A comparison of tools for assessing ecosystem service trade-offs in ground-mounted photovoltaic system decisions

Sub-Task 6.1 (Milestone 1.6)

Amy Waananen[1], Aaron Hanson[1], Nathaniel Springer[1]

[1]Institute on the Environment, University of Minnesota - Twin Cities

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Deploying Solar with Wildlife and Ecosystem Services Benefits funding program, award number DE-EE0010385.

Summary

As the transition to renewable energy accelerates, decisions about solar land use and management increasingly impact ecosystem services, including water quality, soil health, biodiversity, cultural values, and energy provision. Researchers, developers, advocacy groups, and policymakers have developed a variety of tools and resources to predict ecosystem services or integrate such considerations into decision-making processes. However, these resources vary in the spatial scale they address, their context-specificity, and their basis of evidence (e.g., data, models, principles), making it challenging for stakeholders to determine which resources might be appropriate for their specific contexts. This report reviews prominent tools and frameworks for ecosystem service evaluation in ground-mounted photovoltaics, including tools designed to calculate or estimate ecosystem services (InVEST, PV-SMaRT) and decision-support resources (AFT Smart Solar, scorecards, GIS-based multicriteria evaluation analyses). We summarize their key characteristics and the contexts in which they are most applicable. Significant gaps remain, particularly in quantifying and integrating cultural ecosystem services. To address these challenges, we propose the development of meta-tools and outline design features to enhance tool selection and integrative analyses for ecosystem services in solar land use planning.

Table of Contents

Background

Reaching sustainable energy production goals in the U.S. will require a substantial increase in the footprint of ground-mounted photovoltaics (PV) on the landscape[1], a transition that has already begun. This expansion has implications for ecosystem goods and services, or the benefits that people derive from nature through provisioning of products (e.g., food, fiber, medicines), regulation of natural processes (e.g., nutrient and water cycling), and cultural connections[2]. However, ecosystem service trade-offs of land use change are often context-dependent and may be difficult to quantify. For instance, early studies of the impact of solar farms on ecosystem services emphasized negative impacts of development in intact ecosystems, especially in the North American Southwest[3,4]. More recently, studies and reviews have introduced the concepts of agrivoltaics[5,6] and ecovoltaics[7], which emphasize the potential for ground-mounted PV facilities to provide environmental and agricultural co-benefits, including enhanced soil carbon storage[8], water quality[9–11], or pollinator habitat[12,13], at least in comparison to intensive agriculture. Cultural benefits that people derive from landscapes, such as sense of place, agency, and local identity, are often intangible and difficult to distill into simple metrics[14–16].

Lacking generalizable conclusions about the impact of ground-mounted PV facilities on ecosystem services, decision-makers require tools and resources to evaluate and integrate across multiple ecosystem service impacts in their specific contexts. Interest in ecosystem service assessments in solar decision making aligns with broader recognition of the multifaceted values of ecosystem services in numerous sectors and contexts. To meet demands to quantify and value ecosystem services, tools to measure, model, and predict ecosystem services have proliferated. While some tools and resources are specific to solar, many are designed for more general use. As a result, there is an emerging need for guidance about which resources are appropriate for solar-related decision-making. Available tools and resources vary in many key dimensions: the scale they address, degree of generalizability, basis of evidence, software requirements, quantitativeness, and the extent to which a decision-making process is embedded in the tool itself (Table 2). The broad suite of options that are available to decision-makers can lead to confusion and hinder uptake.

The goal of this assessment is to provide an overview of the tools available for integrating ecosystem service considerations in decision-making processes surrounding solar site siting, construction, and management. We aim to clarify the differences between tools and discuss use cases that may be appropriate for different stakeholders or decision-makers. For example, relevant decision-makers include solar developers, state regulatory agencies, and potential host communities, groups which have divergent questions and priorities. We focus on ecosystem services related to five key issues (Table 1): water quality, soil health, habitat provisioning, aesthetics and cultural values, and energy provisioning. These issues relate to a wider range of ecosystem goods and services, which may contribute to one or more issues.

Table 1. Summary of solar-related ecosystem services and associated resources related to broad biophysical and social outcomes. For each ecosystem good and service, indicators are listed in parentheses.

Biophysical or Social Outcome	**Ecosystem Goods and Services (Indicators in Parentheses)**	**Resources**
Access to clean water	Water quality maintenance (nutrient runoff and sedimentation); water provisioning (quickflow, local recharge, and baseflow).	InVEST PV-SMaRT SPIES Scorecards GIS-Based Siting Analyses SWAT
Healthy soils	Carbon storage and sequestration (above and belowground biomass, soil organic matter); soil function (physical: bulk density, compaction, porosity, biological: microbial biomass C and N, particulate organic matter, potentially mineralizable N, soil enzymes, soil respiration, and total organic carbon; chemical: electrical conductivity, reactive carbon, soil nitrate, soil pH, and extractable phosphorus and potassium).	InVEST PV-SMaRT SPIES AFT Smart Solar Scorecards DayCent
Biodiversity and ecological function	Habitat for pollinators (pollinator abundance[17]; floral diversity and abundance; temporal availability of floral resources), wildlife (wildlife abundance or occupancy), natural enemies (abundance or occupancy, pest control in neighboring fields); maintenance of dispersal and migration corridors (space usage, presence or absence of barriers to movement[18]).	InVEST SPIES Scorecards GIS-Based Siting Analyses
Cultural values and use of landscapes	Recreation (proximity to parks, natural areas, and water features[19,20], abundance of geotagged photos[21,22]); sense of place (place-specific descriptive language[23]); agency (participation in decision-making processes); access to culturally important species and traditional foodways (proximity to hunting and gathering areas; population viability of cultural species; biodiversity).	InVEST Smart Solar Scorecards GIS-Based Siting Analyses InSPIRE Financial Calculator
Provisioning of products	Energy production (power production, irradiance, performance ratio); food production	GIS-Based Siting Analyses SAM

Box 1. Description of tool attributes.

Quantitative or Qualitative: Whether the tool reports quantitative outputs (e.g., predicted nutrient delivery rates) or qualitative outputs (e.g., written guidelines or principles).

Software: Whether the tool requires software and what the software requirements are.

Scalability: The spatial scale at which the tool can be applied. Site-level tools address ecosystem service considerations within a site (e.g., how within-site construction practices influence soil properties and nutrient runoff), while landscape-level tools address across-site considerations (e.g., how solar siting decisions influences water quality in the watershed).

Solar Specific: The degree to which the tool was designed or has been parameterized for application in ground-mounted PV sites. This review focuses on resources that are solar specific and one prominent general ecosystem service tool (InVEST) that has been applied in solar-specific use cases. Comparative assessments for general ecosystem service tools (e.g., ARIES, Ecosystem Valuation Toolkit, Co$ting Nature) and assessment approaches are available elsewhere [24–27].

Action Oriented: Whether the tool explicitly provides guidance on actions that influence ecosystem services or not. Other tools are more information-oriented, providing data or predictions rather than recommendations for specific actions. To be clear, all of the tools listed in this guide are designed to inform decisions about actions. However, some require users to define scenarios (e.g., simulations with different land use types) to identify trade-offs in ecosystem services related to actions; we identify these as not specifically action oriented.

Prioritization: Whether the tool is or can be aligned with priorities or values in using the tool. Some tools are explicitly based on specific values (i.e., AFT Smart Solar) while others provide users options to identify priorities. The degree to which prioritization occurs in the use of the tool may depend on the specifics of the decision process within which the tool is being used.

Spatial: Whether the inputs to the tool have explicit spatial locations and the tool accounts for the effects of spatial heterogeneity ('explicit'), whether the model accounts for spatial variation implicitly through the inclusion of inputs that vary across space ('implicit'), or are non-spatial.

Decision Process Inherent: To what extent the tool encompasses a decision-making process.

Table 2. Description of ecosystem service tools highlighted in this review and their attributes (see Box 1 for attribute descriptions). The acronym ES refers to ecosystem services. All of these resources have been applied in the context of ground-mounted solar facilities; see Box 1 for further details of tool attributes.

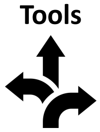
Tool Name	Description	Quantitative or Qualitative	Software	Scalability	Solar Specific	Action Oriented	Prioritization	Spatial	Decision Process Inherent
InVEST	Spatial models for multiple ES	Quantitative	GIS software or InVEST Workbench	Site or Landscape	No	No	No	Explicit	No, users must define and develop integration with decision-making.
PV-SMaRT	Model for stormwater runoff at solar sites	Quantitative	Spreadsheet calculator download	Site	Yes	No	No	Implicit	No, though tailored to inform permitting decisions. Users define how output informs decision-making.
SPIES	Literature synthesis of management decisions in relation to ES	Qualitative	Online software	Site	Yes	Yes	Yes	Not Spatial	No, users must define and develop a process for decision-making.
AFT Smart Solar	Solar development guidance based on principles of preserving farmland	Qualitative	None	Site or Landscape	Yes	Yes	Yes	Not Spatial	Yes, the tool is designed to fit in existing processes.
Solar Scorecards	Assessment tool, possibly for multiple ES	Qualitative	None	Site	Yes	No	Possible	Usually Not Spatial	Yes, designed to fit in existing decision-making processes.
GIS-Based Siting Analyses	Map-based analyses for solar siting	Quantitative	GIS Software	Landscape	Yes	No	Possible	Explicit	Possibly, depending on the approach to layer selection and analysis.

Overview of Ecosystem Service Tools and Resources

"Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful." - George Box

To describe differences in goals and uses for tools for measuring and assessing ecosystem services, we use the broad categories of calculators, estimators, and decision-support tools (Table 3). Generally, the difference between calculators and estimators reflects a trade-off between model precision and generality. Models that more precisely represent reality in a given place and time are often less generalizable, and vice versa—both approaches can be useful for different questions and needs. Similarly, decision-support tools provide features to support evaluating alternative options. While other studies have compared general or biodiversity-focused ecosystem service tools and resources[24–26], these assessments have not addressed tools specifically for use in ground-mounted PV facilities. Our overview focuses on several prominent tools and resources for evaluating ecosystem services in the context of solar land use decisions. We do not review every possible tool, but rather highlight examples spanning a range of goals and approaches reflected in resources that are available today.

Table 3. Categories of ecosystem service modelling approaches.

	Description	Examples
"Tier 3" **Calculators** 	These models involve relatively high levels of detail, often relying on a combination of sampling and modeling to yield precise and accurate results. These models are referred to as a "Tier 3" model under the IUCN Ecosystem Service tool framework and we adopt this terminology here. Because results are tuned to detailed aspects of the environment, the results of these models are usually applied at smaller scales (i.e., site-level) and may not generalizable to the broader landscape.	SWAT, PV-SMaRT
Landscape-Scale **Estimators** 	The goal of estimator-type models is to estimate ecosystem service delivery and how it is impacted by decisions at broad scales, rather than to calculate it precisely. Thus, these tools are typically applied at a larger spatial scale (i.e., have higher generality) with lower accuracy and precision than calculator-type models. These models may also be appropriate at small scales when data is not available to support the use of a calculator-type approach or if high precision is not necessary.	InVEST and other GIS Siting Analyses
Decision-Support Tools 	These tools are more closely integrated with a decision process, e.g., evaluating trade-offs between alternative management techniques. Such tools often help with making values, beliefs, and preferences explicit and clarifying how these relate to alternative options being considered.	SPIES, Solar Scorecard, AFT Smart Solar

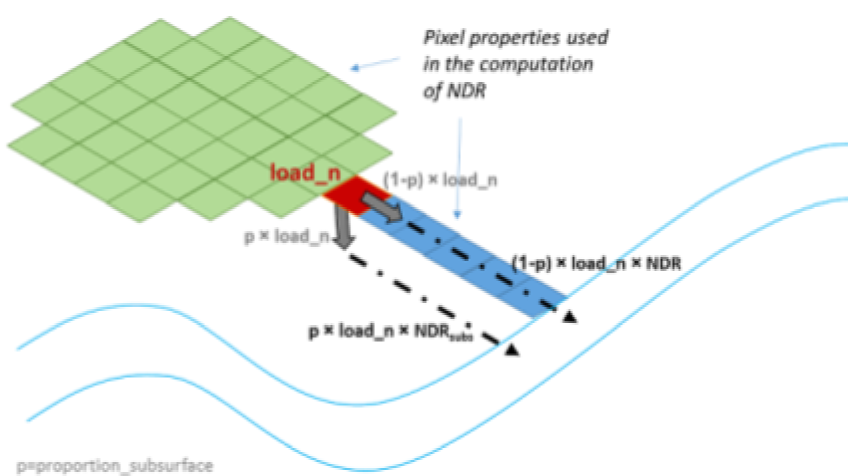
InVEST

One of the most common approaches to ecosystem service modeling is using the InVEST® (Integrated Valuation of Ecosystem Services and Trade-Offs) platform[28]. The InVEST modeling suite, a free and open-source data and software platform, has been widely used to model a wide range of ecosystem services (see Table 1) in over 60 countries and at local, national, and global scales[17,29–31]. Although the level of complexity, data requirements, and parameterization vary among tools for each ecosystem service in InVEST, InVEST models are generally spatially explicit and designed to be widely applicable and potentially linked to economic valuation. InVEST models tend to be relatively simple, process-based models that require input landscape scale data inputs that are widely available for different geographies, such as land use, topography, or soil type.

InVEST offers four modules that provide insights related to water and water quality: (1) annual and (2) seasonal water yield, (3) water purification, and (4) sediment retention. The seasonal water yield model estimates the amount of water delivered by a watershed into streams over the course of a year. For soil health, InVEST offers modules to estimate sediment retention and carbon storage. There is a habitat quality module, which could be used to estimate impacts of land use conversion on biodiversity and conservation. The InVEST platform does not currently provide tools designed specifically for solar land use, however, it is possible to adjust the parameters of InVEST models to do this[17]. In Walston et al., for example, the effect of conversion of agricultural land use to solar was modeled by flipping land use from row crop agriculture to either herbaceous ground cover or turfgrass, representing different solar vegetation management alternatives. These modifications may not capture all relevant details necessary to represent a ground-mounted PV facility—for instance, soil compaction. However, the models may be adequate depending on the specific analysis needs, especially if relevant services are relatively unaffected by details not included in the models.

InVEST
Integrated Valuation of Ecosystem Services and Tradeoffs

Figure 1. Conceptual representation of the InVEST nutrient delivery model. The load on each pixel, load_n, is divided into two parts, and the total nutrient export is the sum of the surface and subsurface contributions. From the InVEST User Guide.



The InVEST platform provides two modules that relate to cultural values and services: scenic quality and recreation. The scenic quality module assesses the visual impact of coastal development and thus, at present, is not widely applicable for solar decision spaces. However, with substantial adaptation this tool might offer a valuable resource for understanding the aesthetic impact of ground-mounted PV facilities, especially in flat landscapes where the model assumptions about visibility over water could be met sufficiently. The recreation module uses visitation data derived from geotagged posts on flickr to associate land use type with recreational visits. Thus, this module could be applicable to solar siting decisions. However, it seems unlikely that impacts on recreation would be a major consideration, because sites used for recreational activities are rarely considered for the development of ground-mounted PV facilities, and ground-mounted PV facilities are generally inaccessible for recreation. Nevertheless, if this were the case, the InVEST recreation module would provide a resource to quantify the impacts of solar development on recreational activities.

Service-Specific Calculators (e.g., PV-SMaRT, SWAT)

Ecosystem service-specific "calculators" (Table 3) are highly parameterized models that provide precise results suitable for use cases where quantitative predictions are required, such as in environmental regulatory processes. Decisions about whether to use specific and fine-tuned models or a coarser but more general ecosystem service modelling approach will likely depend on whether additional a broader suite of ecosystem services are of interest, whether sufficient data are available, and the time or degree of expertise required to use or interpret results[32]. Relevant examples of service-specific calculators which have been applied in the context of ground-mounted PV facilities include PV-SMaRT and SWAT.

The Photovoltaic Stormwater Management Research and Testing (PV-SMaRT) Solar Farm Runoff Calculator[33] is a specialized, spreadsheet-based tool designed to estimate the effects of ground-mounted PV facilities on overland stormwater run-off of C and N, accounting for the effects of a variety of site conditions. The model was developed based on empirical research at ground-mounted PV facilities located across the U.S. (Colorado, Georgia, Minnesota, New York, and Oregon). These facilities represented a cross-section of key site parameters such as ground cover (e.g., both turfgrass and perennial vegetation), array type, and panel arrangement (see Table 2 in Ref. 16). In the absence of alternative models, many jurisdictions classify ground-mounted PV facilities as impervious surfaces for stormwater regulation purposes. Thus, estimates were derived from models developed for context such as parking lots. The PV-SMaRT calculator implements models that captures the hydrologic impact of solar panels and their arrangement, soil and topographic characteristics (soil texture, soil depth, soil bulk density, slope), ground cover (row crop, turf, pollinator habitat, etc) and climatic factors (precipitation). PV-SMaRT's decision-relevance stems from its ability to inform regulatory decisions (i.e., the need for quantitative runoff predictions) as well as to predict how site management decisions, about ground cover, in particular, would influence runoff outcomes. Thus, it not only calculates measures related to water quality, it can also be used to inform actions. Given the specialized nature of the PV-SMaRT calculator, the calculator can provide insights about ecosystem services related to water quality and soil health only.

Soil Texture	Clay Loam
Soil Depth (inches)	36
Bulk Density (g/cm^3)	1.4
Vegetation Present	Newly Established Pollinator
Are Solar Panels Present?	YES
Panel Width (feet)	10
Panel Spacing (feet)	25
Array Orientation	Follows slope contours
Percent Slope	5

BLUE CELLS REQUIRE USER INPUT

MAROON CELLS REPRESENT TOOL OUTPUTS

Runoff Curve Number	66.0
24-Hr Precip Event (inches)	10.00
Expected Runoff (inches)	5.70

Figure 2. The user interface for the PV-SMaRT Solar Farm Runoff Calculator. The calculator is spreadsheet based and can be used within familiar platforms such as Microsoft Excel.

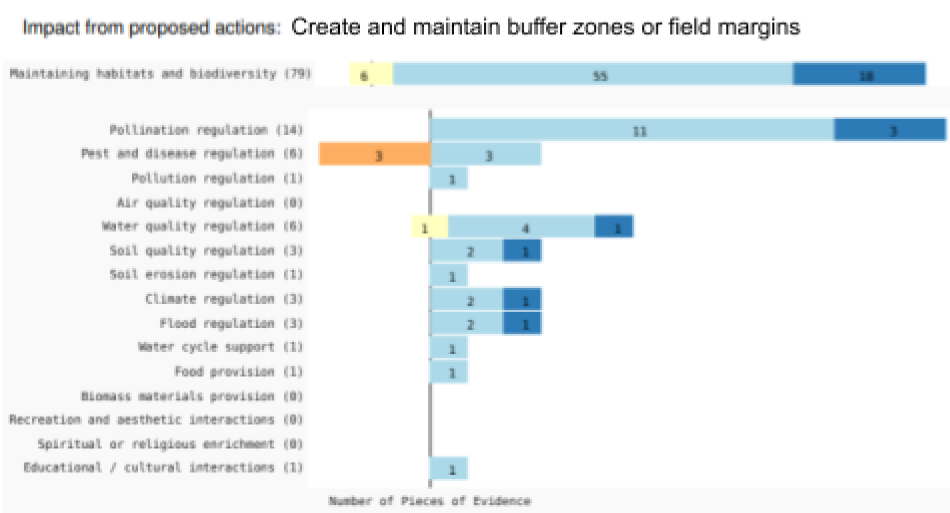
An objective of the PV-SuCCESS project (of which this report is a component) is to use field data collection to calibrate and validate a Hydrus 3D runoff and infiltration model and incorporate this new model into the existing PV-SMaRT calculator. This model will improve upon PV-SMaRT by adding capabilities to model belowground runoff flow. Similarly, the updated PV-SMaRT runoff calculator, will be used to calibrate and validate the InVEST Sediment Retention model and the Carbon Sequestration model to measure the impact of ground-mounted solar facilities on soil health and soil carbon, respectively. Currently, the InVEST models are less detailed, and provide less utility for making predictions, than the PV-SMaRT and Hydrus 3D model currently and will provide. The result will be an InVEST model that can assess soil health and soil carbon with field level granularity while enabling scaling to the broader landscape. This is an example of how “calculator” and “estimator” approaches can be integrated.

Similarly, the Soil & Water Assessment Tool (SWAT) is a medium- to large-scale (i.e., small watershed to river basin-scale) model that simulates the quality and quantity of surface and groundwater based on detailed models of hydrological processes and data, as available, about the soil and landscape. The SWAT model can be used to predict the environmental impact of land use, land management practices, and climate change. The SWAT tool is commonly used to assess soil erosion prevention and control, non-point source pollution control and regional management in watersheds, and has been applied in the context of ground-mounted PV facilities in two instances.

Solar Parks Impacts on Ecosystem Services (SPIES) Decision Support Tool

The SPIES Decision Support Tool provides a framework for relating management choices within ground-mounted PV facilities to effects on ecosystem services. The basis of evidence for this framework is a systematic literature review, encompassing studies in both solar and non-solar contexts. In this review, the SPIES developers created a database of studies reporting positive, negative, or neutral associations between management-related variables (i.e., increasing grazing intensity) and ecosystem service-related indicators. The DST presents this information in an interface which prompts users to select either management choices or ecosystem services of interest. If one or a set of management choices are selected, the tool will return a summary of the evidence for ecosystem service impacts: the number of studies reporting a positive, neutral, or negative effect and whether the inference from the study was strong or weak. In the same way, if the user selects one or more ecosystem services of interest, the tool will return a summary of evidence for association with different management choices. As it is focused on management choices, the framework generally provides decision support at the site, rather than landscape, level.

The SPIES decision support tool provides literature synthesis about how management actions in solar facilities may influence ecosystem services related to water quality, soil health, habitat provisioning, and cultural values. For example, the tool reports that water quality regulation can be linked to several management actions: reducing grazing intensity (eight studies indicate positive effects on water quality, one showed neutral effects), creating or maintaining buffer zones (one study found strongly positive effects, four studies indicated positive effects, and one showed neutral effects), among others actions. Similarly, the tool offered options for ecosystem services related to soil health (soil erosion regulation and soil quality regulation), habitat provisioning, and cultural values (educational/cultural interactions, recreation and aesthetic interactions, spiritual and religious enrichment).



SPIES

Figure 3. Sample summary report output from SPIES, summarizing evidence (horizontal bars) for how a proposed action (creating and maintaining buffer zones or field margins) would impact ecosystem services, listed vertically.

In using SPIES for decision support, it is important to note that the amount and quality of evidence linking services to management actions varies widely. The synthesis reflects the over- and underrepresentation of certain management actions and ecosystem services in the literature. Evidence will also reflect biases in publication practices, including overreporting of positive results and overrepresentation of studies from the global north. Furthermore, while the tool was designed to provide insights relevant to ground-mounted PV facilities, and the management choices are limited to the set of options that are feasible within that context (e.g., no prescribed burning), the evidence base is broad and mostly was not derived from studies within ground-mounted PV facilities.

American Farmland Trust's Smart Solar

The American Farmland Trust's Smart Solar decision support tool consists of a set of principles and policy recommendations developed with the goal of ensuring that ground-mounted PV facilities strengthen U.S. farm viability and preserve agricultural land. The core goals upon which the Smart Solar recommendations are made are "(1) safeguarding land well-suited for farming and ranching, (2) strengthening farm viability, and (3) accelerating solar energy development." Based on these guiding principles, the Smart Solar recommendations seek to minimize conflict between solar land use and agriculture. The qualitative recommendations provided by the Smart Solar framework address both the landscape level—where to locate ground mounted PV facilities in alignment with the core goals—and the site level—how to manage ground mounted PV facilities to preserve future utility for farmland. The guidelines are specific to decision making around PV land use. The guidelines will also be broadly applicable to a wide range of stakeholders whose interests are aligned with the core goals (policy-makers and the national, state, or local levels; community members; solar developers). As demonstrated by several Smart Solar case studies across the U.S., these guidelines can be applied across geographies where farmland is culturally valued.

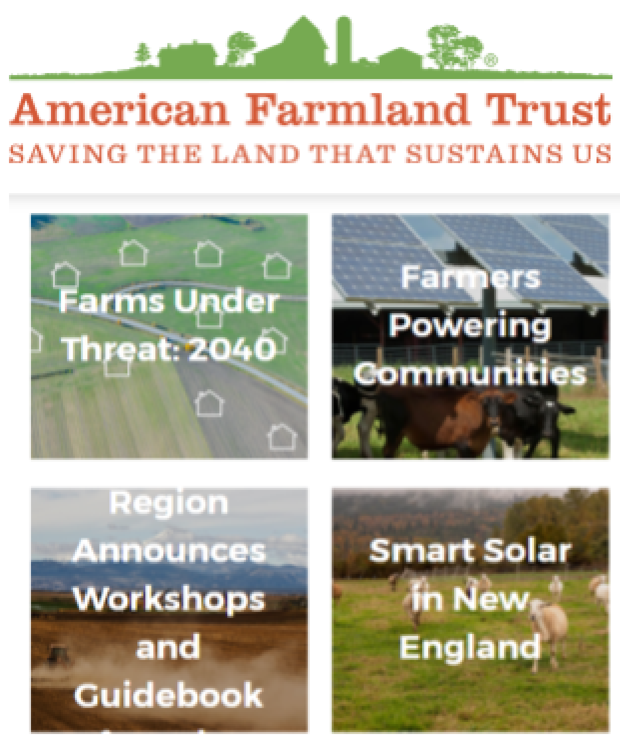


Figure 4. AFT Smart Solar: example projects and resources (see https://farmland.org/solar/).

Smart Solar addresses ecosystem services related to water quality, soil health, and cultural values related to preserving farmland viability and access. Rather than serving as an approach to measure or quantify services, the tool focuses on recommendations for actions to promote them. For example, the case studies developed based on Smart Solar principles provide recommendations for practices during construction, operation, and decommissioning to maintain soil health, soil productivity, and future access to water rights. Cultural valuation of farmland is embedded within the core goals that are the foundation of Smart Solar. Given the specific perspective of this tool, other cultural values are not considered. Energy provisioning is not addressed directly, but recommendations of policies that incentivize energy efficiency imply that trade-offs with energy provisioning should be considered.

Scorecard-Based Tools

Scorecards (or 'balanced scorecards') are a common decision-support tool used in a wide range of sectors and contexts[34]. Scorecards are designed to provide users with a rubric to evaluate multiple criteria of interest quantitatively (e.g., with points) or qualitatively (e.g., high, medium, or low). Following the publication of pollinator scorecards for Minnesota and Vermont in 2016, scorecards have emerged as a popular tool for habitat- or pollinator-friendly solar programs that offer regulatory or financial incentives for site-level management plans that promote and enhance pollinator habitat[35]. Indicators of plant diversity and use of insecticides often correspond to the bulk of the points available on such scorecards (often 60% for plant diversity and 30% related to insecticides). The scorecards have been developed on a state-by-state basis, often reflecting modest adaptations from early scorecard examples (Minnesota, Vermont, Michigan). A recent analysis conducted by the independent non-profit Electric Power Research Institute criticized existing pollinator-friendly solar scorecards as representing a concerning lack of "rigor, consistency and oversight"[36]. For example, whether distribution of points among different categories in a scorecard corresponds with habitat quality is unclear. Ongoing field research or integration with other, more research-based tools (e.g., PV-SMaRT) could improve the accuracy of scorecards and their ability to provide reliable representations of how ground-mounted PV facilities influence ecosystem services.

In New York, the scorecard format has also been used for more holistic assessments of environmental co-benefits of solar siting. The NYSERDA Smart Solar Siting Scorecard assigns points for criteria whether a solar site would replace sensitive or protected lands such as natural habitat and prime farmland, as well as its effects on wildlife (including pollinators), soils, and water. Projects that implement dual uses of solar with agriculture (crops or grazing) are given extra credit. Unlike some of the pollinator scorecards, the NYSERDA Smart Solar Siting Scorecard also includes criteria for operations and maintenance. Finally, the NYSERDA scorecard also includes benefits associated with hard-to-quantify aspects of cultural ecosystem services, such as agency, by including criteria related to community engagement.

Scorecard Section	Number of Points Available		Total
	Avoidance	**Minimization**	
Agricultural Protection	50	45	**95**
Forested Lands Protection	35	10	**35***
Community Benefits & Collaboration	25		**25**
Extra Credit: Innovation	5		**5**
TOTAL POINTS AVAILABLE			**160**

*Maximum of 35 points available

Figure 5. Distribution of points in the NYSERDA Smart Solar Siting Scorecard.

GIS-based Multicriteria Evaluation Analyses

Geographic Information Systems (GIS) are often used to evaluate readily available landscape-scale factors that influence siting decisions for ground-mounted PV facilities; we term approaches that fall under this broad categorization to be 'GIS-based siting analyses.' Commonly considered factors include those related to power production and efficiency (irradiance, proximity to transmission lines) and siting constraints (residential or protected areas). This flexible approach has been applied in many places globally[37–40], with specifics of the analysis varying depending on data availability and the priorities or questions of interest for each analysis. Platforms exist to make the process of combining data layers accessible without GIS skills (e.g., formerly the Solar Energy Environmental Mapper and the BLM Utility-Scale Solar Energy Development data mapper). GIS-based analyses are often used in preliminary desktop studies, i.e., a stage of gathering readily accessible information to research needs. However, the flexibility and relative simplicity of the approach also provides an opportunity for community engagement. For example, the Murray County siting project used input from community stakeholders to identify priorities, which were reflected in the variables included in the analysis and their weights (Strategic Solar Siting in Murray County, Minnesota). In this way, GIS-based analyses provide an opportunity for integration with the decision-making process.

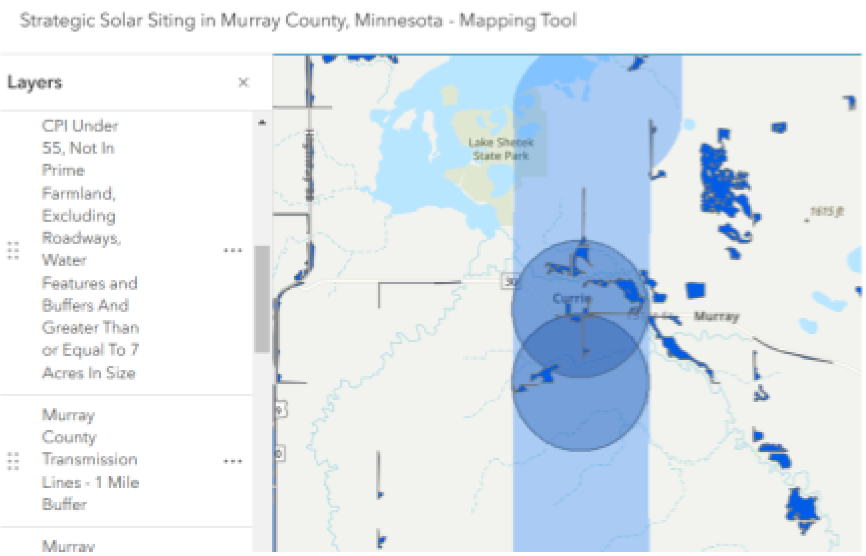


Figure 6. Example output from the Murray County Strategic Solar Siting mapping tool, showing areas of high suitability (dark blue) based on crop productivity, land use (i.e., excluding roadways and water), and proximity to transmission lines and substations (light blue).

A GIS-based siting analysis can account for many different ecosystem services, depending on the data that are available and selected consideration. Unlike the other tools discussed in this assessment, GIS-based siting analyses often explicitly consider energy production and suitability for ground-mounted PV facilities (sufficient irradiance and appropriate topography). To assess water quality, a GIS-based siting analysis could incorporate a GIS-based hydrologic model to assess the potential water quality benefits. To account for ecosystem services related to soil health, some have excluded protected soil types or assessed erodibility based on DEM (add citations). We note here that InVEST models have many similarities to GIS based siting analyses in that they are spatially explicit and often rely upon similar data sources—we distinguish between InVEST and GIS-based siting analyses here because use of one approach does not necessarily imply use of the other. However, the compatibility of scale and data type make these approaches compatible. It is common for GIS-based siting analyses to consider land use conflicts with protected areas and areas of prime farmland, reflecting cultural ecosystem service and values. Some analyses have considered overlap with areas of significance for biodiversity, such as migration corridors. Making assumptions about beneficial spillover effects of pollinator habitat, one could estimate the degree of benefit by evaluating the proximity of a PV facility to animal-pollinated crop fields (e.g., see Walston et al[12]).

Synthesis

Evaluating ecosystem services for ground-mounted photovoltaics involves diverse tools, each reflecting differences in purpose, trade-offs between precision and generality, and the state of scientific knowledge. These tools can be broadly categorized based on their focus: some emphasize quantitative calculation, while others provide guidance for decision-making. Calculation-oriented tools, such as InVEST, PV-SMaRT, GIS-based siting analyses, and scorecards, are designed to predict or assess ecosystem service indicators, often requiring technical expertise to model outcomes and weigh trade-offs. In contrast, guidance-oriented resources, such as AFT Smart Solar and SPIES, offer broader frameworks to support decisions about siting or management practices, like choosing between grazing or mowing.

While these guidance tools may be less precise, they are valuable for structuring discussions around ecosystem service trade-offs.

The accessibility of these tools varies significantly, shaped by their complexity and technical requirements. Tools like InVEST and GIS-based analyses require users to have experience with geospatial methods and access to specialized software, though advancements such as the InVEST Workbench have reduced some of these barriers. PV-SMaRT, developed in a spreadsheet format, is more user-friendly due to the widespread familiarity with Excel, making it accessible to many practitioners. Conversely, SPIES relies on a web application that can be challenging to navigate for some users, while AFT Smart Solar's written principles are easy to access but require substantial adaptation to fit specific contexts. Scorecards, which are widely used by state agencies, have proven effective for regulators and developers, indicating a balance of simplicity and utility that facilitates adoption.

The scientific rigor of these tools also varies based on their foundations. Process-based models, such as InVEST and PV-SMaRT, are informed by empirical data to varying degrees, offering precision but requiring detailed input. SPIES, by contrast, synthesizes existing literature, providing a broad but less detailed evidence base. AFT Smart Solar emphasizes guiding principles aligned with specific policy stances, prioritizing clarity over scientific specificity. These distinctions highlight the trade-offs between general applicability and precise, data-driven outputs.

Finally, the ability of these tools to integrate stakeholder input and adapt to decision-making processes is another key consideration. Some tools, like the NYSERDA solar scorecard, explicitly incorporate criteria for community engagement into their design, while SPIES prompts users to identify and prioritize specific issues or actions. Others, such as InVEST and PV-SMaRT, rely on users to define the context and assign importance to ecosystem services, making their values implicit rather than explicit. Case-specific adaptations, like Murray County's solar siting project, demonstrate how tools can be tailored to incorporate local priorities identified through community engagement. These differences underscore the importance of aligning tool characteristics with project goals, user expertise, and stakeholder needs to effectively evaluate ecosystem service trade-offs.

Designing a Framework for Navigating Tools and Processes

As this review highlights, a wide range of tools exists for evaluating ecosystem services and their trade-offs in solar land-use contexts, with more likely to emerge as the field evolves. However, the diverse needs and questions of stakeholders mean that a "one-size-fits-all" tool is unlikely to ever exist. Instead, what appears to be needed is guidance for selecting tools that align with specific contexts and integrating these tools into decision-making processes. Drawing from other fields that have addressed similar challenges, we identify several design options—summary tables, decision trees, and process + tools frameworks—that could serve as components of a meta-framework for supporting ecosystem service evaluation in ground-mounted solar facility planning.

Summary Tables

Summary tables provide a compact way to compare tools based on key attributes, such as functionality for specific ecosystem services, type of output, level of expertise required, or format. By enabling users to identify features of interest and narrow down options, they serve as a quick reference for tool selection. These tables can also summarize diverse variables, such as the purpose of each tool, its technical requirements, and its strengths and limitations. An interactive platform based on such a database could allow users to filter and prioritize tools based on their specific needs, streamlining the decision-making process.

Decision Trees

Decision trees guide users through a flowchart-like structure of choices based on criteria such as project goals, data availability, and technical expertise. For example, a guide developed by the IUCN successfully used decision trees to help users select ecosystem service tools, demonstrating their effectiveness for structured decision-making. In the solar land-use context, decision trees could help stakeholders navigate complex trade-offs by visualizing how different priorities, such as precision or usability, lead to specific tool recommendations.

Process + Tools Frameworks

Process frameworks provide a structured pathway for identifying questions and priorities, selecting appropriate tools, and applying them to generate results that inform decisions. Unlike summary tables or decision trees, process frameworks emphasize the integration of user input and stakeholder concerns into the tool selection and application process. These frameworks can incorporate elements like summary tables and decision trees but go further by guiding users through iterative steps, from defining goals to visualizing outcomes, ensuring tools are applied effectively within the decision-making context.

Conclusion

In summary, tools for evaluating ecosystem services in the context of ground-mounted photovoltaics offer valuable but varied capabilities, reflecting differences in purpose, evidence base, user-friendliness, and integration with stakeholder processes. However, significant gaps remain, particularly in addressing sociocultural dimensions such as sense of place and identity, which are difficult to quantify but essential for holistic decision-making. Bridging these gaps will require robust community engagement processes and improved data, tools, and indicators, as well as efforts to better translate between biophysical processes and sociocultural values.

While many tools are available, they often differ in focus, with some emphasizing generality and guidance and others prioritizing precision and prediction. Decision-makers can benefit from frameworks or decision trees to navigate these options and select tools that align with specific goals and ecosystem service trade-offs. Although integrative approaches, such as multi-criteria decision analysis, hold promise for connecting biophysical and sociocultural dimensions, most tools currently lack platforms for such comprehensive analyses. Advancing the integration of diverse ecosystem service perspectives will strengthen the foundation for more sustainable and inclusive photovoltaic siting decisions.

References

1. Calvert, K. & Mabee, W. More solar farms or more bioenergy crops? Mapping and assessing potential land-use conflicts among renewable energy technologies in eastern Ontario, Canada. *Appl. Geogr.* **56**, (2015).
2. IPBES. *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. 1148 (2019).
3. Hernandez, R. R., Hoffacker, M. K., Murphy-Mariscal, M. L., Wu, G. C. & Allen, M. F. Solar energy development impacts on land cover change and protected areas. *Proc. Natl. Acad. Sci.* **112**, (2015).
4. Hoffacker, M. K., Allen, M. F. & Hernandez, R. R. Land-Sparing Opportunities for Solar Energy Development in Agricultural Landscapes: A Case Study of the Great Central Valley, CA, United States. *Environ. Sci. Technol.* **51**, 14472–14482 (2017).
5. Barron-Gafford, G. A. *et al.* Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nat. Sustain.* **2**, (2019).
6. Dinesh, H. & Pearce, J. M. The potential of agrivoltaic systems. *Renew. Sustain. Energy Rev.* **54**, (2016).
7. Tölgyesi, C. *et al.* Ecovoltaics: Framework and future research directions to reconcile land-based solar power development with ecosystem conservation. *Biol. Conserv.* **285**, 110242 (2023).
8. Armstrong, A., Ostle, N. J. & Whitaker, J. Solar park microclimate and vegetation management effects on grassland carbon cycling. *Environ. Res. Lett.* (2016) doi:10.1088/1748-9326/11/7/074016.
9. Barnard, T., Agnaou, M. & Barbis, J. Two Dimensional Modeling to Simulate Stormwater Flows at Photovoltaic Solar Energy Sites. *J. Water Manag. Model.* (2017) doi:10.14796/JWMM.C428.
10. Al-Saidi, M. & Ellahham, N. Solar energy farming as a development innovation for vulnerable water basins. *Dev. Pract.* **29**, 1–16 (2019).
11. Liu, H. *et al.* Effect of Solar Farms on Soil Erosion in Hilly Environments: A Modeling Study From the Perspective of Hydrological Connectivity. *Water Resour. Res.* **59**, e2023WR035067 (2023).
12. Walston, L. J. *et al.* Examining the potential for agricultural benefits from pollinator habitat at solar facilities in the United States. *Environ. Sci. Technol.* (2018) doi:10.1021/acs.est.8b00020.
13. Dolezal, A. G., Torres, J. & O'Neal, M. E. Can solar energy fuel pollinator conservation? *Environ. Entomol.* **50**, 757–761 (2021).
14. Moore-O'Leary, K. A. *et al.* Sustainability of utility-scale solar energy – critical ecological concepts. *Front. Ecol. Environ.* **15**, (2017).
15. Moore, S., Graff, H., Ouellet, C., Leslie, S. & Olweean, D. Can we have clean energy and grow our crops too? Solar siting on agricultural land in the United States. *Energy Res. Soc. Sci.* **91**, 102731 (2022).
16. Moore, S. & Hackett, E. J. The construction of technology and place: Concentrating solar power conflicts in the United States. *Energy Res. Soc. Sci.* **11**, 67–78 (2016).
17. Walston, L. J. *et al.* Modeling the ecosystem services of native vegetation management practices at solar energy facilities in the Midwestern United States. *Ecosyst. Serv.* **47**, (2021).
18. Levin, M. O. *et al.* Solar energy-driven land-cover change could alter landscapes critical to animal movement in the continental united states. *Environ. Sci. Technol.* **57**, 11499–11509 (2023).
19. Scholte, S. S. K. *et al.* Mapping recreation as an ecosystem service: Considering scale, interregional differences and the influence of physical attributes. *Landsc. Urban Plan.* **175**, 149–160 (2018).

20. Paracchini, M. L. *et al.* Mapping cultural ecosystem services: A framework to assess the potential for outdoor recreation across the EU. *Ecol. Indic.* **45**, 371–385 (2014).
21. Keeler, B. L. *et al.* Recreational demand for clean water: evidence from geotagged photographs by visitors to lakes. *Front. Ecol. Environ.* **13**, 76–81 (2015).
22. Wood, S. A., Guerry, A. D., Silver, J. M. & Lacayo, M. Using social media to quantify nature-based tourism and recreation. *Sci. Rep.* **3**, 2976 (2013).
23. Wartmann, F. M. & Purves, R. S. Investigating sense of place as a cultural ecosystem service in different landscapes through the lens of language. *Landsc. Urban Plan.* **175**, 169–183 (2018).
24. Bagstad, K. J., Semmens, D. J. & Winthrop, R. Comparing approaches to spatially explicit ecosystem service modeling: A case study from the San Pedro River, Arizona. *Ecosyst. Serv.* **5**, 40–50 (2013).
25. Meraj, G., Singh, S. K., Kanga, S. & Islam, Md. N. Modeling on comparison of ecosystem services concepts, tools, methods and their ecological-economic implications: a review. *Model. Earth Syst. Environ.* **8**, 15–34 (2022).
26. Neugarten, R. A. *et al. Tools for Measuring, Modelling, and Valuing Ecosystem Services*. (IUCN, 2018). doi:10.2305/IUCN.CH.2018.PAG.28.en.
27. Peh, K. S.-H. *et al.* TESSA: A toolkit for rapid assessment of ecosystem services at sites of biodiversity conservation importance. *Ecosyst. Serv.* **5**, 51–57 (2013).
28. Natural Capital Project. InVEST 0.0. Stanford University, University of Minnesota, Chinese Academy of Sciences, The Nature Conservancy, World Wildlife Fund, Stockholm Resilience Centre and the Royal Swedish Academy of Sciences (2024).
29. Chaplin-Kramer, R. *et al.* Global modeling of nature's contributions to people. *Science* **366**, 255–258 (2019).
30. Mukhopadhyay, A. *et al.* Global trends in using the InVEST model suite and related research: A systematic review. *Ecohydrol. Hydrobiol.* (2024) doi:10.1016/j.ecohyd.2024.06.002.
31. Scordo, F. *et al.* Modeling Water Yield: Assessing the Role of Site and Region-Specific Attributes in Determining Model Performance of the InVEST Seasonal Water Yield Model. *Water* **10**, 1496 (2018).
32. Vigerstol, K. L. & Aukema, J. E. A comparison of tools for modeling freshwater ecosystem services. *J. Environ. Manage.* **92**, 2403–2409 (2011).
33. McCall, J. *et al. PV Stormwater Management Research and Testing (PV-SMaRT): Final Technical Report*. (2023).
34. Martinsons, M., Davison, R. & Tse, D. The balanced scorecard: a foundation for the strategic management of information systems. *Decis. Support Syst.* **25**, 71–88 (1999).
35. Pollinator-Friendly Solar Scorecards: Comprehensive Analysis of Scorecard Attributes.
36. EPRI. *Pollinator-Friendly Solar Scorecards: Comprehensive Analysis of Scorecard Attributes*. (2021).
37. Reviews, M. U.-R. and S. E. & 2013, undefined. GIS-based solar farms site selection using analytic hierarchy process (AHP) in Karapinar region, Konya/Turkey. *Elsevier*.
38. Brewer, J., Ames, D. P., Solan, D., Lee, R. & Carlisle, J. Using GIS analytics and social preference data to evaluate utility-scale solar power site suitability. *Renew. Energy* **81**, (2015).
39. Nordberg, E. J., Julian Caley, M. & Schwarzkopf, L. Designing solar farms for synergistic commercial and conservation outcomes. *Sol. Energy* **228**, 586–593 (2021).
40. Gacu, J. G., Garcia, J. D., Fetalvero, E. G., Catajay-Mani, M. P. & Monjardin, C. E. F. Suitability Analysis Using GIS-Based Analytic Hierarchy Process (AHP) for Solar Power Exploration. *Energies* **16**, 6724 (2023).

Addendum: Technical Advisory Committee (TAC) Feedback
A comparison of tools for assessing ecosystem service trade-offs in ground-mounted photovoltaic system decisions

Sub-Task 6.1 (Milestone 1.6)

Amy Waananen[1], Aaron Hanson[1], Nathaniel Springer[1]
[1]Institute on the Environment, University of Minnesota - Twin Cities

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Deploying Solar with Wildlife and Ecosystem Services Benefits funding program, award number DE-EE0010385.

Summary

Our project team sent out our draft report to the TAC on Dec. 6 as a pre-read for our Dec. 11 TAC meeting. We asked for them to prepare thoughts and feedback in advance of the meeting. We also included a google form link in the document so they could provide written feedback in advance and/or after the TAC meeting.

Meeting Feedback

Feedback was positive and centered mostly on a discussion of usefulness at the site scale and landscape scale. Most TAC member commented on the usefulness of site specific tools, although one suggested both would be useful. We noted that there were no developers on the call, so the usefulness of landscape scale decision tools may have been underrepresented in this meeting. We also discussed the usefulness of tools that measure landscape-scale impacts of site-specific decisions, and whether such ES tools are needed versus measuring such impacts as indicators as the field level as a proxy for landscape scale impact. ES impacts discussed included water quality, water quantity, soil health, nutrient retention, and tradeoff of services in the short (permitting) and long-term (post-solar land quality) depending on solar land use management type. We also discussed how a tool could be used to inform the overlay process in different ways.