ENVIRONMENTAL AND SOCIAL CONSIDERATIONS OF LAND CONVERSION TO SOLAR GENERATION

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Table of Contents

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Introduction

As the cost of solar power has dramatically fallen, development is expanding across the globe. Based on a conversion rate of 3.5 to 6.2 acres/MWac of installed capacity for typical large-scale photovoltaic (PV) systems, the amount of land expected to be occupied by solar power facilities is significant. *Globally*, roughly 10–15 million acres, or the size of New Hampshire and Vermont combined, may be developed for solar by 2030 and 32–46 million acres by 2050 [1]. The equivalent footprint of Rhode Island will be taken up by 2030 and the size of Connecticut by 2050. If solar deployment accelerates to meet decarbonization goals, land use could be several times larger. *Nationally*, for a scenario with decarbonization, ambitious electrification targets, and enhanced demand flexibility, the U.S. Department of Energy (DOE) expects solar PV will require 3.58 million acres by 2030 and 10.29 million acres by 2050 [2].[1] Much of the land under consideration is agricultural land, desert land, and federal and state lands.

As solar power development expands, conversion from other land uses, such as agriculture, urban development, and wildlife habitat, poses benefits and conflicts. Solar may provide opportunities for improved land stewardship, such as increased biodiversity and habitat, pollinator habitat, soil quality, soil carbon sequestration, reduced soil erosion, and less nutrient runoff. Solar development can also offer community benefits, such as increased tax revenue and farm viability. This white paper focuses on the social and environmental implications of land conversion and land management at utility-scale solar power facilities, 25 MW or larger. This white paper begins by outlining the reasons for public resistance to land conversion to solar, particularly in agricultural communities, such as aesthetics and displacement of tenant farmers, and suggests mitigation measures. It then reviews utility-scale solar power job creation, eclectic tax models and revenue across states, glint and glare, and residential property values. Next, the white paper focuses on opportunities and feasibility issues for dual land use, particularly pollinator habitat, grazing, growing crops, and opportunities for improving soil quality from land conversion. Subsequently, it addresses the ecological issues of land conversion, reviewing effects on wildlife, including birds, and module end-of-life practices. After that, it reviews two emerging land-sparing op-

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[1] These figures are mainly drawn from the 2021 DOE Solar Futures Study's decarbonization and electrification scenario, although DOE used land requirements from other scenarios when they were larger. These figures are not predictions but anticipated requirements to meet a scenario.

tions: siting on water and brownfields. The white paper concludes by outlining recommended areas for future research.

The information in this white paper comes from a thorough review and synthesis of peer-reviewed academic literature, as well as publicly available government and nonprofit reports. Additionally, we conducted 59 interviews with 64 interviewees, focused on 19 states in the Midwest (Arkansas, Iowa, Illinois, Indiana, Michigan, Minnesota, Missouri, and Wisconsin), the Southeast (Alabama, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Virginia), and the Southwest (Arizona, New Mexico, Nevada, and Texas) (See Figure 1.) We interviewed a government and regulatory representative, a solar developer or utility company, and a vegetation management or wildlife expert representing each state. We sampled interviewees based on referrals to EPRI's utility company members; a LinkedIn and Google search of employees at energy, fish and wildlife, and agricultural policy agencies; a sample of solar developers working on the largest projects in the state by installed capacity; and referrals to vegetation management and pollinator habitat experts. The interview data is reported anonymously to encourage frank conversation during the interviews.[2] Throughout the white paper, the interviews are labeled with a number and category. The 21 agricultural interviewees (labeled ag) included farming community members, farming organizations, soil scientists, and vegetation management specialists. The 23 government interviewees (labeled gov) included representatives from the U.S. Bureau of Land Management (BLM), departments of natural resources, U.S. Fish and Wildlife Service, local governments, public utility commissions, and state energy agencies. The 15 energy sector interviewees (labeled energy) included utility companies and solar developers. We described the interviewees' role depending on their preference stated during the interviews. The interview category and number are occasionally omitted when other identifying features are used to describe interviewees who wanted to be anonymous. "They" is used as a singular pronoun to avoid disclosing the sex of the interviewees.

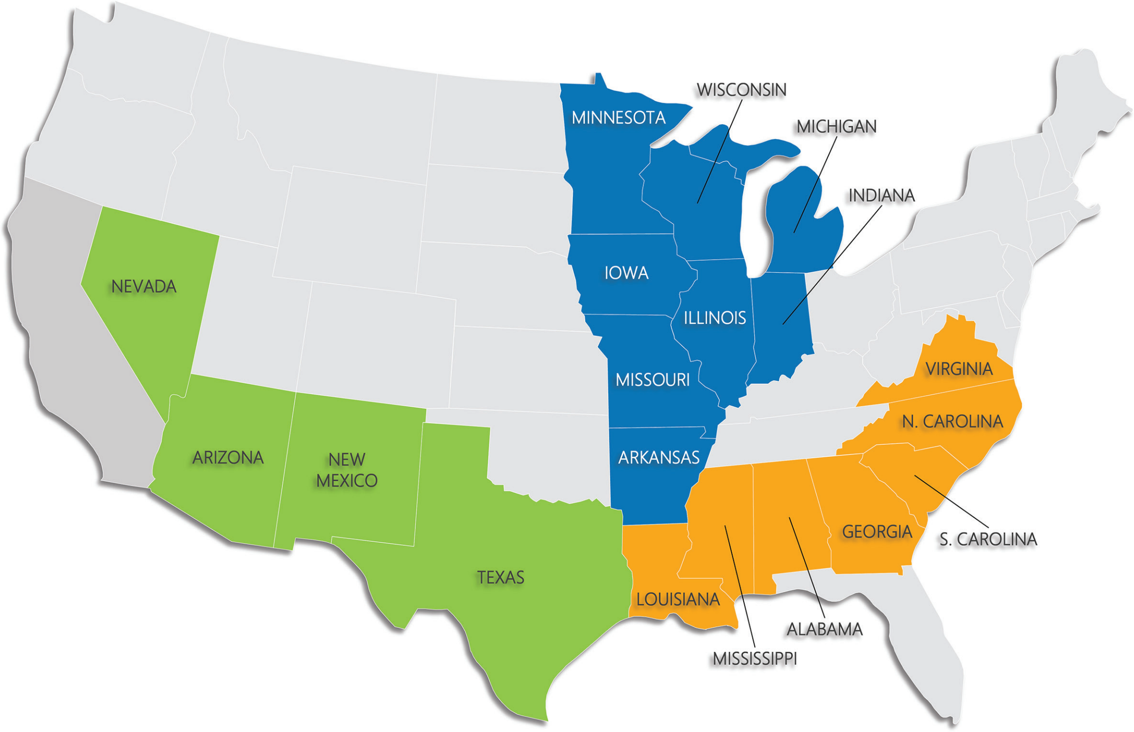

Figure 1. States included in this study. Green—Southwest; Dark blue—Midwest; Orange—Southeast. Map Source: 24slides.com free Creative World Map PowerPoint template

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[2] This study was approved as exempt by the human subjects review boards at Michigan State University and Arizona State University.

Community Perceptions, Benefits, and Drawbacks

This section summarizes the general drivers of community opposition to solar land conversion, focusing on aesthetic impacts. Community opposition has led to canceled projects and fraught relationships between communities and developers. Suggestions for alleviating resistance are provided.

Aesthetic Impacts and Public Acceptance

Public opposition to changes in the landscape from the development of utility-scale solar power plants is a leading cause of community pushback [3]. Developers should not assume that partisan polarization is driving this opposition. Research has not uncovered a straightforward relationship between partisanship and solar development. In Michigan, Bessette and Mills (2021) found that majority Democratic areas are more likely to oppose wind power development than majority Republican areas [4]. However, in Utah and California, Democrats are more likely than Republicans to support a nearby utility-scale renewable energy facility [5],[6].

While the opposition is commonly described as a not-in-my-backyard (NIMBY) movement, there is a consensus among social scientists that NIMBY is an insufficient analytical explanation of renewable energy opposition [5]–[10]. By characterizing opponents as self-interested NIMBYs, developers could misunderstand the reasons for resistance and overlook potential solutions or try to develop sites where they are unlikely to secure a permit. See Table 1 for an explanation of why NIMBY is an insufficient analytical descriptor [8].

Instead of NIMBY, social scientists have found that opposition stems from peoples' "*place attachment*," which is the emotional bond people form with places they live and sometimes even places they visit [13]. Places shape peoples' individual and community identities [13]. Some values affecting place attachment are *tangible* (property values, visibility of solar arrays and equipment, glint and glare, recreational land values, and access to local jobs). Others are *intangible* (natural beauty, cultural history, the removal of trees where a person played as a child with a loved one who has passed away) [13],[14]. Psychologists have found that particular place attributes even allow psychological restoration, and disrupting them can negatively affect mental and physical health. Stronger place attachment often increases renewable energy opposition [3]. Financial compensation and other transactional benefits can alleviate the tangible value conflicts. However, financial compensation can fail to address intangible value conflicts or even exacerbate opposition [11]. For example, an opponent to a project in California saw the desert landscape around their house as sacred and described being enraged by developers offering her a residential solar system as compensation for changes to the viewshed from her house [11].

Additionally, the trade-offs of land use for solar energy are not directly made up for by decommissioning fossil fuel generation because the facilities are typically sited in different places. Furthermore, solar facilities typically require more land to produce an equivalent amount of electricity compared to conventional generation facilities. Carlisle et al. (2014) conclude that place attachment is not a significant explanatory factor in understanding renewable energy opposition [16]. However, they incorrectly define place attachment as the number of years a resident has lived in an area.

Solar visual impacts assessments typically overlook place attachment [17]. In one study, scientists visited renewable energy sites and identified visual impacts as large size, regular geometry, high reflection, visibility for long distances, as well as effects on adjacent

Table 1. Analytical Shortcomings of NIMBY

Variable	Explanation
Definition of a backyard	Backyard lacks a clear definition and spatial boundaries. In the U.S. Southwest, researchers have observed opposition to renewable energy projects far from houses [3],[11].
Duration of opposition	Opposition changes across the planning, permitting, construction, operation, and decommissioning stages [12]. NIMBY does not capture this. An interviewee in Texas (ag 12) noted that opposition dissipated as local citizens saw the economic benefits.
Reasons for opposition	Opposition relates to the use-values of the land (agriculture, recreation), but also the non-use values (ideology, religion, identity) [9].
Measurement of opposition	Which stakeholders and how many stakeholders developers consult will influence project proponents' understanding of the reasons for opposition or support. Vocal opponents may not represent the average resident.

parks and scenic landscapes with touristic value [18]. However, local community members are likely to perceive the aesthetic effects on the landscape differently based on their cultural and identity-based attachment to the land. Visual impacts go beyond the literal visibility of renewable energy, as illustrated by the aesthetic values in Table 2 [19]. Even the perception of physical attributes differs between developers and the public. For example, near Primm, Nevada, a group of environmental opponents to a solar power plant site saw an "old growth" desert with rich with pristine biodiversity and associated with spiritual and recreational values. In contrast, developers saw the same area as a "world-class" solar site, with high insolation and low temperatures, previously disturbed from ranching, and next to complementary infrastructure, such as transmission, roads, and a highway providing easy access for workers [11]. Place attachment explains why solar power still engenders opposition, despite being less visible than tall wind projects.

Social science research has demonstrated that trust among the key stakeholders can reduce opposition caused by place attachment [13]. Community stakeholders' resistance increases when they perceive that siting processes are inequitable [22]. (See sidebar: ***Solar Power in Linn County, Iowa*** on page 11). Developers should engage community members early and often and build a trusting relationship with stakeholders [11]. Additionally, if local government entities communicate the uses of tax income to the public, particularly those beneficial to place attachment, it could alleviate conflict. Project scoping should include discussions with community leaders and surveys to measure place attachment. There will be intangible values associated with all sites. However, developers could avoid areas where a large percentage of the population, or local government officials, espouse strong intangible values related to culture and rural place attachment. These areas have the most significant potential for intractable conflict. For example, a solar program manager (gov 19) indicated that some local government officials "don't want to see solar in their county no matter what. It just doesn't fit [the community's] character."

To mitigate the tangible visual project impacts, Donaldson (2018), a BLM visual resource specialist who conducts visual assessments for environmental impact statements, recommends project modifications.

- Minimize cutting and filling (grading and blading)
- Limit vegetation removal where possible
- Reduce lighting use at night
- Use finishes that reduce glare
- Select finishes that blend into the landscape

Donaldson also recommends specific avenues for reducing conflict over land stewardship [23].

- Provide "good neighbor" payments to compensate affected neighbors who are not benefiting from land lease revenue.

Table 2. Aesthetic Values

Place Characteristic [20]	Description
Visual scale	The height of the technology and the amount of space it consumes.
Land stewardship	The perception of care, order, and upkeep of the landscape, for example, vegetation management and pollinator habitat
Landscape ideal	How a landscape compares to the inhabitants' ideal, and solar's fit within residents' imagination of an ideal landscape.
Disturbance	Land uses that intrude on, alter, and impact the landscape. Local environmental impacts (such as to endangered species, biodiversity, habitat and soil) cause community opposition [21].
Naturalness	Community perceptions of wilderness and habitat value.
Distinguishing features	Qualities of the landscape that make them distinguishable and memorable. Present in totality or through natural or cultural landmarks and special features.
History	The historical richness of the landscape and continuity with past land uses. This history can be hard for newcomers/outsiders to perceive.
Seasonal change (ephemera)	The effects of weather and seasons on a place (for example, land cover, vegetation, animals, colors, fall leaves). Solar power can disrupt ephemera since it is unchanging.

Aesthetic Design and Smaller Solar Sites

Survey research conducted in the Swiss Alps sought to determine if artwork and other visual designs could reduce solar opposition. They found that local ownership or co-ownership of solar facilities and colored solar modules could reduce resistance, albeit with a loss in panel efficiency [25]. See also the Land Art Generator for examples of artistic solar installation techniques for smaller projects (https://landartgenerator.org/). The organization indicated that custom film graphic images adhered to a solar module reduce the efficiency by 2%. In some urban applications, unusual designs or layouts could be built, such as Alliant Energy's spotlight solar trees in Wisconsin [26]. Designs can match the local context to better fit into the community. At the Solar Strand project at Rochester Institute of Technology, a portion of the solar field is laid out to resemble a DNA strand, and the facility includes walking paths, shade structures, and educational signage [27]. In a community of color in Chicago, the Bronzeville microgrid incorporates murals on the battery storage units featuring Black leaders painted by local artists [28]. These features add costs that may require grants or support from local governments.

Figure 2: Alliant Energy, Spotlight Solar trees

- Add community amenities on or near the site, for example, trails, restrooms, exhibits, parking, and plantings.
- Pay to preserve an equal amount of land elsewhere.
- Develop maintenance and decommissioning plans and disclose them to the public. Interviewees demonstrated that concern was pervasive across states that developers will leave the solar modules on site at the project's end or fail to care for the vegetation.

The study's interviewees also identified fencing as a visual concern. Developers should avoid chain link fencing for aesthetic reasons (energy 8, 9, ag 16). Local governments often set requirements for vegetative screening and setbacks from residences. Ranch style (or deer) fencing can improve the fit with the existing landscape in rural areas (see Figure 6) [24] (energy 2, 9). Vegetation around the perimeter of the solar installation, such as hedgerows, can provide both a visual buffer and habitat [23] (energy 5, 8, gov 16). In South Carolina, developers have planted Leyland Cypress trees, which a government interviewee (gov 12) found aesthetically pleasing. Developers must account for water availability when selecting visual buffers, as Arizona developers reported vegetative screening failing because of a lack of water. For urban projects, fencing that matches the local aesthetic (such as brick piers) can mitigate visual concerns, and walkways around the solar facility that include pollinator habitat or other vegetation can provide a park-like atmosphere for community recreation (energy 2).

DOE has developed guidance on developing Community Benefit Agreements (CBA) for solar power between developers and communities [29]. The process convenes developers and members of the public affected by solar development to identify stakeholder needs and secure community support. Community stakeholders can include neighborhood associations, unions, faith-based organizations, local environmental groups, and concerned citizens. Before the government approves a siting permit, the stakeholders and the developer sign an agreement about the project's community benefits. Potential community benefits include:

- Local jobs
- Employee benefits and wages
- Job training
- Road repair
- The establishment of a county trust fund
- Support for small businesses.

Benefits to the developer include public declarations of support, reduced investment risk, and approval of state and local subsidies. The DOE provides a resource guide on creating a CBA that outlines the mutual benefits to communities and developers. (https://www.energy.gov/sites/default/files/2017/09/f36/CBA%20Resource%20Guide.pdf) DOE's SolSmart program also offers resources for communities seeking to scale up solar power.

Agricultural Land Conversion

Benefits of Agricultural Land for Solar Development

Much of the land under consideration for conversion to solar power is agricultural land. Interviewees for this study identified numerous reasons why agricultural land is advantageous for siting utility-scale solar energy (see Table 3). Solar insolation levels are also essential in siting, but this consideration is not specific to agricultural land.

Socioeconomic Considerations of Farmland Conversion

Conversion of agricultural land to solar power coincides with existing socioeconomic pressures in farming communities, including loss of farmland to permanent development (especially housing), agricultural market volatility, changes in annual crop yield due to water availability and climate variability, and an aging farmer population nearing retirement age. Some stakeholders view large-scale solar power plants as a means of mitigating these pressures. Other stakeholders oppose the conversion of agricultural land, particularly prime farmland soils, to energy generation. In this subsection, we overview the challenges and opportunities.

Several interviewees perceived solar power to be a means of farmland preservation. The leasing revenue could bolster the long-term financial sustainability of the farming operation. Solar power development provides a temporary, albeit long-term, land use for farmers who had no other economic choice than to sell or lease their land, whereas housing and business developments are permanent. As one interviewee (ag 4) put it, "I would rather see a solar panel than a Walmart." A Midwestern utility company representative (energy 2) stated, "the whole idea is that [solar power] could be returned to ag land. So we are using it for a different purpose now, but we're not changing the characteristics [so much] that it couldn't be reused and returned to ag land." Main Farmland Trust is open to allowing solar power on conservation easements [30]. Through conservation easements, trusts pay farmers market value for their land's development rights. Since the program is permanent, the farmland would be guaranteed to return to agricultural production at the end of the solar power plant's life. Additionally, some developers argued that solar power would aid in farmland preservation by improving soil quality. This topic is covered in the ***Soil Quality*** section.

Farmers who support solar development often focus on *farming and income generation* because solar leasing revenue can compensate for farming's economic challenges [40] (Nicholls, 2020). Small farm revenue averaged only $93,700 in 2021, and small farm operators are dependent on off-farm income [31],[32]. Furthermore, many U.S. farmers are nearing retirement, as 34% are 65 or older [33]. Leasing income generally exceeds agricultural crop income [34]. A report by Rocky Mountain Institute projects

Table 3. Benefits of Agricultural Land for Solar Development

Benefit	Explanation
Access to transmission	Developers prioritize sites near substations or areas where a transmission line can be tapped. Interviewees quoted a figure of $1 million/mile to reach transmission.
Flat, contiguous land	Agricultural land offers thousands of acres of relatively flat land, improving economies of scale.
Cheap land costs	Agricultural land costs less than urban land, and rural areas often have lower tax rates. There are fewer opportunity costs associated with rural land conversion because of greater land availability than urban areas.
Reduced site preparation costs	Previously tilled agricultural land lacks rocks and trees that developers must remove and precludes blading and grading.
Drainage	Agricultural land often has drainpipes or ditches that prevent flooding.
Low-quality wildlife habitat	Agricultural land is previously disturbed and rarely provides habitat for threatened or endangered species. This also decreases the cost of surveys during permitting.
Willing landowners	Many farmers are interested in leasing or selling land.

that land lease payments from utility-scale solar power projects built from 2020 to 2030 will total $24 billion [34]. Leasing or selling agricultural land for solar power could enable farmers to retire with financial security.

A recent peer-reviewed study critically evaluated claims that solar leasing income improves farm viability [35]. The authors define farm viability as increased access to credit and more considerable capital investment in the farm. They ignored other benefits of energy leasing income, such as retiring or financing children's college education. Using data from the nationwide 2014 U.S. Department of Agriculture's Tenure, Ownership, and Transition of Agricultural Land survey, the authors found no evidence of increased farm viability from energy leasing income. However, these data are too outdated to support this conclusion. The average energy lease payment in 2014 was only $6,000/year total. Solar leasing rates are proprietary, but revenue would significantly exceed $6,000/year based on leasing averages.

Interviewees in Michigan reported that solar leases for private farmland range from $500–$1,200/acre/year. Leasing rates in North Carolina are also between $500–$1,000/acre [36]. In Texas, interviewees indicated a typical rate in rural areas is $500/acre with 2% compounding interest, increasing to $600–$1,000/acre near urban centers. In rural Iowa, lease rates range from $700–$1,000/acre [37]. Solar leasing rates are about $1,000/acre in Maine [38]. Solar leasing rates on New Mexico's state lands are approximately $536/acre [39]. It is common for farmers to rent hundreds of acres. For example, 300 acres at $800/year equals $240,000/year, far exceeding the $6,000/year figure. Research is needed that evaluates farm viability using average solar leasing rates.

The characteristics of opposition to solar power differ across urban, suburban, and rural areas [24]. In Michigan, Bessette and Mills (2021) found higher opposition to large-scale wind energy in communities with scenic views (for example, the Great Lakes coastlines) compared to rural production-oriented agricultural communities [4]. Greater support for renewable energy in production-oriented farming communities is likely attributable to farmers' interest in income diversification [4]. Survey research that gauges differences in the level of acceptance of solar power by agricultural production type (row crops, fruit, vegetable, dairy, beef cattle) would be a valuable area for research.

Even if opposition to solar development is lower in agricultural production communities than in scenic ones, there are conflicts in rural areas due to place attachment. Agricultural community members who oppose utilizing agricultural lands for solar power focus on *idealized rural land uses* [40]. Nicholls found that dual-use initiatives, such as grazing sheep, did not placate community members because they perceived such efforts to be disingenuous. Newcomers to rural areas often migrate for the landscape's rural character, thus opposing any change [8],[15]. Social scientists call this *rural aspirationalism*, in which residents, often newcomers to an area, resist development that threatens what they imagine as a pastoral ideal. Furthermore, in-migrants are usually not dependent on the rural agricultural economy and do not share farmers' pressures to maintain farms' economic viability. They perceive that solar power industrializes the rural landscape and disrupts close ties between farming and rural life (See sidebar: ***Solar Power in Linn County, Iowa*** on page 11 for an example in Iowa). Figure 3 shows solar protest signs at neighboring houses to a solar installation in an agricultural community. Many farmers view farming as a lifestyle that is part of their identity rather than simply a job [41]. Their place attachment relates to their land management, farming, and recreational activities on their land (for example, hunting and hiking) [42]. Furthermore, many farmers believe they have a "moral obligation to conserve" their land [43]. These aspects of place attachment may lead some farmers to oppose leasing land for solar power.

Figure 3. Picture of solar protest signs near the Assembly Solar, Ranger Power, facility in Shiawassee County, Michigan. The signs line roads throughout the small town. (Photo by Sharlissa Moore, May 2021. Adjusted in Adobe Lightroom.)

Some farmland conservation organizations, particularly the American Farmland Trust (AFT), oppose solar siting on prime farmland (see definition in sidebar: ***What is Prime Farmland?***) [46],[47]. AFT's research demonstrates that agricultural lands were converted at a rate of 2,000 acres/day between 2001 and 2016–totaling eleven million acres–all of which are lost to low-density residential development and urban- and highly-developed land uses [48]. A state agency employee (gov 23) stated, "I think that appropriating land that would otherwise be used to generate food is a kind of bargain with the devil." A representative of a farming organization (ag 20), argued that solar developers should select non-prime agricultural land, which "is challenged by nutrient deficiencies or is drier than prime agricultural land would be, or the soil type isn't suitable for commercial production of crops."

Several states have taken legislative action. Oregon has limited utility-scale solar based on USDA's capability class system for soils. A solar installation can only use 12 acres of class I and II soils [49]. Additionally, New York restricts large-scale solar energy systems to 50% prime farmland [50]. Massachusetts requires projects built on prime farmland to include agrivoltaics. The ***Pollinator Habitat and Public and Local Government Perceptions*** section discusses how dual land use initiatives might affect public perceptions of utility-scale solar power.

Interviewees explained that stakeholders' definitions of prime farmland sometimes diverge from USDA's definition in sidebar: ***What is Prime Farmland?*** A renewable energy developer (energy 12) explained, "prime farmland means a different thing to everybody. So, what one neighbor might consider prime farmland, another neighbor might say, 'Look, I couldn't grow anything. I have no water in this area. There's nothing to grow.' Or 'The cattle don't get enough... feed out here. You need too many acres per head.'" In Pinal County, Arizona, prime farmland, which by definition requires irrigation or sufficient rainwater, is being lost because of Lake Mead's historic low water levels. Because of a 21-year drought, the U.S. Bureau of Reclamation cut 18% of Arizona's annual apportionment of water from Lake Mead Reservoir starting in October 2021 [51]. Drought has also increased the price of animal feed, forcing some ranchers to sell livestock and even their land [51]. Arizona farmers will experience a 60% decrease in their water allotment, leaving one-third of Pinal County's farmlands fallow [52]. Pinal County farmers are selling or leasing land for solar development because they can no longer farm due to a lack of water. Pinal County has deemed solar development to be compatible with its rural character. However, some people in the county disagree and do not want to see more solar development. Because of this, a solar developer reported that the state government had encouraged developers to begin developing state lands rather than private lands.

What is Prime Farmland?

The U.S. Department of Agriculture (USDA) defines *prime farmland* as "the best combination of physical and chemical characteristics for producing food, feed, forage, fiber, and oilseed crops and is available for these uses.... The soil quality, growing season, and moisture supply are those needed for the soil to economically produce sustained high yields of crops.… 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" [44].

USDA also has more specific ratings. One is the *crop productivity index* with ratings ranging from 0–100. Higher numbers apply to soil with more significant production potential. The rates are not specific to a particular crop. Second, the *USDA capability classes*, range from Class 1 to 8. Soil quality is best for class 1 and worst for class 8 (Web Soil Survey: Definitions, n.d.). *Class I* "soils have slight limitations that restrict their use." *Class II* soils "have moderate limitations that reduce the choice of plants or require moderate conservation practices" [45].

Developers interviewed for this study argued that it is difficult or even impossible to entirely avoid prime farmland. (See also Katkar et al., 2021 [53] in the GIS section to follow.) A representative of the Great Plains Institute (energy 9) explained that in some states, "trying to avoid prime farmland is kind of a fool's errand because it's where you're going to be siting [solar power]. It's everywhere. We have counties where you can't spit without hitting prime farmland." Instead, they explained, developers should aim to stack benefits and prioritize dual land uses. Solar developer interviewees also emphasized that the land being used is a small percentage of overall agricultural land in the states where they are developing. A Midwestern utility company employee (energy 5) explained that

land meeting USDA definitions of prime farmland is distributed unevenly across the landscape. In contrast, solar projects are built in large contiguous blocks to reduce operations and maintenance (O&M) costs. An interviewee from a large renewable developer (energy 4) explained:

> *The way I think about project siting is almost like a Venn diagram of a hundred circles, and we're trying to find that perfect little spot in the middle that represents [all objectives]. That little spot is getting tighter and tighter as the more obvious locations have been identified, and some percentage of them have been built already.*

Figure 4 shows a USDA map that identifies soil quality using the Crop Productivity Index, illustrating how soil quality varies across the landscape. Most of the added solar capacity for Alliant Energy is being developed in Southern Wisconsin. While soil quality is lower in Northern Wisconsin, the utility company's service territory is in the southern part of the state.

A representative of a company that develops, owns, and operates solar power (energy 3) explained that farmers benefit from the leasing revenue without any inputs. They stated, "I think the price [of the lease] outweighs the production potential and the value that they're getting off any kind of farming or ranching. And so most of them would allow prime farmland to be signed up for solar." A vegetation management specialist (ag 8) argued that solar

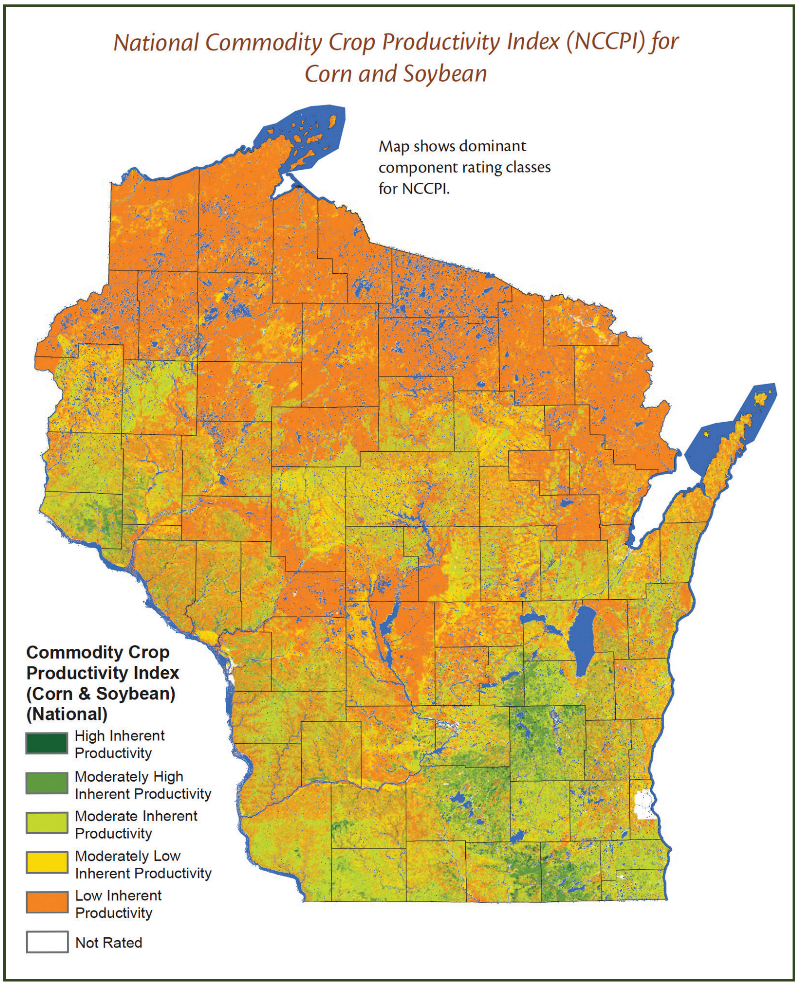

Figure 4. Wisconsin map of soil quality for corn and soybean production. (U.S. Department of Agriculture, 2016) [54]

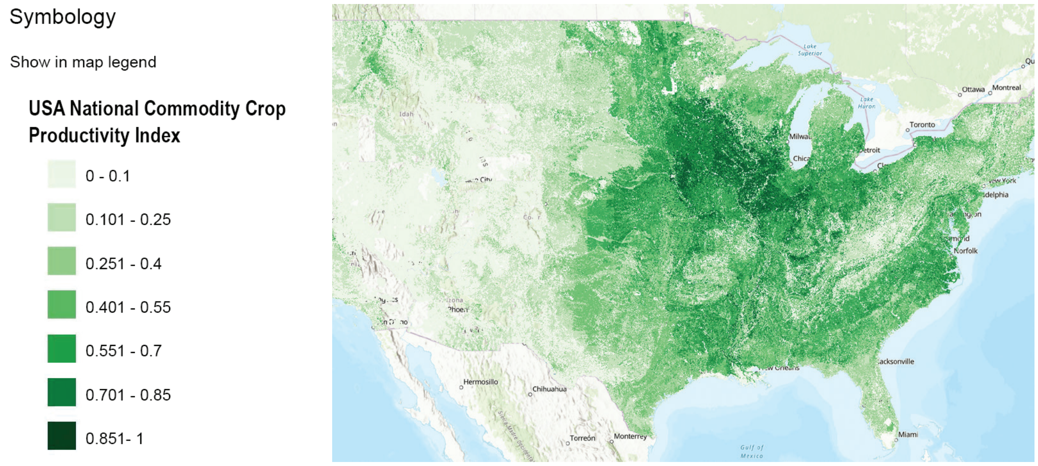

Figure 5. Crop productivity index map, United States. The darker green hue indicates higher soil quality. Source: ESRI, ArcGIS [55]

Solar Power in Linn County, Iowa

There are two in-progress solar projects in Linn County, Iowa (population 226,706). One is Clēnera Solar's 750-acre 100 MW Coggon Solar project. Additionally, NextEra has proposed a 3,500-acre 690 MW solar power plant. The NextEra facility is set to replace the Duane Arnold nuclear power plant, which NextEra is decommissioning due to the higher cost of nuclear power than solar and the expenses required to repair the damage caused by a derecho (windstorm) in 2020. Many local community members oppose both projects. The county is trying to balance renewable energy goals with the protection of farmland, and renewable energy is part of its comprehensive plan. A local planner argued that the tradeoff between land for agriculture and energy was acceptable, especially considering the land being converted is farmed for corn for ethanol rather than table food.

The county held two virtual public meetings with record attendance, and community leaders petitioned for a moratorium on solar projects but were unsuccessful. Citizen interviewees felt that trust had been broken between local developers and the community because nondisclosure agreements for leasing created an aura of secrecy among neighbors. Furthermore, they reported that project employees had trespassed on land that farmers were still leasing from landlords. Additionally, they perceive that developers do not understand rural communities and how local agricultural economies would be affected.

Local opposition has centered on concern about home values, partly because the setbacks are only 50-ft. Local citizens' opposition to the project also reflects the concept of *rural aspirationalism* defined earlier in this white paper. An interviewee stated, a "*person today can see [the] countryside. If this project goes through, that person will be looking at chain-link fencing and a sea of black glass across all sides of their home. And the developers continue to tell us that this does not negatively impact your property values. I think it impacts people's emotional status, and I also think it impacts your property values.*" NextEra commissioned CohnReznick L.L.P. to study property value effects, but residents distrusted the report because of perceived conflict of interest (see *Residential Property Values* section). They were also fearful that a derecho would damage the solar modules and contaminate the land.

Finally, citizens oppose the use of prime farmland. An interviewee stated, "*In my opinion, it's not practical to cover tens of thousands of acres across the Midwest [of] productive land with solar panels.*" Over half of Iowan farmers rent part of their farmland, exceeding the national average [57]. These projects could disproportionately affect renters (see ***Displacement of Tenant and Renter Farmers***). An interviewee perceived proposals to graze sheep skeptically because sheep grazing is not a developed industry in the area.

developers could assuage controversy over using prime agricultural land by demonstrating good land stewardship.

> *In the ag community, land management demonstrates stewardship. There's an appreciation for the way land is managed, through erosion prevention, through species diversity. You're taking prime farmland, and you're giving it to a solar developer. Then the ag community watches from afar how that land is managed, and it's a disappointment…to see solar projects either grow up in eight feet tall weeds or have tremendous erosion. If the right people can connect the right dots, there's a tremendous opportunity for solar development to be a shining star of land stewardship.*

Developers can improve land stewardship by planting pollinator habitat, installing bird and bat boxes, minimizing the use of pesticides, preventing erosion, maintaining hedges, and reducing mowing [56].

Displacement of Tenant and Renter Farmers

Interviewees identified displacing farmers from land they rent as a critical solar land conversion concern (ag 1, 12, 14, 16, 17; gov 3, 6, 11, 16; energy 3). Data is neither available on the scale to which this is occurring nor on the socioeconomic effects, which may be site-specific. Only 10% of farm acreage is rented by full-tenant farmers, meaning farmers who lease all their land [58]. Full-tenant farmers are disproportionately young and, while majority White,

represent a much higher percentage of People of Color compared to other farmer categories [58],[59]. A project that displaces tenant farmers may disproportionately affect young farmers. Almost all U.S. landlords, or 96%, are White [59]. A project that displaces tenant farmers of color could pose environmental justice issues by causing disproportionate harm to a minority group while primarily benefitting White landowners.

Compared to full-tenant farmers, a more significant proportion of farmers (39%) own some land and also lease nearby land to improve the economies of scale of their operations [57],[58]. The percentage of rented land varies by state and crop type, meaning the impacts of solar land conversion on farmland tenants will be uneven nationwide [60]. Land displacement will affect crop producers more than ranchers because over 50% of cropland is rented compared to only 25% of pastureland [58]. Most U.S. agricultural landlords (87%) are not current agricultural operators and are on average 66.5 years old [61]. According to interviewees in Iowa, some landlords do not even live in the same state as their land. They found it unfair that these landowners will reap the benefits of leasing without coping with the local, aesthetic drawbacks of solar power.

An interviewee who works in farmland conservation (ag 1) worried that solar rentals would reduce the local farmland rental supply in a region and therefore increase the rental costs of the rental land that did not receive solar leasing offers. A solar developer (energy 3) argued that the two markets within a state or region—land rental for solar power versus land rental for agricultural land—would likely remain separate. They reasoned that agricultural producers would not generate a profit at above-market rental prices; therefore, landowners would not find a tenant, or keep an existing tenant, if they tried to charge more. However, displacement remains a concern. A landowner signing a solar leasing agreement will gain far more income than renting the land for agricultural uses. The renter cannot afford such high leasing costs. For example, an interviewee living in a Texas agricultural community stated:

> *Over the past five years, I've leased to the same farmer-rancher, and his price has not gone up at all. But…I'm under a solar contract [now]. There's absolutely no way I would say, 'okay, I'm just going to continue to lease this [to the farmer-rancher].' I don't think the farmer would be able to pay enough. So, eventually, he will be priced out of the land just because of the [pending] solar agreement.*

In that area, there is other land available. However, nationwide most landlords have long-term relationships with renters. Therefore, USDA infers that access to new farm rental land is limited [58].

We also heard concerns from interviewees in Wisconsin and Michigan (gov 3, ag 18) about displacing dairy producers from the land where they apply their manure. "So, manure is generally viewed as a positive thing because it contains nutrients, but then it becomes a liability because trucking costs are more than the nutrients in the manure are worth." Therefore, if solar development displaced dairy farmers' manure land, they would need to treat and dispose of the manure. Trucking it elsewhere would not be economically feasible. The other anecdotal concern was that the price of farmland for sale in the area was higher than average due to solar development and that this would preclude young farmers from purchasing land to begin farming. Finally, interviewees raised concerns about the impacts of solar development on local goods and service providers, such as seed and fertilizer companies and grain elevators. Interviewees in Iowa (ag 12, 16) were concerned that 4,250 acres converted to solar power will reduce demand for agricultural goods and services. Additionally, farmworkers, who are disproportionately Latino [59],could also experience disruption to their livelihoods from decreasing labor opportunities in the agricultural industry.

Studies are needed to understand how many acres of farmland and what types of crops grown on that farmland would affect local agricultural economies. Such a figure would be more complex than a simple amount of acreage because land leases and sales affect the price of farmland and the resilience of specific farming communities.

GIS Approaches to Site Identification

To alleviate conflict, Apostol et al. (2017) recommend a zoning approach that excludes certain lands [24]. Geographic information systems (GIS) is often used to identify solar exclusion zones. GIS scientists layer land-use types to identify favorable sites or sites that developers should avoid. GIS solar mapping processes focus on meeting techno-economic criteria and avoiding areas with high conflict potential (for example, national parks, tourist hotspots, threatened and endangered species, high-quality habitat) [62]. For example, Argonne National Laboratory's Solar Energy Environmental Mapper includes 67 data layers focused on site selection

on BLM lands.[3] As another example, the Nature Conservancy's (TNC) GIS map for North Carolina identifies areas with significant biodiversity likely to be impacted by climate change [63]. The organization recommends avoiding these sites, especially since wildlife relocation is often unsuccessful. Additionally, local and programmatic environmental impact statements for solar technologies in the Southwest have identified solar development zones. Stakeholders should not view GIS methodology as a panacea but rather a first cut at excluding lands likely to garner opposition because of their charismatic features. This is because social science data about specific local opposition are rarely included in the map layers [62].

Only one GIS study has mapped appropriate agricultural lands for solar development [53]. In New York State, Katkar et al. (2021) categorized land as least suitable, poor, medium, or good by considering slope, proximity to a substation, land cover (such as forested or cropland), and farmland quality. Eighty-five percent of the good-suitability land and 82% of the medium-suitability land is agricultural land [53]. Suppose development on prime farmland is forbidden and new transmission lines are not sited. In that case, there is only enough land that scores well across all four suitability criteria to develop 5 GW of solar power, insufficient for meeting 2030 goals.

Like all other GIS studies to date, Katkar et al. did not consider land suitability based on community and local government acceptance [53]. Nor did they account for land costs or the opportunity cost of developing urban land. For example, the map identifies Long Island as an area with a high potential for ground-mount solar development. Sward et al. (2021) recommend incorporating social science data into GIS mapping and other quantitative approaches to site identification [62]. Successfully identifying low-conflict areas depends on inputting social science data into the model. This social science data could include interviews, well-designed surveys, and community modeling, in which members of the public help identify suitable sites. While this requires an up-front investment in social science research, it has the potential to save money by avoiding proposed development where a permit is likely to be denied. Methodologies that gauge overall general public opinion are insufficient [64] because of the "*social gap*" between general public acceptance of solar power and local opposition [6]. The fact that Katkar et al. find available land very limited without using prime farmland, but do not consider social opposition, illustrates how difficult it is to find ideal solar sites.

Job Creation

Job data for the large-scale PV sector (25 MW or greater) is lacking. Furthermore, the data for utility-scale and distributed solar jobs are often combined. The sole public data source is B.W. Research's annual survey of clean energy companies. The survey only captures employment at one time during the year. It is impossible to accurately measure national utility-scale jobs from this data since construction jobs fluctuate throughout the year.

The job categories for utility-scale solar power include development, construction, O&M, supply chain, and induced jobs. Construction jobs are the largest segment but are temporary, lasting only one or two years. The Solar Jobs Census defines a "*solar worker*" as someone who spends "50% or more of their time working on solar-related activities." According to the Solar Census, there were 231,474 solar workers in the United States in 2020 [65]. DOE et al. (2021) provide a larger figure of 316,675 solar jobs (in the fourth quarter of 2020) because the report includes workers who devote less than half of their time to solar technologies [66].[4] Two-thirds of overall "solar worker" employment was in construction and installation.[5] Of these, 30,017 workers–or 19%–are employed on utility-scale projects [65],[66].[6] The census does not provide utility-scale data for other job categories, including sales and distribution, supply chain, and O&M.[7] A source familiar with the data indicated that the number of O&M jobs

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[3] California Energy Infrastructure Planning Analyst, California Statewide Energy Gateway, Crucial Habitat Assessment Tool, Environmental Review Tool (Nature Serve), Georgia Low Impact Solar Siting Tool (The Nature Conservancy), How to Solar Now (Scenic Hudson), Solar Computer Vision (Defenders of Wildlife), Solar on Closed Landfills (Minnesota Environmental Quality Board), Western San Joaquin Valley Least Conflict Solar Energy Assessment (The Nature Conservancy), Maine Audubon Renewable Energy Siting Tool, Murray County Minnesota Mapping Tool, and COMPASS Mapping Oregon's Wildlife Habitats. Oregon will release a Renewable Energy Siting Assessment tool soon.

[4] These workers may have full-time jobs, but they spend less than half of their time on solar power.

[5] By comparison, only 4% of solar jobs in 2020 were in maintenance across all types of solar deployment (Solar Energy Industries Association et al., 2021).

[6] The census does not define the size range of utility-scale solar power.

[7] In-progress, utility-scale installation represented nearly 75% of all solar capacity installed in 2020. Construction encountered few delays, partly because the work was deemed essential, although labor availability fell by 4.3% during the pandemic [65] (Solar Energy Industries Association, et. al., p. 6).

for utility-scale solar power is limited (0.01 jobs/MW), although the jobs contracted to other companies for module washing or vegetation management often go uncounted. No data are available for whether or how many jobs battery storage adds, although one interviewee suggested it provides some O&M employment.

Governments and developers can use the IMpact Analysis for PLANning (IMPLAN) tool to estimate jobs for upcoming projects. Several state-based studies use the now-defunct National Renewable Energy Laboratory (NREL) Jobs and Economic Development Impact, or JEDI, model or the IMPLAN model to evaluate construction job hours for utility-scale PV plants. Job estimates vary based on the model inputs. A California study estimates 14.4 construction job-years/MW for utility-scale PV installations of 20 MW or larger [67]. For the 14.4 job-years/MW figure, a 50 MW solar PV power plant would create 720 job-years, or 360 workers working for two years. An Illinois study estimates approximately 11.6 construction job-years/MW for a scenario with 2,292 MW of utility-scale installed capacity [68]. These are short-term jobs, although an industry average for the length of construction is not available. An interviewee familiar with the data indicated that 5–20 MW projects take approximately 3 months to construct while larger projects take 12–18 months. Some interviewees saw the lack of permanent jobs as a drawback of solar power compared to some other generation sources.

Several interviewees emphasized that the construction jobs, while temporary, are high paying. Two interviewees from the Southwest (gov 5, ag 14) indicated that some workers have left $12/hour positions to make $30–$50/hour in utility-scale solar construction. Furthermore, some workers will sustain their employment by moving from one construction project to another within a region (gov 5, ag 11). Several interviewees expressed concern that the jobs were not going to in-state workers. Some solar developers partner with unions, such as the Utility Workers Union of America, to maximize local employment and guarantee high wages. Utility companies or government entities can institute requirements guaranteeing a certain percentage of local workers. For example, local governments in Texas are allowed to make the tax abatements contingent on giving local companies and workers preference for construction and contracting jobs.

The job creation and induced economic benefits of solar power are relatively significant for small rural communities. During construction, towns have experienced significant induced economic benefits through increased local demand for services and housing [34]. Anecdotally, several interviewees (ag 14, energy 11) commented on benefits from sustained wind and solar construction in an area related to local supply chains and the restaurant and hospitality industry. A study found that between 2001 and 2017, the indirect and induced economic benefits from renewable energy development in rural Arizona totaled $23.8 million [69].

Tax Revenue

Tax Structures

Some local governments view tax revenue from utility-scale solar installations as crucially important because it funds local schools, infrastructure, emergency response, and other public services. Moreover, solar power creates few costs for local governments [70]. Conversion to solar power can substantially change local tax revenue, particularly compared to agricultural land uses. However, tax revenue varies across states and localities due to disparate tax structures, as described in this section.

Haggerty et al. (2017) found that a $100 million solar investment's projected tax revenue would vary greatly across Arizona, California, Colorado, Idaho, Montana, New Mexico, Nevada, Oregon, Utah, Washington, and Wyoming [71]. They based this on the property tax rates for a sample of rural counties. However, the tax structure for solar power often diverges from standard property tax rates. Under a traditional model, an assessor would account for the land's value. They also account for the improvement value after the solar arrays, batteries, and other structures are developed, which depreciate over time [72]. An alternative, called a payment in lieu of taxes (PILOT), taxes the facility based on a flat rate per MW installed.[8] Several states have established a state-wide PILOT rate, while others allow local jurisdictions to negotiate PILOT rates. In Michigan, local governments contested a 2020 state legislative proposal for a PILOT of $3,500/MW/year because they thought it was too low [73]. The governor vetoed the bill because the state tax commission was not consulted to develop an evidence-based rate. A University of Michigan report suggested that a $7,500/MW rate is more evidence-based considering assessed property values in the state and the average state property tax millage [74]. This rate is closer to Ohio's PILOT, which ranges

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[8] Alternatively abbreviated as PILT or called a fee in lieu of taxes (FILOT).

from $6,000/MW to $8,000/MW. Developers who hire more local workers secure the higher rate [75].

A flat PILOT rate does not account for the difference in property values and property tax rates across tax jurisdictions. Therefore, some states have left the tax structure to local governments. An interviewee from a wind and solar development company explained that the most significant pushback they receive to siting solar power in the Central and Southwest United States is not aesthetics or use of prime farmland but negotiating the tax structure with local governments. Some states reduce the assessed property value rate for solar power or charge a fee per kWh of generated electricity. Table 4 reviews the tax structure for utility-scale solar in the states included in this study. Additional information is included in ***Appendix 1***.

The lowest tax revenue we found outside of some Indiana projects is in *Iowa*. A hypothetical 200 MW project in Iowa would generate $49,490.50 in local taxes each year (or $3.96 million over 40 years) [76]. In Wisconsin, this 200 MW project in an 88,000-person county would provide $200,000 in taxes per year.

Tax Benefits for Rural Counties and Municipalities

Rural counties, where few other economic development options exist, benefit from various tax structures for utility-scale solar power. Often 50% or 60% of the tax revenue supports school districts, which is particularly important for underfunded rural schools. Interviewees reported the revenue was used for computer and science labs in schools, public hospitals, improvements to roads, fire service and trucks, and law enforcement. In a public meeting,

Table 4. Utility-scale Solar Tax Models

Tax Model		States and Details
1.	Land and equipment taxed without abatement	• **Alabama:** Very little solar has been installed so far, therefore taxation without abatement is the default for now. • **Michigan:** Legislature is considering a PILOT.
2.	Property value and equipment value assessment reduction	• **Arizona:** Equipment assessed at 20% of its original cost (minus the value of tax credits and grants), property tax rate of limited primary value or full cash value based on county rates, one-time construction sales tax. • **Illinois:** Standard cash assessed value of $218,000/MW. Depreciation mostly offset by inflation adjustment. • **Missouri:** Solar is tax-exempt. • **North Carolina:** 80% reduction in solar equipment valuation. First year rollback tax: 3 years of past property tax at the commercial rate. • **Virginia:** Option 1: 80% reduction in machinery & tools tax for 5 years, 70% next 5 years, 60% years 11+. SolTax Model can be used to compare Option 1 and 2. (See option 2 in row 4).
3.	Local government determines taxes or can opt out of state property tax exemption	• **Indiana:** Many counties have retained agricultural property tax rates. State government has issued guidance to tax at commercial rates. Tax abatement requires county council vote. • **Louisiana:** Industrial Tax Exemption offered, but parishes can and have opted out. • **Nevada:** Up to 2015, Nevada provided $500 million in tax abatements between wind and solar power • **New Mexico:** State property tax abatement with local PILOTs, for example, 75 MW Roswell facility taxes: $396,000 annually or $5,657/MW. • **South Carolina:** Orangeburg County attracts investment with PILOTs; reduces tax rate from 10.5% to 6%. • **Texas:** County governments and hospitals have negotiated PILOTs. Chapter 313 for school districts are at the discretion of local governments: 60% of project value for 5 years, 40% years 6–10, 100% after 10 years.
4.	PILOT on installed capacity (MW)	• **Mississippi:** PILOT for solar investments greater than $60 million for first 10 years of operation, approved by Mississippi Development Authority. • **Virginia:** Option 2: PILOT of $1,400/MW, increasing with inflation. SolTax Model allows for comparison. • **Wisconsin:** PILOT of $4,000/MW (with a per capita limit). As a siting incentive, the rate is higher for counties hosting solar and wind.
5.	Fee for energy generated (MWh)	• **Iowa:** Replacement tax of 0.06 cents/MWh for local governments using average annual radiation and solar capacity factor. Replacement tax on delivery of electricity if within the utility service area. State collects 3 cents/$1,000 of property value for general fund. • **Minnesota:** $1.20/MWh, plus property taxes at commercial/utility property rate.

See ***Appendix 1*** for a written version of this table, with references.

a *Michigan* official reported that if a proposed solar project were built in his county, it would avoid a current ballot measure to increase millage to cover animal control and animal shelter costs. Alternatively, the revenue would cover the costs of three full-time police officers. In *Illinois*, large-scale wind and solar projects have contributed $306 million in state-wide taxes since 2003, including $41.4 million in property taxes in 2019 alone [77]. Much of this revenue has gone to school districts ($193.7 million or 61%) and the rest to county governments, community colleges, and fire and road and bridge districts [77]. In Taylor County, *Georgia*, a PILOT will provide $1 million a year in tax revenue to the Taylor County School District (48%), Taylor County (40%), and several municipal governments [78]. After 10 years, the standard assessed property tax rate will apply. The 690 MW Gemini Solar installation is the largest facility under development in *Nevada*. Even with a state-mandated property tax abatement, Nevada will receive $63,934,533 in taxes over the Gemini project's lifetime [79]. The majority of the revenue (52.1%) will go to the Clark County School District, amounting to $2 million/year. The other beneficiaries are Clark County, Las Vegas Metropolitan Police, the State of Nevada, and the Las Vegas Library District [79].

Examples of Net Tax Revenue

A report by the *North Carolina* Sustainable Energy Association added the revenue from all solar facilities built in North Carolina up to 2017 for the year after each facility's construction. They found that rural communities netted a total of $10.6 million in property taxes in the year after solar power plants' development [80]. The $10.6 million in revenue is a 2,000% increase compared to the $513,000 in taxes paid in the year prior to solar development. This magnitude of increase only applies for one year because North Carolina assesses a one-time rollback tax, which reclaims the last three years of real property taxes on the former agricultural land at the commercial rate. A 20 MW facility in Twiggs County in *Central Georgia* (population 8,120) provides $100,000 annually in property taxes [81]. In *South Carolina*, Orangeburg County (population 86,175 and a majority-minority county) has attracted solar energy investment through a PILOT tax abatement. Despite this tax abatement, two solar projects totaling 206 MW will provide $11 million in tax revenue over their 40-year lifetime [82].

Some rural *Louisiana* parishes are clamoring for state approval of solar plants to gain property and sales tax benefits. In April 2021, an official from Morehouse Parish (population 24,874) in northern Louisiana requested approval for the 98 MW Bayou Galion project from the Board of Commerce and Industry of the Louisiana Economic Development Corporation [83]. The official explained that few other economic development opportunities exist in northern Louisiana. The parish anticipated the sales tax alone would provide $1.2 million to the school system, $900,000 to the sheriff's office, and $300,000 to the parish. Additionally, property taxes will significantly increase from recategorizing the land from agricultural to industrial. The board delayed approval because they wanted a bond for decommissioning to be required.

Minnesota's 1 GW of utility-scale solar power capacity nets more than $1.8 million/year in Production Tax Credits for 38 counties. The county with the most solar power, Chisago County (population 56,621), received over $350,000 in production tax revenue in 2020 [84]. In *Wisconsin*, projects under development will generate between $200,000 and $600,000/project/year for municipalities and counties. Project examples include:

- **Crawfish River Solar** (75 MW): $125,000/year to the Town of Jefferson (population 10,633) and $175,000 to Jefferson County (population 83,686)
- **Onion River Solar** (150 MW): $250,000/year to the Town of Holland (population 3,756) and $350,000/year to Sheboygan County (population 115,340)
- **Beaver Dam Solar** (50 MW): $200,000/year to Dodge County (population 87,839)
- **Wautoma Solar** (99 MW): $396,000/year to Waushara County (population 24,443)[9]

A report examined county tax income from *Texas'* existing wind and solar facilities as of 2020, finding they will provide $4.7 to $5.7 billion in tax revenue to local governments over their lifetimes [85]. Furthermore, solar development is quickly expanding. As of 2020, revenue from both existing wind and solar facilities and those with a transmission interconnection agreement is anticipated to net between $8.1 and $10 billion. Over the lifetime of a 100 MW solar facility, a local government would receive between $9.4 million and $13.1 million in taxes. The amount depends on the equipment depreciation rate over the first ten years and the tax per megawatt rate in years 11 through 35. Oldham County cut property taxes by one-third using a PILOT. However, the county

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[9] All population estimates are from the 2019 U.S. Census, other than Holland, Wisconsin, where a U.S. Census has not been conducted since 2010.

of 2,112 people still makes $2.5 million in tax revenue annually from wind energy. A local economic development organization we interviewed in Texas reported an increase in the tax base from $600 million to $3.4 billion in a county of approximately 15,000 people because of wind and solar development.

In *Arizona*, which has had utility-scale solar installations for longer than many states, a report found that 2 GW of solar PV, concentrating solar power (CSP), and wind provided $16.7 million in tax revenue from 2001 to 2017 [69]. In 2018, Arizona schools received $882,000 in tax revenue from renewable energy. A 100 MW solar PV facility with 30 MW of battery storage built in Yuma County would annually generate $165,700 in annual property tax revenue for the county and $677,500 for schools. Including tax revenue, the report found a total of $4,618,000 in direct economic and fiscal benefits to Arizona from rural renewable energy activity. The direct and indirect economic benefits for Arizona total $9.4 billion. A solar developer working in Arizona reported that Yuma County is eager for this income. In contrast, a county planner from a wealthier county, with half of Yuma County's poverty rate, perceived that the property tax revenue was inconsequential to their county, despite being higher than the previous agricultural land use. While the interviewee viewed the construction sales tax as favorable, they noted it only lasted a year or two.

In *Nevada*, a high renewables scenario (3,638 MW of added total renewable capacity) would net $323 million in annual tax revenue from solar power [86]. In a low renewables scenario (or 1,472 MW), the state and local governments could still bring in $76 million in annual tax revenue from solar power. Boulder City, Nevada, is a town of only 16,207 people, and the only economic enterprise is tourism from the Hoover Dam. The completed 150 MW Copper Mountain Solar complex is expected to generate $200 million in total tax revenue for Boulder City over its lifetime [86]. The Copper Mountain facility has grown to 802 MW, so the tax revenue has increased.

If the local government owns the land used for solar power, it can gain revenue from a land lease or sale. Public institutions also benefit from the conversion of state lands to renewable energy. For example, beneficiaries of renewable energy leases on state trust land in *New Mexico* include K-12 schools, universities, community colleges, hospitals, water reservoirs, Rio Grande improvements, and state parks [39]. Conversion of grazing land to solar power generation will increase revenue for these beneficiaries. On New Mexico's state lands, agricultural land revenue only provides about $1.10/acre, whereas solar power generates approximately $536/acre [39].[10]

Glint and Glare

Glint is a momentary flash of reflected light from the sun. *Glare* is a continuous reflection of the bright sky around the sun, which is less intense than glint [87]. Whether glint and glare pose problems depends on weather conditions, type and tilt of the solar modules, topography, vegetative screening, distance from roadways, and location of viewers [87],[88].

Reflective structures other than modules might also produce glint and glare, such as "support structures, piping, fencing, and transmission towers and lines" [88]. In addition to daytime glint and glare, solar facilities could produce nighttime light pollution and skyglow [88]. Developers and government employees interviewed for this white paper did not mention glare other than to note that they completed the required analyses.

Possible glint and glare hazards from utility-scale solar facilities include annoyance, discomfort, distraction, after image, temporary blindness, and ocular damage [87],[88]. Nearby residents and commercial observers (for example, hikers, motorists, and mass transit users) may experience these impacts. The Federal Aviation Administration determined that risks to pilots are "similar to glint and glare pilots routinely experience from water bodies, glass facade buildings, parking lots, and similar features" [89]. Air traffic control workers–who are less accustomed to glint and glare than pilots–are more likely to be affected. Therefore, the Federal Aviation Administration recommends continued monitoring and assessment of glint and glare impacts from solar sited within or nearby airports.

BLM recommends that developers prepare an assessment, mitigation, and monitoring plan that examines "potential health, safety, and visual impacts associated with glint and glare" [88]. Organizations that conduct glint and glare analyses include the Federal Aviation Administration and entities that prepare environmental impact statements, such as public utilities commissions or natural resources

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[10] Nevada solar facilities use on average 9 acres/MW, with 71 MW providing $342,580 per year. Agriculture on Nevada state lands uses 9,000,000 acres of land (mostly grazing), providing $9,960,492 per year [39].

departments. There are several modeling tools for evaluating the potential impacts of glint and glare from PV modules and mirrored collectors for CSP. These tools calculate configurations that reduce glare on proposed solar sites and aid in developing mitigation strategies for reducing these impacts. For example, in partnership with other organizations, Sandia National Laboratories developed a Solar Glare Hazard Analysis Tool sold by ForgeSolar.[11] It analyzes flight paths and incorporates surrounding structures, such as buildings or billboards, to evaluate potential glare impacts.

Mitigation strategies for reducing glint and glare include considering it during site selection, maintaining vegetation underneath PV arrays and collector fields, colorizing the backs of PV modules to reduce visual contrast, and screening methods such as "fencing with privacy slats, earthen berms, or vegetative screening" [88]. Monitoring strategies include photographing sites at different times of the day [18]. Monitoring also involves viewing the arrays from various angles.

Residential Property Values

Survey research finds that most Americans, or 70%, believe that solar power plants will decrease the property value of nearby residences [90]. Several interviewees (energy 11, gov 4, 9 ag 12, 16) explained that affected members of the public are concerned about property values (see sidebar: ***Solar Power in Linn County, Iowa*** on page 11). People who are worried about this issue frequent public meetings. Neither a national study on utility-scale solar power's effects on property values nor peer-reviewed publications are available on this topic. Both NREL and the Solar Energy Industries Association have fact sheets educating the public that solar reducing property values is a myth [91],[92]. While the evidence suggests that solar power has little to no effect on property values, it is insufficient to reach a conclusion.

Several reports have found potential negative impacts for houses immediately adjacent to solar facilities, although both have methodological drawbacks described here. Varun Rai, an energy policy and engineering professor, and colleagues published a public, non-peer-reviewed report on solar power and property values [93]. They distributed a survey to property assessors in all 430 US counties with solar installations of 1 MW or larger. Only 37 of 400 surveys (or 8.6%) were returned, which is an acceptable response rate but a small sample size that is not large enough to compensate for state and regional variations in property assessment. They asked the assessors for their opinions of how solar facilities of different sizes would affect property values. However, many of the assessors surveyed had not previously assessed homes near solar power plants. They also reported being uncertain about the impacts and lacking professional training or standards for weighing the effect of a nearby solar facility on property values. Therefore, the survey results are of questionable validity.

Overall, they found that property assessors predicted no effect on property values in most cases, and a positive outcome where solar installations include vegetative fencing or replace previously undesirable land uses (such as feedlots) [93]. Assessors surveyed did predict home value would decline for properties within 100-ft of a large solar installation. However, the study's GIS data of the 956 U.S. solar facilities of 1 MW or larger show there is on average less than one house within 100-ft of a solar installation. Therefore, even if the assessors' prediction is correct, very few U.S. property owners would be affected by reduced property values. If a more rigorous follow-on study finds this is indeed a problem, the problem could be addressed by using at least 100-ft setbacks. In some cases where 100-ft setbacks have been infeasible, developers have purchased properties within 100-ft of an installation [94]. A contentious solar project in Iowa has 50-ft setbacks (see sidebar: ***Solar Power in Linn County, Iowa*** on page 11), and homeowners used Rai's study in hearings. Additionally, federal and professional policy changes could rectify the lack of professional guidance and standards for solar power property assessment.

Gaur and Lang (2020) from the University of Rhode Island published a non-peer-reviewed report on property values near 208 solar installations over 1 MW in Massachusetts and Rhode Island [95]. Albeit with a high error bar, they found that houses within one mile of a solar installation experience a property value loss of 1.7%, and those within 530 feet a 7% loss. Most of these plants were on previous farm or forested land in suburban areas. This study used a large sample of housing sales from the online real estate platform Zillow.[12] Since land is constrained in these states, these findings may not apply nationwide.

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[11] ForgeSolar offers a free trial and paid subscriptions.

[12] The sample included 71,337 home sales within one mile, which the researchers treated as the affected group, and 347,921 sales within 1–3 miles, which the researchers treated as the control group.

Consulting firms paid by solar developers have conducted numerous non-peer-reviewed studies. The most prominent is CohnReznick L.L.P., a large accounting firm with a real estate evaluation group that performs property appraisals. Their methodology is sound. However, given the appearance of conflict of interest, local communities do not always perceive the studies to be legitimate (see sidebar: ***Solar Power in Linn County, Iowa*** on page 11). CohnReznick uses Randolph Bell's paired sales analysis methodology to compare the sale of properties near solar power plants to sales in control areas [96],[97]. The firm has studied solar power plants in California, Florida, Hawaii, Illinois, Indiana, Michigan, Minnesota, Missouri, New York, North Carolina, and Virginia and has found no quantifiable and consistent detrimental impact from proximity to solar power plants, including to sale price, marketability, and time on the market. For example, in 2018, Cypress Creek Renewables contracted CohnReznick to study 15 homes in Illinois and Indiana that have sold near five solar installations (20 MM, 1.5 MW, 11.9 MW, 1 MW, 1.3 MW) within the last seven years compared to 63 comparable sales in control areas. The homes ranged from 83–1,196-feet from the solar array to the residential lot [98]. Their 2020 study of eight solar facilities in Minnesota, Michigan, Indiana, North Carolina, and Virginia (47 MW, 100 MW, 11.9 MW, 71 MW, 61 MW, 40 MW, and 19 MW) found little to no adverse effect on property values [94]. They compared 24 property sales near solar facilities to 81 comparable sales in control areas. In addition to the paired sales analysis, they interviewed realtors and assessors familiar with the sales. While Al-Hamoodah et al. (2018) surveyed assessors without solar appraisal experience, CohnReznick's method interviews realtors involved in the sale, purchase, and assessments of homes near solar facilities to gauge how the solar installation affected the appraisal and prospective buyers' perceptions [93].

Dual-use Land: Pollinator Habitat, Agrivoltaics, and Grazing

Dual-use applications in which solar power generation is co-located with another activity or ecosystem service is one possible approach to lessen land conversion concerns. A strategy gaining momentum through scorecards and proof-of-concept is planting pollinator habitat underneath and around solar arrays. This section first discusses pollinator habitat feasibility, followed by growing crops under arrays and grazing sheep on solar sites. The most effective dual-land use applications are site-dependent. While we found that grazing is already cost feasible, it may be inappropriate for a facility near a riparian zone because manure could pollute the water (ag 2, ag 13). Other sites might be better suited for native or managed pollinator habitats. Interviewees indicated that growing crops under arrays is not currently cost feasible without subsidies. In general, the appropriateness of dual-use agricultural activities–growing crops, planting pollinator habitat, or grazing–will be site-dependent.

Pollinator Habitat

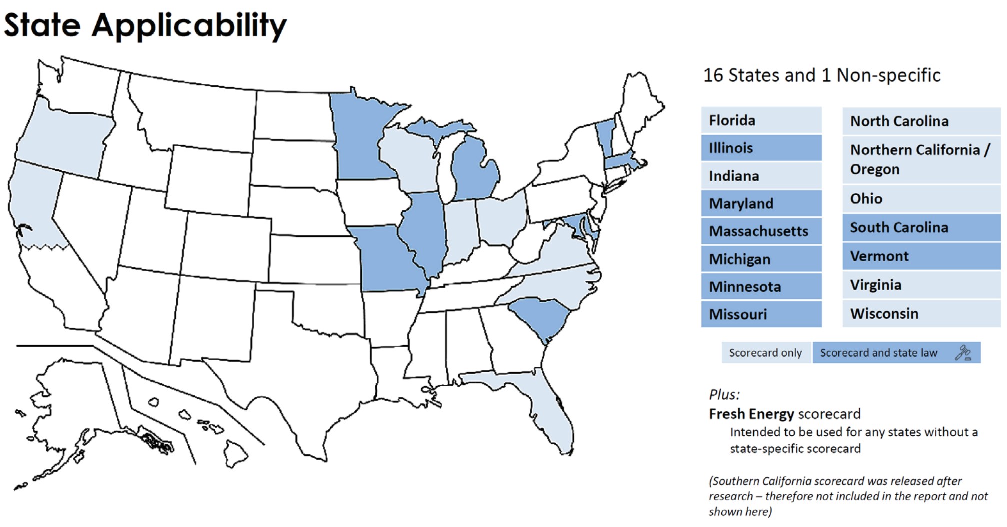
Many of the first utility-scale solar installations built in the Southwest used blading–removing the vegetation, rocks, and other materials from the site–and grading to level the surface. In some cases, developers would then apply herbicides and lay gravel (see Figure 13 on page 34), although gravel increases costs. These practices can cause erosion and drainage issues; therefore, using vegetative ground covers has become more common. Typically, a ground cover is seeded to prevent erosion and dust at the end of project construction. Turfgrass is a common ground cover. Low-growing species identified by interviewees include:

- Native grasses (side-oats grama, blue grama, buffalo grass),
- Forbs (prairie coreopsis, native milkweeds, upright prairie coneflower, lupine, blanket flower, black-eyed susan),
- Dandelions (a non-native, weedy forb, which provides value to pollinators because it blooms early and late in the season),
- Native legumes (purple prairie clover), and
- Non-native legumes (alfalfa, crimson clover, white clover, red clover).

Furthermore, low-growing native forb species suitable to the desert southwest could include mule's ear, sulphur buckwheat, red dome blanket flower, and scarlet globemallow. Developers commonly use non-native clover and fescue mixes under the solar arrays. Selecting ground cover that benefits pollinators may mitigate the environmental impacts of land conversion by providing forage for native bees, butterflies, and birds or managed honey bees [73].

Scorecards

Many states have created or are developing scorecards to evaluate pollinator habitat at solar facilities. The scorecard aims to ensure that the site is aesthetically pleasing and has tangible ecological value to pollinators. EPRI recently completed a review of the



16 States and 1 Non-specific

Florida	North Carolina
Illinois	Northern California / Oregon
Indiana	Ohio
Maryland	South Carolina
Massachusetts	Vermont
Michigan	Virginia
Minnesota	Wisconsin
Missouri	

Scorecard only | Scorecard and state law

Plus:
Fresh Energy scorecard
Intended to be used for any states without a state-specific scorecard

(Southern California scorecard was released after research – therefore not included in the report and not shown here)

Figure 6: Map of pollinator scorecards. Source: EPRI

attributes of fifteen state scorecards and one nonspecific scorecard [99]. The assessment revealed substantial overlap in the scoring elements, possibly because many scorecards have a common origin. Generally, scorecards include requirements for: site planning and management, site preparation, the avoidance of insecticide use, species diversity, native plants, bloom time, and the number of acres of habitat. The differences relate to the inclusion (or exclusion) of criteria that affect the balance among ecological value, ease of site management, and attainment of "pollinator-friendly" designations [99]. A map of state scorecards can be found in Figure 6.

Approximately half of state scorecard programs are associated with state legislation [99]. However, obtaining and maintaining a pollinator-friendly designation is voluntary at the state level. The only exception is in Michigan, where developers must meet a minimum score on the state's pollinator scorecard to use agricultural land enrolled in Michigan's farmland preservation program. Massachusetts offers three levels of pollinator certification with a third-party review, a detailed checklist, an annual maintenance log, and inspection by University of Massachusetts researchers [99]. It provides a unique "Compensation Rate Adder" of $0.0025/kWh for sites that obtain and maintain a silver or higher certification from the University of Massachusetts Clean Energy Extension Pollinator-Friendly Certification Program. However, several interviewees (energy 10, ag 4) indicated the rate adder is insufficient to make the state's habitat requirements cost feasible. Energy 10 stated, "We have not pursued the incentive in Massachusetts because the compliance costs are so high." In general, the voluntary nature of the scorecards means developers might not use them. A government biologist (gov 4) from the Southeast stated:

> *We do have a scorecard, but it's not used, mainly because we have no driver behind it to really push [developers to use it]. As far as pollinator habitat, unfortunately, there are no benefits or nothing really held out there for solar companies to do it. And that's what's made it really hard here. [When developers have used scorecards] it has really just been by the company being willing to step up and do it.*

The main incentive for developers to select pollinator habitat over other types of vegetative ground covers is potentially reduced O&M costs, discussed later in this section.

Most state agencies also lack the resources to conduct research (such as quantitative species monitoring studies) or ongoing monitoring on solar pollinator habitat to determine its level of success in meeting its goals (ag 1, 15, gov 8, 10, energy 10). Several states have self-approval processes for the original certification and any renewal certifications [99]. Interviewees recommended regulators conduct a site visit after three years when species are established. Some people suggested that developers should pay for monitoring and research since governmental environmental agencies' capacity for monitoring is limited. An interviewee from Monarch Joint Ventures, a Minnesota nonprofit organization, indicated that the energy companies should finance the monitoring but ought to involve landscape restoration practitioners. Conducting this research

is essential for determining whether solar pollinator habitat is benefitting pollinators and identifying potential improvements.

Site preparation and design is among the most crucial aspects of solar pollinator habitat development. If O&M managers do not thoroughly remove existing invasive, annual and perennial weeds, the seed mix could fail to take hold, resulting in lost investment [73]. Furthermore, ongoing maintenance is required to prevent invasive species and ensure habitat success. PV array ground clearance limits the species that can feasibly be planted within the array without causing shading issues or interference with mechanical or electrical equipment. Other technology design features, such as equipment access and drive train operation, also affect what can be planted under the arrays [281]. A vegetation management specialist (ag 4) reported that their sites on the East Coast often have a 36-inch clearance because of snowpack. This higher clearance increases the number of suitable plant species compared to 18 to 24-inch array ground clearance since few species, especially native ones, have mature heights below 24 inches. Some developers interviewed were concerned about the cost of increasing the pile height. Two energy interviewees stated that cost increases for greater array clearance are minimal up to the point where ladders and lifts must be used for installation. One developer (energy 7), who typically builds projects in the 10-20 MW range, indicated that increasing clearance from 20 to 36-inches increases labor and materials costs by 15%, which they estimated would be a less than 5% increase in total project costs. They are confident this will be outweighed by the reduced O&M costs. (See the ***Agrivoltaic Crop Production*** section for a discussion of greater array clearance.)

Seed Mix

The cost of pollinator seed varies by state and region and scorecard requirements for diversity, number of native species (including how close to the site seed must be sourced), and seed availability. Mixes with more non-native legumes (for example clover) are cheaper. In contrast, Cardno, an environmental consulting firm, sells a Solar Field Pollinator Habitat Mix designed for the Midwest for $955/acre (in early 2021), with 13 native forbs, five native grasses and sedges, and an oat nurse crop [100]. Ernst Seeds sells a Northeast solar power mix for four feet module clearance for $675.15, with 12 forbs and 3 grasses (applied using a broadcast method with a grain oats cover crop.) A vegetation management specialist and seed producer (ag 4) reported that Massachusetts' rigorous scorecard standards require a mix that costs up to $1,400/acre. This is because Massachusetts limits the percentage of legumes in the mix and requires high diversity of native species, including species that produce a small quantity of seeds and are therefore limited on the market. In contrast, a typical native seed mixture that meets pollinator requirements in Pennsylvania, Maryland, and Virginia costs approximately $600/acre or less (ag 4). In Minnesota, an interviewee (gov 8) reported that the average seed cost to meet scorecard requirements fluctuates but ranges from $300 to $600/acre, depending on seed source, soil type, and seed availability. Minnesota's south and west pilot seed mix includes 25 native forbs, 3 legumes, 3 sedges, and 1 oat cover crop. Because of pile height concerns and seed costs, some companies opt to plant taller native pollinator habitat in a project's buffer zones rather than under the modules.

Some developers and O&M interviewees anticipate impending seed shortages due to an uptick in demand for solar pollinator seed mix and fluctuating annual seed harvests. A Midwest regional ecologist (gov 8) explained:

> *This year [2021] is a drought. Our ability to harvest seeds off of native plants this year is going to be reduced. We also have to be respectful of the resource. And because we're in a drought we don't want to over-harvest sites and cause future damage.*

They encouraged developers to plan for large seed orders. According to an academic expert (ag 15), developers on the East Coast are partnering with regional seed suppliers to broaden the availability of seeds best suited to the local ecoregion.

Operations and Maintenance Costs

While the upfront costs of pollinator habitat are higher than turfgrass, some evidence suggests long-term reduced O&M costs will offset upfront costs. Established pollinator habitat does not require regular mowing like turfgrass, which reduce costs. However, some engineering, procurement, and construction developers sell the project after construction is completed and have no incentive to spend more upfront to reduce long-term maintenance costs. Utility companies should be aware of this issue if they plan to purchase the solar plant at the end of construction. EPRI is studying cases in which lower O&M costs offset higher upfront costs for solar pollinator site preparation, vegetation establishment, and hardware [101]. The project includes a structured survey to collect data from solar owners, operators, developers, and other involved parties, followed by a techno-economic analysis. Results are expected in spring 2022. The InSPIRE project, led by NREL and Argonne National Laboratory, is also examining O&M costs for pollinator habitat. This project includes experimental research in Minnesota across three site categories: dry and sandy soil, prime farmland, and a wetland. The researchers expect to publish results in fall 2022.

Several developers interviewed for this study (energy 3, 7) are confident that O&M costs will more than compensate for the increased expenses of pollinator habitat establishment. As one developer (energy 12) put it, "every penny saved on O&M is a massive save to a project: whether or not it can go forward." All developers interviewed who use pollinator mixes prioritized economic feasibility: lowering O&M costs from reduced mowing, increasing bifacial modules' electricity generation by planting reflective groundcover, and meeting environmental demands from corporate and industrial customers. Most developers addressed ecological benefits as a secondary consideration. These included benefitting pollinator species, protecting ground-nesting birds by reducing mowing, preventing runoff and erosion by increasing water absorption, reducing herbicide spraying after establishment, and improving soil quality. Several interviewees mentioned improving aesthetics and benefiting nearby pollinator-dependent crops. Four developers interviewed graze sheep and are therefore interested in pollinator plants palatable to sheep. Several other utility companies and developers (energy 11, 13) were concerned about the increased upfront costs and feasibility issues and were therefore reluctant to make planting pollinator habitat standard practice.

Hanging cables decrease construction costs but increase O&M costs. They can be a problem for sites without pollinator habitat, and even with pollinator habitat because the site still requires some mowing. This is especially the case for CAB wiring, which hangs low to the ground [102] ("CAB Solar Cable Management," n.d.). Specifically, interviewees (ag 4, 8, energy 5, 9) reported that unburied cabling potentially reduces capital expenditure (CapEx) costs by 1 cent/watt; however, it increases vegetation management costs. A vegetation management specialist (ag 8) stated that unburied cables increase mowing expenses by $200/acre. They explained:

> *Three or four years ago, cables were buried. We could traverse the site unrestricted… with large equipment. Well, it seems like in the last 18 months, cables are not buried. They're in trays (see Figure 7)….I've seen access restricted to as small as 60 inches. So now we have to manage 1,000 acres with equipment that is only 60-inches wide.… We basically have zero turn lawn mowers that we're managing a utility-scale project on because of cabling or drivelines.… It's probably the most impactful design feature there is.*

Similarly, an experienced solar beekeeper reported not bidding on the vegetation maintenance contract for a solar site because the wiring required mowing 200-acre plots with a push lawnmower.

Figure 7. Tray wiring at Assembly Solar in Shiawassee County, Michigan. Cab wiring hangs lower to the ground. (Photo by Sharlissa Moore, May 2021. Adjusted in Adobe Lightroom)

Plant Selection and Pollinator Goals

Experts disagree over whether non-native plants are the best option for solar pollinator habitats. Selecting native plants adapted to local growing conditions eliminates the need for inputs such as water and fertilizer and could increase carbon sequestration in the soil (see ***Soil Quality and Land Conversion*** section). Native seeds cost more and take longer to establish. (Forbs are native flowers or introduced legumes that benefit pollinators, such as blanket flower, white prairie clover, and prairie coneflower.) Additionally, native plants often grow taller than non-native plants and may require maintenance to prevent array shading.

The selection of appropriate plants depends on the project goal. For solar pollinator habitats designed to support honeybees, non-native clovers are beneficial since they are nectar-rich, yielding high levels of honey production. Clovers are less expensive compared to native forb species but also less beneficial to native pollinators because native bee and butterfly species will visit the clover but also require a diverse suite of floral resources to support their dietary requirements. While honey bees also benefit from diverse forage, which provides multiple amino acids, substantial honey production comes from melliferous crops such as clover and alfalfa. A 2020 study showed that honey bees housed on native prairie habitat seek out clover instead [103]. If a project seeks to benefit both native bees and honey bees, the seed mix needs to be tailored to that goal because they prefer different plants [104]. Bergamot species will benefit both, although lower-growing varieties should be chosen.

Solar pollinator habitat can also benefit butterflies. For example, agricultural land has consumed 77% of potential monarch butterfly habitat, and conversion of prairie to corn and soy crops has contributed to 98% of the loss in milkweed [105]. Solar pollinator plants could include native milkweed species, which is the only host plant for monarch caterpillars. Monarch Joint Venture is quantitatively evaluating milkweed and monarch species at small-scale solar sites. Wisconsin's Wood County solar project will include lupine seed because the site is within the endangered Karner blue butterfly range. At another Wisconsin site, developers are going to plant leadplant to benefit the rare leadplant flower moth. However, some developers worry about attracting threatened or endangered pollinator species to their site, as it could trigger onerous regulations under the Endangered Species Act.

Figure 8: Pollinator habitat at a Georgia Power (Southern Company) site showing coreopsis tinctoria, blanket flower, and Lemon beebalm (Mondarda citriodora). Wes Cunningham, Stantec

Another goal that has been discussed for native pollinator habitat on sites of 25 MW or greater with native bees is benefitting nearby agricultural crops. Direct empirical evidence is lacking in this area. NREL is conducting an in-progress study with results expected in 2022. Research will be needed with different pollinator habitat designs in various regions of the country. Achieving benefits is contingent on siting near pollinator-dependent crops (such as fruits and vegetables). There is some evidence that native bee populations located near pollinator-dependent crops will aid in pollination, although their flight range is short (only .5 miles) [287]. However, most utility-scale solar power is being built on land used for row crops, such as corn and soy. The peer-reviewed literature does suggest that although soybeans are self-pollinating, additional pollination from nearby native pollinating insects would increase soybean yield at some sites with certain soybean cultivars [106]–[109]. Honey bees could hypothetically be located permanently next to pollinator-dependent crops, instead of being moved, and forage on the native habitat when the nearby crops are not in bloom. Alternatively, bees could be brought back to the solar pollinator habitat in between trips to pollinate monocrops. Research on the market-feasibility and interest from relevant stakeholders is limited.

Pollinator Habitat and Public and Local Government Perceptions

While state governments are generally not requiring pollinator habitat, local governments with permitting authority can do so. A developer in Arizona indicated that every county they are working with has requested pollinator habitat. A local planner (gov 9) shared that his county requires solar power plants to include a high-quality pollinator mix with native vegetation. Therefore, including pollinator habitat can be very important to local permitting authorities' acceptance.

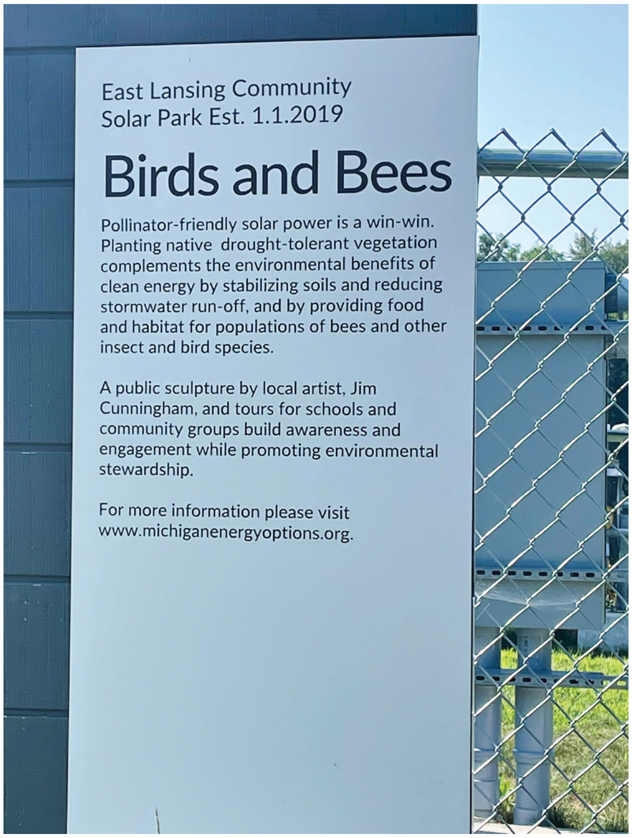
Energy sector interviewees and some government interviewees anticipated that pollinator habitat would improve public acceptance of solar power. However, many interviewees (gov 4, 9, energy 14, 15, ag 19, energy 20) indicated that the inclusion of pollinator habitat would not persuade people who oppose solar power plants to accept them. When asked whether including pollinator habitat would assuage local opposition, an interviewee (gov 9) stated that it would have "no effect at all. The people who are against it are going to be against it, and nothing's going to change their mind." An interviewee (energy 14) indicated that in Michigan, "Pollinator habitat just didn't seem to carry a lot of weight with the locals who were standing in opposition to [a solar] project." Stakeholders should bear in mind our previous discussion explaining why aesthetic opposition to renewable energy is not simply about literally seeing renewable energy on the landscape. Milkweed can also garner pushback from farmers worried about infestations in their fields, even though most modern herbicides would prevent establishment. Public perception of solar pollinator habitat and its relationship to acceptance of solar power is an important topic for future social science research.

Interviewees did report that land management is vital for positive public perceptions. A vegetation management specialist (ag 8) argued that land management demonstrates stewardship in agricultural communities, and community members' trust can be broken when they observe erosion, weeds, and other signs of poor land management at solar sites. Another interviewee (energy 9) pointed out that local citizens might not be clamoring for pollinator habitat, but it will not worsen public opposition.

There is potential for public misunderstanding as the pollinator habitat is taking hold. While the species are developing, the site will not look well-manicured like a mowed site. A biologist (gov 4) explained that communities have concerns with the aesthetics of native/pollinator plantings stating: "we have had some sites where we've had buffer areas planted and... you're reproducing basically a meadow system. So, it is kind of messy looking, and it's not a mowed lawn." An employee of a state environmental regulatory organization (gov 7) stressed the importance of educating the public on "understanding why the solar site might not look so pretty in the first couple years." In some cases, native seed mixes may actually fail to establish, resulting in predominately weedy species being supported at the site (Figure 9). The establishing vegetation in Figure 9 appears unmanaged and includes weeds, and in Figure 10 only dandelions have grown so far. Some scorecards require signage to inform the public (see Figure 11), but further communication will likely be needed to manage public expectations.

Figure 9. The O'Shea solar project in Detroit has resulted mostly in undesirable weed species but provides forage for honey bees that have produced more honey than apiarists expected. (Photo by Sharlissa Moore, August 2019. Adjusted in Adobe Lightroom.)

Figure 10. Scorecard-compliant pollinator habitat in its first season on preserved farmland at the Assembly Solar facility in Shiawassee County, Michigan. People who toured the facility were surprised to only see dandelions and not wildflowers. (Photo by Sharlissa Moore, May 2021. Adjusted in Adobe Lightroom.)



East Lansing Community
Solar Park Est. 1.1.2019

Birds and Bees

Pollinator-friendly solar power is a win-win. Planting native drought-tolerant vegetation complements the environmental benefits of clean energy by stabilizing soils and reducing stormwater run-off, and by providing food and habitat for populations of bees and other insect and bird species.

A public sculpture by local artist, Jim Cunningham, and tours for schools and community groups build awareness and engagement while promoting environmental stewardship.

For more information please visit www.michiganenergyoptions.org.

Figure 11. Example of a pollinator sign, East Lansing, Michigan. (Photo by Sharlissa Moore, August 2021. Adjusted in Adobe Lightroom)

Agrivoltaic Crop Production

The term "*agrivoltaic systems*," or *agrivoltaics*, is being used both in marketing and scientific journal articles to refer to the combination of solar energy and agriculture production on the same land [110]. A growing body of technical literature focuses on solar pollinator habitat and co-location of solar power generation and farming for food or biofuel crops. Researchers are also evaluating crops' shade tolerance, the impacts of water runoff from the arrays on crops, changes in wind patterns and soil temperature, and possible crop protection from hail [111]. In arid climates, a study in Arizona shows that panel shading can reduce heat stress and need for irrigation of cherry tomatoes, chiltepin pepper, and jalapenos [112]. This suggests that agrivoltaics may have greater advantages in arid, drought-prone climates in the southwest than in other regions.

Tables 5 and 6, on the following page, overview the existing literature on agrivoltaics and pollinator habitat. The wide range of issues explored in the literature illustrate the plurality of goals related to implementing pollinator habitat or growing crops on solar sites. Table 5 overviews these issues. They include the provision of ecosystem services, growing food crops, growing biofuel crops, minimizing irrigation needs through water runoff and shade from the solar arrays, growing different types of grass, applying seed to the site using various methods, grazing, evaluating pollinator habitat options, and providing wildlife and bird habitat.

Much of the technical literature uses computer modeling and thought experiments. Furthermore, scientists have experimented on relatively small solar sites: 1 MW or smaller. There is a dearth of data on solar sites over 50 MW. This gap is significant because larger projects have different feasibility issues than smaller ones. The existing projects are still brand new, so long-term data are not available.

The large solar developers we interviewed have not yet experimented with growing crops under the arrays. Some developers expressed both interest and concerns about cost and feasibility. One interviewee questioned the irrigation needs and expenses for projects in arid parts of Texas. They also had questions about safety:

> *We have a high-voltage power plant, right? So, safety is number one for us. So, bringing in folks to harvest those crops, there's just a lot of things to take into account. But [it's] certainly not out of the question: just not what we've done so far.*

Table 5. Pollinator and Agrivoltaics Technical Literature by Thematic Focus

Focus Area	Studies	Sub-Focus
Providing Ecosystem Services	[112]–[115]	Food production Reduce heat stress for crops Pollination Economic services (honey, medicinal plants) Sediment retention Carbon sequestration Increased module efficiency
Growing Food Crops	[111],[112], [116]–[125]	Solar for greenhouses Chiltepin pepper, jalapeno, cherry tomato Grapes, wheat, lettuce, cucumber, corn, potato Agave for biofuel
Minimizing Irrigation Needs	[112],[126],[127]	Irrigation reduced from rain runoff from the arrays Module-washing water reduced Dust/erosion decreased Increase in grass biomass
Growing Different Grasses	[126],[128]	Site revegetation with native grasses Differences in moisture & temperature observed across site
Applying Seed	[128]	Similar results from seeding with a nurse crop, straw mat with fiber backing, and bare ground
Grazing	[129]	Feasibility of sheep grazing demonstrated (*not peer-reviewed*)
Planting Pollinator Habitat	[113],[130]–[132]	Plan to plant melliferous crops at solar sites Site-specific nature of habitats affects pollinator design
Observing Animal and Avian Use of Site	[128]	Grass and arrays provided deer bedding and bird perches
Soil Quality	[133]	Microclimates and soil quality observed
Decision-Support Tool	[56]	Decision support tool for ecosystem co-benefits at solar parks
Cost	[134]	Added cost of agrivoltaics examined

Table 6. Pollinator and Agrivoltaics Technical Literature by Geography and Scale

Methodology	Studies	Geography	Solar Size
Computer Models	[114]–[116],[118],[119],[121],[124]	Arizona, California, France, India, Italy, Japan, Midwest United States, Spain	Very small
Experiments	[112],[120],[126],[128],[133],[135],[136]	Arizona, Oregon, Colorado, France	1.4 MW or smaller (except [135]
Economic Analysis	[134]	Germany	Up to 10 MW
Literature Review	[56],[111],[113],[117],[123],[125],[130],[131]	Italy, India, California	Less than 1 MW

For agrivoltaics to be successful, particularly on projects of 20 MW or larger, developers must amend the solar facility's design during the siting and construction phase. CapEx costs can increase from higher pile height and larger spacing between array rows or between the piles to accommodate agricultural machinery. For example, soybeans are low-growing but harvested using 30-foot-wide combines.

Additionally, increased pile height raises CapEx costs. According to interviewees, the additional materials do not significantly increase overall project costs (energy 6, 7, 10). Instead, the chief increase stems from extra labor hours owing to workers using a scissor lift to install the modules. Additional workers are required per pile under the U.S. Occupational Safety and Health Administration's standards [281]. Sites with uneven and unstable ground result in delays because workers must stabilize the ground before starting each array row. This doubles the construction time and labor costs and adds insurance costs and workers' compensation for injuries. According to interviewees, workers installing modules on lifts also risks material damage to the project. Moreover, piping may be required for wiring at the increased height to comply with applicable codes, increasing costs, and labor. Because the scissor lifts are not designed for solar sites, especially those with unstable ground, mechanical failure can result.

A solar developer (energy 10) stated:

> *if there is an innovation area in the sector, it's creating an all-terrain scissor lift that is unequivocally capable of handling [these challenges]. That I think could be a really influential factor in reducing costs [of] elevated panels… [All of these] design changes are now super apparent whereas you didn't have to think of them with the lower project.*

Multiple interviewees indicated that a 9-foot increase would be necessary for cattle grazing and for running a small tractor under the arrays. The manager of Jack's Solar Garden, a 5-acre community solar agrivoltaic project in Colorado, indicated that 8-feet should be the minimum for growing crops under arrays and 10-ft is preferred. Jack's clearance is between 4 and 6 feet, which has required additional manual labor and precludes use of a sit-on-top tractor. Additionally, the higher array must be designed to withstand windshear. For example, the panels at Jack's Solar Garden are stowed at night due to windshear. There are also concerns that higher pile height will increase conflicts over visual impacts; local jurisdictions will need to amend their ordinances if they currently restrict higher profile projects.

According to cost estimates from an experienced developer of large projects put into a model provided by NREL, an increase in pile height from 2-feet to 9-feet would increase pile costs by 555% and overall project costs by 12.44%. A large developer indicated this cost increase would make the projects of 25 MW and larger economically infeasible. Another developer explained that for large projects, the cost of agrivoltaics must compete with current O&M costs [281]. Farmers would receive a contract from the developer for growing crops, which would compensate for the added costs of farming under an array and, in some cases, lower yield because of shading. The crop revenue would go to the farmer. There is a risk that the crop revenue could decline over the project lifetime and the developer would need to increase the contract costs, although crop selection may be amendable. High-value crops, especially those suitable for hand harvesting (for example, borage, calendula, oilseeds, pennycress), might be most economically feasible. The best choice would vary by climate, soil type, and regional markets [137].

State subsidies could alleviate these costs in the upfront stages to enable learning effects. For example, while currently only available to smaller projects, Massachusetts' Agricultural Solar Tariff Generation Unit provides $0.06/kWh for solar canopies with crop production or animal grazing underneath [138]. The site must be farmed throughout its lifespan [139] (Knowlton, 2018). In 2021, the New Jersey governor approved legislation for an agrivoltaics pilot project, and the Board of Public Utilities and Department of Agriculture are crafting the incentive structure [140]. BlueWave Solar has built several dual-use solar projects that benefit from the tariff (see sidebar: ***Pine Gate Renewables, Cranberry Bog Project***). For example, a 2.5 MW array in Grafton, Massachusetts, will include a section for livestock grazing and an area with raised, translucent bifacial modules for growing vegetables [141]. The crop type has not been identified. BlueWave indicated that their Massachusetts agrivoltaic projects would be economically infeasible without the tariff because of the costs and complexity associated with 10-ft pile height. BlueWave also developed a 4.2 MW project on a farm that produces wild blueberries [142]. Maine's producers of wild blueberries have clear economic reasons for signing on to the project. They have been struggling recently because of a late frost, drought, and pandemic labor shortages [142]. For

Pine Gate Renewables, Cranberry Bog Project

Pine Gate Renewables is building two projects over functioning cranberry bogs in Carver, Massachusetts. Cranberries are shade tolerant. The projects will have 10-ft array clearance, with 30-ft pile height using wooden utility poles, which can be mounted at a lesser depth than steel poles. The total combined capacity across three installations will be 7 MW of PV with 42 MWh of battery storage, costing $53 million [252],[253]. According to an interviewee, the state's agrivoltaics adder, variable rate adder for clean storage, and ability to sell stored electricity on the regional spot market during high periods of demand make the project economically feasible. The project also improves farm viability. Cranberry farmers often make insufficient revenue farming but cannot sell their land for housing development because cranberry bogs are wetlands [254]. The project is on hold because of community concerns that the wood poles, treated with chromated copper arsenate, will contaminate the water and cranberries [255].

five years, University of Maine Agricultural Extension researchers will study the solar project for blueberry yield and quality and soil quality and moisture [142]. The arrays offer hail protection and protection from heat stress [140].

For agrivoltaic production to be scaled up, there would need to be interested, committed farmers. Further, the energy system design likely needs to be flexible and tailored to the farming operation. Energy interviewee 10, who develops 1–10 MW agrivoltaic projects stated,

> *And once farmers understand [agrivoltaics] and they come up the curve, they'll probably jump over that valley of death a lot quicker. So, we just want to make sure that that welcome mat is real and tangible.*

Perspectives from farmers illustrate that energy markets and agricultural markets are temporally incongruent and bear different technical and financial risks, uncertainties, and profit opportunities. Pascaris, Schelly, and Pearce (2020) conducted ten interviews with farmers to examine their potential adoption of growing crops under solar modules [110]. Farmers worried that in contrast to the 20-to-30-year solar installation lifetime with a power purchase agreement (PPA), agricultural markets might change dramatically over that time [110]. Yet, it could be challenging to retrofit the solar design to meet the current market-feasible agricultural product. In addition, the long-term financial benefits would need to outweigh the risks a farm operator would assume when initiating an agrivoltaic opportunity. For example, solar companies may need to pay farmers to undertake risky operations in exchange for the benefits of the marketing narrative because extra effort and technological adaptation must occur.

Grazing

Grazing is another dual land-use option for large-scale solar installations. While there is no peer-reviewed literature on solar grazing, interviewees that develop projects larger than 20 MW reported that grazing is currently cost feasible, but growing crops under the arrays is not. For example, a solar developer (energy 8) stated, "I find, or feel, strongly that managed sheep grazing is one of the few agricultural enterprises that meets our operational needs of veg management." Therefore, this developer is solely focused on grazing and not growing crops under modules. A Midwest regional ecologist working for a state government (gov 8) also argued that grazing is compatible with utility-scale solar while conventional row-crop agriculture is not. Examples of hobbyist solar grazing exist. For example, a Rural Electric Cooperative in Michigan with close ties to the agricultural community allows nearby ranchers to graze sheep on their 1.2 MW solar site. However, rather than hobbyist examples, this section focuses on the professionalization of solar grazing to scale. An interviewee (ag 13) estimated that grazing is occurring on 12–15,000 acres of solar installations, and the industry is growing fourfold each year. Currently, approximately five graziers provide professional, utility-scale services nationwide. This section discusses benefits, feasibility issues, and other considerations of solar grazing.

According to interviewees, sheep are currently the only feasible livestock to graze on solar sites. Unlike goats, sheep do not climb on solar arrays or gnaw wires. A solar grazier (ag 2) explained that "sheep don't chew on cables. It's not to say it could never happen. But we've grazed tens of thousands of animals across thousands and thousands of acres, and we've never seen it yet." This interviewee also noted that hogs would ruin the site's vegetation. Cattle require an increase in pile height to 9 or 10-feet, which is economically infeasible under current conditions. However, several research projects are underway to explore options for cattle grazing.

A Midwest regional ecologist (gov 8) stated, "I don't think cows are going to be compatible with a solar site– just because they're large. And most solar developers I've met aren't super wild about having cows walking in between their panels because they have the potential to damage panels."

Solar companies sometimes misunderstand that grazing will be cheaper than mechanical vegetation management because the forage on site is of value to the sheep. Graziers we interviewed argued that this is a misunderstanding because the free forage does not compensate for the overall costs the grazier incurs from grazing solar sites. For example, they must mow areas that the sheep did not graze, including the site's perimeter, and potentially mow the vegetation in the spring to improve the nutrition and palatability for sheep. They also control invasive species as the vegetation is being established. Therefore, graziers incur capital costs for mowing equipment. Labor is needed to manage the sheep, and the sheep must be moved from one site to another, adding travel and lodging costs. A sheep grazier explained (ag 2), "If you're not living in very close proximity to the land, not only do you have that labor, but you've got the travel time back and forth." Multi-year solar grazing contracts provide graziers with stable cash flow that improves farm viability and enables investment in equipment and livestock. Accounting for the additional costs plus profit means solar grazing costs are comparable to mechanical vegetation management. However, interviewees identified benefits from solar grazing that exceed that of mechanical vegetation management.

Benefits

A solar grazier (ag 13) argued that sheep provide vegetation management with less damage than mowers, which can spark fires and kick up rocks that shatter PV modules. Additionally, interviewees identified benefits related to public relations, community interaction, and human presence on the site. There are few solar employees available on-site, and graziers provide local and accessible staff in the community. A solar grazier (ag 13) stated, "So you're a friendly face in what otherwise is actually just...a solar infrastructure. You give it a very warm and friendly face." Additionally, the grazier interviewees contend that their operations maintain the natural character of the landscape and pastoral aesthetics. Grazing keeps the land in food and fiber production and employs local people to provide veterinary services, fix fences and barns, and provide hay.

The three grazier interviewees have only received community support, not opposition, including phone calls praising their operations. A grazier (ag 13) stated, "I think the solar industry needs to partner with people who understand how to manage land and manage livestock, and they'll have a better go of it [with communities]." A solar developer (energy 8) indicated that communities in Georgia that were not opposed to solar facilities were even more excited that solar grazing would bring a new agricultural industry to their area. However, in cases where communities opposed a solar project, this developer found that solar grazing did not ease opposition.

> *Other communities where some of the land is in conventional annual cropping systems– what we would consider prime ag land–the fact that we're shifting agricultural use by raising perennial forages harvested with livestock that go to market was just different [from] the corn and soy that has been grown on that land. And it felt to me, personally, that it wasn't valued [by] that community that we were going to keep it in ag production because it wasn't a typical corn production model. They didn't want to see our solar panels. I don't feel like any level of agricultural production was going to help that community accept that particular project.*

Similarly, in Linn County, Iowa, an interviewee (ag 12) opposed to utility-scale solar power saw solar grazing as disingenuous since it was not an existing local agricultural practice (see sidebar: ***Solar Power in Linn County, Iowa*** on page 11). Nicholls (2020) observed similar sentiments in the United Kingdom [40].

Feasibility Issues and Management Considerations

A large land area is needed across multiple solar sites to prevent overgrazing. A grazier interviewee (ag 2) runs thousands of sheep on solar sites that are 1,000-acres or larger, and the sheep still require supplemental land. A solar developer (energy 10) explained:

> *You can't expect that one solar site will provide for all of the grazing and rearing and breeding needs of a grazier.… So, to make one project successful, you have to think about the network of projects around it. Or else a grazier's never going to have a profitable model.*

Additionally, for vegetation management, an agricultural scientist (ag 3) explained there should be a sufficient density of sheep to eat what is available rather than picking and choosing, with short duration grazing. The number of sheep a site can accommodate depends on the area's climate and rainfall and the sheep breed. A solar grazier (ag 2) noted that land grant universities provide a local animal unit stocking rate in cow-calf units per acre. Generally, one cow-calf unit can be converted to 5–7 head of sheep. In cold climates, sheep will graze for approximately eight months of the year and then will be fed hay while it snows (ag 3).

Several interviewees (ag 2, energy 8) emphasized that there must be good communication among the grazier, solar company, and solar employees. Sheep need to be fenced out of the inverter pads, or they will rest and ruminate on them and then defecate on them, which creates unpleasant smells that negatively affect the workers. Additionally, sheep need to be fenced out of access to emergency stop buttons, or they might use them to scratch their backs. The additional fencing can cause conflict with the workers who are inconvenienced by working around it. However, most developers we interviewed are open to solar grazing. Some misperceptions about safety will need to be addressed through careful management plans. One solar developer (energy 11) had local ranchers upset that they would not allow their sheep to graze the solar installation. The developer was concerned that the solar facility would electrocute sheep.

To prevent overgrazing and ensure uniformity of vegetation management, some graziers use rotational grazing (see also the soil quality and grazing section). They move sheep from one row to the next using fencing (see Figure 12). According to interviewees, the grazier often includes the paddock fencing costs in their capital costs. The perimeter fencing should reach the ground and avoid large holes to protect the sheep from predators [281]. Additionally, the sheep must have access to water near where they are grazing. If there is no immediate water access, graziers must haul buckets of water to the sheep, increasing labor costs. Without fencing, the sheep will remain near the water source. The developer typically incurs the cost of digging wells. In some cases, rainwater can be collected from the panels [281]. A solar developer in the Central United States (energy 8) noted that they paid to have two water taps installed, which they used both for sheep and module washing.

Figure 12. Sheep grazing vegetation to prepare a site for pollinator planting in mid-Michigan. (Photo by Sharlissa Moore, September 2021. Adjusted in Adobe Lightroom)

The sheep industry is in decline in the United States [143]. Sheep grazing on solar facilities has been scaled up faster in areas with an existing local grazing industry, such as New York State. To scale up solar grazing across the United States, additional graziers will need to be trained, the supply chain for sheep will need to grow, and more veterinarians who treat sheep will be required. Many land grant universities offer sheep grazing training programs. The U.S. market for mutton and other sheep-related products would also be expanded. A sheep grazier (ag 13) noted that there are numerous potential sheep-related products, such as wool fibers to replace the plastic ones often used in clothing, erosion control blankets and fertilizer pellets made of wool, and value-added products such as lanolin creams. State specific market feasibility assessments are needed to gauge the market potential in different states, with vari-

ous existing grazing industries. For example, solar grazing is not currently allowed on state lands in New Mexico (gov 6), but there is a large ranching industry in the state. Environmental assessment would be needed to address risks of livestock stepping on threatened or sensitive species, such as desert tortoises.

Seed Mix and Vegetation Establishment

Several interviewees emphasized that developers should choose a grazing-specific seed mix that is palatable and meets sheep's nutritional requirements. One interviewee (ag 13) struggles with grazing on sites where developers selected vegetation only to close the Storm Water Pollution Prevention Plan, or SWPPP, rather than feed sheep. Another solar grazier (ag 2) has arrived at new sites to find insufficiently developed vegetation and degradation issues from construction, resulting in low feed quality and quantity. Therefore, they must find additional land to feed the sheep until the vegetation is established. A representative from a company that develops, owns, and operates solar power (energy 3) has found that the vegetation needs several years to establish before sheep can graze it.

Solar facilities may be able to co-locate sheep on sites seeded with some vegetation that provides forage for pollinators. Several interviewees argued that this is possible with careful management. Cornell University, the American Solar Grazing Association, and Ernst have developed a seed mix called Fuzz and Buzz designed to support sheep grazing and pollinating insects. The mix includes plants on which sheep can graze and pollinator plants that the sheep dislike and avoid. The mix will not meet the pollinator habitat scorecard requirements in many states because of insufficient number of forbs, species diversity, and native species. Grazing-friendly solar certifications do not yet exist. We interviewed several solar developers (energy 3 and 4) who have had positive experiences with grazing and pollinator habitat. Through rotational grazing, the plants recover after grazing and are allowed to go through a complete life cycle and set seed. Research that measures the pollinator activity and benefits would improve understanding of combining solar pollinator habitat and grazing.

An agricultural scientist (ag 3) explained that a holistically grazed pasture is also a pollinator habitat. However, he did not think developers could achieve these benefits with 18 to 36-inch plants because a holistically grazed prairie mix exceeds this height during the entire life cycle. A solar grazier (ag 6) explained that his mix of warm-season perennial grasses and cool-season annuals benefits pollinators. However, grazing results in less benefit to pollinators than a habitat planned solely for them. Moreover, the mix would likely exclude milkweed because it can cause gastric issues in sheep. Blaydes (2021) found evidence that there is no negative impact on pollinators from grazing overall, but grazing during the summer can reduce the abundance of pollinators by removing floral resources [130]. However, they also found that other maintenance, like mowing early in the season, will have the same effect.

Soil Quality and Land Conversion

Combining carbon mitigation from solar power and a greenhouse gas sink from sequestering carbon and nitrogen in the soil would be a win-win in converting agricultural land to solar generation. Interviewees across agriculture, energy, and government groups expressed interest in whether conversion of agricultural land to solar generation would improve soil quality, reduce erosion and fertilizer runoff, and sequester carbon in soils. Furthermore, a vegetation management specialist (ag 8) and a solar developer (energy 3) mentioned that some corporate and industrial solar customers, such as Home Depot, are demanding soil quality and ecosystem improvements when signing a PPA for solar electricity. Uebelhor et al. (2021) found that agricultural communities in the Midwest are interested in the negative and positive effects of solar land conversion on soil quality [144]. The media has covered the issue, but only in hypothetical terms due to the lack of scientific research. If benefits to soil can be gained, this could support the argument that solar power can contribute to farmland preservation. Although this has not been studied, such benefits might also alleviate public opposition to solar development on prime farmland. Overall, there is almost no research on agricultural land conversion to solar power and soil quality, but the evidence base suggests that benefits could result if the developers use certain perennial ground covers or grazing.

Compaction

Several interviewees concerned about farmland preservation wanted to know whether soil would be degraded owing to soil compaction. Heavy machinery used during construction can cause soil compaction, primarily if used on wet ground (ag 9). Compaction can be significant at solar sites with cut and fill (also called blading and grading) and will have long-term effects (ag 8). The soil is wetted and packed using a vibratory roller to fill in low areas. At sites that do not use cut and fill, interviewees from solar development

companies characterized compaction as limited (energy 3, 4, 5). An interviewee representing a solar developer (energy 4) indicated their company tills the soil where compaction has occurred. Tilling releases soil carbon into the atmosphere [145]. Additionally, an agricultural scientist (ag 3) explained that tilling after compaction loosens the top layers of soil but can create a deep, dense layer of soil called a plow pan. The plow pan reduces water infiltration [146]. Deep tillage might break up the plow pan but will release soil organic carbon (ag 11).

As an alternative, several interviewees indicated that developers should plant deep-rooted native plants to rectify soil compaction. A soil scientist (ag 11) stated, "nothing's better at tillage than a lot of different plant species, like plants growing through your sidewalk and breaking up your concrete. You have to have serious compaction issues for plant roots not to be able to help you with compaction issues." Furthermore, small wildlife such as rabbits, moles, and voles can also help de-compact the soil if allowed on the site through wildlife fencing. Overall, developers can minimize compaction by avoiding cut and fill, controlling traffic/machinery pathways, and avoiding construction activities on wet soil. Alternating work crews by row reduces compaction by avoiding heavy foot traffic on a concentrated area over a short period of time [281].

Potential Improvements in Soil Quality

Agricultural practices in the U.S. Great Plains have resulted in carbon and nitrogen emissions [147]. Several energy sector interviewees argued that converting land from agricultural production to solar power would allow the soil to "rest," thereby sequestering carbon, reducing nutrient runoff, and improving its quality. The four soil scientists we interviewed all indicated that simply allowing the soil to rest from agricultural operations does not improve quality. Agricultural sector interviewees agreed that developers could improve soil quality and carbon sequestration using specific types of ground cover, land management, and other design features.

A helpful land-conversion analogy is the *USDA's Conservation Reserve Program* (CRP), which pays farmers to remove farmland from production for 10 to 15 years and plant native grasses and forbs to reduce soil erosion and improve soil quality [148]. A federal government employee who works in agricultural land conservation policy (ag 17) explained that when USDA founded the CRP in 1985, people assumed that allowing farmland to rest would improve soil quality. The main goal was to prevent topsoil erosion, and non-native grasses were initially used [145]. However, current science shows that perennial ground cover must be added to enhance soil quality and store carbon [147]. The appropriate perennial vegetation for a site will vary based on ecoregion, latitude, amount of rainfall, and soil type.

Research on CRP lands suggests that the vegetation selection, soil type, water availability, and length of time in perennial vegetation will affect carbon sequestration at solar sites. Scientists have demonstrated increases in soil organic carbon on CRP lands with perennial vegetation [149],[150]. Improvements depend on the length of time since the land's conversion to perennial ground cover [148]. Li et al. (2017) studied carbon sequestration on CRP lands in West Texas and found that after five years in the program, sequestration was greater than on cropland, although still much lower than native pasture [148]. After 18 years, CRP fields in Colorado with native perennial grasses had 60% of the soil organic carbon and 67% of the soil nitrogen of undisturbed shortgrass steppe [147]. The amount of sequestration on CRP lands also depends on the type of soil, particularly the percentage of clay and silt, with more significant increases on silty clay loam soil than sandy loam soil [148],[151]–[153]. Clay is better at trapping carbon than sand and silt. Finally, CRP lands with more water availability had greater soil organic carbon [145].

The most significant increases in storage came from microbial activity in the soil and particulate organic matter [148],[154]. These types of carbon indicate improved soil quality, although they are short-term (or labile) carbon pools. Labile pools turn over in several years, whereas long-term (or recalcitrant) pools take thousands of years [155]. When converted back to agriculture, carbon in short-term pools will be emitted [156],[157].

Perennial vegetation with forbs also benefits soil quality. Interviewees across sectors agreed that solar installations with pollinator habitat are more likely to improve soil quality than those without (ag 4, 9, energy 7, gov 7, 8). Interviewees believe that native wildflowers' 3–6-foot roots, compared to turfgrass' 3–6-inch roots, increase carbon sequestration, reduce erosion, fix nitrogen, retain other nutrients in the soil, and improve water infiltration (See sidebar: ***Soil Quality and Water Infiltration***). A metastudy cited nine studies showing that pollinator-friendly legumes and other cover crops reduce erosion and excess soil nitrogen, prevent emission of atmospheric nitrogen, and increase soil porosity, which increases water infiltration [159]. Researchers have been planting and monitoring pollinator-friendly native prairie vegetation strips

Soil Quality and Water Infiltration

A 1% increase in organic matter in soil can increase available soil water by 20,000 gallons/acre through increased infiltration [158].

within agricultural landscapes in Iowa. The strips include a diverse mix of native grasses and forbs. Specifically, they found the strips improved soil quality in just three years by increasing the total nitrogen and soil organic carbon [160].

While findings from the CRP program have some applicability to solar power, research specific to solar photovoltaics is needed for four reasons.

- **Array microclimates:** According to soil science interviewees and Choi et al. (2020), solar power plants may have unique impacts on soil because the arrays create microclimates by blocking the sun during certain times of the day [133]. Blocking the sun could reduce plants' photosynthetic abilities, thereby decreasing carbon accrual. However, some plant species benefit from receiving diffuse rather than direct light. Hassanpour et al. (2018) found a significant increase in late-season grass biomass (90%) compared to early season at a solar site in Oregon with sheep grazing [161]. The overall biomass will depend on the spacing and layout of the arrays, module transparency, vegetation type, and climate. Furthermore, the array shading causes differences in soil moisture and temperature across the site [133].
- **Constrained vegetative height:** The vegetation on solar sites will be shorter than on CRP land: between 18 to 36 inches due to typical array ground clearance and pile height. Ground cover in the Li et al. (2017) study that showed improvements in carbon sequestration on CRP lands included side-oats grama (8–32 inches), yellow bluestem (36–60 inches), purple false foxglove (20 inches), silver bluestem (60 inches), and weeping love grass (30–40 inches) [148].
- **Less diversity:** Vegetation on solar sites is often less diverse than the native prairie vegetation strips or some CRP mixes. The effect mix diversity has on soil properties will need to be studied to understand and quantify potential benefits.
- **Needed changes in O&M culture:** Furthermore, O&M managers are often not trained to holistically manage the land to improve soil quality. A cultural shift in O&M will be needed to achieve soil benefits. Interviewees indicated that identifying a skilled maintenance company for the habitat can be a challenge.

Only one study has examined utility-scale solar power's effects on soil. It compared a 1.1 MW site seven years after revegetation with big grama grass and Canada bluegrass. The site was previously native prairie, and topsoil was removed during construction. It showed much lower soil carbon and nitrogen than an undisturbed reference site with big bluestem grass [133]. The study did not compare the site to agricultural land. CRP lands with native grasses have shown improvement in soil carbon over a seven-year timespan. Therefore, the main contribution of this study is likely to demonstrate that developers should limit the removal of topsoil where possible in order to improve carbon sequestration. It does not mean that increases in soil carbon cannot be achieved on solar sites.

Erosion and Runoff

Anthropogenic erosion is caused by disturbances resulting in the "removal of soil particles from a site due to the forces of water, wind, and ice" [162]. Agriculture is the leading cause of erosion worldwide [169]. Therefore, converting agricultural land to a solar site with well-managed vegetation could improve erosion control compared to agriculture. These disturbances include removing vegetation and topsoil, exposing subsoil to precipitation, and leaving bare soil exposed [164]. Cut and fill results in soil carbon loss into the atmosphere as CO^2 [163],[164]. The interaction between erosion prevention through vegetation management and transport of carbon is not fully understood [165]. But in general, erosion emits soil organic carbon into the atmosphere as carbon dioxide [166]. In addition to carbon, nitrogen oxide is a potent greenhouse gas [167] that solar sites could mitigate through vegetation management. CRP lands with perennial vegetation reduce air emissions of nitrous oxide and local air pollutants that affect people with asthma [168].

Erosion releases nitrogen and phosphorus from soils, which pollute waterways [170]. Converting row crops into solar farms might reduce fertilizer runoff since solar O&M managers rarely apply fertilizer to a site. Nutrient runoff from nitrogen into surface waterways leads to eutrophication [171]. For example, nutrient runoff from fertilizer used in Midwestern row crop farming pollutes the Mississippi River, contributing to seasonal hypoxia in the northern Gulf of Mexico [172]. Nitrogen flowing into creeks and waterways can contaminate groundwater, affecting residents that drink from private wells [168]. In the Great Lakes region, algal blooms result from excess phosphorus fertilizer and manure [173]. Slow release off phosphorus runoff can continue decades after agricultural fertilizer application stops [174],[286]. The duration depends on the soil type, geographic location, and phosphorous concentration [174]. In some areas, vegetation on solar sites could play a role in retaining legacy phosphorous even though fertilizer will likely no longer be applied on site.

Prairie strips planted between croplands and watersheds can decrease nitrate-nitrogen in ground and surface water and prevent runoff into the Mississippi River [175],[176]. CRP lands with perennial vegetation reduce nitrate runoff [168]. This benefit for a solar power plant with perennial vegetation will only apply if it is sited near a body of water. Therefore, Curtis et al. (2020) identified bodies of water in North Carolina with reduced water quality due to nutrient runoff that are also near transmission lines [177]. They found significant potential for siting solar energy on lands adjacent to these bodies of water to decrease nutrient runoff. Researchers or developers could identify such sites in other states.

Erosion is regulated under the Clean Water Act through the National Pollution Discharge Elimination System (NPDES). An employee of the North Carolina Wildlife Resources Commission (gov 10) stated:

> *"We have so many case studies in North Carolina of solar farms that have been installed in agricultural areas with turfgrass, and they have tremendous erosion problems because they've installed something like Bermuda grass, which has a very minimal root system. And all the water's running off. They're losing their plants. They're losing their soil because there's nothing there to absorb that water, and they have no soil structure in place."*

States enforce the NPDES minimum standard and may set their own higher standard. Each solar site requires a Stormwater Pollution Prevention Plan or SWPPP. Permanent vegetation that stabilizes the soil to prevent erosion is needed on 70% of the site to close the SWPPP permit (ag 8). This is challenging to achieve for native pollinator plantings since they take approximately two years to establish. Some states wait to close permits until permanent vegetation is established while others close permits with temporary vegetation while native plants are establishing [281]. This is because open permits require weekly or monthly inspections, which can be onerous for the developer since technicians are not typically on site weekly [281].

Developers should avoid blading and grading solar sites because it causes wind and water erosion [178]. Proper vegetation planting and management will eliminate wind erosion. Without vegetation establishment, developers must spray water to control dust, which increases the water footprint of solar installations [163]. In the Southwest, the median water use for PV during operations is 8.6 gallons/MWh [179]. While module washing is required in dusty areas, interviewees in other areas indicated it is generally unnecessary. Improving wind erosion control at solar power plants through vegetation management is a win-win that benefits the environment and the developer by reducing the need for washing modules in dusty climates [163],[164],[180]. See Figure 13 for a dusty module at a bladed and graded site in the Southwest. Furthermore, in agricultural areas, farmers and community members

Figure 13. Dust visible on solar modules at a bladed and graded site, Gila Bend, Yuma County, Arizona. APS Paloma Solar Power Plant. The utility company was testing the effect of dust on electricity output. (Photo by Sharlissa Moore, 2014. Adjusted in Adobe Lightroom)

also value vegetation to prevent dirt and erosion. An interviewee from a company that develops, owns, and operates solar power (energy 3) stated:

> *"Our farmers around us and folks that live in the area would prefer that we have vegetation on the ground instead of bare dirt. We have a lot of wind here in Texas and Oklahoma, and [with bare dirt] you're just going to have blowing topsoil, dirt and sand.… As long as you have a vegetative layer on the ground to prevent that dust, that's all they care about."*

Soil Quality and Grazing

Five expert interviewees explained that solar power with grazing could improve soil quality and carbon sequestration. However, they argued that companies could only achieve these benefits by using regenerative grazing (interchangeably called holistic grazing), not continuous grazing. Continuous grazing results in animal paths and bare areas, leading to erosion, invasive species taking hold because perennial vegetation is grazed too low, the prevention of plant recovery after being grazed, and reduced soil organic carbon. These five interviewees advocated for the practice of regenerative grazing. U.S. grasslands co-evolved with large ruminant herds that grazed over large land areas, enabling plants to recover after grazing [181]. *Regenerative grazing* emulates this by rotating livestock from one paddock. After each grazing event, paddocks are allowed to recover until vegetation is again ready to be grazed. In addition to rotating livestock, regenerative grazing focuses on adaptive local ecosystem processes related to the mineral cycle, energy flow, community dynamics, and the welfare of livestock. Regenerative grazing is more expensive than conventional grazing, but research has found this grazing technique improves soil health, carbon sequestration, and soil biodiversity, and reduces erosion [182]–[184]. At least one local jurisdiction is hesitant to approve SWPPP permits for sites with solar grazing because they are concerned that plants will be overgrazed, and erosion will result [281]. Rotational grazing may alleviate or eliminate that concern.

Livestock waste products increase soil organic matter [181]. Moderate grazing can improve the soil by removing old grass that inhibits the early growth of new grass at the beginning of the season (ag 9). Livestock walk on perennial grasses, putting plant matter in contact with soil microbes, which facilitates decomposition and adds organic matter to the soil. Sheep help reestablish plants by dispersing seeds and increasing seed to soil contact improving germination success. Additionally, increasing organic material increases soil porosity, enabling water infiltration. Grazing activities mitigate erosion issues that can add O&M costs to the project and prevents nutrient runoff. Will Harris, the owner of White Oak Pastures and a regenerative grazer, stated,

> *"Any thinking person would know and believe that the form of agriculture we practice now is better for the environment than what was done previously. We don't use fertilizer, we don't use pesticides, we don't till, there's less runoff. It's just clear."*

A life cycle assessment of regenerative grazing at the 3,000-acre White Oak Pastures farm found that regenerative grazing increased soil carbon so much that it outweighed emissions from cow belches, gas, and manure, as well as transportation, slaughter, and other farm activities [185]. White Oak Pastures grazes sheep with poultry on solar sites, but a carbon life cycle assessment has not yet been conducted for this grazing.

Several interviewees reported that DOE has recently awarded a $1.7 million research grant to Silicon Ranch, White Oak Pastures, Colorado State University, and Michigan State University to explore regenerative multi-paddock cattle grazing on solar sites. They will also measure the soil temperature, moisture, nutrients, and soil organic carbon from cattle grazing. They will also measure the flux between the carbon in the soil and the atmosphere and develop a land-management carbon sequestration credit system for solar power. The researchers will compare the solar grazing area to a control area. Additionally, BlueWave Solar and American Farmland Trust are studying soil quality and regenerative cattle grazing under an elevated solar array.

If this research demonstrates quantifiable benefits to soil, it is possible that avoided nutrient runoff and sequestered soil carbon from sheep grazing or perennial vegetation on solar sites could be measured and priced. Interviewees did not report any existing examples. Regulations would typically be developed to establish such programs, which could provide incentives for land stewardship at solar sites.

Ecological Impacts

This section addresses the environmental impacts of large-scale solar power, including effects on wildlife, insects, birds, wetlands, and end-of-life disposal or recycling for solar modules.

Wildlife

Solar development poses risks to local ecosystems and wildlife, including threatened and endangered species. How the impact varies from the previous land use is site-specific. For example, a state land manager (gov 18) indicated that conversion from oil and gas drilling on state lands to renewable energy would likely benefit wildlife. Conversion from agricultural land could also improve habitat, depending on the site's design. In contrast, converting forested land to solar generation would increase wildlife impacts. Interviewees indicated there has been little quantitative monitoring of wildlife activity or comparison to prior land uses. Regardless, wildlife impacts can garner public opposition and result in siting delays while a regulatory review is conducted and requirements are met. Designing solar power plants that minimize effects on wildlife, or improve habitat, would alleviate conflict between renewable energy and wildlife conservation goals [186]. In some cases, strategic site selection can avoid impacts. In other instances, mitigation measures can alleviate the effects. Table 7 overviews the species that interviewees mentioned could be or have been affected by solar development. (Note: this list is not comprehensive.)

Many wildlife advocates would prefer avoidance rather than mitigation. Wildlife advocates recommend avoiding areas with sensitive and threatened/endangered species and developing solar on degraded lands, including agricultural lands [187]. Stoms et al. (2013) believe developers should avoid public lands because of their wildlife importance [187]. Additionally, sixteen Western states offer a Critical Wildlife Habitat Assessment tool that energy companies can use to identify potential species of concern on proposed sites. http://www.ndow.org/Nevada_Wildlife/Maps_and_Data/NVCHAT/. Other states have similar tools, such as the Illinois Ecological Compliance Assessment Tool. Hernandez et al. (2015) found that, as of 2015, most solar power in California is on desert shrub or scrubland that is rich in biodiversity and vulnerable to climate change. Agricultural land is the second most utilized land category [188]. They advocate avoiding areas designated as critical habitat and important avian habitat.[13] They believe solar power should be constructed on the built environment, disturbed and degraded agricultural lands, and salty lands, or solar power should be colocated with food production.

Chock et al. (2021) surveyed ecology, conservation, and energy experts to identify wildlife concerns related to solar PV and CSP [190]. Solar power plants can alter habitat use and disrupt animals' food searches. Arrays offer shelter from predators; for example, an interviewee for this study (gov 5) indicated that desert tortoises could hide from ravens under solar arrays. However, the arrays can also impede animals' cues about their predators' location. Two studies provide exhaustive lists of potential environmental impacts from utility-scale solar power plants [163],[164]. Dhar et al. identify the environmental issues as avian mortality, biodiversity drawbacks from habitat loss, noise, visual impacts, and the chemical elements used in solar modules [165]. Hernandez et al. identify habitat loss for wildlife as the biggest drawback of utility-scale solar power, especially since successful relocation of endangered and threatened species in the Southwest has been limited [164]. Still, the authors argue that solar power is less environmentally degrading than other energy generation technologies. As evidence, they reference the low rate of wildlife fatalities, including birds, and point out the relatively low water use for solar PV. Both Dhar et al. and Hernandez et al. assume the sites will be bladed and graded, but this practice is becoming less common.

Development in desert ecosystems in California, Arizona, and Nevada has conflicted with threatened and endangered species. Desert tortoises and greater sage grouse have lost habitat to solar power plants, and construction activities have unavoidably crushed juvenile tortoises. The Agassiz's and Morafka's desert tortoises benefit other wildlife, which use their burrows to escape the desert heat [191]. Desert ecosystems are slow to recover from human disturbances; revegetation is challenging because plants naturally grow slowly due to a lack of water and nutrients. Furthermore, disturbance easily compacts the soil, impeding water infiltration and preventing deep penetration of native plant roots [192]. Solar power can disturb habitat through fragmentation, dust, road construction, construction noise, and glare [191]. Slow recovery rates make caution in siting, construction, and operations essential in the Southwest [189].

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[13] See Fish and Wildlife Service for information on critical habitat https://www.fws.gov/endangered/what-we-do/critical-habitats-faq.html and Audubon Society for information on Important Bird Areas https://www.audubon.org/important-bird-areas.

Table 7. Affected Species Identified by Interviewees

State	Ecoregion	Affected Species
Alabama	8	Indiana bat
Arizona	10,12,13	Antelope squirrel, Mohave ground squirrel, prairie dogs, Sonoran Desert tortoise, western burrowing owl
Georgia	8	Gopher tortoise, Indiana bat
Illinois	8	Illinois chorus frogs, Indiana bat, ornate box turtles, Regal fritillary butterfly, smooth softshell turtle
Indiana	8	Indiana bat, Northern long-eared bat
Iowa	8, 9	Indiana bat, Ring-necked pheasant
Massachusetts	5, 8	Northern spring salamander, Plymouth red-bellied turtle
Michigan	5, 8	Indiana bat, Kirtland's warbler, Northern long-eared bat
Minnesota	5, 8, 9	Deer, silver-haired bat
Missouri	8, 9	Indiana bat
Nevada	10	Antelope squirrel, Desert tortoise, greater sage-grouse, Mohave ground squirrel
New Mexico	6, 9, 10, 12, 13	Arizona shrew, desert tortoise, western burrowing owl
North Carolina	8	Eastern box turtle, deer
South Carolina	8	Gopher tortoise, Northern long-eared bat
Texas	8, 9, 10	Red-cockaded woodpecker
Wisconsin	5, 8	Blanding's turtle, Karner blue butterfly, Kirtland's Warbler, Leadplant flower moth, Northern long-eared bat
Mississippi	8	Indiana bat
Louisiana	8, 9	Northern long-eared bat
Virginia	8	Red-cockaded woodpecker
Alabama	8	Grey bat, Red-cockaded woodpecker

Sinha et al. (2018), employees of First Solar, studied the wildlife impacts and mitigation measures at the Topaz solar PV facility in California [193]. The authors argue that the mitigation measures offset the land and habitat disturbances, particularly compared to the previous agricultural use (grain production). The developer seeded the site with native grasses and forbs to support the rodent population on which the endangered San Joaquin kit fox and the Western burrowing owl prey. The owner uses periodic sheep grazing to keep vegetation at an ideal height for the kit foxes, prevent fire, and control invasive species. O&M managers occasionally spray herbicide to control invasive species. Wildlife fencing allows kit foxes to traverse the project but excludes coyotes, which predate on foxes.

While solar projects could displace raptors, perches included in projects aid raptors. Furthermore, fence reflectors prevent avian collisions. A Southwest federal land manager reported that some Southwestern solar projects have fence cutouts specifically for roadrunners to escape coyote predation. (Otherwise, roadrunners tend to collide with the fence, become confused, and run in

circles, making them vulnerable to predation.) Finally, Moorman et al. (2019) recommend best practices for laydown yards: hollow piles should be capped so birds are not trapped in them, and materials should be stacked in a manner that does not attract wildlife to take shelter in them [194].

Tanner et al. (2020) examined the microhabitats under solar arrays in California's Mojave Desert caused by shading and water runoff and their effects on annuals that provide essential resources for animals, reseed themselves, and have aesthetic value to humans [195]. *On caliche pan habitat*, array shade increased species richness and had positive-to-neutral effects on species diversity and richness. *On gravelly bajada habitat*, array shade decreased plant abundance without effect on richness or diversity. Array runoff had little effect, but there were adverse effects on abundance.

Several scientific studies argue that the effects of solar power on wildlife have been insufficiently studied and understood. Most literature focuses on the impacts of PV and CSP in the U.S. Southwest, notably California, which does not apply to other parts of the United States [189]. Chock et al. (2021) argue that more research on wildlife interactions is needed to design mitigation mechanisms [190]. Agha et al. contend that the most rigorous studies would be Before/After and Control/Impact (BACI) studies, which would help gauge mitigation strategies' success [189]. Depending on the research question, well-designed gradient analysis studies can be viable. In these studies, researchers compare mortality for wildlife in the region independent of the solar power plant to mortality on the solar site. EPRI (2021) suggests that studies should compare wildlife mortality on renewable energy sites to reference plots where wildlife abundance and fatality are measured for comparison, to help identify which fatalities are attributable to the solar facility. A well-designed reference impact study should be prioritized where regulators are likely to implement strict mortality thresholds for a species, such as take permits for endangered species [280].

In addition to wildlife, solar arrays can affect aquatic insects due to "light pollution" [196]. These insects land on the nearly horizontal polarized light of water-reflective surfaces, similar to solar arrays. Eggs laid on solar modules will likely not have enough moisture to hatch, as they need months or even years to develop in water or mud [196]. The academic literature recommends potential mitigation mechanisms, but they are not commercially available and may not be economically feasible. These include painting 1–2-mm white lines on the modules (reducing electricity output), adding an anti-reflective layer, and using microtexture coatings unattractive to insects [196],[197]. Motion-sensitive lighting is a feasible market option for deterring insects at night. A federal land manager (gov 5) in the Southwest requires such lighting to avoid attracting insects and the bats that feed on them.

Wildlife Connectivity and Fencing

Several conservation organizations seek to minimize the effects of large solar projects on animal habitat and connectivity [198]. For example, a state conservation biologist (gov 14) recommended using wildlife permeable fencing to avoid blocking turtles from their nesting sites. A state government employee (gov 7) explained that deer or fawns sometimes enter through the fence and become trapped. This is a concern where ungulate populations (hooved mammals) exist. The North Carolina chapter of TNC is experimenting with fencing that allows animals to traverse the facility, such as foxes, raccoons, or rabbits [200]. TNC is partnering with Pine Gate Renewables to test wildlife-friendly fencing at 15-acre solar sites [199],[201]. They are using cameras to monitor wildlife activity. (See photos here.) An interviewee was surprised by the quantity of wildlife, and the developer is pleased with the results and open to further collaboration. Further experimentation is needed on larger sites.

TNC's Resilient and Connected Landscapes GIS map identifies important wildlife corridors. Wildlife fencing design may vary depending on the species the developer aims to benefit. A Midwest regional ecologist (gov 8) explained:

> *"You've got to think about it all the way from a bison eyeball down to a tiny little bee eyeball. So, there's different types of fencing adaptations that you want to consider depending on the type of wildlife that you're trying to help facilitate movement and connectivity for."*

These adaptations could include a ramp instead of, or in addition to, a fence cut out. TNC also recommends creating unfenced corridors through solar facilities to allow north to south movement.

TNC has found that wildlife-friendly fencing is of similar cost to traditional fencing when installed from the start. Replacing standard fencing with wildlife-friendly fencing is costly. An interviewee from TNC said, "So if you can get to [developers] early and get them to install it upfront, then it's actually not much of a

difference in cost." Developers may even save money by avoiding fence repair from wildlife damage.

Fencing around solar projects must meet the North American Electric Reliability Corporation's critical infrastructure protection requirements. A solar developer working in the southwest interviewed for this study prefers to avoid wildlife fencing, despite its lower costs. They are concerned about small mammals and rodents chewing cables where they run from the array to conduit in the ground. In projects where wiring is unburied to save costs, wildlife would have direct access to wires. Additionally, they have found prairie dogs increase O&M costs by chewing on wires and destabilizing ground due to burrowing. A county also requested that they leave a gap under the entire fence perimeter. This gap would not comply with North American Electric Reliability Corporation standards because it could deliver a mild electric shock to a person since it would not be grounded. Furthermore, the developer worried that a total perimeter gap would enable children to climb under the fence and access electrified equipment, such as inverters. A fence gap that allows threatened or endangered species on site poses benefits and challenges. This practice provides habitat within the solar installation, but desert tortoises could be crushed by motorized vehicles or mowing equipment, requiring mortality monitoring and take permits. Further, if vegetation is not left on the site or replanted, tortoises would lack cover from predators. If the project requires translocation of tortoises, they must be moved further from the site so that they do not return. Practices that may allow safe tortoise habitat include training workers to avoid the tortoise, reducing onsite speed limits, performing fence perimeter checks, and limiting tortoise habitat to portions of the site [281].

Avian Mortality

Renewable energy development, particularly wind power, has prompted concerns over bird and bat deaths. Interviewees from environmental regulatory organizations worried about the lake effect hypothesis, which suggests that birds misinterpret solar fields for water and then die colliding with the arrays. In contrast, developers anecdotally thought that avian fatalities for solar PV were limited. The research on this topic is not conclusive, and there is an insufficient number of peer-reviewed studies of bird deaths at solar facilities. Nationally, avian deaths from solar CSP and PV plants are lower than wind power, fossil fuel generation, communication towers, roadway vehicles, and buildings and windows [202]. Since many solar projects are being built on agricultural land, comparing avian fatalities from solar facilities to agriculture is helpful. Calvert et al. (2013) identified causes of bird death from agriculture as applying pesticides, cultivating, haying, mowing, and harvesting [203]. Harvest, followed by insecticides, were the leading causes of fatalities. Insecticide use, harvesting, and loss of cropped pasture are the most significant agricultural causes of avian mortality [203],[204].

The literature does not include a total death per acre estimate for agriculture to compare with existing birds/MW estimates of avian death from solar power. This is because avian mortality varies by crop. Deaths from insecticide are highest for corn and cotton [204].[14] Scientists estimate that on acreage with significant insecticide application, between one-fourth to one birds/acre are killed per year in the United States [203],[205]. Since insecticides are unlikely to be used at solar sites, bird deaths could decline where insecticide intensive row crops are converted to solar power. Some avian mortality occurs from mowing [203]. A solar grazier (ag 2) explained that he avoids mowing when ground-nesting birds are nesting to avoid disturbing them. Solar power does cause avian habitat loss; mitigation through planting pollinator habitat and vegetation management strategies and other design features addressed in this white paper could reduce this. However, it is not yet known how adding pollinator habitat will affect avian mortality at solar facilities [281].

Kagan et al. (2014) developed the lake effect hypothesis after finding remains of aquatic birds at a single solar PV facility (Desert Sunlight PV in California) reported in a non-peer-reviewed article [206]. Kosciuch et al. (2021) believe that the data were insufficient to draw this conclusion and the researchers should have tested alternate hypotheses [207]. Kosciuch et al. (2020) found that most birds that died were ground-dwelling birds, not birds dependent on water or associated with water [208]. Kosciuch et al. (2021) collected data at three solar PV facilities in California and compared avian mortality, diversity, and abundance at these facilities compared to a nearby lake, an agricultural site, and grassland [207]. Bird fatalities were not higher at the solar facilities than the reference areas. Moreover, overall mortality was low considering the abundance of aquatic birds in the area. However, the research-

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[14] The groups resulting in the largest insecticide deaths by order size are corn, cotton, alfalfa, wheat, potato, peanut, sugar beet, sorghum, tobacco, and citrus [204].

ers could not prove that avian mortality is the same across facilities because researchers did not observe aquatic birds in the grassland. Aquatic bird flocks were not observed trying to land on the solar arrays or circling them. Kosciuch et al. did not have technology to observe during the night, so they may have missed birds that migrate nocturnally. Some birds that depend on aquatic environments, such as loons, were found dead at the solar facilities. Therefore, the lake effect may apply to some aquatic species, but which species and how many depends on the context and region [207].

Methodological challenges make it difficult to determine the cause of avian mortality at solar facilities. Kosciuch et al. (2020) attributed 24% of bird deaths to animal predation [208]. The remaining fatalities had no known cause, and there was no evidence that collisions with the arrays caused the deaths. Much of the evidence of bird mortality is feather spots, and it is difficult to attribute a cause since they could be from natural predation or scavenging. Visser et al. (2018) also struggled to attribute avian mortality to a cause [210]. They studied a 98 MW solar PV facility in South Africa for three months and found eight dead birds, based on finding feathers, not carcasses. The researchers found the feathers under the arrays. Therefore, the birds either did not strike the arrays, or scavengers ate the birds after they hit the arrays. Kosciuch et al. (2021) conducted frequent searches to avoid failing to detect birds eaten by scavengers but could not observe at night [207]. Additionally, ascribing reasons for bird fatalities requires quantifying "background" mortality, meaning regional bird death independent of a specific source [280]. In some regions, background bird mortality is high, whereas it is low in others, such as the Mojave Desert [281]. Studies are needed in different regions, and there is little data east of the Mississippi [281]. Future studies should use reference sites like Koscuich et al. (2021) did to compare solar site fatalities to natural mortality rates in the region.

Bird deaths likely vary based on region, bird density at each site, and facility size [208]. Research has not been conducted for solar PV facilities in agricultural landscapes [207]. DeVault et al. (2013) found that PV sited near airports does not increase the risk of bird-aircraft collisions and that solar siting near airports could reduce hazards to birds because they avoid airports [209]. Kosciuch et al. (2020) calculated an average avian mortality rate at PV installations of 2.49 birds/MW/year in the Southwest United States [208]. To reach this conclusion, they studied companies' environmental monitoring reports of diurnal raptors and water-associated and water-obligate birds at ten Southwestern solar facilities.

Walston et al. (2016) reviewed the reports of bird deaths at one PV facility and two CSP facilities in southern California [202]. They estimated a mortality rate of fatalities known to be caused by solar of 2.7 birds/MW/year for existing solar facilities. Walston et al. estimated the average avian mortality from known and unknown causes to be 9.9 birds/MW/year. Avian mortality, known to be attributable to the solar facility, is higher for CSP than PV, likely due to flux, with 0.5 birds/MW for PV versus the 2.7 average. For fatalities of unknown cause, rates are similar across the two technologies. The PV mortality rate of 0.06 birds/acre compared to the 0.25–1 bird/acre from insecticide use [203],[205] suggests that conversion of an insecticide-intensive row crop such as corn to solar power *might* reduce avian deaths.[15] However, this should be rigorously investigated at a solar PV installation converted from corn compared to a corn farm in the same region.

Researchers are critical of the bird monitoring practices at renewable energy facilities. Conkling et al. (2021) reviewed the techniques used for monitoring avian impacts at U.S. wind and solar facilities (CSP and PV) [211]. They studied 525 monitoring reports, mostly from wind facilities. Only 22% of the reports provide data from both pre- and post-construction. Only 29% used experimental study designs. Very few estimated the probability of detecting avian mortality. Conkling et al. recommend standardization of avian impact reporting to ensure all reports include pre- and post-construction data, use experimental designs, and disclose detection probability. The article does not address the economic costs of this monitoring. Interviewees indicated that mitigation measures were being taken at some solar facilities. In Nevada, developers install pinwheels on perimeter fencing to alert birds that they are approaching a barrier.

EPRI is leading a DOE-funded project to develop remote sensing technologies that monitor avian fatalities at utility-scale solar facilities. EPRI designed a fixed platform, 3-D infrared LiDAR-based Animal Activity Monitoring system[16] to detect collisions. This technology enables monitoring at night, addressing a drawback of the Kosciuch et al. (2021) study. Additionally, an Unmanned Aerial System technology will identify avian carcasses and nests,

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[15] The PV facility in the Walston et al. study was 250 MW on 1,966 acres, so 7.8 acres per MW. This was formerly a grazing site.

[16] Light Detection and Ranging.

potentially at a lower cost and a faster rate than human surveys (visual detection while walking the site). Several large-scale studies are underway including a U.S. Geological Survey study and a DOE study led by the University of California, Los Angeles [281]. Researchers need access to bird carcasses from solar facilities [281].

Wetlands

Many states allow but discourage solar from being sited on or near wetlands. Herbaceous and woody wetlands are among the least suitable land for solar because they provide environmental benefits (such as flood protection and wildlife habitat) and are saturated with water, which would increase solar construction costs [212]. Siting near a wetland brings obligations under the Clean Water Act [213]. In general, developers try to avoid siting near wetlands or areas where runoff could impact a wetland. Multiple interviewees (energy 1, 2, 3, 12) indicated that one of the first steps in site selection is to rule out areas that would impact wetlands. Developers want to avoid wetlands because the siting process is lengthy, requires more permits, and includes multiple government agencies. A solar developer (energy 12) explained that in their state, the involved agencies include the state Fish and Wildlife Agency, Parks and Recreation, National Fish and Wildlife Services, the Environmental Protection Agency (EPA), and the DOE. Additionally, construction is more expensive due to the unstable ground. Finally, conversion of wetlands releases soil organic carbon [145].

Module End-of-life, Leachate, and Recycling

The future waste stream for solar modules is predicted to reach between 60 and 78 million metric tonnes by 2050 [214]. Stakeholders and community members have expressed concern about end-of-life practices for solar PV and potential chemical leachate from broken or landfilled modules. Elements of concern include Cadmium, Copper, Lead, Nickel, Tin, and Zinc). The heavy metals differ based on the module type, and the potential for leaching depends on module construction and other factors. There are two main relevant technologies: crystalline Silicon (c-Si) modules, which typically include Lead, and thin-film Cadmium Telluride modules, which contain Cadmium. While more research is needed, the scientific literature finds few environmental and health impacts of solar module leaching.

The only exception is Lead, which is included in solder and pastes in some Silicon-based modules. Manufacturers do not typically disclose bill of material details, but studies suggest that the quantity of Lead in PV modules is small (~0.1%) [215],[216]. There is far more Lead in car batteries and twice as much lead in a typical 12-gauge shotgun shell than in one solar module [217]. The industry anticipates that lead-free pastes will be used in the future, and some manufacturers have already switched to lead-free solder [218].

Limited availability of leach testing data and various methods to sample PV modules to determine toxicity make it challenging to determine the prevalence of Lead and other toxic materials in solar modules. Furthermore, bill of material differences can exist among modules with the same model number. In the United States, the EPA's Test Method–1311: Toxicity Characteristic Leaching Procedure (TCLP)–and any other applicable state protocols are used to determine if modules should be classified as hazardous waste. This classification carries significantly higher handling and disposal costs. Landowners, jurisdictions, and other solar project stakeholders may perceive decommissioning and end-of-life management of PV modules as a risk. If a company abandoned a project, it would be costly to restore the site, or it could be left unavailable for other uses [219]. Decommissioning policies and requirements vary, and most regulations are at the county or local levels. Solar land use concerns related to decommissioning can be addressed through specific decommissioning, abandonment, and removal terms and often financial assurance, such as bonds, parent guarantees, or reserve, trust, or escrow accounts [219].

The International Energy Agency (IEA) studied the human health risks of Cadmium, Selenium, and Lead from landfilled solar modules on air and water under a worst-case scenario. They considered three technologies, c-Si, Cadmium Telluride, and Copper Indium Selenide modules. In a worst-case scenario, smaller than real-world module fragments are disposed of in an improper landfill with an acidic environment and lack of: liners, leachate collection, groundwater monitoring, covered waste, and stormwater management [220]. Even under those conditions, Cadmium, Selenium, and Lead levels were within the EPA's regulatory limits set for soil, air, and water, suggesting low risk of leaching and adverse human health impacts. Water impacts considered included drinking water, showering, and consuming fish from the affected water. Panthi et al. (2021) tested two commercially available Silicon cell types and an emerging Perovskite solar cell of higher efficiency than commercially available cells [221]. They tested broken cells, unbroken cells, and a worst-case scenario in which broken cells were tumbled and abraded. None of the chemical elements exceeded EPA stan-

dards for leaching other than Lead from Silicon in some, though not all, of the broken samples. Collins and Anctil (2017) found that Lead leachate exceeded the regulatory limit by a small amount in one of their tests [222]. However, their main goal was to study the testing method, not to determine toxicity. EPRI is creating a database of leach testing data using a new ASTM module sampling protocol (E3325 Standard Practice for Sampling of Solar Photovoltaic Modules for Toxicity Testing) to reduce variability in TCLP test results for c-Si and CdTe modules [218],[223].

Some stakeholders also worry about potential soil contamination caused by rainwater runoff on cracked modules in the field. Extreme weather (such as hurricanes, hailstorms, and tornados) is the most common cause of early modules end-of-life [218]. For example, a hailstorm in Pecos County, Texas damaged 400,000 modules, and climate change could increase such extreme weather events [224]. Exposing modules to hail in a laboratory simulation resulted in microcracks, which reduced modules efficiency [225]. However, like a car windshield, if a module endures major damage from a storm, it does not shatter but rather remains in one piece [217]. Further, researchers crushed solar modules in a landfill and found that the front-back encapsulation remains on the module fragments, inhibiting leaching [220].

The IEA found there is a low risk of contamination from cracked modules exposed to water. Researchers studied worst-case scenarios for Lead and Cadmium leachate from cracked modules [226]. Exposure point concentrations for Lead and Cadmium were well below the EPA health screening values in soil, air, and groundwater. The IEA also studied the health risk to workers of exposure to Lead, Cadmium, or Selenium from solar modules in the case of a building fire [227]. The cancer risk levels from inhaling smoke were within acceptable levels (based on 10-minutes of exposure), and the risk of groundwater contamination from the water used to put out the fire is below maximum contaminant levels for all three elements. Note that the three IEA reports studied risk to human health, not ecological risks.

Future research is required to test a broader range of chemicals and further investigate ecological and human health impacts across the wide range of commercially-available PV products as well as emerging technologies, such as Perovskites. Even small changes in the sampling and testing procedures affect the results [218],[222]. Furthermore, use of worst-case scenario testing may be leading to overregulation in the sector [222]. For example, the best method for modeling leaching from damaged solar modules is to crack them and subject them to rainwater, rather than breaking them into small pieces and tumbling them in a solvent, which does not represent a real-world situation [228]. Recycling modules will be an essential part of a transition to low-carbon energy [214]. One challenge to cost-efficient recycling is that solar modules are encased in tempered glass to prevent breakage in the field, which also makes it difficult to remove the glass to access the raw materials [220]. The EU requires the recycling costs to be covered upfront [214]. The United States does not yet require recycling. However, some states are working on regulations, and Washington State enacted legislation to require module manufacturer takeback for recycling or reuse [284, 285]. Most of the existing recycling is occurring in Europe and Japan. The recovery of materials varies, and greater recovery of materials is expected to improve the recycling economics [218]. For c-Si PV waste, Veolia in France claims materials recovery of 95%. Site decommissioning plans often allow landfilling of modules and can include recycling, salvage, and reuse of materials [288]. Some states require an upfront decommissioning plan or even bonds to be put in place to ensure all materials are removed from the site.

Emerging Siting Options

Brownfields and water provide alternative siting options to reduce demand for greenfields.

Brownfield Siting

"A *brownfield* is a property, the expansion, redevelopment, or reuse of which may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant" [229]. Examples of brownfields include landfills, former mines, spent foundry sands disposal sites, coal-fly-ash storage areas, oil spill sites, former oil and gas sites, sites contaminated by fertilizers, weapons testing ranges, gravel pits, and former dry cleaners. *Grayfields* are abandoned, blighted sites that are not contaminated (for example, abandoned shopping malls, big box stores, gas stations, parking lots) [230]. Often grayfields are categorized as brownfields, but the distinction is interesting for solar power since these grayfields avoid issues of liability related to contamination. Massachusetts leads the country in landfill solar installations because it provides an economic incentive for brownfield development (see Table 8) [231]. In 2019, there were 352 renewable energy projects on U.S. brownfields [231].

Table 8. Examples of Brownfield Initiatives

Brownfield Program	Description
Illinois' Energy Transition Act and Illinois Power Agency's Procurement Process	Illinois Power Agency provides renewable energy credits for brownfield site projects.
Nature Conservancy: Mining the Sun	TNC is working in Nevada and West Virginia to redevelop former mines into solar power sites.
Massachusetts Brownfield Generation Unit Adder	3 cents/kWh for the first 80 MW of brownfield solar development (declining by 4% with each successive 80 MW of development)

Example: Dubuque Solar Project: Alliant Energy built a solar project on a 5.9-acre foundry sand site in Dubuque, Iowa. It includes walkway paths that connect to the bike path and brick pier fencing that matches the buildings in downtown Dubuque. The engineered barrier is a four-foot cap of clean soil. The project won an Envision Platinum Award from the Institute for Sustainable Architecture [232].

The EPA program called RE-Powering America's Land developed a list of U.S. brownfield sites that could be used for solar power [233]. Municipal development organizations may also maintain brownfield site databases. There are many benefits from brownfield redevelopment, and it avoids the environmental impacts associated with greenfield development since the sites are previously disturbed. Utility companies already own sites contaminated by coal generation. Brownfield sites rarely provide habitat to wildlife. Converting brownfields may remove blight from a neighborhood, and solar power may be the only feasible option for land use at a severely contaminated site (see Figure 14). Several government interviewees viewed brownfield development favorably, as did interviewees concerned about converting agricultural land to solar generation. However, developers should not assume that community members living near a brownfield will support its conversion to solar power. An interviewee described a situation in which a low-income community had a vision for redevelopment for a brownfield site to provide various community services and were disappointed when it was converted into a warehouse.

Figure 14. 300 kW community solar power plant built on a landfill, with pollinator habitat that is still establishing, in a residential neighborhood. No other development options were available for this site. East Lansing, Michigan. (Photo by Sharlissa Moore, August 2021. Adjusted in Adobe Lightroom)

As with other solar projects, developers must assess the solar irradiance at brownfield sites, measure the distance to transmission lines, or identify a nearby demand source for the energy. Both brownfield and greenfield project developers must survey for nearby wetlands and wildlife, but brownfield sites may require lengthier setbacks from wetlands or other environmentally sensitive areas. The upfront costs are higher because surveying and permitting processes take longer, and additional engineering work is needed. For mines, one developer has found that the project's development cycle costs two to three times more than a greenfield solar facility, and the EPC costs are 10–20% greater than a comparably sized greenfield project [281]. Furthermore, abandoned mine sites sometimes have open remediation permits that can be difficult to close, as the companies have often gone bankrupt and insufficient funds are available to complete remediation [281]. Spiess & de Sousa (2016) overview the unique challenges of converting brownfields to solar generation [234].

- **Contamination:** Several energy companies we interviewed will not develop brownfield sites because of concerns about liability for contamination. Construction work can spread contamination through deep or shallow ground penetration and even by driving and moving equipment across the site. Sometimes developers discover further issues with contamination once development begins.
- **Securing capital:** Securing capital can be difficult for brownfield sites due to investor fears about liability and uncertainty.
- **Project size:** While greenfield projects on agricultural land can easily exceed 50 MW, brownfield projects are typically much smaller, impeding economies of scale. Several interviewees mentioned this as a drawback. The transaction costs of larger projects, such as licensing, permitting, zoning, and approval, still apply, but the payback is lesser than large sites.
- **Expertise:** Since brownfield development is less common than greenfield development, developers and utility companies may lack brownfield redevelopment expertise.
- **Geotechnical issues and landfill caps:** While Spiess & de Sousa do not identify this as a concern, geotechnical issues related to shifting and settling are unique to solar development on landfills. Additionally, developers must avoid penetrating the landfill cap. Figure 15 shows a ballasted system on a landfill. Ballasted systems increase costs from 5–15% [235].
- **Opportunity costs:** There are more significant opportunity costs for utilizing brownfields in urban areas than greenfields in rural areas due to limited urban land. Cities can gain more tax revenue from some other kinds of development. An interviewee noted that cities are often disappointed by the lack of jobs associated with brownfield solar development compared to other types of development. Additionally, one interviewee explained that because former coal sites are often near water, they are sometimes better converted to loading/unloading sites for barges than developed for solar power.

An environmental expert working at a state environmental agency described the process for avoiding liability for contamination. First, the developer must pay to characterize the contamination on the site. Brownfield contamination may not need to be remediated before solar development, but mechanisms must be put in place to prevent workers and other people from encountering the contamination. To address soil contamination, developers must implement an engineered barrier (such as a parking lot, clean soil). For groundwater contamination, developers may need to sign an agreement forbidding the development of a well for potable water. Regarding landfills, developers may not breach the cap. The state regulator will determine the required barriers or actions and then issue a letter indicating no further remediation is needed, exempting the developer from liability for cleanup, which helps them to secure financing. The developer will still be liable for violating any of the conditions set out by the regulator, such as worker protection and building engineered barriers.

Any site with a cap and shifting land requires a geotechnical assessment and corresponding design for an anchoring system for the solar arrays. Often, a ballasted system is used that 'floats' on top of the landfill and does not penetrate the cap [236]. See Figure 15. Not all landfill sites will be suitable for PV, based on, for example, the cap's characteristics, methane off-gassing, erosion and runoff issues, and the stability and slope of the landfill. According to an expert familiar with solar siting on landfills, municipal waste landfills often shift and settle differently in different areas. Contractors

Figure 15. 300 kW solar power plant built on a landfill before pollinator habitat establishment, East Lansing, Michigan. Ballasted system is visible [on the right].(Photo by Sharlissa Moore, July 2020. Adjusted in Adobe Lightroom)

monitor the site's shifting and settlement and may recommend avoiding areas with significant movement. The ballast and module support structure must withstand sinking and settling as well as wind loading and snow weight in cold climates. Perhaps because the geotechnical features of each site are unique, we could not find an average percentage CapEx increase for solar development on landfills compared to greenfields.

Maco et al. (2018) found that climate change and extreme weather, such as hurricanes, heavy rainfall, wildfires, drought and water stress, and heatwaves, affect contaminated sites [237]. The effects include changes to "contaminant toxicity, exposure, organism sensitivity, fate and transport, long-term operations, management, and stewardship." Therefore, remediation plans for brownfields may need to account for predictions of future extreme weather. The authors suggest "resilient remediation" plans that account for environmental and social vulnerability. See the Sustainable Remediation Forum for details (https://www.sustainableremediation.org/programs).

Floating Photovoltaics

As with brownfields, installing solar PV on water could spare land from development. Cagle et al. (2020) find that freshwater floating PV uses less area, with an average land sparing ratio for installed capacity of 2.7:1 square meters compared to ground-mount PV [238]. Based on electricity generated (MWh), floating PV uses on average 2.3 times less area than ground-mount PV [238]. Some scientific articles have conducted analyses of the feasibility of floating photovoltaic arrays (FPV), also called floatovoltaics. Spencer et al. (2018) identified 24,419 reservoirs in the United States and found that covering 27% of them with solar arrays would meet 10% of U.S. power generation needs [239]. Siting options include oceans, lakes, lagoons, reservoirs, irrigation ponds, wastewater treatment facilities, wineries, ponds on farms, dams, and canals [240]. The modules are mounted on a floating platform with mooring lines secured to the lakebed or seafloor. Developers must ensure materials are selected that withstand the stresses of an aquatic environment [248]. FPV CapEx costs are estimated to be 25% higher than ground mount [241]. As with ground mount solar power, larger installations will have lower CapEx costs because of economies of scale.

Ocean installations are costly because they must withstand corrosion, sea spray, wind, and vibration [240],[242]. These stresses are harsher than on inland water bodies. A 2014 study suggests that modules built with corrosion-resistant materials (as determined by IEC 61701:Salt mist corrosion testing of PV modules) are needed for ocean installations [289]. A model of pontoon-mounted FPV on the North Sea showed an average 12.9% higher output on sea compared to land, predominantly due to the lower temperature. The solar resources were also better at sea compared to the land-based location [243]. Impacts of FPV on shading, biofouling, and anchoring on seagrass and coral, marine life, and spread of invasive species are poorly understood [244].

The literature identifies several benefits of FPV.

- Reservoirs already have *access to infrastructure and roads* [239].
- The water *increases modules' efficiency* through cooling, with 1.5% to 22% efficiency gains [239],[245],[246].
- The arrays *reduce evaporation* and *impede algal and bacterial growth* [247].
- *Ocean species* might benefit from using FPV as an artificial reef [244].
- FPV provides *bird perches* [281]

Florida has the most pronounced potential for FPV in the United States due to an abundance of water surface area and small ponds and high land costs. New Jersey has the second greatest potential because of the high cost of land ($31,506/hectare compared to the $9,738/hectare U.S. average) [239]. Japan has installed the most FPV capacity in the world owing to its limited land area, followed by South Korea and China [239],[248]. The costs are more feasible in Japan than in the United States due to Japan's lack of domestic fuel resources, high energy costs, and the effects of the Fukushima accident on public opinion of nuclear power. In Turkey, FPV was combined with hydrogen production to power a fuel cell to provide electricity at night [247]. Table 9 provides examples of U.S. projects and the reasons for selecting FPV.

The need for washing FPV and the best techniques are still under investigation. Washing modules is uncommon in the United States. A solar developer (energy 12) stated, "it's just not cost-effective in the United States to wash panels very often, if ever. You've really got to rely on rainwater to do that." Whether and how often cleaning is required and the best methods to use are based on the environment, nearby dust sources, and whether the PV is installed over freshwater or seawater [249]. Soiling for FPV may be greater than on land because the slope of the arrays

Table 9. Examples of Floating Photovoltaic Projects

Example Project	Description
Florida Miami Dade Airport	As a proof-of-concept, Florida Power and Light has a 160 kW FPV ocean installation near Miami Dade Airport, with a sign welcoming visitors [250].
Fort Bragg, North Carolina	Duke Energy is building a 1.1 MW FPV installation, with 2 MW of storage, at Fort Bragg on a remote lake near a special operations training facility [251]. The lake is primarily used for recreational fishing. The project will provide resiliency for the military base.
Water retention pond, Sayreville, New Jersey	In 2020, Ciel & Terre USA completed a $7.2 million, 4.4 MW FPV array in Sayreville, New Jersey on a water retention pond at a water treatment plant. The small town wanted renewable energy access, but the only available land was forested [283].
Healdsburg Floating Solar Project	White Pine Renewables developed a 4.8 MW project in Healdsburg, California, completed in 2021. It is built over ponds at a wastewater treatment facility to impede algal growth. It will provide electricity to the city and wastewater treatment facility.[256]
City of Ann Arbor, Michigan	The city is planning a 24 MW solar installation on a landfill site that is mainly ground-mount but includes a portion of FPV over a 12-acre pond [257]. The city selected floating solar because of constrained urban land availability.

tends to be lower than for ground-mount PV [249]. Finally, for marine applications, the impact of biofouling on washing requires research [244].

None of the developers we interviewed had direct experience developing FPV. Several developers had not considered the possibility. Several have considered it and are interested. Multiple developers stated they felt confident it is something they will build in the future. For example, a developer (energy 11) said, "I'm sure if there's an opportunity to develop floating solar, then we'll definitely do that." Reasons that the developers have not deployed FPV included cost, concerns about avian impacts, and lack of sufficient commercial demonstration. A representative from a large independent power producer explained that "we're a little bit hamstrung on deploying equipment that has not been commercially proven around the world…. [But we are] watching with excitement for maybe some of that equipment to become more commercially proven before we really take a substantial dive into that." Several developers thought their company would deploy it in states with ample water access but not in the state where they develop projects due to a lack of non-navigable bodies of water.

The shading from the arrays over the water can reduce the water temperature (which changes according to depth), affecting the mixing of the water layers, which changes the water's oxygenation and nutrient distribution [258]. These effects differ between human-made and natural bodies of water. Changes in water temperature can affect water quality and aquatic wildlife. Estimating the impacts may be necessary to obtain siting permits.

Academic research has not yet been conducted on public perceptions of FPV or public opposition to it. Coastal and marine spatial planning attempts to avoid conflict through stakeholder planning processes. This literature shows that place-based conflict stemming from place attachment and sense of place is common on water like on land [14]. Offshore energy infrastructure on the ocean and Great Lakes has already been demonstrated to cause stakeholder conflict [259],[244]. Reservoirs in the United States, which would be prime candidates for constructing larger FPV installations, play an important role in recreation and are economic development boons. For example, the Tennessee Valley Authority's 28 reservoirs generate $12 billion from recreational activities annually, or $1 million/shoreline-mile, and provide 130,000 jobs [260]. FPV in these locations could engender opposition from stakeholders who are financially dependent on the reservoirs.

Interactivity conflict is already prevalent at U.S. reservoirs (for example, fishing/angling vs. waterskiing, motorized vs. non-motorized boating, boating and fishing vs. swimming, indigenous cultural values for the water vs. other uses), as is *intra-activity conflict* (or crowding affecting people participating in the same activity such as hunting, fishing, and boating, as well as hikers seeking solitude). Water also contributes to onshore recreation (such as scenic views while hiking) [261]. Because of this, proposals to decommission small hydropower facilities, resulting in the loss of reservoirs, have caused substantial conflict in Michigan [263]. Conflict among recreation, scenic values, and economic activities already exists (for instance, boating, fishing, aesthetically pleasing views from houses and hiking trails, aquaculture, energy genera-

tion, irrigation, drinking water, industrial water use, flood control, effluent) [262]. Understanding public and stakeholder conflict over FPV would be an important area of social science research before scaling up FPV installations. None of the existing scientific literature addresses these issues.

Outlook

The steep reduction in the cost of solar power has led to greatly expanded markets for utility-scale solar power plants. EPRI's *2020 Solar Technology Status, Cost, and Performance* report overviews the current costs of PV technologies [1]. Stemming from solar power's recent expansion and anticipated growth, this report identified research and development needs related to the socioeconomic impacts of farmland conversion to solar power, dual land-uses, ecological issues, and alternate sites.

Socioeconomic Impacts of Farmland Conversion to Solar Power

Existing research has addressed the reasons for public opposition to renewable energy projects. However, the drivers of renewable energy opposition in agricultural communities, the socioeconomic impacts on agricultural communities, and the best mitigation measures to alleviate resistance are insufficiently understood. Researchers from rural sociology and agricultural economics should investigate the effects of conversion to solar power on local agricultural economies and supply chains. Social scientists could identify the main variables influencing opposition and support. For example, resistance might vary based on the adjacent agricultural production type (cattle grazing, row crop production, dairy, or specialty crops). Research is needed to determine whether the economic viability of farms improves using current, average U.S. solar leasing rates (rather than historic energy lease data). Studies that gauge the potential for displacement of full- and partial-tenant farmers would aid in understanding whether land conversion has adverse socioeconomic effects on a particular farmer demographic. Additionally, research could quantify and qualify the amount of tax revenue and how it is benefitting communities across the United States. This likely differs based on the specific tax structure used.

Dual Land Uses

Interviewees widely agreed that quantitative monitoring is needed to measure the benefits of solar pollinator habitats to insects and wildlife. Researchers should study this across installations designed to meet different goals (for example, benefiting native insects, supporting threatened and endangered pollinators or monarch butterflies, providing refugia for honey bees, producing honey, and combining grazing and pollinator-friendly ground cover). Separately or in tandem, research is needed to understand whether solar pollinator habitat improves public perceptions and ways for avoiding public misunderstanding as the habitat is being established. Researchers could study whether some project designs or goals increase public acceptance compared to others. For example, the public might be more interested in honey production than protecting native species or the reverse. EPRI has published an overview of pollinator-friendly solar energy and organizes an annual pollinator party, with 2,338,852 people in attendance at the 2021 party. EPRI recently completed a report that reviewed the attributes of 16 scorecards. A separate ongoing study is addressing the *Feasibility of Co-locating Solar PV and Pollinator Habitat*. EPRI also has a study underway on monarch habitat [264].

Similarly, only anecdotal evidence is available about how growing crops under arrays or grazing livestock affect public acceptance of solar power. It is also vital to research how scaling-up agrivoltaic options will affect local agricultural economies. Scientists could combine this public acceptance research with engineering trials of crops. While numerous experiments have explored crops that can be grown in the shade of the arrays, few have studied the economic feasibility of these crops, both in terms of the solar design and the agricultural market feasibility. From an energy standpoint, interviewees identified an all-terrain scissor lift designed to reduce the CapEx costs of increased pile height for agrivoltaics as a research priority. From an agricultural perspective, farmers' willingness to undertake agrivoltaic initiatives is poorly understood. More research on market feasibility could alleviate financial risks to farmers. Finally, a complete market analysis of sheep grazing costs, barriers to developing a robust solar grazing market (for example, trained graziers, sheep supply chain), and the demand for value-added sheep products is necessitous.

How land conversion from agriculture to solar power will affect soil quality, soil carbon sequestration, and nutrient runoff are complex and poorly-understood topics. Specific solar land-use practices, such as adding pollinator habitat, will affect the soil quality. The microclimates created by solar arrays and the vegetation height restrictions require solar-specific research on soil quality and carbon sequestration.

Ecological Impacts

A better understanding of how wildlife interact with solar systems would be a valuable area of research, particularly for studies outside of the U.S. Southwest, where most investigation has occurred. As with pollinator habitat, quantitative monitoring of sites with wildlife fencing across various regions would quantify the benefits to wildlife. Studies are also needed on whether wildlife fencing poses impediments to the safe operation of the solar facility. If there are problems with wildlife chewing cables, chew-proof cabling or other protective measures will be important innovations in this area. Most studies on avian mortality at solar installations have also focused on the U.S. Southwest. Research on other regions, especially agricultural landscapes, is essential. Comparing avian death at a cornfield to a nearby solar installation would show whether bird deaths are lower at solar sites than sites with intensive insecticide use. Additionally, few studies on renewable energy, particularly solar power, have compared avian mortality at solar facilities to avian mortality in the region (or "source-independent" mortality). More research is needed in different regions to evaluate whether a region with higher source-independent mortality contributes to avian fatality rates at solar facilities. EPRI is leading a DOE-funded project to develop remote sensing technologies that monitor avian fatalities at utility-scale solar facilities. These technologies will improve avian fatality detection at solar sites.

Finally, additional research is critical on the potential impacts of solar leaching on ecological and human health. In 2018, EPRI published a solar module end-of-life study. EPRI is creating a database of leach testing data using a new ASTM standard practice module sampling protocol to reduce variability in TCLP test results [219].

Siting Alternatives

Brownfield sites and FPV offer promising alternatives, or additions, to greenfield development. The literature lacks a generalized estimate of the increased CapEx and O&M costs of brownfield development on different types of sites compared to agricultural sites. Investigation for landfills is critical for understanding economic feasibility because of the added geotechnical costs. In 2021, EPRI published a report on repurposing coal combustion sites to solar installations that demonstrates there are 429 sites with solar development potential and 15 existing projects [235]. For FPV, module washing requirements and techniques for removing biofouling and soiling in a safe and water-efficient way would improve FPV's benefits. The impacts of FPV on aquatic life and birds–and for marine installations, coral, and seagrass–are poorly understood. The concept of floating PV installations needs upfront research by social scientists to assess feasibility related to public acceptance and stakeholder conflict over other uses of lakes and reservoirs and potential disruption to revenue generated by existing uses of reservoirs. Siting solar power on reservoirs may engender opposition from citizens and stakeholders. This issue requires further social science research to assess the feasibility of floating PV.

Acronyms

Before/After and Control/Impact (BACI)

capital expenditure (CapEx)

community benefit agreement (CBA)

concentrating solar power (CSP)

Conservation Reserve Program (CRP)

crystalline Silicon (c-Si)

Geographic information systems (GIS)

Environmental Protection Agency (EPA)

IMpact Analysis for PLANning (IMPAN)

International Energy Agency (IEA)

National Renewable Energy Laboratory (NREL)

not-in-my-backyard (NIMBY)

Operations and Maintenance (O&M)

Payment in Lieu of Taxes (PILOT)

power purchase agreement (PPA)

The Nature Conservancy (TNC)

U.S. Bureau of Land Management (BLM)

U.S. Department of Agriculture (USDA)

U.S. Department of Energy (DOE)

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Appendix 1: Tax Structure Information

Taxes based on a reduced assessment rate for property value: Many of the states included in this study provide a reduced assessment rate for the property value, including Arizona, Illinois, Missouri, North Carolina, and Nevada. In Arizona, tax revenue for renewable power plants is 20% in the first year, compared to 35% for fossil fuels, but depreciation is applied to fossil fuel plants and not renewable installations [71]. In 2018, Illinois passed legislation determining the fair cash value for a utility scale solar installation per MW ($218,000). This revenue does decline at 4% per annum due to depreciation but is mostly offset by an inflation adjustment [77]. The Missouri legislature passed legislation making solar installations not being held for resale tax exempt [265],[266]. In North Carolina, the owner of the solar facility receives a tax incentive consisting of an 80% reduction in valuation on the property taxes on the equipment [80]. North Carolina assesses a roll back tax, which reclaims the last three years of real property taxes on the former agricultural land at the commercial rate. A property tax abatement is one of two options in Virginia. A local government can use HB 1434/SB763 to obtain revenue from the machinery and tools tax over time, which starts at 80% for the first five years, decreasing to 70% for the next five years, and then remaining at 60% for the rest of the plant's lifetime [70].

Locally determined taxes: In some states, local governments determine tax rates and incentives. In West-central Georgia, Taylor County offered property tax abatement for the first 10 years of the solar facilities' operation through a PILOT rate [81]. In South Carolina, local governments have negotiated PILOT agreements. Orangeburg County, where much of the state's solar development has occurred, approved a payment (or fee) in lieu of taxes for solar power, which reduces the county's typical 10.5% tax assessment to 6% [267]. Unlike in Illinois, in Indiana, there is no state set valuation of solar facilities. The assessed value is up to local tax assessors. Some assessors taxed the solar installations at the same rate as agricultural land, while others set high tax rates that made solar installations financially infeasible [268]. Guidance from the Indiana Department of Local Government Finance clarified in mid-2020 that local assessors are still responsible for assessing the land but that land underneath solar modules should be assessed as commercial or industrial land, not agricultural land [269]. Furthermore, any tax abatements are at the discretion of the relevant local government entity. The office suggested local governments could establish a standard solar tax assessment value per acre. A bill proposed in the legislature in 2021 sought to establish a standard tax valuation [268]. Louisiana offers an Industrial Tax Exemption for projects that create and maintain jobs, with approval from local governments [270]. At least one parish council (West Baton Rouge) opted out of providing the Industrial Tax Exemption for a solar facility [271]. Similarly, in New Mexico, solar facilities are exempt from property taxes under an industrial bond, but the local government can negotiate a PILOT [71]. For example, the 70 MW Roswell solar facility includes a property tax abatement worth $791,270, replaced by a PILOT of $396,0000 annually, equating to $5,657 per MW [272]. In Texas, local governments have negotiated PILOTs. For example, Oldham County reduced the tax burden for solar facilities by about ⅓ through a PILOT [84]. Between wind and solar power up to 2015, Nevada provided $500 million in property tax abatements, but tax revenue has still been substantial for rural governments [85].

Payments in lieu of taxes: Four states in this study tax solar facilities with a state-level PILOT policy. Mississippi offers a property tax exemption, with a local PILOT for the first ten years of operation for solar facilities with an investment of $60 million or more [273],[274]. In Virginia, a PILOT (or shared revenue model) is the second option, allowing local governments to assess an electricity capacity tax of up to $1,400 per installed MW for facilities over 25 MW. If local governments select this option, the solar owner is then exempt from machinery and tools (equipment) taxes. Wisconsin also uses a shared revenue model with a PILOT of $4,000 per MW for renewable energy, compared to $2,000 per MW for fossil fuels [275]. The revenue is collected by the state and split between the relevant municipality and county.

Energy generation tax revenue model: Finally, Iowa and Minnesota assess taxes based on a fee per MWh of energy generated. A county government official explained that solar power will generate local tax revenue using a replacement tax on the energy generated from the facilities. The tax is 0.6 cents per MWh generated. State property tax of 3 cents per $1,000 of property value is also assessed on local installations for the state's general fund [75]. Iowa exempts renewable energy equipment from sales tax [276]. Like Iowa, Minnesota taxes utility-scale solar installations based on a set rate for the energy produced. Minnesota's rate is much

higher than Iowa's at $1.20 per MWh generated [277]. Minnesota also charges real property taxes for solar property based on class 3a "commercial, industrial and utility property." Solar facilities larger than 1 MW on agricultural land result in a land reclassification from agricultural land to utility property, increasing the tax rate from 1% to 2%. The solar equipment is exempt from sales tax [278].

No property tax abatement: Finally, Alabama allocates taxes for public utilities based on an appraisal of the real and personal property value [279].

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