large-scale solar projects if 2020-era policy and market conditions hold for the next two decades. AFT developed the solar model as part of its *Farms Under Threat 2040* future scenario mapping (Hunter et al. 2022).

Projecting Land Requirements for Utility-Scale Solar

Utility-scale solar projects can benefit rural areas by providing tax benefits to communities, providing local workers with jobs, creating new markets for local contractors, and diversifying landowner income (U.S. DOE 2021). Most large-scale solar developments are either distribution-side, utility-scale photovoltaics (DUPV) or large-scale utility photovoltaics (UPV) (Brown et al. 2020). Distributed photovoltaics are situated close to urban areas where they can be directly connected to existing grid-nodes. The U.S. Department of Energy's National Renewable Energy Laboratory (NREL) Renewable Energy Deployment System model (ReEDS), used by AFT to estimate solar demand by state, defines DUPV as being small (about 6 acres) (Beck et al. 2022). The average community solar facility has a capacity of 2.0 megawatts (MW), which can help support or supplement community-level energy needs (U.S. EIA 2019). In contrast, UPV average 100 MW and require significantly more land for development (average of 633 acres). They usually have an onsite station or a feeder that travels several miles (generally less than 5 miles) to an existing privately owned substation for distribution to the utility and can thus be sited further from existing substation or transmission nodes than DUPV development.

Many PV plants lease rather than buy their land. These lease payments and the perceived security and length of these payments are the key motivating factors for most landowners when considering leasing land to solar development. Typically, a PV power plant has a lifespan of 20-30 years or more and can then be either refurbished and repowered or decommissioned (Wiser et al. 2020; Curtis et al. 2021). Solar lease payments can be significantly higher per megawatt of capacity than wind generation systems, likely because they restrict land use to a much greater degree (Schultz et al. 2021). For example, in

Maryland, farmers lease crop or pastureland for between $25.50 to $175 per acre while lease rates offered by solar companies can range from $800 to $1,200 per acre (Schmidt-Perkins 2019). The impact on farmland that is available to lease is starting to be felt. Currently, 39% of agricultural lands are leased to farmers by non-operating agricultural landowners. When solar outbids farmers for this land, it can reduce the amount of farmland available to lease and drive rental rates for the remaining leasable acres (Grout and Ifft 2018). Respondents to a 2021 AFT survey of 803 farmers, local government officials, and land trusts in New York indicated that solar development was already making farmland more scarce and costly for some farmland renters (Levy et al. 2022). In some cases, solar development was causing farmers to lose access to rented land, a particularly troubling challenge for New York's dairy farmers.

Projections for how much total land may be required for solar installations in the U.S. vary widely. An analysis of potential solar land requirements for the European Union, India, Japan, and South Korea in a decarbonized future projects that solar energy could occupy 0.5 to 5% of total land by 2050 (van de Ven et al. 2021). There is no single uniform solar market across the U.S. and differences in regional and state deployment of solar systems are largely driven by economics. Economics, in turn, depend on the amount of sunlight, capital and operating costs, grid power prices (retail and wholesale), and financial incentive policies (Schultz et al. 2021). For example, there is more sun in the desert Southwest than the upper Great Lakes. The capital costs for utility-scale solar are highest on a per watt basis in Connecticut, Minnesota, New Jersey, Alaska, and Massachusetts and lowest in Oklahoma, North Carolina, Wyoming, South Dakota, and Texas. Wholesale power prices are lowest in the Northwest, highest in New England. And while some states have no significant incentives beyond net metering (e.g., Wyoming), others offer large incentives for solar (e.g., Arizona and Oregon). Even if one factor doesn't appear to be favorable (e.g., amount of sunlight), the other factors may more than compensate in many locations, making solar a good economic investment. The deployment of utility-scale solar installations can also be influenced by transmission and distribution capacity, utility and state renewable energy mandates, corporate procurement through power purchase agreements, landowner interest, and the local and state zoning and permitting environment. About half of the growth in U.S. renewable energy generation since 2000 is attributed to state renewable energy standards. Thirty states, Washington D.C., and two territories have active renewable or clean energy requirements, while an additional three states and one territory have set voluntary renewable energy goals (NCSL 2021).

The factors affecting solar markets are among many variables that modelers must consider when projecting solar deployment into the future. They must also make assumptions about future demand, fuel prices, technology costs, changes in policy and resource, and system constraints in their projections and strike a balance with other renewable energy sources. Since no one knows what the mix of wind, solar and renewable energy will wind up being, how high the level of electrification might reach and how innovations and costs could factor in, modelers run many different scenarios and look at the outcomes.

AFT's solar modeling uses the NREL "Mid-case Scenario" to project solar demand between 2020 and 2040. The reference "Mid-case" Scenario from NREL extrapolates future renewable energy capacity/generation based on the economic and renewable energy development conditions in 2020 and reflects policies at the state and federal levels as of June 30, 2020. It projects 456,000 MW of UPV and DUPV solar capacity by 2040 (Cole et al. 2020). Using the generalized national array-density estimate for UPV and DUPV developed by NREL (39MW/km2 or 6.3 acres/MW), this translates into about 2.9 million acres of land.

However, because of policies enacted since June 2020 to drive renewables, this estimate will now be surpassed, probably by a significant amount. For example, Virginia's landmark Clean Energy Act of 2020 committed the state to renewables and mandated 16.7 gigawatts of solar. Illinois passed legislation in September 2021 (the Climate and Equitable Jobs Act) with substantial funding for solar incentives. Even more consequential, in mid-August 2022, Congress passed the Inflation Reduction Act (IRA), providing a suite of tax incentives that is expected to spur record-setting growth in wind and solar capacity (Jenkins et al. 2022). In 2020, an average of 10 GW of utility-scale solar was being added to the grid every year. With the IRA in place, this is now projected to climb to about five times the 2020 pace in 2025-2026 (to 49 GW/year) and increase even more thereafter (to a peak of 129 GW/year by 2031-2032) (Jenkins et al. 2022).

This huge boost to solar energy makes the outcomes envisioned by solar modeling scenarios that lead to net-zero GHG emissions in the energy sector much more likely. These scenarios anticipate a much larger demand for solar, significantly increasing the amount of land needed to host solar projects. For example, one of the scenarios modeled in the Net-Zero America report from Princeton University (Larson et al. 2021) projects 5.3 million acres (*E+ High Electrification scenario*) in 2040 while a scenario in the Department of Energy's Solar Futures Study (U.S. DOE 2021) projects 7.4 million acres (*Decarbonization with Electrification scenario*). In each of these cases, wind turbines, hydroelectric dams, and nuclear power plants provide the additional low-carbon energy needed to reach net zero, further increasing land-use impacts. To fully electrify transportation, heating, and other energy needs, even more of these renewable energy sources will be needed, resulting in even higher land-use impacts—potentially doubling the amount of solar that would be deployed by 2050 (U.S. DOE 2021).

Since the Princeton and DOE net-zero pathway analyses employ different methodologies and assumptions, they result in different land-use implications. They both assume that costs will fall, solar will become more efficient, and regulatory, incentive and business model barriers will be addressed. They also assume more storage capacity, transmission expansion, and flexibility in load and generation. The Princeton Net Zero analysis models inputs at the state level and uses energy service demand projected to 2050 by the U.S. Energy Information Administration for 14 regions (Larson et al. 2021). The model finds the mix of sources that minimize total energy system cost and downscales the modeling results to state or sub-state geographies. The Solar Futures analysis uses 356 wind and Concentrating Solar Power resource regions and 134 model balancing areas where solar and all other technologies are represented. The Princeton Net Zero analysis shows a greater build-out of solar in the Southeast and Central/Midwest while the DOE projection shows more solar in Arizona, Minnesota, Wisconsin, and Kentucky.

Siting Utility-Scale Solar on the Agricultural Landscape

To understand why agricultural land is so attractive to solar developers, consider what these two land uses have in common. Solar photovoltaic (PV) panels basically depend on both incoming solar radiation (which is strongly dependent on geographic location) and temperature (which can determine the efficiency of the solar cells) to function. Solar panels are most productive with plentiful incoming solar radiation, light winds, moderate temperatures, and low humidity – the same conditions that are best for agricultural crops. Taking solar radiation, air temperature, wind speed, and humidity into account, cropland has the greatest median solar power production potential per acre worldwide followed by grasslands (including pasturelands and some rangelands) and wetlands (Adeh et al. 2019). Barren lands, which these researchers pointed out had been traditionally prioritized for solar, are ranked fifth.

A significant percentage of solar installations in the U.S. have been or are being built on agricultural lands. In 2010, researchers examined lease and license data in five major terrestrial ecosystems in western North America and concluded that solar development could cumulatively impact 1.5 to 49 million acres of shrubland or rangeland (Pocewicz et al. 2011). In California, researchers identified 161 planned, under construction, and operating solar installations as of 2014 and found that most installations (6,995 MW) were sited in shrublands and scrublands (rangeland), accounting for about 93,000 acres (Hernandez et al. 2015). Nearly 30% were sited in croplands and pastures, comprising 38,000 acres. An analysis of 192 large-scale solar facilities in the Midwest region that were operating in 2018 found that 70% of the pre-construction land cover type was row crop agriculture (5,900 acres) and 5.4% was pasture and hay fields (Walston et al. 2021).

By 2018, at the state level, 44% of the distributed solar energy projects in New York were on agricultural land (Katkar et al. 2021). Virginia's 38 active solar facilities primarily impact forestland (58.1%), cropland (24.9%), and pastureland (7.0%) (Berryhill 2021). However, after removing the outliers in the data (very large facilities built in forested areas), the author concluded that individual solar facilities in Virginia are more likely to be sited on cropland (46%) than on forestland (38%). In Maryland, more than 30 solar generation facilities are currently under construction or review by the state and the vast majority are located on agricultural land (Governor's Task Force on Renewable Energy Development and Siting 2020). In Maine, Audubon mapped the 180 solar projects submitted for review and found that 58% overlap at least five acres of continuous cropland or 10 acres of pasture and 89% overlap, at least in part, with high value agricultural lands (Gordon et al. 2022).

Future projections of solar show a significant percentage of utility-scale solar installations will continue to be deployed on agricultural land. In the previously cited New York state analysis, Katkar et al. (2021) used slope, proximity to electric substations, protected lands, and soil quality as criteria to identify land suitable for future solar energy development. The solar energy potential on non-agricultural land was 22.5 GW, just sufficient to accommodate New York's 2030 goal of 21.6 GW. But these researchers felt that agricultural lands in New York will continue to be a leading target for future utility-scale solar development because even when prime and statewide important soils are removed from the model, 84% of the land that is suitable for solar (about 140 GW potential) is agricultural. Maryland projected that while half of its current solar capacity comes from large-scale solar arrays, 75% may come from utility-scale solar in the future and a range of 60 to 100% of these would occur on agricultural lands (Minnemeyer and Wiggins 2020).

Based on historical patterns of land conversion from solar development, the AFT solar model (discussed in more detail below) projects that roughly 83% of projected solar development in the contiguous U.S. is likely to occur on agricultural lands. Nearly half was deployed on Nationally Significant agricultural land, identified as the land best suited to intensive food and other crop production by the land quality metric developed by AFT's *Farms Under Threat* initiative (Theobald et al. 2018). The AFT model does not exclude placement on prime farmland since most states do not limit energy development on prime farmland (Hall et al. 2022).

The Princeton Net Zero study, also mentioned earlier, includes the mapping of hypothetical utility-scale wind and solar deployments that would lead to a national 2050 net-zero greenhouse gas emission target (Larson et al. 2021). The mapping scenarios in this study make assumptions about energy demand and energy supply technology options available in the future and pit wind against solar. The scenarios also assume further reductions in non-CO_2 GHG emissions and enhanced carbon capture by soils (land sinks). Prime farmland is excluded for solar development by the model. Rangeland is not identified, and grasslands and shrub/scrub land are separate categories. In each scenario except for the reference case, the authors of the study apply a 10% per year growth limit to the build out of wind and solar. Assuming the shrub/scrub land and grasslands modeled are rangeland, 40% to 60% of the solar deployment modeled nationwide occurs on agricultural land depending on the assumptions made (Leslie et al. 2021).

Protecting the best farmland

In addition to favoring agricultural land, solar siting also tends to favor the attributes of the best farmland over more marginal farmland since better farmland is more likely to be flat, dry, cleared, and close to existing infrastructure (Trainer et al. 2016; Grout and Ifft 2018). For example, in New York state, 58% of the solar projects as of 2018 had been built on good quality soil, defined by the authors as prime farmland or farmland of statewide importance (Katkar et al. 2021). The majority of respondents to AFT's New York survey were concerned that solar projects could take tens of thousands of acres of high-quality farmland acres out of production and negatively impact local farming communities (Levy et al. 2022). In

Virginia, solar facilities were found to use a higher proportion of prime agricultural land (close to 61% of the cropland used was rated as highly suitable) (Berryhill 2021). AFT's solar model projected that almost half of the agricultural land under utility-scale solar installations by 2040 will be Nationally Significant land. For this reason, AFT advocates for "smart solar" or "solar done right" (See section on "Achieving Sustainable Energy and Food Production" for more details). The smart siting of renewable energy installations on farmland can provide critical income streams to landowners, however it can also displace farmer-renters who are unable to compete with the prices solar developers offer, and impact the viability of the farms that remain in the community (e.g. land prices, viability of support services) should a large percentage of land be taken out of production (Levy et al. 2022). An analysis of data from USDA's 2014 Tenure, Ownership, and Transition of Agricultural Land (TOTAL) survey found that farms with energy income (from oil, gas, wind, and solar) were significantly more likely to report some capital investment (of any amount) and were significantly less likely to have negative net farm income (Grout 2018).

The long-term impacts of solar siting on soil quality and food production capacity and whether the unique physical, chemical, and biological properties of quality farmland can be retained or restored are unanswered questions. The land-use requirements of utility-scale solar installations, especially in agricultural communities, have led to increasing interest in low-impact site development plans (Schultz et al. 2021). These plans seek to preserve topsoil and plant vegetation that supports pollinators and other insects beneficial to nearby farmland, but this alone is not enough to achieve "smart siting." In the Midwest, restoring and managing native grassland vegetation beneath ground-mounted solar energy facilities could potentially increase pollinators, carbon sequestration, and sediment and water retention (Walston et al. 2021). Over 865,000 acres of agricultural land near existing solar energy facilities in the U.S. could benefit from increased pollination services through the establishment of solar-native vegetation (Walston et al. 2018). Five pollinator-dependent crop types accounted for over 90% of the agriculture near solar facilities (soybeans, alfalfa, cotton, almonds, and citrus). So far, seven states (Illinois, Maryland, Michigan, Minnesota, New York, South Carolina, and Vermont) have enacted or are hoping to enact legislation to promote pollinator-friendly development (Terry 2020). Michigan currently allows solar developers to locate or site solar panels on preserved farmland if they develop habitat on this land to support pollinators. However, integrating pollinator habitat into solar facilities still needs additional research to ascertain impacts and tradeoffs with farming uses (Moore et al. 2021).

Agrivoltaics or agricultural dual-use systems are also being deployed and studied. In agrivoltaic systems, agricultural production is still possible under or around the solar installation itself. The systems are specifically designed to support a viable farm operation and may include features that require additional investments. For example, elevated panels and wider spacing may allow for crop or forage production and/or livestock grazing (Levy et al. 2022). Sheep grazing is a common example, which—when done well—also can help to improve soil health, manage undergrowth, and reduce operation and maintenance costs for project operators. But novel systems are being developed for vegetable production, vineyards, and small grains (Adeh et al. 2018). Encouraging research shows that shading from solar panels can help conserve water and increase crop yields in some production systems, especially in hot, dry climates (Adeh et al. 2019; Laub et al. 2022).

Further applied research is needed to determine feasibility and best management practices but agrivoltaic systems have the potential to provide off-grid power to rural communities increasing their resilience while adding the economic value of the crops produced (Weselek et al. 2019). These types of agrivoltaic systems preserve a measure of agricultural productivity on lands used for solar and can help reduce the tension over solar being sited on farmland. While AFT is working to expand dual-use, most new solar installations going on farmland will be conventional, ground-mounted for the foreseeable future.

Viewing solar siting in a broader context of potential farmland loss

Rapid solar deployment is not taking place in a vacuum. Between 2001 and 2016, the U.S. lost an average of 2,000 acres a day of farmland and ranchland to urban and highly developed and low-density residential land uses (Freedgood et al. 2020). At the same time, the capacity to produce food is increasingly under threat from climate change. As the population expands and the sea level rises, more farmland and ranchland will be converted to housing, businesses, and industrial uses. AFT's *Farms Under Threat: Choosing an Abundant Future* modeling projected the extent of urban and highly developed land and low-density residential land uses by 2040 under different scenarios (Hunter et al. 2022). If the U.S. continues to develop at the same rate and in the same patterns as previous decades, another 18.4 million acres of farmland and ranchland will be paved over, fragmented, or compromised by 2040. If rural sprawl accelerates, the loss could be as high as 24.4 million acres. Nearly half of the projected development by 2040 will be on Nationally Significant agricultural lands, the nation's best land for long-term production. AFT's 2040 solar modeling takes the projected *Farms Under Threat* "Business as Usual" development into account when placing future solar installations on the landscape.

The U.S. also faces an impending transfer of farmland due to aging farmland owners (Freedgood et al. 2020). In most states, farmers who are 65 or older comprise at least a third of the farming population. When non-operating landlords are included, seniors aged 65 or older own more than 40% (more than 371 million acres) of the agricultural land in the U.S. The impacts of solar installations and lease payments on intergenerational transfer appear mixed. In AFT's New York survey, some respondents felt that solar, particularly agrivoltaic projects, might help support farms and make it possible to transition to the next generation (Levy et al. 2022). Others saw solar as an attractive option if farmers were unable to identify a successor.

At the same time, if the world stays on its current climate trajectory, farmers and ranchers will face a rising litany of climate risks including droughts, heat waves, floods, and windstorms. Changes in temperature and rainfall are increasingly impacting where crops can be grown and reducing crop yields (IPCC 2021). In locations where groundwater supplies are overdrawn, conversion from agriculture to renewable energy may become a more economically attractive option for landowners (Leslie et al. 2021). Climate disruptions will make each acre more important. In 2020, the combustion of fossil fuels to generate energy accounted for over 94% of CO_2 emissions (U.S. EPA 2022). The shift to use less CO_2-intensive natural gas for generating electricity and a rapid increase in the use of renewable energy in the electric power sector has helped lower net emissions over the last few years but GHG emissions are now starting to rise again. Only immediate action to reduce GHG can help reverse the course of the climate trajectory – and to fully decarbonize the nation's electrical grid, significantly more utility-scale projects will need to be built. The challenge is to do so in a way that achieves sustainable energy and food production and protects U.S. agricultural resources.

AFT's National Level Solar Modeling

Brief Modeling Methods

To better understand the potential impacts of rapid solar expansion on U.S. farmland and ranchlands, AFT developed a solar model to illustrate patterns of future solar siting and help inform solar siting policies and practices (Beck et al. 2022). The modeling was undertaken as part of AFT's *Farms Under Threat* initiative.

The predictive solar analysis uses the NREL ReEDS model baseline scenario dataset (Brown et al. 2020) to site future utility-scale solar development throughout the continental United States. The resulting projection model places new solar development based on a technical suitability/conditional transition probabilities map and other land-use characteristics derived from historical-use patterns.

The AFT model determines demand (how much), suitability (where), spatial attributes (size, shape, and density), and transition rates (how likely a given land use is to be developed) for solar development on a per pixel basis within seven distinct regions throughout the contiguous U.S. AFT deployed these models at regional scales to help capture localized development patterns that might otherwise be missed if modeled at the national level. AFT developed the base map of land cover and land quality as part of its *Farms Under Threat* initiative (CSP 2020). Using this base map, AFT incorporated solar energy demand, suitability, spatial attributes, and transition rates into a coupled Markov-Cellular Automata spatial allocation procedure using Dinamica-Ego.

AFT's model includes utility photovoltaics (UPV) and distributed utility photovoltaics (DUPV). As mentioned previously, the ReEDS model defines UPV as being large (~600 acres) and likely to be sited in rural areas (Brown et al. 2020). Their size makes it viable to build grid interconnections, so it is possible to site them farther from existing substation or transmission nodes than DUPV facilities, but proximity to transmission lines is still important. In contrast, the ReEDS model defines DUPV as being small (~6 acres) and situated closer to urban areas where they can be directly connected to existing grid-nodes. This distinction is important when planning for siting of each type within AFT's model, which allows for some flexibility in the sizing of UPV and DUPV development types. Concentrating Solar Power (CSP) is a third category of large-scale solar development that is restricted to California and parts of the desert Southwest. Since CSP is projected to shrink in many places in favor of UPV and DUPV development, AFT did not include it.

AFT integrated the solar projection with the *Farms Under Threat 2040* future urban development modeling that projects new urban and highly developed (UHD) and low-density residential (LDR) land uses from 2016-2040 (Xie et al. 2022). An estimate of projected UHD and LDR areas under a Business as Usual development scenario was used to mask the landscape before AFT applied the solar model to determine areas for new solar development. While this does not perfectly reflect the way that these three land uses interact in the real world, it simplifies the modeling process and avoids potential conflicts that could result in unrealistic landscape patterns. The model also restricts solar development on land in the upper 5% of national value, using a specialized land value index (Nolte et al. 2020). This modeling decision recognizes that wealthy landowners will have the resources to fight solar developments proposed in their line-of-sight. In nearly every state, residents, community-based groups, or nonprofit organizations with a local presence have contested specific solar projects (Aidun et al. 2022).

AFT also excluded solar from federal lands, in line with the rest of the *Farms Under Threat* future scenario modeling – although some solar will be built on public lands. On June 1, 2022, the U.S. Department of the Interior announced that it was implementing a "rate reduction policy" for solar and wind energy projects on public lands and establishing Renewable Coordination Offices in the Bureau of Land Management offices throughout the West. Although this change in policy could be a substantial driver of renewable energy on public lands, determining which federal lands are suitable for solar development was beyond the scope of the analysis.

The resulting analysis shows likely patterns for the future deployment of utility-scale solar. AFT quantified the agricultural lands under these installations and determined how much is Nationally Significant farmland (CSP 2020), the nation's best land for long-term production.

Findings

AFT's model projected 2,534,800 acres of new utility-scale solar installations (DUPV and UPV) from 2020-2040. This is slightly lower than the NREL ReEDS Mid-case Scenario total of about 2.9 million acres due to modeling challenges, including the integration with the *Farms Under Threat* 2040 projections of new UHD and LDR land use (Beck et al. 2022). Some of the transition rules the model used may have over-restricted solar development in some cases. For example, although a small proportion of urban and highly developed and low-density residential land uses were converted to solar between 2001 and 2016, the model excluded them from future utility-scale solar development due to limitations of the underlying datasets.

The NREL ReEDS Mid-case Scenario that drives the AFT model does not eliminate all fossil fuels from the electricity sector by 2050, the stated goal of the Biden administration. The estimate used by the model will be surpassed, probably by a significant amount. The 2022 Inflation Reduction Act, which helps set the nation on a net-zero path, could result in as much as 9-10 million acres of solar by 2050 (Larson et al. 2021; DOE 2021). Given the percent of agricultural lands and Nationally Significant land projected to be impacted by roughly 2.5 million acres of solar installations, the acreage of agricultural land at risk could be significantly higher. Even if solar deployment is minimal, the projected impacts on agricultural land shown by our modeling reinforce the need for good planning and effective permitting processes to minimize conversion of the best agricultural lands.

AFT's national modeling effort uncovered four major concerns.

1. 83% of solar land conversion projected to 2040 happens on agricultural lands

Based on historical patterns of solar land conversion, roughly 83% of the 2,534,800 acres of projected solar development is likely to occur on agricultural lands. Of the projected 2,098,500 acres of agricultural land under solar installations, 48% was on cropland, 17% was on pastureland, 31% was on rangeland, and the remaining 3% was on woodlands associated with farms.

Table 1: Projected total acres of land converted to utility-scale solar across the contiguous U.S. from 2020-2040, by land-use type

Land Use	Acres
Cropland	1,017,500
Pastureland	358,500
Rangeland	652,000
Woodland	70,500
Forestland	340,900
Other	95,300
Total	**2,534,800**

Most of the non-agricultural conversion occurred on forestland (340,900 acres), discussed below. The land-use category of "Other" includes locations not classed in other cover/use categories, typically occurring on or along rural roads, in barren areas with little vegetation cover, or on steeper slopes.

2. Nearly half of the projected solar is built on Nationally Significant agricultural land

If standard siting practices continue to mirror historical patterns, 49% of the total agricultural land conversion happens on Nationally Significant land (1,018,100 acres), the land best suited to intensive food and other crop production with the fewest environmental impacts. This *Farms Under Threat* designation is based on the PVR land quality metric that AFT developed in consultation with experts to quantify the potential or quality of agricultural land based on its productivity, versatility, and resiliency (CSP 2020). Simultaneously, the projected conversion of agricultural land by urban and highly developed land uses and low-density residential land uses finds that nearly half of the projected conversion from 2016 to 2040 will also occur on Nationally Significant land, over 12 million acres (Hunter et al. 2022). Only 38% of the nation's farmland and ranchland qualifies for this category and only 18% of the land mass in the continental U.S. is Nationally Significant farmland.

Our modeling shows that nearly half of the projected conversion to solar will occur on Nationally Significant land, even though only 38% of the nation's farmland and ranchland qualifies for this category. This means that Nationally Significant land is 50% more likely to be converted to solar development than the rest of the agricultural land. In some states, where development pressure and high-quality land are concentrated in the same areas, conversion of Nationally Significant land is projected to be even more disproportionate: the best land will be converted over three times faster in ten states, and almost eight times faster in Arizona (Table 2).

Table 2. Factor by which Nationally Significant land is more likely to be converted to solar as compared to other agricultural land.

State	Factor	State	Factor
Arizona	7.80	New Jersey	1.86
Nebraska	6.19	Pennsylvania	1.82
Utah	6.09	Montana	1.81
West Virginia	4.76	Rhode Island	1.76
Connecticut	4.13	Kansas	1.74
Idaho	3.89	Florida	1.73
New Hampshire	3.41	Louisiana	1.70
Oregon	3.24	Washington	1.65
Wisconsin	3.23	Missouri	1.62
South Carolina	3.09	Vermont	1.61
New Mexico	2.95	Virginia	1.58
Massachusetts	2.77	Indiana	1.44
South Dakota	2.51	Colorado	1.43
Georgia	2.49	Maryland	1.41
Michigan	2.48	Tennessee	1.40
Illinois	2.22	California	1.24
Kentucky	2.16	North Dakota	1.23
Ohio	2.12	Arkansas	1.16
Maine	2.09	Delaware	0.99
North Carolina	2.07	Oklahoma	0.96
Alabama	2.02	Texas	0.90
Mississippi	1.97	Minnesota	0.90
Iowa	1.95	Nevada	0.65
New York	1.95	Wyoming	0.12
Contiguous U.S.	**1.54**		

3. Most of the solar happens in states where development is expected to convert significant acres of farmland by 2040

Table 3 shows both the number of acres of state agricultural land projected to be under solar installations or converted to development (urban and highly developed (UHD) and low-density residential (LDR) land uses) by 2040 under *Farms Under Threat's* "Business as Usual" scenario (Hunter et al. 2022).

States with historically aggressive solar development strategies are projected to have the lion's share of new solar installations on agricultural lands over the next 20 years. The top three states with the highest projected solar development on farmland are Texas, California, and Florida. These states account for roughly 40% of all farmland-to-solar conversion. In states that currently lack a clear/ambitious state policy driver (e.g., Texas, Florida, South Carolina, Oklahoma, and Louisiana), solar is being market-driven by opportunistic corporations and utilities. As shown in Table 3, as solar installations rapidly expand, the top 12 states will also lose, fragment, or compromise between 306,000 and over 2 million acres of farmland and ranchland to development. Texas, California, North Carolina, and Tennessee particularly stand out as states where agricultural land converted by 2040 to solar and development exceeds 1 million acres. This highlights the need for land-use policies that simultaneously address farmland loss and promote smart solar siting.

Table 3. Acres of state agricultural land projected to be under solar installations or converted to development (UHD and LDR) by 2040.

State	Acres to Solar	Acres to UHD and LDR (BAU)	State	Acres to Solar	Acres to UHD and LDR (BAU)
Texas	345,200	2,192,700	Mississippi	20,600	513,300
California	311,200	797,400	Utah	20,000	210,100
Florida	188,000	620,200	Idaho	19,700	113,100
South Carolina	138,500	436,700	Nebraska	16,000	103,800
Michigan	93,900	483,800	West Virginia	15,000	157,600
Arizona	89,100	444,500	Pennsylvania	11,800	543,800
Illinois	82,400	363,400	New Jersey	11,500	125,000
Oklahoma	60,200	458,900	Missouri	10,800	568,200
Wisconsin	54,300	515,200	Massachusetts	10,400	73,800
North Carolina	51,100	1,197,300	New Mexico	9,000	205,000
Louisiana	48,000	306,000	Alabama	6,700	545,000
Virginia	45,900	594,100	Connecticut	6,600	55,000
New York	45,100	452,000	Oregon	6,300	109,100
Kentucky	42,700	456,500	Arkansas	6,000	480,400
Georgia	41,900	798,400	Washington	5,800	192,300
Nevada	41,500	155,700	Delaware	5,400	65,100
Kansas	36,600	196,900	North Dakota	4,900	198,500
Ohio	32,600	518,500	New Hampshire	2,400	35,600
Minnesota	29,700	369,500	Maine	1,500	53,400
Maryland	28,200	178,200	Montana	1,500	171,700
Colorado	27,400	417,500	Vermont	1,200	41,200
Indiana	23,300	451,100	Wyoming	1,000	86,600
Tennessee	23,300	1,014,600	Rhode Island	1,000	8,100
Iowa	22,600	183,400	South Dakota	800	156,900

Figure 1 (below) shows projected agricultural land conversion by large-scale solar installations by 2040 on a county-to-county basis across the lower 48 states.

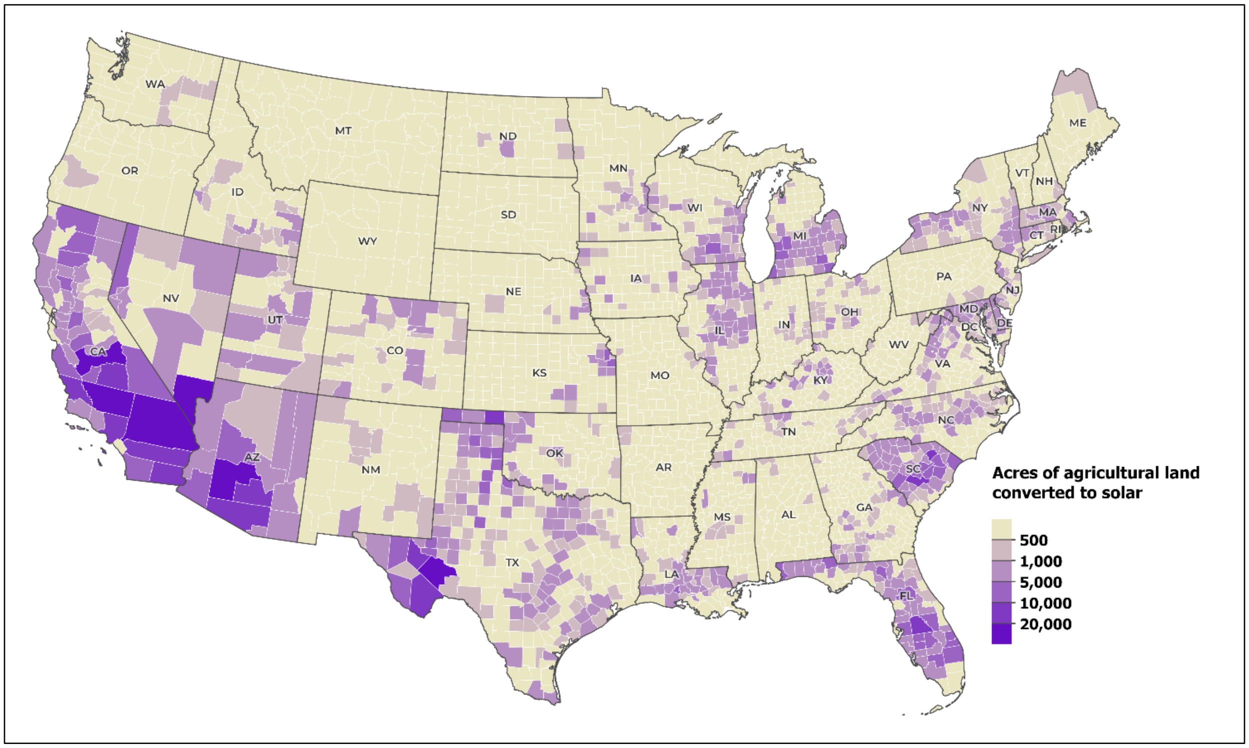

Figure 1: Projected acres of agricultural land converted to utility-scale solar photovoltaics energy generation facilities by state from 2020-2040.

Table 4 (below) provides the acreage totals for the 30 counties with the highest number of acres projected to be under solar installations by 2040 along with the acreage projected to be converted by development under *Farms Under Threat's* Business As Usual scenario (Hunter et al. 2022). The table also lists the percent of solar projected to be on Nationally Significant land.

The counties of Maricopa, AZ, Riverside, CA, and Pecos, TX have the highest combined totals of agricultural land impacted by solar deployment and future development.

Table 4: Counties with the highest number of acres of agricultural land projected to be under solar installations or converted to development (UHD and LDR) by 2040, and the factor by which Nationally Significant land is more likely to be converted to solar as compared to other agricultural land.

County	State	Acres to UHD/LDR	Acres to solar	Conversion of Significant Lands Factor*
Kern	California	48,100	57,400	1.03
Pecos	Texas	12,247	43,200	0.04
Fresno	California	52,900	32,500	0.83
Maricopa	Arizona	230,100	26,300	1.38
San Bernardino	California	61,800	24,200	0.52
Clark	Nevada	102,500	20,300	6.16
Pinal	Arizona	52,700	19,100	2.82
Polk	Florida	48,300	17,900	2.49
Brewster	Texas	995	17,500	0.00
Reeves	Texas	2,914	14,600	0.00
Imperial	California	18,690	13,600	2.34
Darlington	South Carolina	5,888	13,600	2.93
Beaver	Oklahoma	2,078	13,100	1.62
Los Angeles	California	48,000	12,000	2.08
Pima	Arizona	40,500	12,000	1.44
San Luis Obispo	California	17,021	12,000	1.42
Tulare	California	29,791	11,800	1.00
Riverside	California	127,208	10,600	1.25
Orangeburg	South Carolina	11,197	10,200	4.39
Culberson	Texas	588	9,900	0.00
Siskiyou	California	2,485	9,600	1.88
Collingsworth	Texas	5,262	9,000	1.44
Yavapai	Arizona	22,319	8,700	2.23
Colusa	California	3,056	8,600	1.06
Tehama	California	6,421	8,500	1.97
Hendry	Florida	3,183	8,400	4.15
Presidio	Texas	2,782	8,300	N/A
Berrien	Michigan	5,460	8,200	2.18
Kings	California	12,017	8,100	0.81
Jackson	Florida	8,839	8,100	1.76

The need to minimize the loss of agricultural lands due to utility-scale solar deployment given projected farmland conversion due to future development is especially acute given that our projected national total of 2.5 million acres of solar conversion on agricultural lands is likely to be a substantial underestimate. As the world moves away from fossil fuels to help mitigate the worst effects of climate change, many U.S. states are in the process of adopting or strengthening policies to aggressively expand renewable energy production. The NREL ReEDS Mid-case Scenario does not account for these potential future policies. Likewise, while NREL does assume that the cost of solar energy production will decline and efficiency will increase, unexpected innovations could drive the costs even lower and acres even higher. Already, in a significant majority of counties worldwide, utility-scale solar PV is the least costly option for adding new electricity capacity, especially with rising natural gas and coal prices (IEA 2021).

4. Projected siting on rangelands and forestlands may have additional impacts
AFT projected solar installations on 652,000 acres of rangeland, which is included in the total for agricultural land, but is much less likely to be designated as Nationally Significant. Since rangelands tend to retain some natural vegetation cover and have relatively limited human influence, they have a greater potential to support wildlife movement and consequently, for wildlife habitat disruption when developed (Suraci et al. 2022). The highest projected losses for rangeland were in Texas (about 254,000 acres), California (about 178,000 acres), Arizona (about 76,000 acres), Nevada (about 38,500 acres), and Oklahoma (about 33,000 acres).

Further compounding the potential impacts stemming from solar expansion, AFT projected that nearly 341,000 acres of forestland will be converted to utility-scale solar development. Florida was projected to have the highest acreage of solar projects on forestland (nearly 85,000 acres), followed by South Carolina (nearly 59,000 acres), New York (over 39,000 acres), Maryland (over 22,000 acres), and Georgia (over 18,000 acres). Forests are not only net sinks for carbon but forested watersheds filter and improve water quality, slow runoff that lessens flood frequency and severity, and provide important habitat for a variety of wildlife that could not survive otherwise (McGuire et al. 2011). Forests often serve as important buffers to agricultural lands and other open spaces (FAO 2016). Their conversion can have cascading effects that remove agricultural runoff and flooding controls, reduce biodiversity and pollinator habitat, and increase pest abundances – all of which can detrimentally impact farmland.

It is important to point out, however, that although land use and land cover change impacts from utility-scale solar need to be carefully thought out and planned for, their impacts are relatively small compared to other energy systems (Hernandez et al. 2013). In addition, there are opportunities to increase the environmental co-benefits of utility-scale solar (Hernandez et al. 2014). Early results shows that the co-location of solar energy and vegetation can provide benefits to both solar developers as well as land managers, including farmers and ranchers (Macknick et al. 2013; Jossi 2018).

Challenges with Modeling Future Solar and the Limitations of AFT's Model

AFT developed the solar model as part of the *Farms Under Threat 2040* future scenario mapping (Hunter et al. 2022). Although AFT believes a large expansion of solar is needed to fight climate change, poorly planned solar development could impact farmers, ranchers, and local communities. AFT undertook the modeling to better understand the potential impacts. The original intent was to add projections of new utility-scale solar development to projections of various development scenarios to 2040.

After completing the model runs, AFT discovered several issues with the mapping that will need to be addressed in future modeling efforts. Because of these concerns, we opted not to include the solar deployment mapping layer in our future scenario maps. However, because solar deployment is likely to have significant potential impacts on agricultural land, we included a section on Smart Solar in our report (*Farms Under Threat 2040: Choosing an Abundant Future*).

AFT's primary concern, as previously mentioned, is that the NREL ReEDS Mid-case Scenario now significantly underestimates the amount of solar that will be installed by 2040. The data from the DOE Solar Future Study and the Princeton Net-Zero America project were not available at the time the modeling was undertaken but could be used in a future analysis. It is likely that modeling the higher solar demand projected in these studies would still project disproportionate conversion of agricultural land and a significant loss of Nationally Significant land.

Second, AFT found significant discrepancies between what the NREL ReEDS Mid-case Scenario had projected for utility solar in the Pacific Northwest and what was happening on the ground. The NREL model projects 5,000 and 1,000 MW by 2040 in Washington and Oregon, respectively. However, AFT's regional staff verified that these projections are too low based on current solar build-out. The NREL modeling team confirmed that the NREL model is most challenged in the Pacific Northwest. They are trying to understand shortcomings in their approach (Wesley Cole, personal communication, March 25, 2022). AFT's regional staff also felt that the NREL projections might be too high for South Carolina.

Finally, AFT's model did not consistently project patterns within states that lined up with where current solar development projects were being proposed. The model projected the past solar siting trends forward and this could indicate that assuming more solar will be placed in areas where it has occurred in the past works in some areas but not others. For example, in New York, the model was projecting a lot of solar in the Hudson Valley that had no large-scale projects proposed as of 2021 (only a few 20+ MW projects were in review, permitted, or receiving state funding in the greater Hudson Valley as of 2021) and little solar in the North Country and the Mohawk Valley where two fifths of the proposed projects as of 2021 were located – likely due to the relatively low cost of land when compared to other regions (Levy et al. 2022). While AFT's model did include a measure of land value, it was not able to fully account for economic considerations or the local political environment, which can strongly influence where solar installations are sited.

These anomalies underscore the complexities of trying to model future solar installations. However, AFT's initial modeling efforts help increase our understanding of the potential impact of solar energy development on farmland and agricultural and rural communities and identify important areas for future research. Projecting solar deployment using AFT's *Farms Under Threat* land cover and land quality mapping provides a clearer picture of the need to get this right.

Achieving Sustainable Energy and Food Production

The U.S. needs to rapidly deploy solar in a way that minimizes its impacts on agricultural land and makes any solar built on farmland more beneficial for farmers and for agriculture. With good planning and well-regulated permitting processes, the impact of solar development on agricultural lands could be minimized, and the positive attributes of solar projects on agricultural land maximized to strengthen agricultural viability and soil health.

AFT bases its "Smart Solar^SM" approach on four guiding principles[1]:

1. Prioritize solar siting on buildings and land not well suited for farming.
2. Safeguard the ability for land to be used for agriculture.
3. Grow agrivoltaics for agricultural production and solar energy.
4. Promote equity and farm viability.

AFT's detailed spatial mapping of potential solar deployment is the first step in understanding the potential impacts of solar energy development on farmland, agriculture, and rural communities. But much

[1] AFT Smart Solar^SM guiding principles

more research lies ahead before the U.S. can reap the benefits of "solar done right." For example, what are the site-specific impacts of different scales of solar on soil health and farm viability? What should best practices for construction and decommissioning include so that solar installations preserve the land's suitability for farming in the future? How do agrivoltaic systems work in different climates, regions, and with different cropping systems? And if research provides proof of concept for agrivoltaics for both the farmer and the developer, can we incentivize them financially? The U.S. Department of Energy's Innovative Solar Practices Integrated with Rural Economies and Ecosystems (InSPIRE) project is currently using field research sites around the country to provide data on low-impact solar development opportunities as well as region-specific benefits and tradeoffs. These efforts seek to improve the environmental compatibility and mutual benefits of solar development with agricultural and native landscapes. In addition, on May 5, 2022, the U.S. Department of Energy announced $8 million in funding for foundational agrivoltaic research.

In practice, planning, zoning, and siting decisions for renewable energy projects ultimately take place at the local level (Leslie et al. 2021). But there are several policy actions that all levels of government can take to guide solar deployment (Hunter et al. 2022; Levy et al. 2022).

Solar Research and Policy Recommendations

Based on modeling and field work, AFT has identified four major priorities for research. To advance smart solar siting, continued research on the viability and generation potential of siting solar development on rooftops, other existing infrastructure, brownfields, and marginal lands would help inform future build-out. Modeling the impacts of the millions of additional acres of solar (e.g., DOE's Solar Future Study) needed to meet 2050 decarbonization goals could confirm AFT's initial modeling results demonstrating that even smaller amounts of solar development pose a threat to each state's better farmland and the nation's Nationally Significant land.

To minimize the impacts of solar installations that do end up on agricultural land, researching, developing, and implementing best management practices for the construction, operation, and decommissioning of solar projects will help ensure the viability of the land for immediate agricultural production after the life of the project. More research is also needed on the technical and economic viability of agrivoltaics across geography, crops, livestock, and farm scale to explore the possibilities of solar energy and agricultural production from the same acreage. And finally, to sustain robust agricultural and rural communities and ensure equitable access to benefit, additional research can help to evaluate the beneficiaries and economic impacts of solar projects on farmers, farmer-renters, and farm communities.

Simultaneously, local, state, and federal agencies should take steps to minimize impacts on agricultural land and ensure that solar built on farmland is beneficial for farmers and for agricultural economies (Hunter et al. 2022). For example, communities or counties should incorporate smart solar siting into local land-use decisions; develop solar land-use laws and permitting through inclusive processes; ensure that solar strengthens farm viability and make sure that best practices for soil health are followed when siting solar on farmland. States can reinforce smart solar siting by incentivizing solar development on the built environment, previously disturbed and marginal agricultural lands. If solar displaces farming from productive agricultural lands, states can require mitigation through the protection of agricultural land elsewhere. States can also provide guidance and resources to communities for smart solar, including best practices for construction and decommissioning. States should also consider funding research on agrivoltaics and pending proof of concept, define and incentivize it. Finally, the federal government has a role in incentivizing solar development on existing structures, brownfields, and marginal lands. It should continue funding research on best practices for developing solar on agricultural lands, including agrivoltaics. Federal agencies should also equip local, state, and regional leaders with smart solar resources while they expand their interagency cooperation.

Additional Resources on Solar

To help states and communities plan and develop policies to drive smart solar siting, AFT collaborated with the Vermont Law School's Farm and Energy Initiative to compile a farmland solar policy design toolkit (Byrne 2020). The Initiative's Farmland Solar Policy Project seeks to balance solar development with farmland preservation and provides the policy design toolkit, a state law database, and other research at *farmandenergyinitiative.org/projects/farmland-solar-policy*. AFT's Farmland Information Center also provides information on smart solar siting and dual-use opportunities at *farmlandinfo.org/solar-siting*.

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Glossary

Agricultural land (cropland, rangeland, pastureland, woodland): American Farmland Trust's *Farms Under Threat* agricultural land cover dataset defines agricultural lands as non-federal cropland, pastureland, rangeland, and woodland associated with farms. *Farms Under Threat* uses the USDA NRCS Natural Resources Inventory definitions[2] to identify these agricultural land types. These are commonly referred to as farmland and ranchland by the public and include:

> **Cropland:** Land used to produce adapted crops for harvest. It includes cultivated and non-cultivated cropland. Cultivated cropland includes land in row crops or close-grown crops. It also includes other cultivated cropland like hay land or pastureland that is in a rotation with row or close-grown crops. Non-cultivated cropland includes permanent hay land and horticultural cropland. (NRI values 1 (cultivated) & 2 (uncultivated)).
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> **Pastureland:** Land managed primarily to produce introduced forage plants for livestock grazing. Pastureland cover may consist of a single species in a pure stand, a grass mixture, or a grass-legume mixture. Management usually consists of cultural treatments: fertilization, weed control, reseeding or renovation, and control of grazing. The NRI definition includes land that has a vegetative cover of grasses, legumes, and/or forbs, regardless of whether it is being grazed by livestock. (NRI value 3).
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> **Rangeland:** Land on which the vegetation is composed principally of native grasses, grass-like plants, forbs, or shrubs suitable for grazing and browsing, and introduced forage species that are managed like rangeland. Rangeland productivity is limited by water and nutrients (primarily nitrogen) and varies widely both seasonally and annually. Rangelands are vital for the ecological, environmental, and economic services they provide.
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> **Woodland:** Woodlands is a new agricultural land cover developed by *Farms Under Threat* to identify forested acres that are part of a functioning farm unit. Woodland acres are estimated based on Census of Agriculture data and mapped in forested areas that are contiguous to and no further than 1/10 mile from nearby crop or pastureland.

Agrivoltaics (dual-use solar arrays): These types of solar installations integrate solar arrays and farming activities on the same land. For example, they may include elevated panels and/or wider spacing to allow for crop or forage production or for livestock grazing within the facility area. The potential of dual-use solar arrays to minimize conflict between food and energy production is promising but conditional on continued research, field testing and, ultimately, economic viability.

Brownfields: As defined by U.S. Environmental Protection Agency, these are properties where the potential presence of a hazardous substance, pollutant, or contaminant complicates any expansion, redevelopment, or reuse of the property.

Business as Usual Scenario: This data layer from *Farms Under Threat* reflects the placement and amount of urban and highly developed and low-density residential land uses in 2040 (adjusted to state to reflect projected population growth) if development continues to follow recent trends (2001-2016). The U.S. is projected to convert an additional 18.4 million acres of agricultural land by 2040 in this scenario.

Carbon-free energy (clean energy): Energy that is produced without carbon dioxide emissions.

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[2] U.S. Department of Agriculture. 2015. *Summary Report: 2012 National Resources Inventory*, Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. http://www.nrcs.usda.gov/technical/nri/12summary

Distribution-side, utility scale photovoltaics (DUPV): The ReEDS model defines DUPV as being small (~6 acres) and situated closer to urban areas where they can be directly connected to existing grid-nodes. The model reflects these distinctions in array size and infrastructure requirements.

Farmland owners: About 40% of farmland in the U.S. is owned by non-farmers and rented out. In some counties, that number is nearing 30%. Over a third of this land is owned by women. Rented land is less likely to be managed with conservation goals in mind and, for these non-operating farmland owners, rental payments may be the driving factor in how this land is used. Solar developers can pay higher rental fees, driving up rental costs and reducing the amount of land available to farm.

Federal lands: Federal lands are excluded from AFT's solar modeling. *Farms Under Threat* maps federal lands from the USGS Protected Areas Database/National Conservation Easement Dataset v2. State, county, or tribal lands are not included. The Bureau of Land Management (BLM) oversees private livestock grazing (mostly cattle and sheep) on 155 million acres of federal land and the U.S. Forest Service (USFS) oversees grazing on roughly 102 million acres of National Forest or National Grasslands. The amount of grazing that is allowed each year changes each year depending on annual assessments of forage and range conditions. In a first-of-its kind analysis, *Farms Under Threat* maps federal lands used for grazing using the most recent BLM and USFS grazing permits (2016-2018).

Forestland: *Farms Under Threat* uses the NLCD definition of forest. These are areas "dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover." *Farms Under Threat* identifies forestland that is associated with farms and re-classes it as woodland.

Intergenerational transfer of farmland: The average age of farmers is over 57 years old with roughly a third over the age of 65. Farmland owners who are 65 or older now own more than 40% of the agricultural land in the U.S. As they begin to retire, up to 370 million acres of farmland could change hands by 2035.

Low-density residential land uses: LDR is a new land use class developed in *Farms Under Threat* to identify agricultural lands in areas where the average housing density is above the level where agriculture is typically viable. It is the first nationwide attempt to map the impact of large-lot residential development on the agricultural land base. LDR land use is concentrated in areas where development pressure is increasing and developed and undeveloped land are interspersed, often on the edges of cities and towns.

Megawatt (MW): Megawatts measure the output of a power plant. One MW is a thousand kilowatts or 1 million watts. A typical coal plant is about 600 MW in size.

Nationally Significant agricultural land: The agricultural land that is best suited to intensive food and other crop production with the fewest environmental limitations. The *Farms Under Threat* designation is based on the PVR land quality metric, which AFT developed. The metric quantifies the potential or quality of agricultural land based on its productivity, versatility, and resiliency following consultation with expects. Nationally Significant agricultural lands include soils that are prime, unique, or prime with limitations; cropland and pastureland; relevant cropland types (fruits, vegetables, staple foods, grains); and agricultural land in USDA NRCS Land Capability Classes (LCC) I and II.

National Renewable Energy Laboratory (NREL): A federally funded research and development center based in Golden, Colorado. NREL is sponsored by the Department of Energy. Its mission is to conduct research that advances renewable energy and energy efficiency.

Prime farmland: Prime farmland, as defined by the U.S. Department of Agriculture, is land that has the best combination of physical and chemical characteristics for producing food, feed, forage, fiber, and oilseed crops and is available for these uses. It can be cultivated land, pastureland, forestland, or other land, but it is not urban or built-up land or water areas. The soil quality, growing season, and moisture supply are those needed for the soil to economically produce sustained high yields of crops when proper management, including water management, and acceptable farming methods are applied. In general, prime farmland has an adequate and dependable supply of moisture from precipitation or irrigation, a favorable temperature and growing season, acceptable acidity or alkalinity, an acceptable salt and sodium content, and few or no rocks. The water supply is dependable and of adequate quality. Prime farmland is permeable to water and air. It is not excessively erodible or saturated with water for long periods, and it either is not frequently flooded during the growing season or is protected from flooding. Slope ranges mainly from 0 to 6%.

Photovoltaics (PV): Photovoltaic devices generate electricity via sunlight using an electronic process that occurs naturally in certain types of materials called semiconductors. The sunlight frees electronics in these materials. The electrons can then be induced to travel through an electrical circuit, sending electricity to the grid.

Regional Energy Deployment System Model (ReEDS): The ReEDS model, along with the Distributed Generation Market Demand Model (dGen), project utility-scale power sector evolution and distributed photovoltaic adoption, respectively, for the contiguous U.S. The ReEDS model takes a system-side, least cost approach in making decisions and the dGen uses a customer-centric approach. The ReEDS model accounts for unique traits of renewable energy, including variability and grid integration requirements,

Smart solar: Smart solar seeks to maximize renewable energy generation while minimizing negative impacts on agricultural land and to make any solar that is built on farmland more beneficial for farmers and for agriculture.

Soil health: Soil health is a measure of the soil's biological, physical, and chemical functions. Soils include mineral particles, organic matter, water, and soil. Soils also include micro- and macro-organisms that support plant, animal, and human life. Organic matter is a key component of soil and as it breaks down, it provides sources of plant nutrients.

State's Best Farmland: *Farms Under Threat* uses this designation to identify the better half of each state's farmland and ranchlands (i.e., PVR values above the state median) based on the land quality metric (PVR), which AFT developed. The metric quantifies the potential or quality of agricultural land based on its productivity, versatility, and resiliency following consultation with expects.

Statewide Important Farmland: In some areas, land that does not meet the criteria for prime or unique farmland is considered to be farmland of statewide importance for the production of food, feed, fiber, forage, and oilseed crops. The criteria for defining and delineating farmland of statewide importance are determined by the appropriate state agencies. Generally, this land includes areas of soils that nearly meet the requirements for prime farmland and that economically produce high yields of crops when treated and managed according to acceptable farming methods. Some areas may produce as high a yield as prime farmland if conditions are favorable. Farmland of statewide importance may include tracts of land that have been designated for agriculture by state law. The NRCS designation of farmland of statewide importance with limitations indicates that certain conditions must be addressed before the soil qualifies as prime farmland, such as providing supplemental irrigation or drainage.

Utility-Scale Photovoltaics (UPV): Large-scale utility photovoltaics are defined by the ReEDS model as being large (~600 acres) and likely to be sited in rural areas (Brown et al. 2020). Their size makes it viable to build grid interconnections, so they can be sited farther from existing substation or transmission nodes than DUPV facilities, but proximity to transmission lines is still important.

Urban and highly developed land uses: Largely built-up areas where most of the land has been converted into commercial, industrial, or residential uses, though opportunities may exist for urban agriculture. *Farms Under Threat* uses the U.S. Geological Survey National Land Cover Dataset to map UHD. UHD areas are commonly found in and around cities and towns, but also may include distributed energy production (e.g., well pads or wind turbines).

Well suited for agriculture: Climate, along with soil conditions and terrain, determines whether land is suited for agricultural uses and best used as cropland or pastureland or managed as rangeland. These same biophysical factors also limit the kinds of crops that can be grown. To support crop production, cropland soils must be deep enough, drain well, and have the right texture, chemical and fertility properties and the terrain must accommodate cultivation. Growing crops in locations that have an unfavorable climate, rugged terrain, poor soils, lack of soil water and/or too much soil water can be unprofitable or even impossible. In contrast to cropland, hay and grasslands can tolerate more marginal soils that are too steep to cultivate, too wet or too shallow or otherwise poorly suited to growing crops. Rangelands are managed as a natural ecosystem and are generally characterized by low and/or erratic precipitation, poor drainage, rough topography, and often low soil fertility.