Agrivoltaics: Solar Farming for a Greener Future

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National Renewable Energy Laboratory

ENERGY2023

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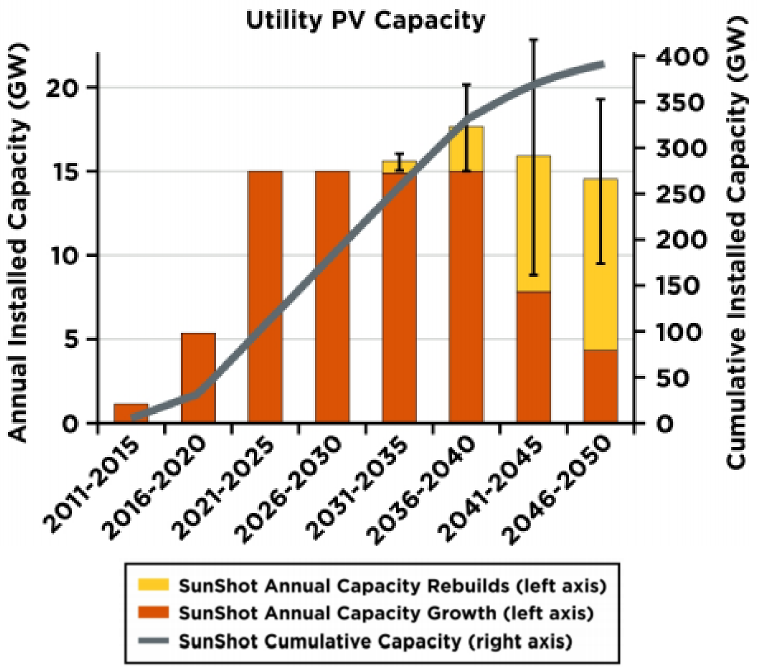
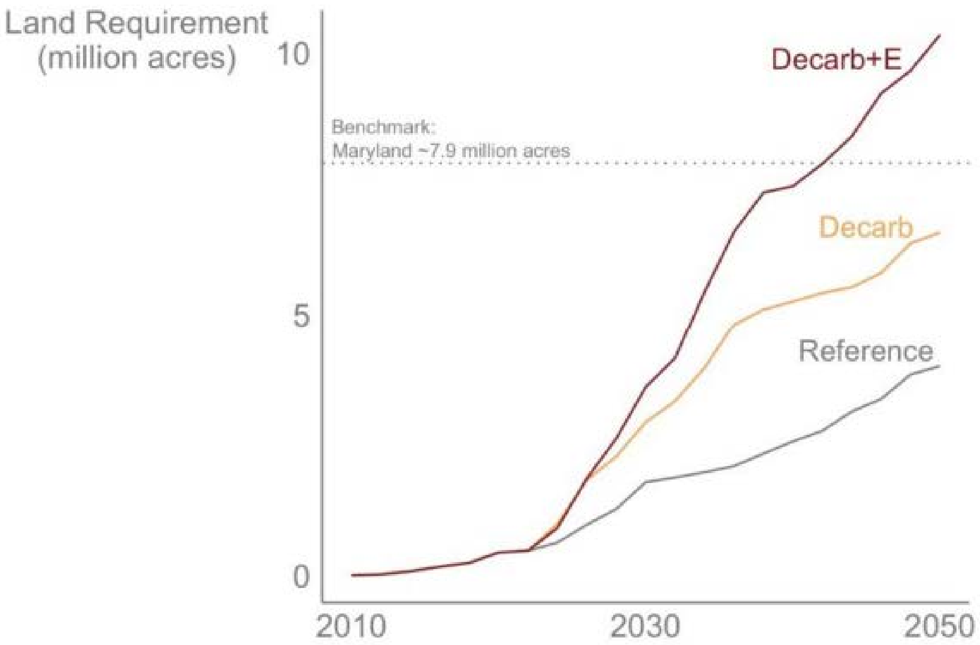
Outline

Context: Solar Power Deployment is Growing Rapidly



2030: 2 - 4 million acres
2050: 4 - 10 million acres



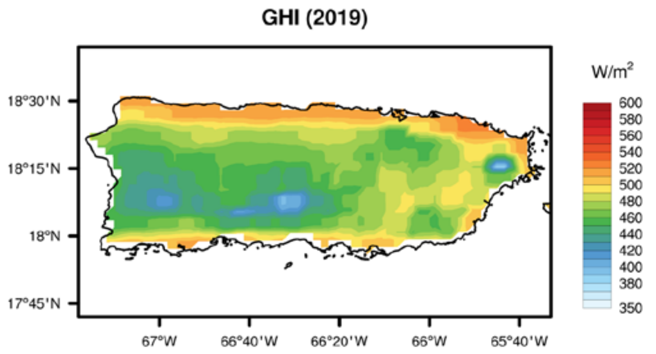
Land Requirements for U.S. Solar Deployment in the Solar Futures Study Scenarios

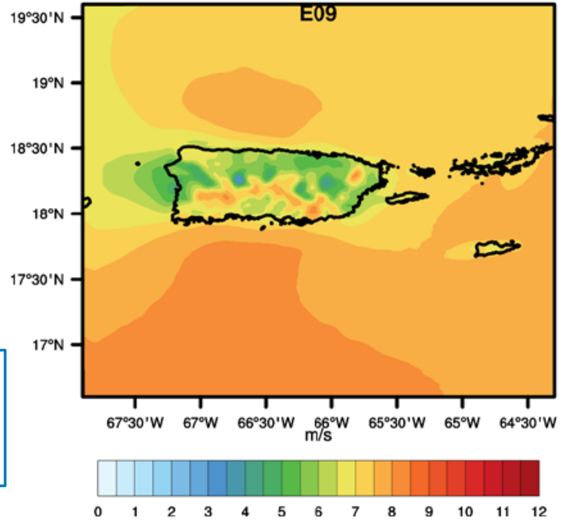
Source: Heath, Garvin, Dwarakanath Ravikumar, Silvana Ovaitt, Leroy Walston, Taylor Curtis, Dev Millstein, Heather Mirletz, Heidi Hartmann, and James McCall. Environmental and Circular Economy Implications of Solar Energy in a Decarbonized US Grid. No. NREL/TP-6A20-80818. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2022

Renewable Energy Potential in Puerto Rico

- As part of the PR100 study,* NREL:
  - Conducted renewable energy potential assessments for a variety of resources in Puerto Rico.
  - Generated high-resolution, multiyear resource data sets for land-based wind, offshore wind, and solar, as well as wind and solar forecast data:
    - Solar resource data from 1998–2021: https://nsrdb.nrel.gov
    - Wind resource data from 2000–2021: https://www.nrel.gov/grid/wind-toolkit.html.
- Marine, hydropower, and pumped storage hydropower assessments are in progress; data sets will be made available.

*PR100 is a 2-year study of possible pathways for Puerto Rico to achieve its goal of 100% renewable energy by 2050, based on extensive stakeholder input; led by FEMA, DOE, and NREL, leveraging the unique tools and capabilities of five additional national laboratories.





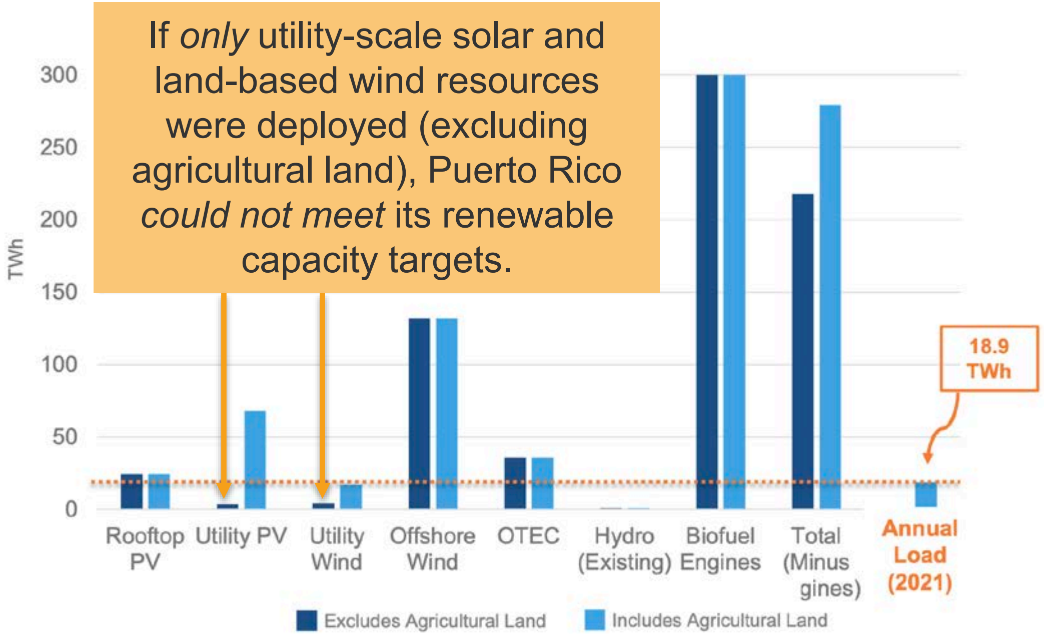
Average solar global horizontal irradiance (GHI) for 2019 (at right, above); 1-yr averaged wind speed at 80m in 2019 (at right, below). ***Graphics by NREL.***

Source: Blair, Nate,, et al.. (2023.) *PR100 One-Year Progress Summary Report: Preliminary Modeling Results and High-Resolution Solar and Wind Data Sets.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-85018. https://www.nrel.gov/docs/fy2023/85018.pdf.

Preliminary Findings from *Renewable Energy Potential and Distributed Energy Resource Adoption (PR100)*

Preliminary Findings:

- Resource potential in PR is more than **10 times** the current and projected annual loads through 2050.
- Adoption of **distributed solar and storage** is expected to increase considerably in all scenarios.

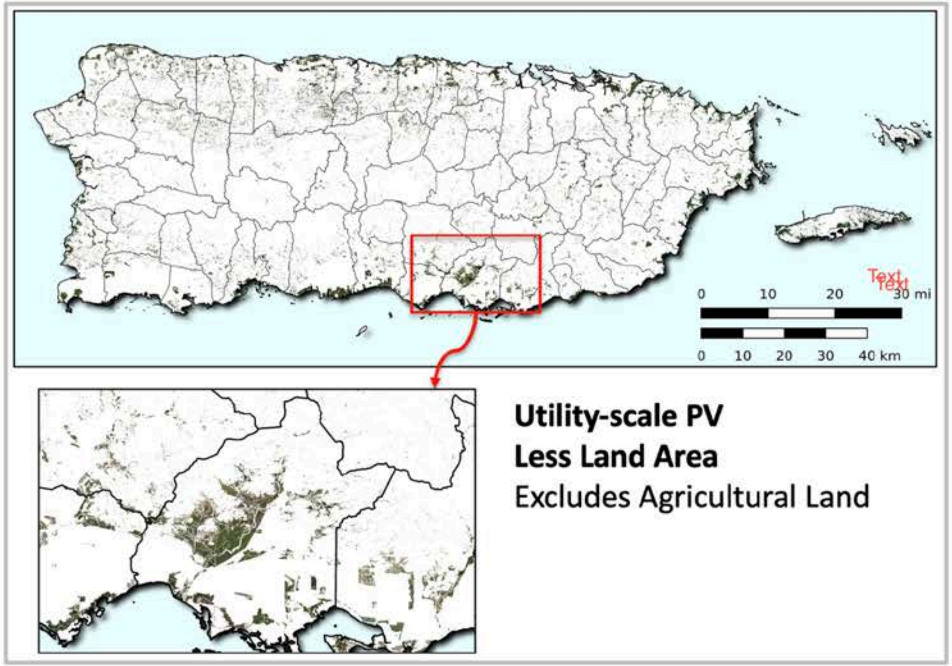


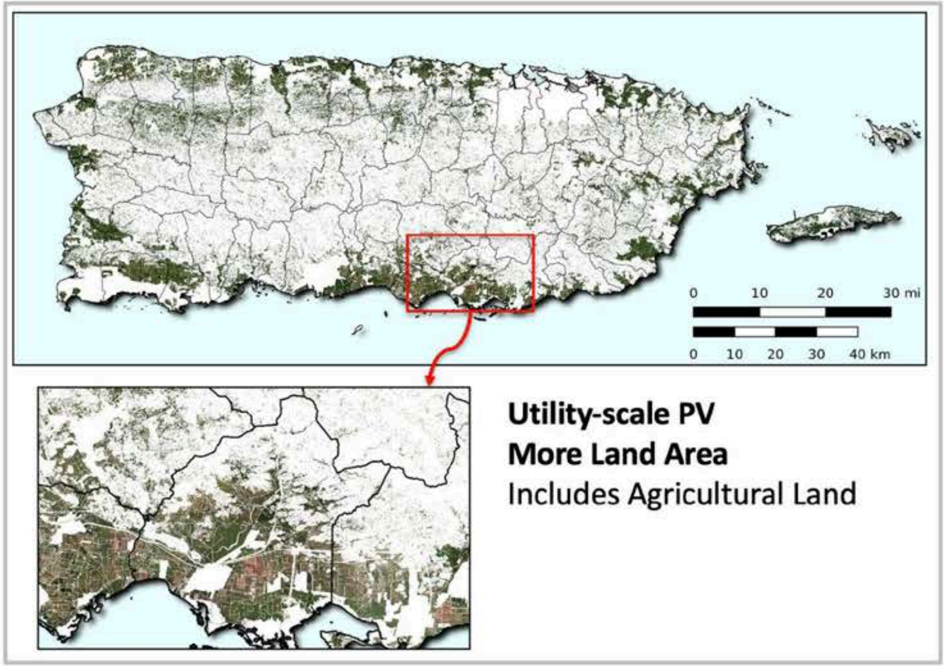
Potential annual generation in TWh of various renewable technologies compared to load (in 2021). *Graphic by NREL.*

*Final PR100 study findings will be available through the study website by January 2024

Source: Blair, Nate,, et al.. (2023.) *PR100 One-Year Progress Summary Report: Preliminary Modeling Results and High-Resolution Solar and Wind Data Sets.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-85018. https://www.nrel.gov/docs/fy2023/85018.pdf.

Challenge: Land Availability for Utility-scale Solar Deployment





Graphics by NREL

Legend:
White = Excluded area
Green = Developable area

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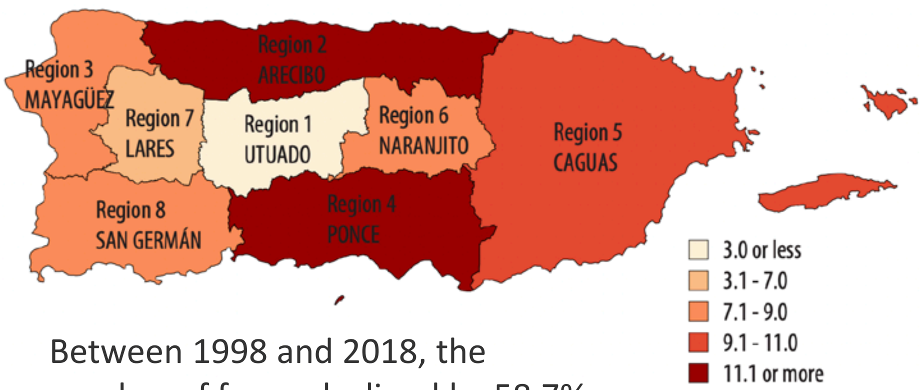
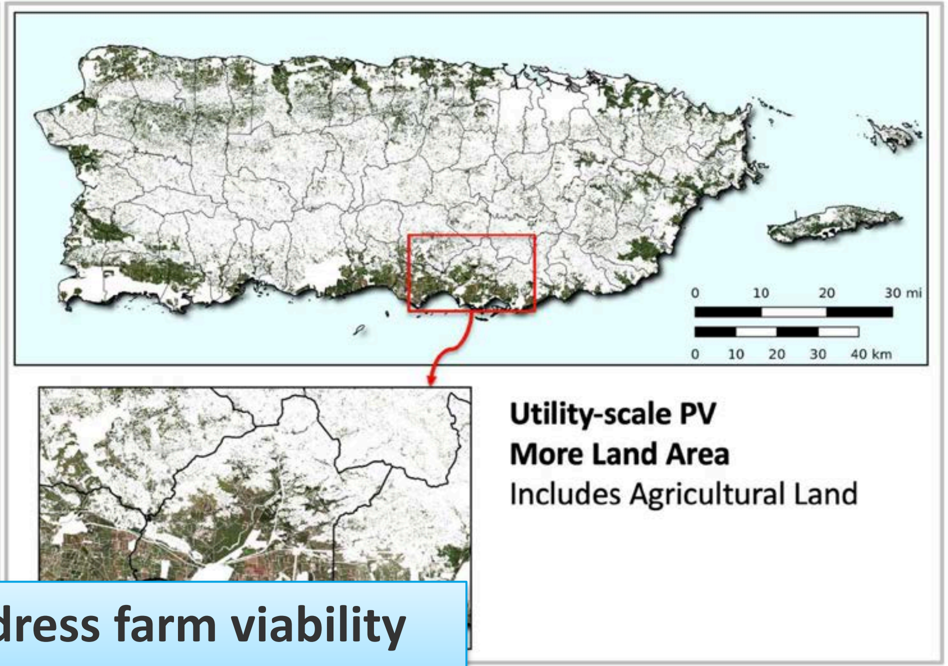
Opportunity: Create Synergy Between Critical Land Uses

Puerto Rico Agricultural Sales by Location

Total Value of Production by Region as Percent of Island Total, 2018



Between 1998 and 2018, the number of farms declined by 58.7%; amount of farmland declined 43.6%



How might utility-scale solar help address farm viability and resilience challenges, rather than exacerbate them?

Legend:
White = Excluded area
Green = Developable area

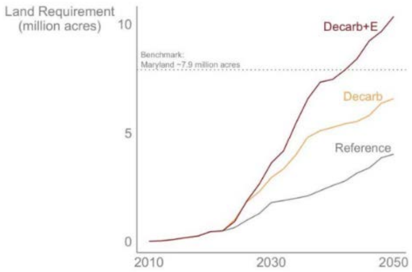
*Final PR100 study findings will be available through the study website by January 2024

Graphic and statistics by USDA NASS, 2017

Graphic by NREL

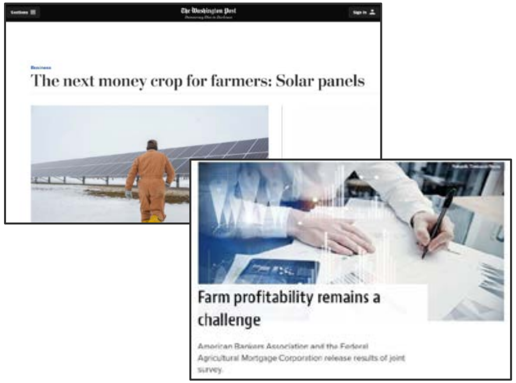
Agrivoltaics Motivation: Confluence of Solar and Agricultural Trends

Rapid Expansion of Utility-Scale Solar



Solar Land Requirements:
2030: 2 - 4 million acres
2050: 4 - 10 million acres

Potential Economic Benefits



Public Opposition to Solar on Agricultural Lands


Solar projects increasingly meeting local resistance

The New York Times

He Set Up a Big Solar Farm. His Neighbors Hated It.

A push toward renewable energy is facing resistance in rural areas where conspicuous panels are affecting vistas and squeezing small farmers.

Agrivoltaics offers an opportunity to:

- Improve economic resilience of our food system and farmers
- Keep agricultural lands in production and in beneficial use
- Improve social acceptance of solar in agricultural communities

Source: Heath, Garvin, Dwarakanath Ravikumar, Silvana Ovaitt, Leroy Walston, Taylor Curtis, Dev Millstein, Heather Mirletz, Heidi Hartmann, and James McCall. Environmental and Circular Economy Implications of Solar Energy in a Decarbonized US Grid. No. NREL/TP-6A20-80818. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2022

Vision: Mutual Benefits of Solar and Agriculture




Photos courtesy Werner Slocum, Dennis Schroeder, NREL; AgriSolar Clearinghouse

Agrivoltaics 101

Agrivoltaics is the practice of **combining agriculture and solar PV** on the same land in novel configurations.

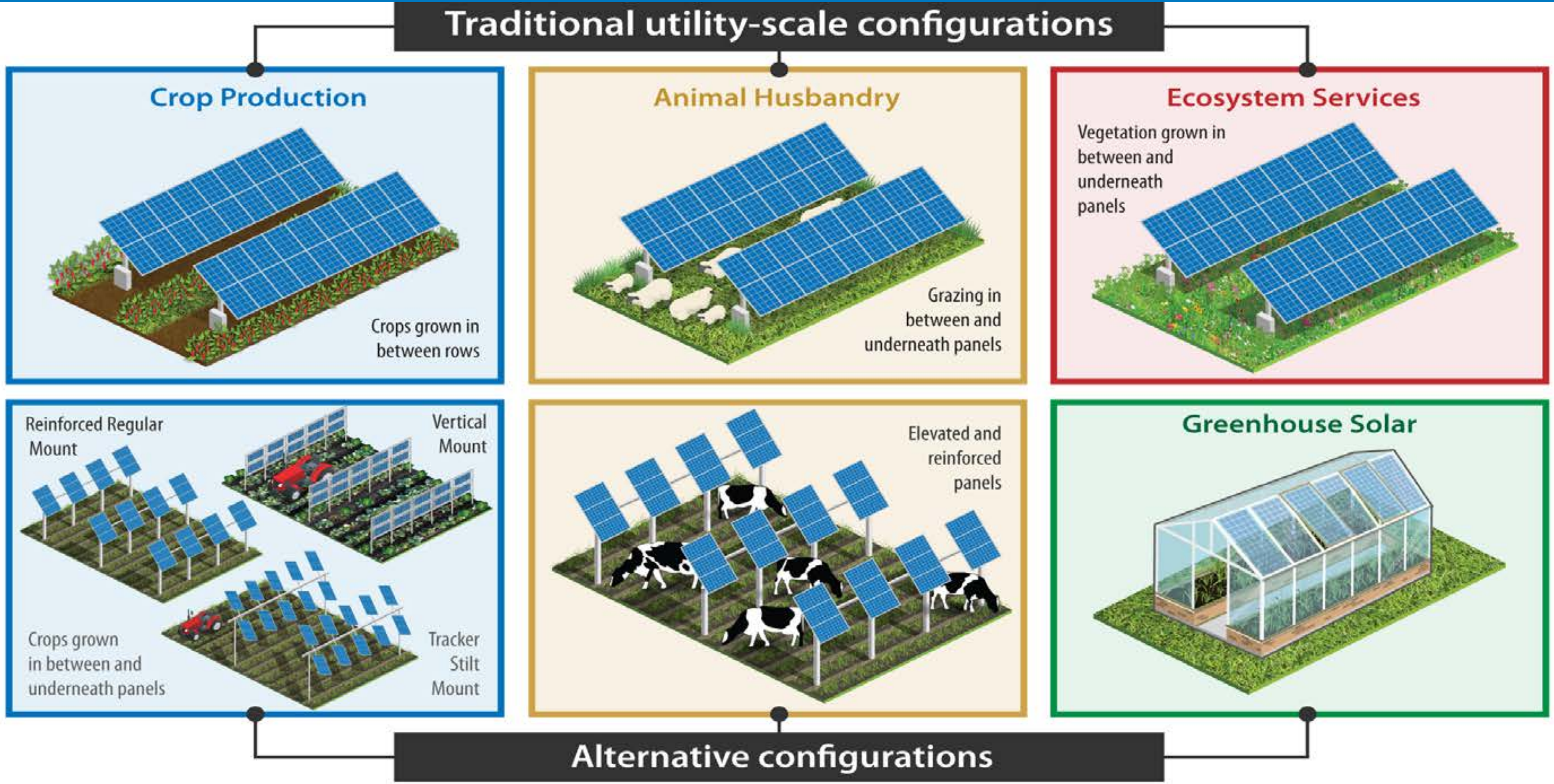
NREL is a pioneer in Agrivoltaics research. We're exploring how Agrivoltaics can help us facilitate the beneficial adoption of renewable energy, save water, and create a sustainable long-term food system.

What is Agrivoltaics?

Agricultural activities performed underneath and around solar arrays:

- ❖ Crop production
- ❖ Grazing
- ❖ Pollinator Habitat and Apiaries (“Ecovoltaics”)
- ❖ Solar Greenhouses

Diverse Agrivoltaics Applications



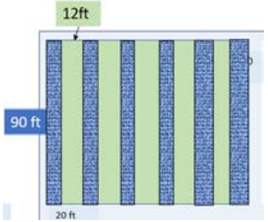
Macknick, Jordan, Hartmann, Heidi, Barron-Gafford, Greg, Beatty, Brenda, Burton, Robin, Seok-Choi, Chong, Davis, Matthew, Davis, Rob, Figueroa, Jorge, Garrett, Amy, Hain, Lexie, Herbert, Stephen, Janski, Jake, Kinzer, Austin, Knapp, Alan, Lehan, Michael, Losey, John, Marley, Jake, MacDonald, James, McCall, 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. https://doi.org/10.2172/1882930

Configuration Tradeoffs

Energy-Focused | Farmer-Focused

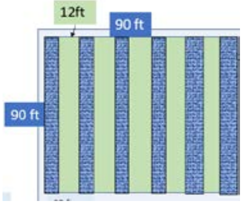
Utility Scale Height and Spacing ("Traditional")

- Highest energy production and lowest cost
- Least ergonomic for farmers and lower compatibility with a range of agricultural equipment



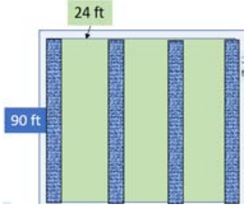
Elevated Panels, Traditional Row Spacing

- More ergonomic for hand labor
- Higher construction cost for same energy production as Traditional



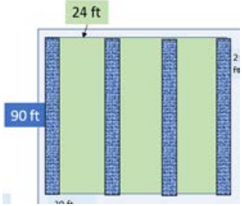
Utility Scale Height, Wide Row Spacing

- Allows for wider ag equipment and farming of more land
- Difficult for farmers to navigate around the field



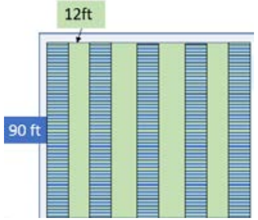
Elevated Panels, Wide Row Spacing

- Ergonomic for farmers, allows for wide ag equipment, and easier to navigate the field



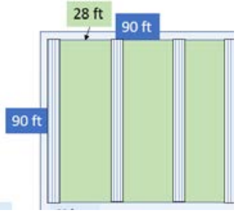
Elevated Panels, Interspaced Panels, Traditional Row Spacing

- Allows more sunlight to enter around/under panels
- Can plant directly under panels
- Does not allow for wide equipment (only farmer friendly for certain operations)



Vertical Bifacial Panels, Wide Row Spacing

- Most ag equipment friendly/widest space between rows
- Largest tradeoff for energy production



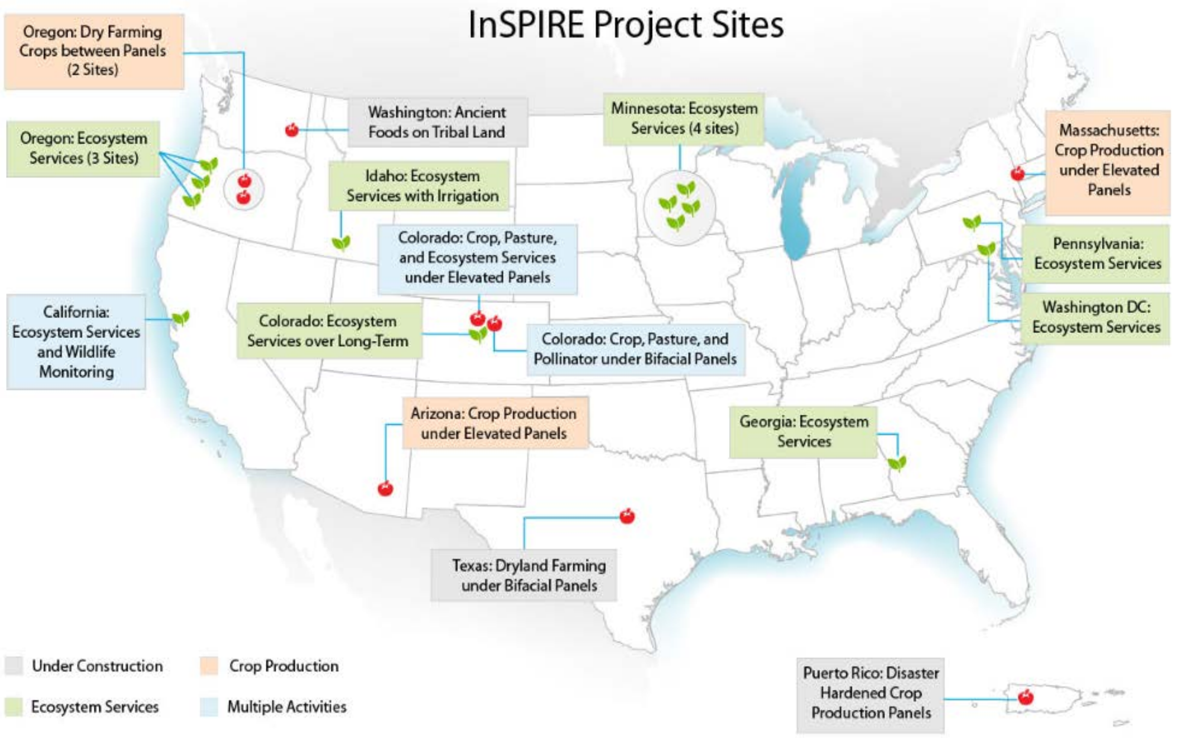
Increasing Energy Production

The InSPIRE Project

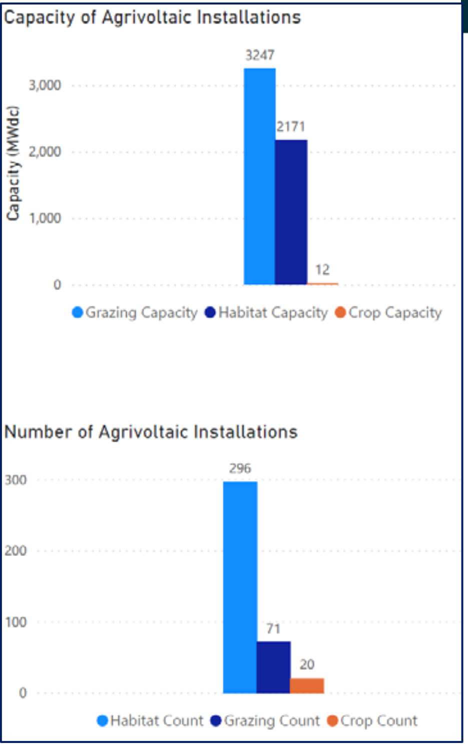
Innovative **S**olar **P**ractices **I**ntegrated with **R**ural Economies and **E**cosystems

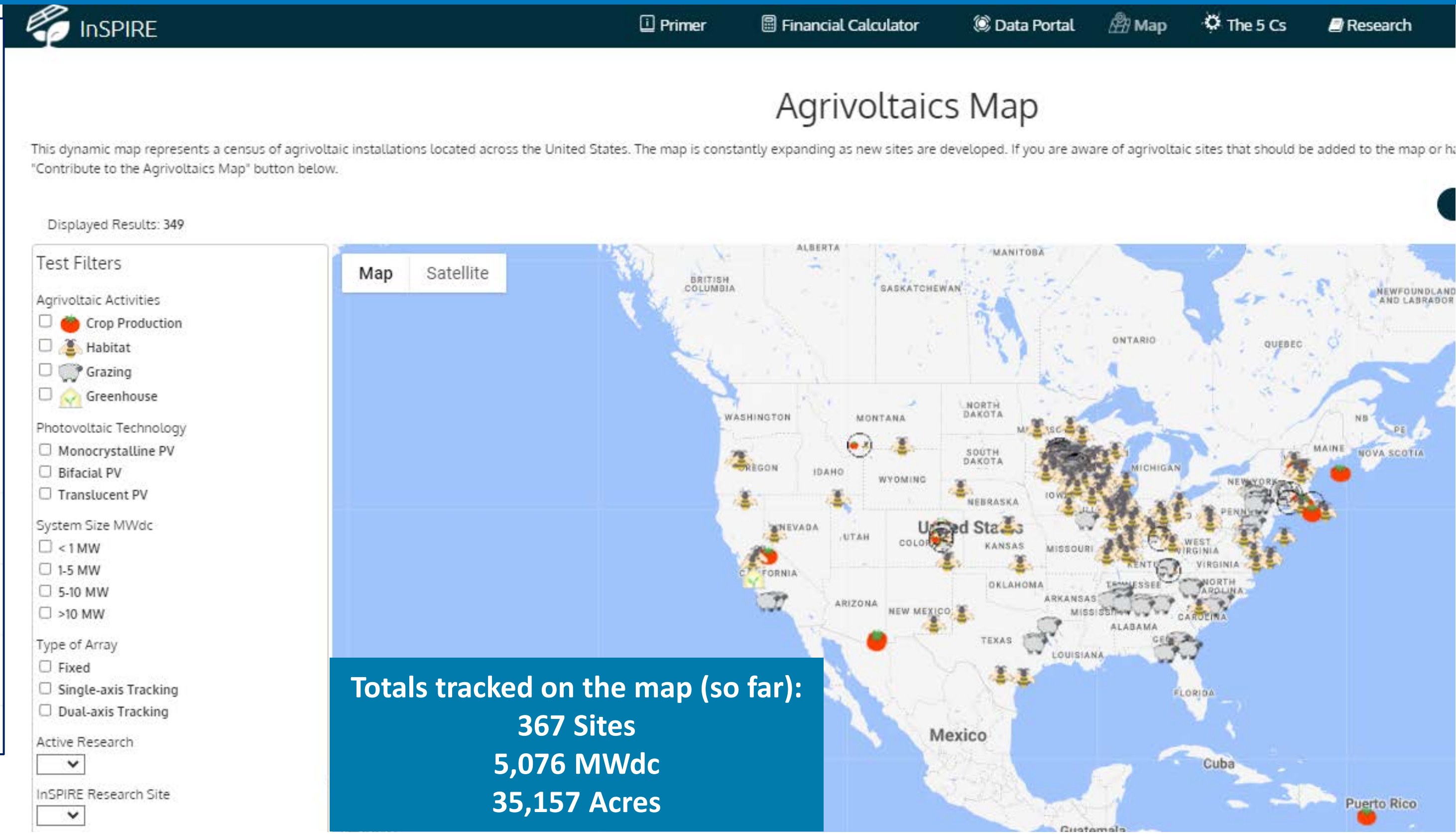
- InSPIRE has 24 active field research projects across the United States
- **Analytical research:**
  - Cost-benefit tradeoffs of different agrivoltaics configurations
  - Assessing research gaps and priorities
  - Tracking agrivoltaics projects across the United States
- **Field-based research:**
  - Novel agrivoltaic and traditional utility-scale PV designs integrated with multiple activities
  - Assessing agricultural yields and irrigation requirements in arid environments
  - Grazing standards and best practices
  - Pollinator habitat and ecosystem services

https://openei.org/wiki/InSPIRE



Tracking Agrivoltaics Projects – Map Resource





Interactive Map (updated weekly): https://openei.org/wiki/InSPIRE/Agrivoltaics_Map

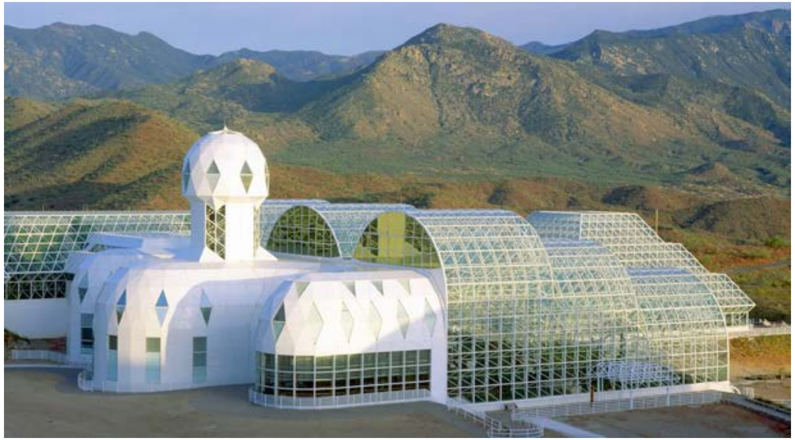

Crop Production Under and Around Solar Panels – Lessons Learned

- Crops can be grown directly underneath elevated panels or in between rows
- Hand-harvested or small machine-harvested crops
- Crop performance varies based on location and solar design configurations

Cost and Design Factors:

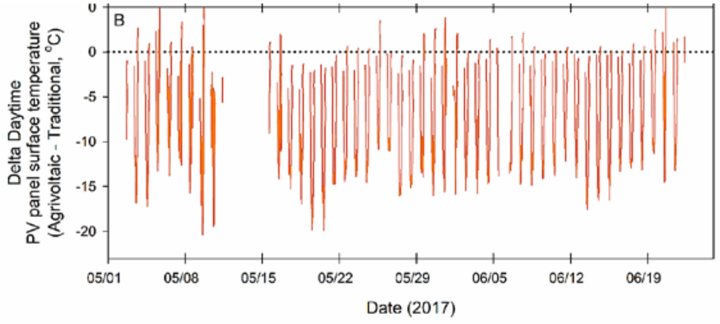
- Increased panel heights (optional)
- Increased panel spacing (optional)
- Change in O&M needs (more frequent presence on-site)
- Access to water
- Agricultural revenue

Agrivoltaics at the Biosphere 2 Living Lab

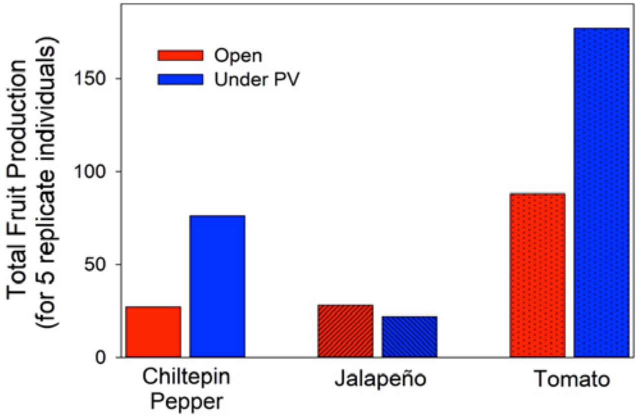


Key Highlight: Energy+Water+Food Impacts of Agrivoltaics

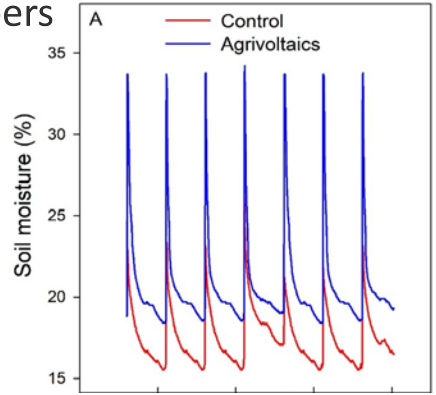
- **Energy Impacts**
  - Summertime average cooling from vegetation underneath panels: ~9°C
  - Annual generation increase: ~2%



- **Food Impacts**
  - 3x yield for chiltepin peppers
  - 2x yield for tomatoes
  - Slightly reduced yield for jalapeno peppers



- **Water Impacts**
  - Peppers need 50% less water
  - Tomatoes need 30% less water



University of Arizona Agrivoltaics system

- Elevated (10 ft) solar panels
- Tucson, AZ (Professor Greg Barron-Gafford)
- Barron-Gafford et al. (2019) *Nature Sustainability*
- https://www.barrongafford.org/agrivoltaics.html

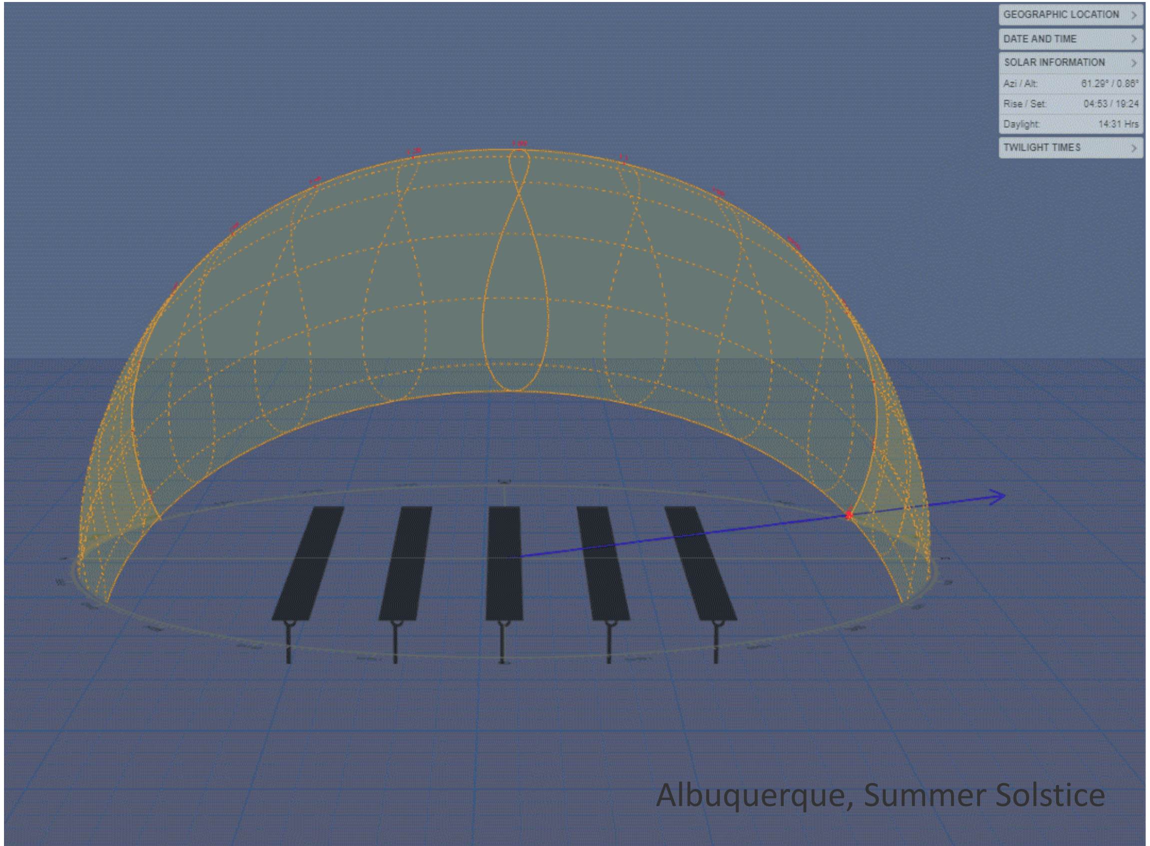
Crop yields as a function of crop placement: Broccoli in Massachusetts

Massachusetts Test Facility

Herbert et al., under review

Broccoli harvested in different locations under panels

Shade moves throughout the day, especially when the trackers move, too!



Standard Utility Scale Spacing with Elevated Panels: Jack's Solar Garden

Inter-Panel Spacing and Vertical Bifacial Panels

Photo by Next2Sun



Solar-integrated Grazing – Lessons Learned

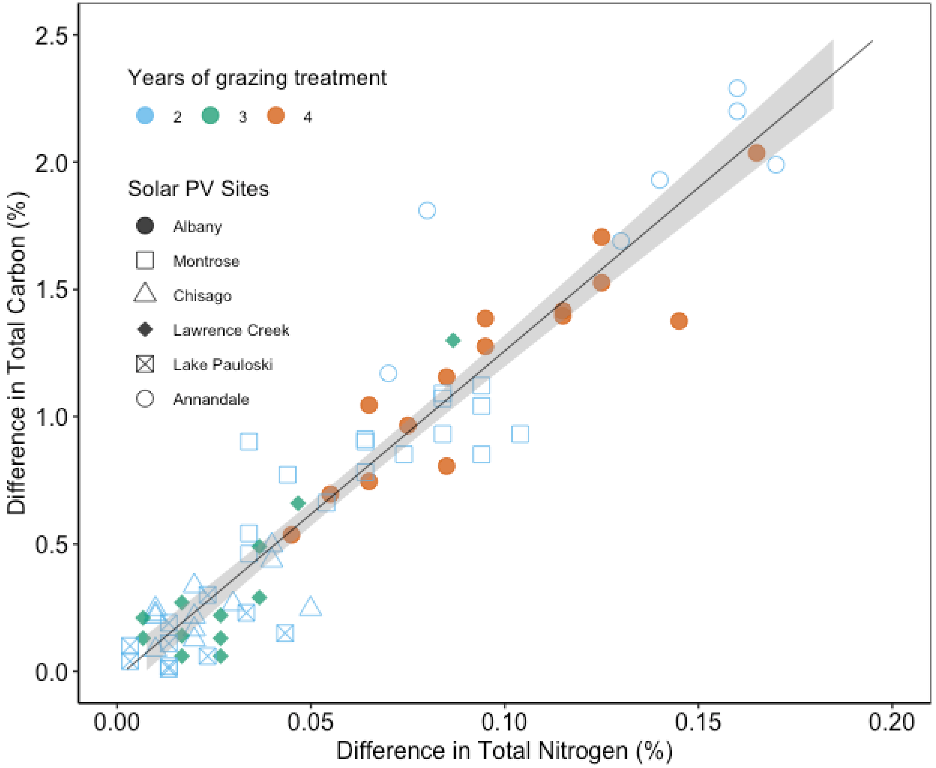
- Sustainable grazing practices can improve soils
- Potential cost reductions from standard mowing practices
- Ongoing work evaluating pastureland performance
- Can be compatible with pollinator habitat

Cost and Design Factors:

- Temporary fencing on-site
- Fencing considerations around site
- Water access
- Panel heights (for cattle)

https://solargrazing.org/

Impacts of Sheep Grazing on Soil Carbon at Solar Sites



- Higher content of both carbon and nitrogen in grazed sites compared to control sites
- No correlation with grazing frequency

- 6 commercial solar PV sites in Minnesota (ENEL Green Power)
- Native pollinator friendly vegetation under panels
- 500-700 sheep grazing treatment for 2-3 weeks per year



Pollinator-friendly Vegetation "Ecovoltaics" – Lessons Learned

- Native and pollinator-friendly vegetation can host beneficial insects
- Increased beneficial insect populations can benefit nearby farms
- Ongoing research evaluating species that thrive in partial shade of solar panels

Cost and Design Factors:

- Panel heights (to increase or not to increase?)
- Seed mix selection and purchase
- Reduction (usually) in O&M needs over time
- Potential stormwater management benefits

2018 - 2022 Preliminary Results

Onsite floral abundance & plant species richness increased over time

2018

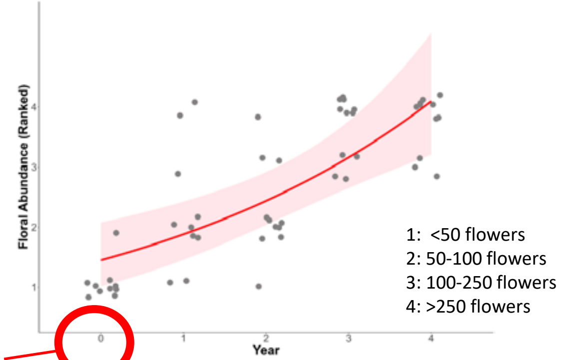
2022

Same transect, 4 years apart

2018 - 2022 Preliminary Results

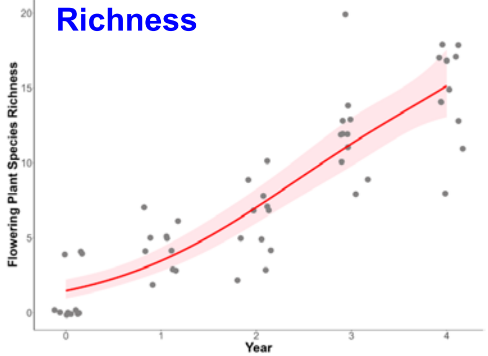
Onsite floral abundance & plant species richness increased over time

Floral Abundance



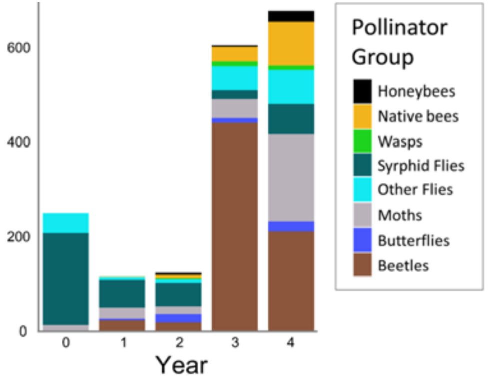
Seeding in Year 0 (2018)

Flowering Plant Species Richness



Pollinator Abundance & Diversity Increased

>650 transect observations
>13,000 insects identified to group



Soldier beetle
(Chauliognatha sp.)

Syrphid fly
(Toxomerus sp.)

Walston et al., under review

Potential Benefits Across Stakeholders

Photo by Werner Slocum, NREL

Pascaris et al., 2020; 2021; 2022; 2023

Farmer Benefits	Community Benefits	Industry Benefits
Enhanced farm viability (economic and climate resilience)	Local food-energy resilience through distributed resources	Improved community acceptance and company reputation
Revenue diversification	Economic and workforce development	Savings on O&M (site-specific)
Maximized land use, innovative dual-uses	Reduced pressure on farmland	Increased land access
Water and energy savings (region-specifi	Protect cultural heritage and local inte	Maximized system co-benefits

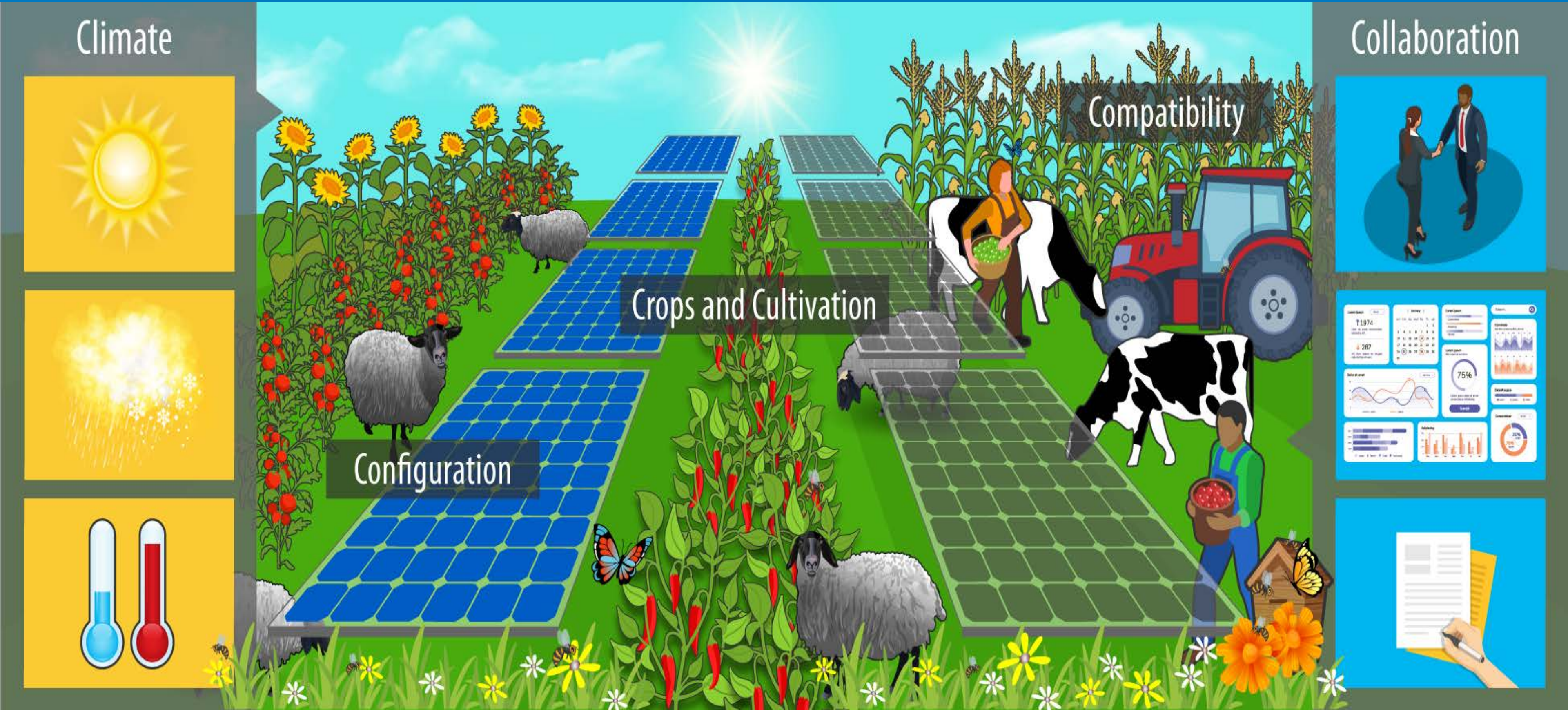
Potential Concerns Across Stakeholders

Photo by Werner Slocum, NREL

Pascaris et al., 2020; 2021; 2022; 2023

Farmer Concerns	Community Concerns	Industry Benefits
Impacts on soil, crop/forage productivity, land access, farmland preservation	Impacts on cultural heritage and landscapes	The "liability of newness" (technical, economic, and political unknowns)
Operational challenges with infrastructur	Distributional justice	Cost-benefit analysis uncertainties
Long-term planning, decommissioning	Land type, aesthetic	Political feasibility

The 5 C's of Agrivoltaic Success



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Disaster-Hardened Agrivoltaics in Puerto Rico
Pilot Study: Shade-Grown Coffee

Objectives:

- Quantify costs, benefits, and tradeoffs of **hurricane-resilient agrivoltaics in rural PR**
- Proof of concept of disaster-hardened agrivoltaic systems for PR's agricultural sector

https://openei.org/wiki/InSPIRE/Sites/Puerto_Rico:_Crop_Production

Pilot Study: Shade-Grown Coffee in Puerto Rico

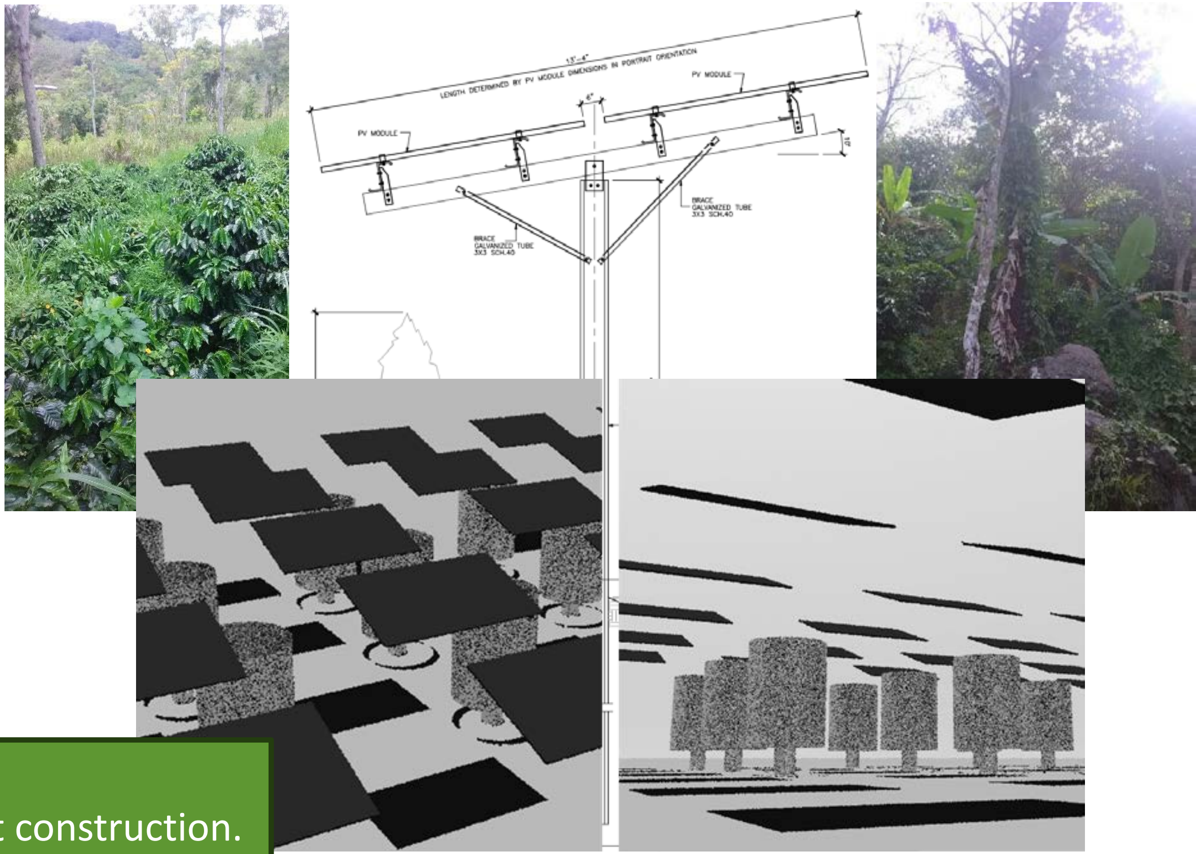
Process:

1. Open and transparent selection process with on-site scoping survey (2021-2022)

2. Collaborative design of PV system to meet farmer requirements

3. Shading and cost analysis to co-optimize agricultural and energy performance

4. Multi-stakeholder partnerships



Project construction is imminent!
In need of additional funding to support construction.

https://openei.org/wiki/InSPIRE/Sites/Puerto_Rico:_Crop_Production

Shading analysis and design visualization – Coffee Trees in Adjuntas, PR

Puerto Rico Coffee Agrivoltaic Project – Lessons Learned

- Direct **engagement and iteration with farmer is essential** to develop systems that will be successful
- Systems in PR need to be **hurricane resistant**, which can add complexity to elevated agrivoltaics
- There are **opportunities for capacity building**, new training, and workforce development for agrivoltaic systems in PR
- For agrivoltaics to thrive in PR, **systems must be customized** to local terrain, agricultural practices, and preferences

Food-Energy-Water Resilience

- Modular systems
- Disaster recovery and resilience
- Remote locations with unreliable or at-risk infrastructure
- Integrated with water pumping and treatment systems

Implications and Opportunities

Goal: 100% Renewable Energy

→

Challenge: Technical/Land constraints

→

Opportunity: Unique dual-use applications

↓

Purpose: Mitigate solar impacts on farmland and improve farm viability

←

Target outcome: Distributed, resilient food-energy systems

How can we ensure our solar goals do not impact other critical land uses?

When and where is agrivoltaics appropriate for Puerto Rico?

Agrivoltaics as one piece of the puzzle!

Reliable and affordable energy
Community resilience
Agricultural viability
Land use efficiency

What is needed for agrivoltaics to grow?

More research on:

- Agronomic impacts across geographies
- Environmental (soil and hydrologic) impacts
- Cost comparisons across stages of development

Innovation in:

- Soil management/construction best management practices
- System hardware (e.g., racking)
- Farm equipment
- Cross-sector partnerships

-Workforce development

-Training & curriculum

Thank you!

InSPIRE website: https://openei.org/wiki/InSPIRE

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