Final Technical Report (Abbreviated) for the InSPIRE 2.0 Project

Jordan Macknick[1] and Heidi Hartmann[2]

1 National Renewable Energy Laboratory
2 Argonne National Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-6A20-85280
February 2023

Final Technical Report (Abbreviated) for the InSPIRE 2.0 Project

Jordan Macknick[1] and Heidi Hartmann[2]

1 National Renewable Energy Laboratory
2 Argonne National Laboratory

Suggested Citation
Macknick, Jordan and Heidi Hartmann. 2023. *Final Technical Report (Abbreviated) for the InSPIRE 2.0 Project*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-85280. https://www.nrel.gov/docs/fy23osti/85280.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-6A20-85280
February 2023

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy (EERE) Solar Energy Technologies Office (SETO), Agreement No. 34165. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via www.OSTI.gov.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

Final Technical Report (FTR)

Cover Page

a. **Federal Agency**	U.S. Department of Energy	
b. **Award Number**	34165	
c. **Project Title**	InSPIRE 2.0	
d. **Recipient Organization**	National Renewable Energy Laboratory (NREL)	
e. **Project Period**	*Start*: 6/1/2018	*End*: 9/30/2021
f. **Principal Investigator (PI)**	Name: Jordan Macknick Title: Lead Energy-Water-Land Analyst Email address: jordan.macknick@nrel.gov Phone number: 303-275-3828	
g. **Business Contact (BC)**	Name: Kristen Ardani Title: Program Lead Email address: Kristen.ardani@nrel.gov Phone number: 303-384-6461	
h. **Certifying Official (if different from the PI or BC)**	Same as PI	

Signature of Certifying Official **Date**

1. **Acknowledgement:** This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE). This work was authored by NREL, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy (EERE) Solar Energy Technologies Office (SETO), Agreement No. 34165.

3. **Project Summary:** Co-locating solar projects and agriculture can provide mutual benefits to local farmers (e.g., dual revenue streams, increased yields from pollinator services, irrigation reductions) and to the solar projects (e.g., reduced timeline/costs for installation and operations and maintenance (O&M), expanded market, increased photovoltaic [PV] efficiency from a cooler, vegetated microclimate). While prior work sought to demonstrate the feasibility of agricultural co-location (or “agrivoltaic”) opportunities, there is a fundamental gap in the data available to developers, landowners, and state agencies that prevents widespread deployment of these mutually beneficial practices. This project addressed this gap by (1) establishing a multi-sector stakeholder research working group composed of industry leaders and academics to provide guidance and assist with outreach; (2) undertaking targeted field-based research projects to evaluate solar and agriculture co-location tradeoffs; (3) conducting analysis and modeling studies that complemented the field-based research; and (4) developing a data portal to consolidate all the data on this topic in one location.

4. **Project Objectives and Outcomes:** This project’s objective is to help remove barriers to low-impact solar development, while also facilitating expanded solar markets in different regions by providing foundational data and analysis on mutual solar and agricultural benefits to key stakeholders. This project facilitated the replication and scaling up of solar-agriculture research, evaluated co-located agriculture-solar designs, filled key knowledge gaps related to solar energy co-location opportunities, and developed a dynamic data platform to improve public access to data on solar-agriculture co-location.

   This project was organized into four interrelated tasks that each contributed to an improved understanding of agrivoltaics tradeoffs:

1. Establish a working group of solar and agricultural stakeholder leaders to provide feedback on project activities and facilitate outreach.
2. Conduct co-location field research to address data gaps related to (1) economic viability of PV and agriculture systems; (2) increasing yields in arid regions; (3) potential benefits in off-grid areas; and (4) potential benefits to ecosystems.
3. Conduct three analysis and modeling studies to augment field research: (1) satellite imagery analysis of land management practices at solar facilities; (2) economic assessment of O&M groundcover practices; and (3) quantification of ecological services from groundcover.
4. Augment the Innovative Site Preparation for Impact Reductions on the Environment (InSPIRE) website to incorporate a wiki-style data portal for solar-agriculture co-location research data.

The objective of Task 1 was to form and convene a decentralized research working group, the Agriculture and Solar Together: Research and Outreach (ASTRO) group, which provides direct feedback to the project team on research activities and facilitates the outreach of results. ASTRO group members came from across the country, with representatives from leading solar industry partners, state agencies, vegetation management companies, solar purchasers, and other organizations with missions in research, food and agriculture, and environmental conservation. Key milestones included forming the group, holding quarterly meetings, and developing a final report summarizing lessons learned. ASTRO activities were successful in accelerating the spread of information, increasing research investments from the public and private sectors, and catalyzing additional agrivoltaic project development by industry. Some key factors contributing to ASTRO's success include: the diversity and magnitude of ASTRO stakeholders' expertise; an open and sharing environment supporting new design philosophies; research tailored to the most pressing needs across sectors; collaborations across institutions; and early feedback from experts to accelerate research progress. ASTRO accomplishments are summarized in a publication, "ASTRO: Facilitating Advancements in Low-Impact Solar Research, Deployment, and Dissemination" (Davis and Macknick 2022).

The objective of Task 2 was to conduct field-based research driven by key scientific questions to provide foundational insights that support economic, environmental, and agricultural evaluations of solar-agriculture co-location. Research test plot locations were selected based on scientific research questions and the suitability of the site to address these questions. The project leveraged existing solar energy and agricultural infrastructure located throughout the country, allowing the project budget to be devoted solely to addressing targeted regional solar-agriculture research questions. Research sites included facilities at the University of Massachusetts Amherst, the University of Arizona Biosphere 2, and Colorado State University, as well as sites in Oregon, Minnesota, Puerto Rico, Pennsylvania, Idaho, Washington D.C., and Indonesia. These test plot locations were selected based on the suitability of the site to address the following key research topics: (1) the economic viability of solar-agriculture co-location configurations; (2) increasing agricultural yields in arid environments; (3) energy, water, and food security in remote, off-grid areas; and (4) pollinator habitat and ecological services. Key milestones included baseline data collection, study designs, instrumentation and implementation of research sites, data collection and analysis, and dissemination of results. Field sites produced novel data and started multiple long-term data collection sites that are still operating. Publications arising from the work in this task included: “Agrivoltaics Provide Mutual Benefits Across the Food–Energy–Water Nexus in Drylands” (Barron-Gafford et al. 2019); “Techno–Ecological Synergies of Solar Energy for Global Sustainability” (Hernandez et al. 2019); “Effects of Revegetation on Soil Physical and Chemical Properties in Solar Photovoltaic Infrastructure” (Choi et al. 2020); “Combined Land Use of Solar Infrastructure and Agriculture for Socioeconomic and Environmental Co-Benefits in the Tropics” (Choi et al. 2021); and “The 5 Cs of Agrivoltaic Success Factors in the United States: Lessons From the InSPIRE Research Study” (Macknick et al. 2022).

The objective of Task 3 was to conduct analysis and modeling studies that would fill key knowledge gaps related to solar energy co-location opportunities and complement the field research of Task 2. Each analysis study produced data that was incorporated into publications and/or made available on the InSPIRE website as well as being included in public webinars. The three analyses included: (1) a satellite imagery analysis of current land groundcover practices at existing solar facilities to provide a baseline assessment of solar groundcover; (2) a detailed economic cost-benefit analysis of various O&M groundcover practices at utility-scale solar facilities; and (3) modeling and quantification of ecological services of various groundcover options at utility-scale solar facilities that made use of the Integrated Valuation of Environmental Services and Tradeoffs (InVEST) suite of models. Key milestones included developing study designs, conducting feasibility studies, collecting and analyzing data, and summarizing and disseminating outcomes These analytical studies produced novel data that is still being cited and utilized today. For each study, a manuscript was developed, data was disseminated in multiple ways including webinars, and data was uploaded to the InSPIRE website. Two publications have not yet been publicly released, but the ecological services publication, “Modeling the Ecosystem Services of Native Vegetation Management Practices at Solar Energy Facilities in the Midwestern United States” (Walston et al. 2021), is available. Activities in this task also led to contributions to the publication “Capital Costs for Dual-Use Photovoltaic Installations: 2020 Benchmark for Ground-Mounted PV Systems with Pollinator-Friendly Vegetation, Grazing, and Crops (Horowitz et al. 2020).

The objective of Task 4 was to update and augment the InSPIRE website to incorporate additional features, including a wiki-style data portal for solar-agriculture co-location data and an associated map of solar-agriculture sites. This web-based resource contains useful information on solar-agriculture co-location and is built on the Open Energy Information (OpenEI) InSPIRE web platform to enable stakeholders to contribute data relevant to solar-agriculture co-location. The project team conducted outreach on the tool through workshops and webinars, and measured usage across the solar community to evaluate its utility as a wiki-style data portal. Key milestones included data portal and website updates, inclusion of additional publicly available data, and outreach activities. The data portal (https://openei.org/wiki/InSPIRE/Data_Portal) currently hosts more than 275 research articles on agrivoltaics. The agrivoltaics map (https://openei.org/wiki/InSPIRE/Agrivoltaics_Map) currently hosts more than 300 agrivoltaic sites across the country. Both of these represent the most comprehensive and up-to-date assessment of available agrivoltaic d, and are widely used in the agrivoltaic community.

The long-lasting impacts of this work include providing foundational scientific data and publications to interested stakeholders, responding to weekly questions from the public and state agencies about agrivoltaics, and educating through publicly available webinars and other outreach mechanisms. This project serves as the most comprehensive assessment of agrivoltaics and low-impact solar in the nation, and InSPIRE team members are regularly sought out to provide insights and guidance.

5. **Path Forward:** The work from InSPIRE 2.0 has been instrumental in helping to highlight future research needs in agrivoltaics. These research needs range from opportunities to reduce solar installation costs, to the need for greater information about wildlife and insect interactions with solar projects, to scaling up crop-based agrivoltaic systems beyond 1 MW of capacity. InSPIRE 2.0 research was leveraged by the U.S. Department of Energy (DOE) in the development of new funding opportunities related to agrivoltaics, including the Deploying Solar with Wildlife and Ecosystem Services Benefits (SolWEB) and the Foundational Agrivoltaic Research for Megawatt Scale (FARMS) programs. The InSPIRE 2.0 project has evaluated multiple solar and agrivoltaic configurations, which could hold promise for additional technology transfer or commercialization opportunities.

6. **Inventions, Patents, Publications, and Other Results:** The InSPIRE 2.0 project has resulted in at least eight publications, at least 50 prominent news features, and at least 80 public presentations, as well as the public release of information and agrivoltaic resources on the InSPIRE website. The InSPIRE website (https://openei.org/wiki/InSPIRE) includes pages that contain an agrivoltaic primer, a financial calculator, a data portal, an agrivoltaics map, an overview of InSPIRE research and publications, and other relevant information for the public.

Table 1. Summary of InSPIRE 2.0 Project Presentations, News Features, and Publications

	Presentations	News Features	Publications
FY19	27	19	2
FY20	37	13	2
FY21+	24	19	4

1. Davis, Rob; Macknick, Jordan. ASTRO: Facilitating Advancements in Low-Impact Solar Research, Deployment, and Dissemination. NREL/TP-6A20-83442. 2022.
2. Horowitz, Kelsey; Ramasamy, Vignesh; Macknick, Jordan; Margolis, Robert. Capital Costs for Dual-Use Photovoltaic Installations: 2020 Benchmark for Ground-Mounted PV Systems with Pollinator-Friendly Vegetation, Grazing, and Crops. NREL/TP-6A20-77811. 2020.
3. Choi, Chong Seok; Ravi, Sujith; Siregar, Iskandar Z.; Dwiyanti, Fifi Gus; Macknick, Jordan; Elchinger, Michael; Davatzes, Nicholas C. Combined Land Use of Solar Infrastructure and Agriculture for Socioeconomic and Environmental Co-Benefits in the Tropics. Article No. 111610. 2021. Renewable & Sustainable Energy Reviews 151 (November 2021), 12 pp.
4. Choi, Chong Seok; Cagle, Alexander E.; Macknick, Jordan; Bloom, Dellena E.; Caplan, Joshua S.; Ravi, Sujith. Effects of Revegetation on Soil Physical and Chemical Properties in Solar Photovoltaic Infrastructure. Article No. 140; 2020. Frontiers in Environmental Science 8 (August 2020), 9 pp.
5. Walston, Leroy J.; Li, Yudi; Hartmann, Heidi M.; Macknick, Jordan; Hanson, Aaron; Nootenboom, Chris; Lonsdorf, Eric; Hellmann, Jessica. Modeling the Ecosystem Services of Native Vegetation Management Practices at Solar Energy Facilities in the Midwestern United States. Article No. 101227; 2021. Ecosystem Services 47 (February 2021), 9 pp.
6. Macknick, Jordan; Hartmann, Heidi; Barron-Gafford, Greg; Beatty, Brenda; Burton, Robin; Seok-Choi, Chong; Davis, Matthew; Davis, Rob; Figueroa, Jorge; Garrett, Amy; Hain, Lexie; Herbert, Stephen; Janski, Jake; Kinzer, Austin; Knapp, Alan; Lehan, Michael; Losey, John; Marley, Jake; MacDonald, James; McCall, James; Nebert, Lucas; Ravi, Sujith; Schmidt, Jason; Staie, Brittany; Walston, Leroy. The 5 Cs of Agrivoltaic Success Factors in the United States: Lessons from the InSPIRE Research Study; NREL/TP-6A20-83566. 2022.
7. Barron-Gafford, Greg A.; Pavao-Zuckerman, Mitchell A.; Minor, Rebecca L.; Sutter, Leland F.; Barnett-Moreno, Isaiah; Blackett, Daniel T.; Thompson, Moses; Dimond, Kirk; Gerlak, Andrea K.; Nabhan, Gary P.; Macknick, Jordan E. Agrivoltaics Provide Mutual Benefits Across the Food-Energy-Water Nexus in Drylands; 2019. Nature Sustainability 2 (2 September 2019), pp. 848-855.
8. Hernandez, Rebecca R.; Armstrong, Alona; Burney, Jennifer; Ryan, Greer; Moore-O'Leary, Kara; Diédhiou, Ibrahima; Grodsky, Steven M.; Saul-Gershenz, Leslie; Davis, Rob; Macknick, Jordan; Mulvaney, Dustin; Heath, Garvin A.; Easter, Shane B.; Hoffacker, Madison K.; Allen, Michael F.; Kammen, Daniel M. Techno-Ecological Synergies of Solar Energy for Global Sustainability; 2019. Nature Sustainability 2 (9 July 2019), pp. 560-568.

7. Project Team and Roles:

Institution	Key Participant	Role
Argonne National Laboratory	Heidi Hartmann	Lead field work on insect populations and monitoring
University of Massachusetts Amherst	Stephen Herbert	Conduct field research on crops in Massachusetts
Cornell University	John Losey	Conduct field and analytical research on beneficial insects
Oregon State University	Amy Garrett	Conduct field research on crops in Oregon
Colorado State University	Alan Knapp	Conduct field research on soil moisture and hydrology in Colorado
University of Arizona	Greg Barron-Gafford	Conduct field research on crops in Arizona
Temple University	Sujith Ravi	Conduct analytical studies on agrivoltaic potential in Indonesia
Hyperion Systems LLC	Michael Lehan	Provide agrivoltaic and agricultural cost and economic consultation
SolCon	Brenda Beatty	Conduct field research on native vegetation and pollinator habitat
Jorge Figueroa Consulting	Jorge Figueroa	Conduct analytical and field work on agrivoltaic opportunities in Puerto Rico
Fresh Energy	Rob Davis	Coordinate and manage ASTRO advisory group