Overview of Opportunities for Co-Location of Solar Energy Technologies and Vegetation

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National Renewable Energy Laboratory

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Executive Summary

Large-scale solar facilities have the potential to contribute significantly to national electricity production. Many solar installations are large-scale or utility-scale, with a capacity over 1 MW and connected directly to the electric grid. Large-scale solar facilities offer an opportunity to achieve economies of scale in solar deployment, yet there have been concerns about the amount of land required for solar projects and the impact of solar projects on local habitat. During the site preparation phase for utility-scale solar facilities, developers often grade land and remove all vegetation to minimize installation and operational costs, prevent plants from shading panels, and minimize potential fire or wildlife risks. However, the common site preparation practice of removing vegetation can be avoided in certain circumstances, and there have been successful examples where solar facilities have been co-located with agricultural operations or have native vegetation growing beneath the panels. In this study we outline some of the impacts large-scale solar facilities can have on the local environment, provide examples of installations where impacts have been minimized through co-location with vegetation, characterize the types of co-location, and give an overview of the potential benefits from co-location of solar energy projects and vegetation. The varieties of co-location can be replicated or modified for site-specific use at other solar energy installations around the world. We conclude with opportunities to improve upon our understanding of ways to reduce the environmental impacts of large-scale solar installations.

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1 Introduction

Large-scale solar facilities have the potential to contribute significantly to national electricity production (Mehos et al. 2009; DOE 2012). The industry already is expanding rapidly, with more than 3.1 gigawatts (GW) of solar projects operating in 2012 and more than 30 GW of solar projects under construction or under development (SEIA 2013). Many of the solar installations are "large-scale" or "utility-scale," with a capacity over 1 MW and connected directly to the electric grid (SEIA 2013). Large-scale solar facilities offer an opportunity to achieve economies of scale in solar deployment and have been the focus of a federal-level siting process to facilitate deployment on Bureau of Land Management (BLM) property (BLM/DOE 2012). Under the U.S. Department of Energy (DOE) SunShot program, utility-scale solar installations are projected to result in the cumulative installation of approximately 302 GW of photovoltaic (PV) and 28 GW of concentrating solar power (CSP) by 2030 and 632 GW of PV and 83 GW of CSP by 2050 (DOE 2012). There have been concerns about the amount of land required for solar projects because of the potential impact on wildlife habitat, critical habitat for threatened or endangered species, and agricultural land availability (Brown and Whitney 2011). The DOE SunShot program level of utility-scale solar electricity use would require 900,000–2,700,000 acres of land by 2030 and 2,100,000–6,200,000 acres of land by 2050 (DOE 2012).

During the site preparation phase for utility-scale solar facilities, developers often grade land and remove all vegetation to minimize installation and operational costs, prevent plants (including crops) from shading panels, and minimize potential fire or wildlife risks (BLM/DOE 2012). However, the common site preparation practice of removing vegetation can be avoided in certain circumstances, and there have been successful examples where solar facilities are co-located with agricultural operations or have native vegetation growing beneath the panels. In this study we outline some of the impacts large-scale solar facilities can have on the local environment, provide examples of installations where impacts have been minimized through co-location with vegetation, characterize the types of co-location, and give an overview of the potential benefits from co-location of solar energy projects and vegetation. The varieties of co-location can be replicated or modified for site-specific use at other solar energy installations around the world. We conclude with opportunities to improve upon our understanding of ways to reduce the environmental impacts of large-scale solar installations.

2 Land-Use and Environmental Impacts of Solar Projects

The local environmental impact of solar installations can be characterized in terms of the total land area required, the site preparation impacts, and the operations impacts.

2.1 Land Requirements of Solar Energy Installations

Many studies have attempted to quantify the land-use requirements for large-scale solar installations (Fthenakis and Kim 2009; Brown and Whitney 2011; BLM/DOE 2012; Ong et al. 2013). A variety of methods and metrics is possible; some reports address only land directly affected by an installation (e.g., land directly occupied by solar arrays, access roads, substations, service buildings, and other infrastructure), whereas others consider the total area enclosed by the solar power plant boundary (Ong et al. 2013). In addition, some studies present values in terms of land area use per unit of energy generation (e.g., gigawatt-hours [GWh]), whereas other studies provide values in terms of land area use per unit of capacity (e.g., MW). In general, comparing across energy types for power plants, PV facilities require less land area than biomass operations but may require more land than natural gas, CSP, coal, geothermal, and nuclear facilities[1] (Brown and Whitney 2011). The range of land use is approximately 3–9 acres/GWh/yr, or 5–10 acres/MW (BLM/DOE 2012; Ong et al. 2013). Thus, a 20 MW solar facility could occupy up to 200 acres, given current technology and practices. Under scenarios developed by the BLM and the Department of Energy as part of the Solar Energy Programmatic Environmental Impact Statement (PEIS), expected deployment of solar power on public lands over the next 20 years could require 214,000 acres (BLM/DOE 2012) . Most studies consider land taken up by large-scale solar projects to be single-use, meaning the land is unavailable for any other use. This is largely due to current standard construction practices at large-scale solar facilities.

Another key issue is the location of future solar energy installations. Based on abundance of sunlight and available land, the BLM has identified several Western states with semi-arid to arid climates as feasible for future solar energy installations. These Solar Energy Zones (SEZ) have special status to encourage quick deployment of large-scale solar installations (BLM/DOE 2012). While public land space is abundant, many of these areas are deserts with thin upper soil horizons, low soil fertility, and low levels of rainfall. These lands may not be ideal for agricultural use but may serve important wildlife habitat, recreation, and cultural functions. Additional large-scale solar development is taking place in other locations throughout the United States, primarily on private land (SEIA 2013). Development of solar projects on these lands and other lands not yet identified, using current industry practices, may impair existing ecosystem, recreation, and cultural functions.

2.2 Environmental Impacts of Common Industry Practices in Solar Development

A typical large acreage solar array installation can have substantial impacts on the ecosystem in which it is built. Current installation and operation practices often render large expanses of land

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[1] This is only for the power plant structure and does not include land required for fuel extraction for coal, natural gas, or nuclear technologies. For a detailed treatment, see Fthenakis and Kim (2009).

unusable for wildlife (Tsoutsos et al. 2005; BLM/DOE 2012). Site preparation activities include land grading, vegetation removal, soil sterilization, and adding gravel cover beneath the array (Figure 1). This, in turn, leads to long-term herbicide use to prevent regrowth of vegetation cover. Developers employ these practices to minimize risk of fires, pests, and shading from vegetation.

Current site preparation and construction practices for utility-scale solar projects lead to direct environmental impacts (e.g., soil disturbance, habitat loss, habitat and fragmentation, wildlife mortality, spread of invasive species) as well as indirect environmental impacts (e.g., changes in surface water quality due to soil erosion at the construction site, degradation of habitat from construction in adjacent areas, herbicide drift into adjacent habitat), which may lead to long-term permanent damage (BLM/DOE 2012). Long-term permanent damage could include the spread of desertification, impaired precipitation infiltration due to soil compaction, a permanent decrease in viable soil depth, reduction in biodiversity, and an inability to control weed growth at solar sites (Hill 2010). Most projects completely clear vegetation and grade land prior to construction, cover areas with gravel, and then use water to suppress dust; these activities lead to the need for environmental mitigation (BLM/DOE 2012). In fragile desert ecosystems where many future solar installations are planned, these impacts can have a greater effect, further emphasizing the importance of careful siting to limit impacts.

In addition, gravel underlayment may contribute to a heat island effect, potentially reducing the efficiency and life span of PV panels (Skoplaki and Palyvos 2009). Use of vegetation beneath the array could help reduce ambient air temperatures by creating a cooler microclimate (Shashua-Bar et al. 2006; Hill 2010).

Figure 1. Typical solar array installation showing land grading and vegetation removal. ***Photo by Brenda Beatty, NREL***

There has been minimal research regarding the potential for large-scale solar facilities to be co-located with agriculture or native vegetation. Certain renewable technologies, such as wind power, are commonly deployed in agricultural areas with little impact on farming activities, yet solar technologies have not yet seen similar developments (Holmes and Papay 2011; Beckman and Xiarchos 2013). There are a variety of ways in which environmental impacts from solar development can be reduced or eliminated through site selection, site preparation, and re-vegetation activities. Impacts on local agriculture and wildlife habitat could be minimized by utilizing already degraded, contaminated, or marginal lands that might not sustain viable wildlife populations or be considered for agriculture production (Mosey and van Geet 2010; Steen et al. 2013). In addition, large-scale solar facilities can be configured in various ways to minimize impacts on the environment and surrounding land (Denholm and Margolis 2008). In some cases, re-vegetation after solar site preparation could be utilized to return disturbed agricultural land and disturbed solar construction land to suitable habitat for identified critical flora and fauna, thus improving the quality of the land (Althouse and Meade 2011). In addition to these mitigation techniques, environmental impacts can be avoided through integrated planning of solar energy and vegetation, also known as co-location.

3 Opportunities for Co-Location of Solar Energy and Vegetation

There are opportunities for large-scale solar energy installations to reduce environmental impacts and environmental mitigation costs through co-location with vegetation. Co-location can be defined as the deliberate production of vegetation and energy in a single location. Vegetation production might occur under or around energy infrastructure. Opportunities and approaches to co-location can be characterized as vegetation-centric, energy-centric, and integrated vegetation-energy-centric.

3.1 Vegetation-Centric Approaches to Co-Location

Vegetation-centric approaches to co-location of solar energy and vegetation are characterized by actions that serve to maximize biomass production activities and minimize changes to existing vegetation management activities, while also incorporating solar energy production activities. Vegetation-centric approaches may be well suited to areas that are land constrained (e.g., the northeast United States) or that are already developed agricultural areas. The basic premise is that the vegetation productivity of the land being utilized is not sacrificed for the sake of solar generation. Ideally, the placement of solar energy infrastructure does not substantially alter the standard vegetation management practices. Solar energy technologies can be strategically placed in the vegetated area to provide electricity without substantially affecting vegetation yields. As there are a variety of vegetation types (e.g., agriculture crops, scrubland, desert, grazing land), there are different strategies that can be employed to accommodate different vegetation types.

3.1.1 Examples of Vegetation-Centric Approaches to Co-Location

Both research studies and commercial agricultural operations demonstrate that solar technologies can be compatible with harvestable crops by modifying panel height and spacing such that harvestable crops can thrive between them.

The University of Massachusetts-Amherst, with assistance from local consulting and construction firms, has developed a series of experimental test plots with elevated PV panels that allow crops to grow underneath (Merzbach 2011) (Figure 2).

Figure 2. Pasture crops growing under elevated PV panels in Massachusetts. ***Photo from Stephen Herbert, University of Massachusetts***

The team has experimented with various spacing lengths between panels and poles within rows as well as distances between rows of panels, panel heights, pole depths, and techniques to improve resilience against high winds. In addition, the team has evaluated yield variation for pasture crops, corn, and barley.

In a commercial operation, the Convergence Energy Solar Farm in Delavan, Wisconsin, grows sunflowers intended for biofuel production under elevated solar panels (Content 2011).

The above facilities provide examples of solar technologies being utilized and designed to allow for harvestable crops to thrive under and between panels. In these cases, returns from agricultural production are considered to be of equal or greater importance than solar production. For these types of systems, more research is required to determine economic tradeoffs associated with solar density and configurations, crop types, crop production practices, and location of the project.

3.2 Energy-Centric Approaches to Co-Location

Energy-centric approaches to co-location of solar energy developments and vegetation are characterized by actions that serve to maximize solar energy output, minimize changes to solar development standard practices, while also promoting vegetation growth under and around the solar installation. Ideally, energy-centric approaches to co-location do not lead to a reduction in expected solar energy output. Energy-centric approaches may be well suited to areas with high quantities of land targeted for solar energy development or areas where solar development has already occurred. Certain types of low-height grasses, agricultural crops, and nursery plants can thrive in low sunlight conditions underneath solar energy technologies and would not require large machinery for harvesting. As there are different sizes of solar installations, certain vegetation activities may be more suitable for smaller solar projects (e.g., agricultural crops could be grown on installations smaller than 1 MW) or larger solar projects (e.g., low-height grasses could be grown on larger installations over 1 MW).

3.2.1 Examples of Energy-Centric Approaches to Co-Location

Energy-centric approaches to co-location have been tested on larger commercial and utility-scale solar installations. In many cases, co-location interventions have occurred after the initial site preparation already occurred and thus involved substantial re-vegetation activities. These efforts, some of them ongoing, have demonstrated that low-height vegetation can thrive in the low sunlight conditions underneath solar energy infrastructure.

In 2009, SunEdison installed a 1.1 MW PV tracking array at the National Renewable Energy Laboratory's (NREL) 305-acre National Wind Technology Center (NWTC), the nation's principal research site for wind power and distributed energy resources with large expanses of open land suitable for solar development and research. Because the PV array was installed and configured similar to standard industry practices, the land was cleared of native vegetation and leveled before construction began. However, as part of its sustainability policy, NREL requires re-vegetation following any ground disturbance activities onsite. In 2010, NREL initiated a three-year re-vegetation test to assess the relative effectiveness of various seeding and mulching combinations in the vicinity of this PV installation (Beatty et al. 2012) (Figure 3).

Figure 3. PV panels and vegetation at NREL site. ***Photo by Jordan Macknick, NREL***

Typically, re-vegetation at NREL would be done using a seed mix containing native grassland species found elsewhere on NREL's campus. However, because shading from the solar panels could have impaired the ability of sun-loving prairie species to germinate and grow, NREL decided to assess the relative effectiveness of re-vegetation in partial shading conditions. The seed mix included only native or adapted (non-invasive) drought-resistant species, seedlings that can establish without supplemental water, species that establish quickly to pre-empt undesirable weedy species, species that could not grow taller than, twine, or climb onto solar equipment, plants that produce adequate cover to control wind and water erosion, plants that would remain as short as possible (without mowing) to minimize the standing dead fuel load, and plants that would help restore wildlife habitat. Electrical lines were encased in conduit or otherwise protected from damage by small mammals. Initial results of the NREL research have provided insights into which types of native grasses grow best in the region under the partial shade conditions of a standard utility-scale PV system design (Beatty et al. 2012).

No information was found in the literature regarding studies conducted in the arid U.S. West to guide decisions regarding species selection or performance under solar energy technologies. Ongoing work in Italy has assessed impacts of PV systems on grass cultivation, soil temperature and quality, and other factors relevant to successful plant growth in that region (Carfagna 2010; de Vanna 2010; Zucconi 2010). To date, co-location has not been studied extensively in the United States, although there are a few promising ongoing studies and activities by the solar industry.

The Ivanpah Solar Electric Generating System Final Environmental Impact Statement quantified a re-vegetation plan based on special-status plant species within the project area in California, taking into account various project activities and components, but no long-term findings exist yet (BLM 2010). The Topaz Solar Farm in Paso Robles, California developed a plan to restore native grassland, encouraging the return of the San Joaquin kit fox, a mammalian keystone species native to the area. The primary short-term goal for restoration and re-vegetation was to eliminate dust and erosion created by construction activities. The stable vegetated surface would then promote the long-term goal of creating native grassland stable enough to support prey and habitat for the keystone species (Althouse and Meade 2011).

3.3 Integrated Vegetation-Energy-Centric Approaches to Co-Location

In addition to vegetation-centric and energy-centric approaches to co-location of solar energy developments and vegetation, there are also hybrid approaches that seek to integrate both energy output and vegetation production goals. These types of approaches are characterized by incorporating both vegetation and energy priorities into system designs. Such integrated approaches could potentially result in lower vegetation productivity or energy output than could be achieved without co-location, but provide additional benefits, including diversity of revenue streams, that make co-location activities desirable. There are a variety of opportunities to encourage both vegetation growth and solar energy production without major changes to system designs, though some integrated systems may involve alternative designs. Integrated energy and vegetation co-location activities could be suitable in areas with existing activities as well as in areas with unutilized land, in agricultural areas that are growing short or tall crops, and could provide an additional income stream or other benefits.

3.3.1 Examples of Integrated Vegetation-Energy-Centric Approaches to Co-Location

A hybrid approach may involve changes to production methods for both vegetation and solar energy, ranging from substantial design changes to small changes. Developers, through choosing strategic locations, can reduce environmental and vegetation impacts of solar installations without substantial changes to panel density, height, and other design configurations. As an example, Roberts (2011) analyzed the potential for PV installation in the non-irrigated corners of center pivot irrigation fields in Colorado (Roberts 2011) (Figure 4).

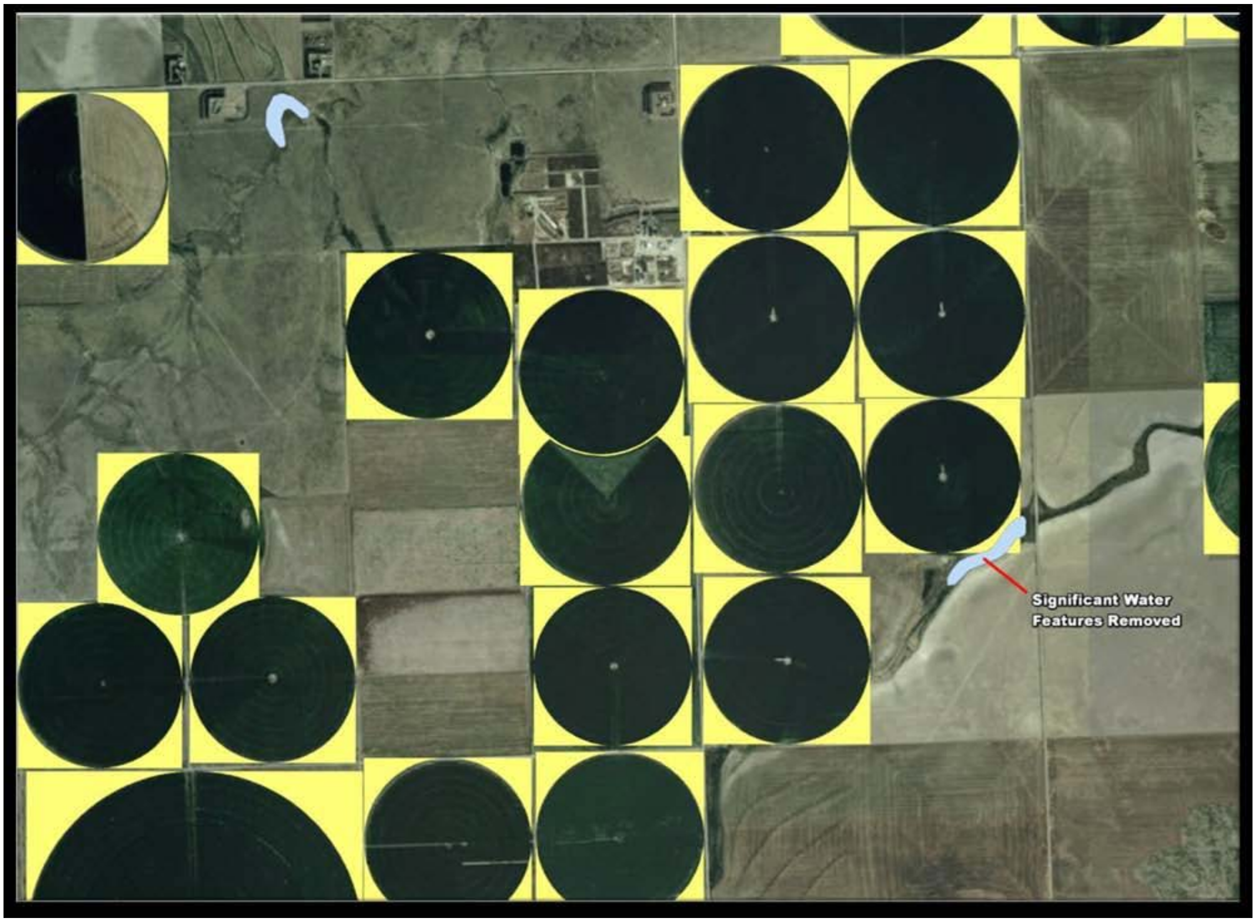

Figure 4. Center-pivot irrigation envelopes with irrigated lands. Yellow areas show unused and non-irrigated lands that could be sites for solar energy technologies (Roberts 2011)

Installing PV in the non-utilized corners of Colorado's agricultural areas could produce approximately 56,821 GWh of electricity each year, which is larger than Colorado's electricity demand in 2010 (Roberts 2011; EIA 2012). This highlights the vast area of currently unutilized agricultural land, much of which could be used to produce solar energy without affecting agricultural production. Producing electricity on these unutilized agricultural lands would not require significant changes to PV system designs, other than restricting siting locations. Further work is needed to characterize the impact solar installations would have on agriculture output, along with operations and maintenance (O&M) issues that would need to be addressed. In addition, further research is required to understand how impacts of agricultural activities and machinery (e.g., dust, irrigation mist, machinery transportation) might affect solar energy generation.

3.4 Summary of Opportunities for Co-Location of Solar Energy and Vegetation by Land-Use Type

Energy-centric, vegetation-centric, and integrated vegetation-energy-centric approaches to co-location can be implemented in a variety of locations, yet due to different land areas, existing vegetation type, and desired vegetation type, one approach may be more appropriate in a certain location than another. Table 1 highlights opportunities for co-location approaches based on different land use types.

Table 1. Opportunities for Co-Location of Solar Energy and Vegetation by Land-Use Type

Land-Use Types	Co-Location Opportunities
Grazing/unused/ scrub/desert land	Energy Centric: - Leave vegetation intact - Plant short shade-tolerant crops
	Vegetation Centric: - Leave vegetation intact - Plant mix of sun-loving and shade-tolerant crops - Elevate solar infrastructure - Space out solar infrastructure - Continue/initiate grazing activities
	Integrated Vegetation-Energy Centric: - Leave vegetation intact - Plant short shade-tolerant crops - Elevate solar infrastructure - Continue/initiate grazing activities
Agriculture (short crops)	Energy Centric: - Plant short shade-tolerant crops beneath and around solar infrastructure
	Vegetation Centric: - Plant mix of sun-loving and shade-tolerant crops - Elevate solar infrastructure - Space out solar infrastructure
	Integrated Vegetation-Energy Centric: - Plant mix of sun-loving and shade-tolerant crops - Elevate solar infrastructure
Agriculture (tall crops)	Energy Centric: - Limited options
	Vegetation Centric: - Elevate solar infrastructure - Space out solar infrastructure - Plant mix of sun-loving and shade-tolerant crops
	Integrated Vegetation-Energy Centric: - Place solar infrastructure in non-utilized parts of agriculture land - Elevate solar infrastructure

4 Benefits of Co-Location of Solar Energy and Vegetation

Co-location of solar energy and vegetation can provide benefits to both solar developers as well as land managers, including farmers and ranchers. From a solar developer's perspective, integrating vegetation into project design may not seem to be relevant or within the scope of common solar industry practices. Similarly, from a land manager's perspective, solar energy technologies may not seem to be compatible with existing agricultural or other land-use activities. However, there can be substantial benefits associated with co-location for solar projects as well as agricultural projects.

4.1 Benefits to Solar Energy Projects

Early results from the examples above indicate that there can potentially be cost and/or performance benefits for solar projects that have integrated vegetation for site preparation, operational, and environmental mitigation activities.

Site preparation methods that preserve native vegetation beneath solar technologies and do not grade land may have lower installation costs than standard site preparation activities that require heavy machinery and labor to remove vegetation and grade land, although there might be additional costs incurred from installing on ground having slopes greater than 1–5%. Installation costs may also vary for co-location depending on whether existing vegetation could remain or new low-height native vegetation would have to be planted. More research could help quantify benefits for specific locations and solar system configurations.

Operational costs could also be lower for solar energy systems with integrated vegetation. Under current practices with no vegetation, labor is required for weeding in de-vegetated areas as well as dust suppression on gravel covered areas. Vegetation beneath the solar installation, if a proper height, would eliminate the need for dust suppression. Depending on local conditions and vegetation type, however, there could be some additional costs for height maintenance of vegetation.

Many solar projects have been subject to environmental litigation due to perceived impacts on the environment (Glicksman 2011). By preserving or replanting native vegetation under a solar installation, solar developers might also reduce the likelihood of environmental litigation and potentially reduce the need for some environmental mitigation options, such as purchasing additional conservation land. Early collaboration between developers and environmental scientists can serve to increase stakeholders' understanding of the potential impacts of a solar installation, and might allow for design modifications to meet stakeholder needs early in the planning and development process.

In addition, PV panels show increased performance under cooler temperatures (Skoplaki and Palyvos 2009). There is a potential for increased efficiencies and longevity of PV panels due to the microclimatic cooling effects that vegetation provides underneath the panels (Shashua-Bar et al. 2006). Verifying or quantifying this potential requires additional study.

4.2 Benefits to Land-Use Activities and Agriculture

Co-location of solar installations and vegetation also has the potential to benefit agricultural areas, especially those where continuing agricultural production is a high priority.

Incorporating solar technologies on existing grazing or agricultural land could provide an additional income stream to land owners and provide diversification of revenue for years when agricultural productivity is low or for crops that are relatively low value. Similar benefits have been demonstrated with wind developments on agricultural lands (Holmes and Papay 2011; Beckman and Xiarchos 2013). Depending on solar installation height and spacing, crops that are shade tolerant and low height may become suitable for production in an area, opening new markets for agricultural producers. In some cases, shade from solar infrastructure may reduce crop productivity. In a pasture landscape, elevated solar infrastructure could provide shade and cover for livestock while not having a substantial impact on productivity. Agricultural activities involving large machinery may have limited options for co-location.

Incorporating elevated solar installation technologies above existing agricultural production land would allow for the continuation of agricultural activities on parcels of land, particularly if the solar infrastructure is elevated enough that the amount of light reaching the crops is not substantially reduced. Such modifications might be an important consideration in areas that have a long history of agriculture and where changes to land-use practices may encounter social opposition. Further study is necessary to determine cost and structural impacts of elevated solar infrastructure.

In regions where critical habitat has been lost and where legally defined special status flora and fauna have been identified, improving natural vegetative land can help restore critical habitat endangered by previous agricultural activities and solar construction activities, helping to proactively address environmental regulations (Althouse and Meade 2011).

5 Discussion

The co-location of solar energy facilities and vegetation can take a variety of forms that can have minimal to large impacts on solar energy and vegetation standard practices. At one extreme, solar energy installations, without modifying existing site preparation activities, can incorporate low-lying vegetation underneath the installation to mitigate environmental impacts. At the other extreme, certain agricultural areas can incorporate solar energy technologies in ways that preserve crop production or harvesting techniques but provide an additional source of electricity. In between, there are a variety of options for solar energy developers and vegetation producers to modify system designs to allow for greater levels of integration. In this emerging field, future research is required to provide greater clarity on potential benefits and tradeoffs.

The benefits of co-location can be analyzed in the context of projected electricity and food requirements for the United States and for the world as a whole. Electricity demands are projected to increase, with renewable energy technologies likely to provide much of the new electricity generation. Certain renewable energy technologies, such as solar PV and concentrating solar power (CSP) technologies, can require larger amounts of land per unit of electricity produced, as compared with other non-renewable technologies. Meanwhile, an increasing population requires an increasing level of food production, and absent substantial changes in crop productivity, increasing areas of land to provide that food. Given the likelihood of large-scale solar development and the current solar industry practice of single use of land, large areas could be affected by PV and CSP systems, which could have an impact on agriculture and/or ecologically sensitive habitats in certain areas. Not every area will face similar land shortages or land conversion issues, but there is a potential for confrontations over best uses of land. There also is the opportunity to avoid these conflicts through smart siting and system configuration decisions made by integrating vegetation and energy production activities.

Re-vegetating land underneath a solar installation can prevent the loss of soil carbon fixation capacity and wildlife habitat. By incorporating some degree of vegetation growth or agriculture in large-scale solar facilities, developers can reduce their environmental impact (and potentially vulnerability to litigation), often while not sacrificing electricity generation. Agricultural operations incorporating solar energy technologies can preserve land currently being used for agricultural purposes, generate additional income streams, and provide a renewable source of electricity for the electricity grid or their facility.

Additional research could help quantify potential benefits and costs associated with different levels and types of co-location. Quantification of benefits and costs could allow solar developers and land managers to make more informed decisions regarding co-location and what options provide advantages over others. As a first step, the examples of co-location projects listed above could be replicated in multiple regions, with rigorous monitoring of results, to better understand regional differences in vegetation productivity and the economics of the solar production. For example, the methods and treatments utilized in the NREL study can readily be adapted and replicated in PV facilities under development (Beatty et al. 2012).

For energy-centric approaches, research could help better understand how different system configurations impact cost and performance of the solar energy installation, how temperature changes may impact long-term efficiency and technology lifetime, the O&M cost differences associated with co-location and standard practices, the impacts of vegetation on dust levels and associated system performance, ideal plant species that could thrive under solar infrastructure, and the differences in construction costs associated with co-location options and standard practices.

Regarding vegetation-centric approaches, future research could illuminate how different solar technology configurations (height, spacing of technologies) cast shade and how that affects crop productivity, the effects of soil moisture variability under large-scale solar installations, the ideal crops suitable for different regions under differing levels of shade, the amount of carbon sequestration that may occur by using vegetation rather than gravel beneath solar installations, the potential for bioenergy crops to be grown and harvested under different conditions, and the differences in construction costs. In addition, the effect of solar installations on maintaining or enhancing local biodiversity is also a viable area of future study.

To best understand tradeoffs and other opportunities associated with integrated vegetation-energy-centric approaches, the above research priorities could be addressed in tandem by multi-disciplinary teams in a variety of configurations. Although much of the prior research has been conducted on PV systems, CSP systems could also be targeted for co-location studies. The quantitative data developed from carrying out such research activities would allow solar developers and land managers to weigh different levels of integration of solar and vegetation activities. Such work could also be improved by the unified support of U.S. Department of Agriculture, DOE, and the U.S. Department of the Interior, all of which have a role in the development of solar energy in the United States. In many cases, solar developers may not have expertise in vegetation management. Similarly, in many cases agricultural land managers may not have expertise in energy development. By recognizing the opportunities to develop renewable electricity resources while strengthening the nation’s agricultural sector, the agencies working collaboratively could help alleviate the initial reluctance of each sector to explore co-location opportunities.

An increased understanding of environmental impacts of solar facilities along with effective means to mitigate impacts can help improve the sustainability of renewable energy systems with respect to a range of metrics that include GHG, other environmental, and social perspectives.

6 Summary

Projected solar development could have impacts on local habitats as well as on land currently being utilized for agriculture. Co-locating agriculture or supporting non-invasive vegetative growth beneath large-scale solar developments provides an opportunity to mitigate potential environmental and social impacts. This work reviewed existing studies of potential land-use impacts of solar facilities and described current site preparation practices for solar developments. We discussed co-location opportunities and categorized into vegetation-centric, energy-centric, and integrated vegetation-energy-centric approaches, along with a qualitative discussion of the potential benefits associated with those approaches. Lastly, we discussed the future research that could provide quantitative information that would allow solar developers and land managers to make informed decisions regarding co-location opportunities. Future work in this area could benefit from coordinated efforts by both the energy and agriculture sectors.

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