Introduction to the 3-Part Agrivoltaics Knowledge Series

Kate Doubleday, Ph.D.

July 23, 2024

The National Renewable Energy Laboratory (NREL) at a Glance

3,675 Workforce, including:

- 2,732 regular/limited term
- 490 contingent workers
- 211 postdoctoral researchers
- 152 graduate student interns
- 90 undergraduate student interns

—as of 9/30/2023

World-class research expertise in:

- Renewable Energy
- Sustainable Transportation & Fuels
- Buildings and Industry
- Energy Systems Integration

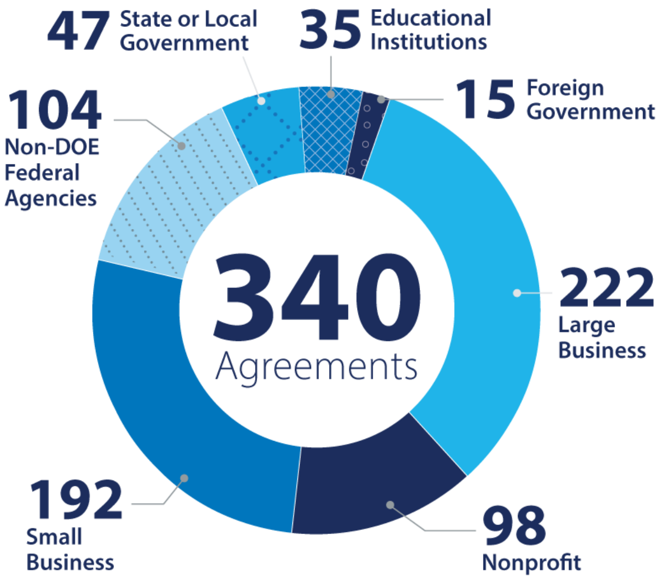
Partnerships with:

- Industry
- Academia
- Government

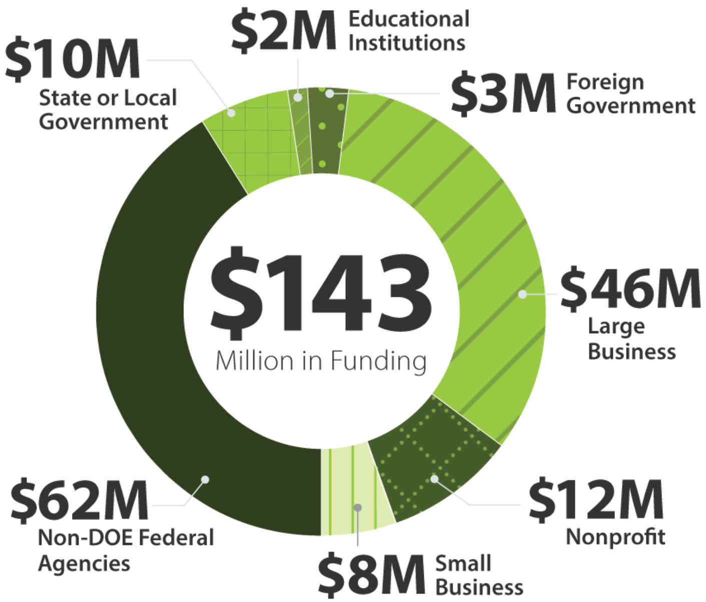
4 Campuses operate as living laboratories

Photo by Werner Slocum, NREL 71582

More Than 1,000 Active Partnerships in FY 2023



Agreements by Business Type



Funding by Business Type

Agrivoltaics at NREL

16-member team, experienced in:

- Solar design and modeling
- Economic analysis
- Small-holder farming
- Agricultural practices
- Environmental science
- Social science
- Public policy

Leading agrivoltaics research and pilot projects since 2015

Agrivoltaics Knowledge Series

Agrivoltaics 101	Agrivoltaics Groundwork	Agrivoltaics Pathway
July 23	**July 30**	**August 6**
Basics, history, and potential benefits	Collaboration and partnerships for success	Steps and processes to develop a project

Kate Doubleday

Model Engineer and Agrivoltaics Researcher

Jordan Macknick

Agrivoltaics Principal Investigator and Lead Energy-Water-Land Analyst

Brittany Staie

Agrivoltaics and Food-Water-Energy Nexus Researcher

Brian Mirletz

Energy Analyst and Software Engineer

Agrivoltaics 101

Kate Doubleday, Ph.D.

SAREP Agrivoltaics Knowledge Series

July 23, 2024

Poll: What sector do you work in?

Agenda

- Introduction to Agrivoltaics
- Opportunities for Stakeholders
- Agrivoltaic Success Stories

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Introduction to Agrivoltaics

Agrivoltaics Definition

Grazing

Sheep, cows, or other grazing animals foraging underneath and/or in between solar panels.

Crop Production

Agricultural production under or in between rows of solar panels.

Greenhouse

Solar technologies placed on top of or integrated with greenhouses.

Habitat

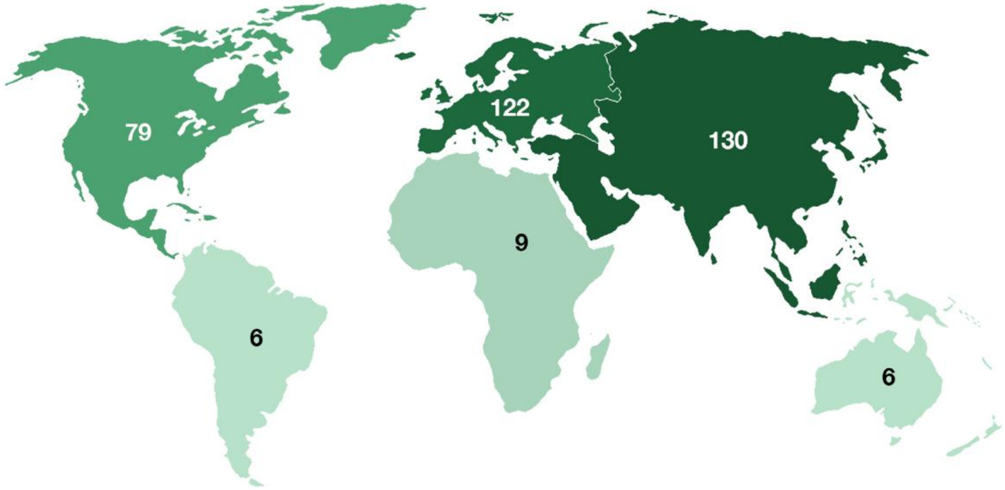
Pollinator habitat, native grasses and vegetation, and naturalized beneficial vegetation.

Vision: Mutual Benefits of Solar and Agriculture

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

History of Agrivoltaics

- First proposed Germany in the 1980s (Goetzberger and Zastrow 1081)
- Japan: An early adopter (Tajima and Iida 2021)
  - Akira Nagashima patented a solar sharing design in 2005
  - Now ~2000 small-holder sites in Japan (<0.1 hectare)
- Now studied and deployed across the globe



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

Agrivoltaics Research Publications

Bangladesh	5
China	46
India	40
Japan	29
Sri Lanka	2

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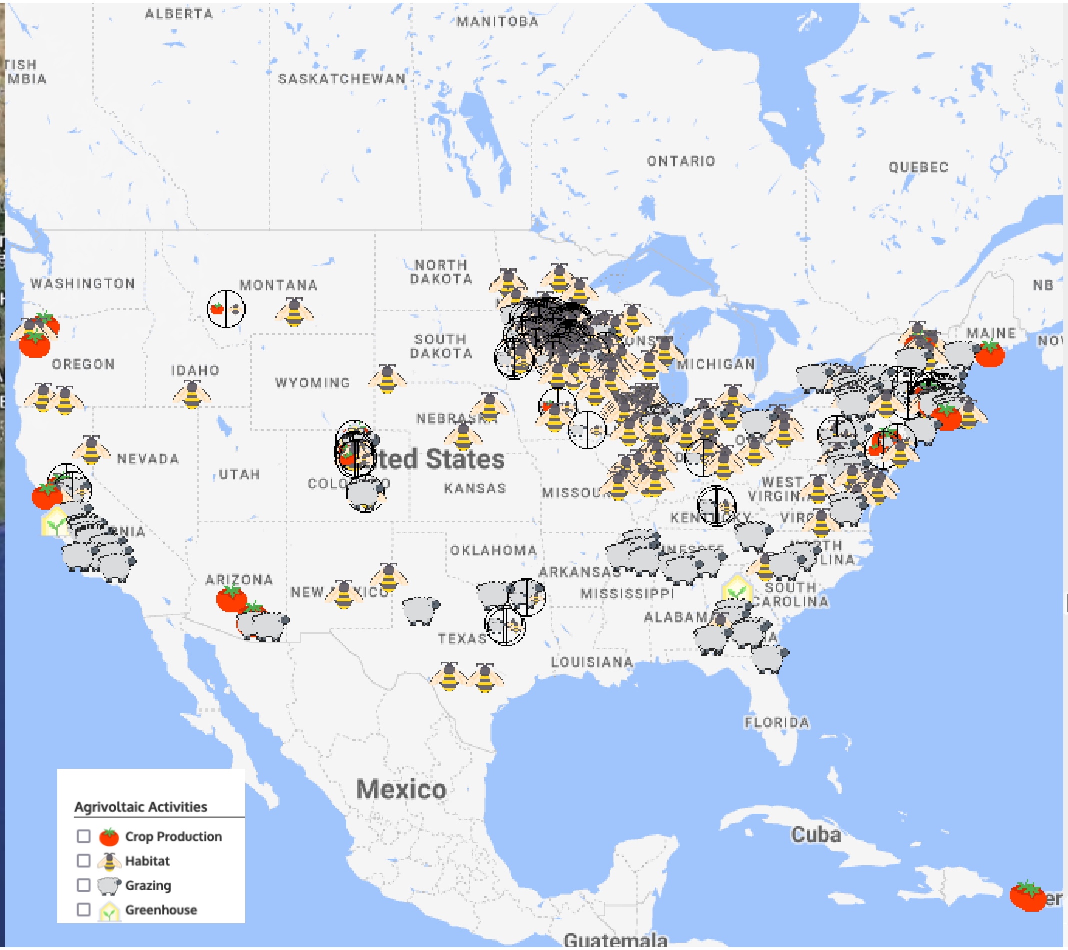
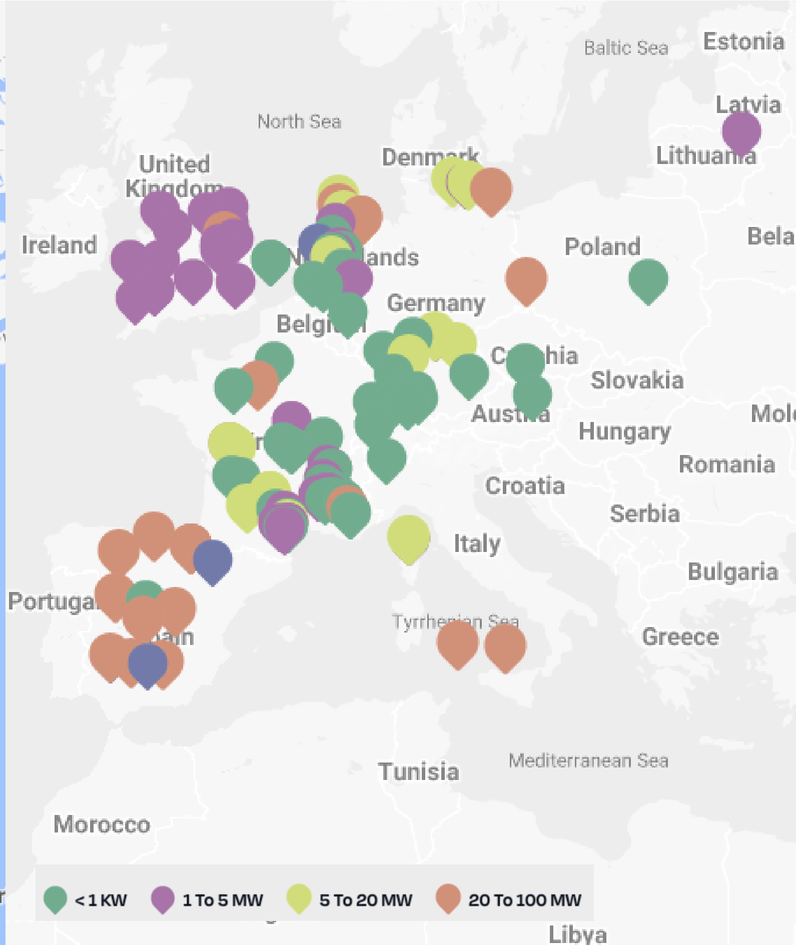
India

United States



Europe



Credit: NSEFI and IGEF
https://www.agrivoltaics.in/agripv-map-of-india

Credit: InSPIRE
https://openei.org/wiki/InSPIRE/Agrivoltaics_Map

Credit: SolarPower Europe
https://agrisolareurope.org/map/

Agrivoltaics are Global

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What is Agrivoltaics? Crop production under and around solar panels

- 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

Photos courtesy Dennis Schroeder, NREL

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



What is Agrivoltaics? Solar-Integrated Grazing

- 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 large livestock)

Photos courtesy AgriSolar Clearinghouse

Photo credit: Davis, 2019

Solar Power World

TOP SOLAR CONTRACTORS | SOLAR ARTICLES | PRODUCTS | LEADERSHIP | SUBSCRIBE

Pine Gate Renewables, Old Sol Apiaries create largest solar farm apiary in America

By Kelsey Misbrener | June 15, 2018

Utility-scale solar developer Pine Gate Renewables, headquartered in Charlotte, North Carolina, is pleased to announce that honey bees are now living on Eagle Point solar farm in Jackson County, Oregon, thanks to the company's SolarCulture initiative. SolarCulture is a Pine Gate environmental stewardship initiative that promotes sustainable agriculture and collaborations with the community to support research for smarter solar development.

What is Agrivoltaics? Solar-Powered Honey Production

- Hives can be located in or outside of project fence
- Innovative branding and marketing opportunities
- Ongoing work evaluating honeybee and native bee preferences

Cost and Design Factors

- Seed mix selection and purchase
- Location of hives (inside or outside fence)
- Safety precautions

Photo source: Mirai Solar

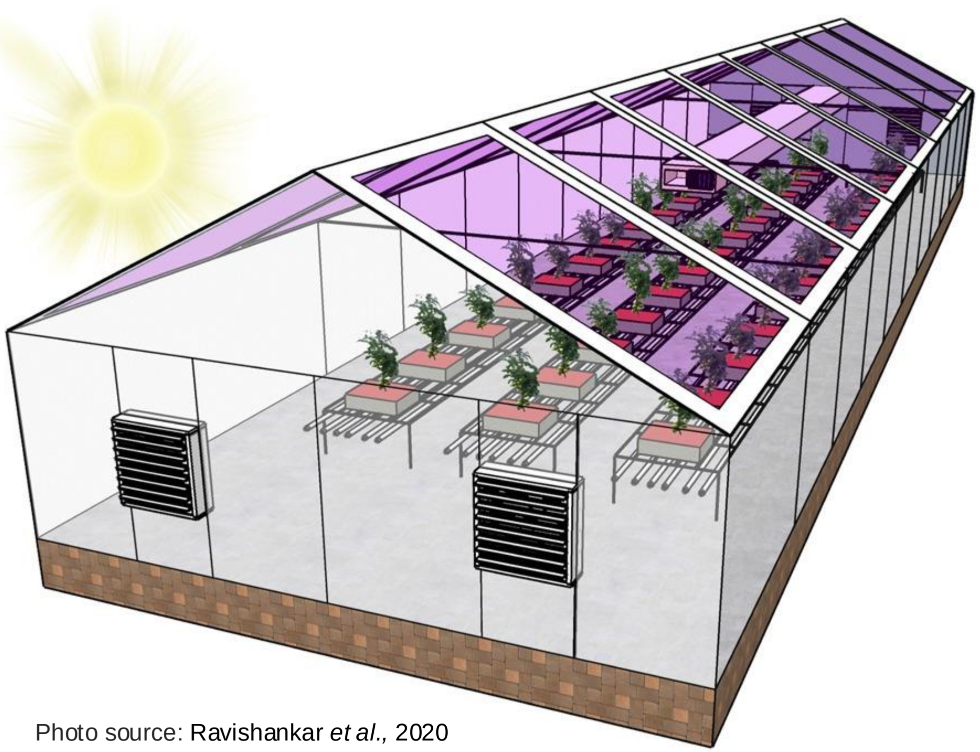

Photo source: Ravishankar *et al.*, 2020

Photo source: ICL Group

What is Agrivoltaics? Solar Greenhouses

- Opportunities for direct use of electricity generated
- Tunable wavelength materials
- Variations in shading

Cost and Design Factors

- Greenhouse vs. indoor vertical designs, etc.
- Solar technology material
- Light, wavelength optimization
- Electricity usage

What is Ecovoltaics? Pollinator-friendly Solar

- 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

5 C's of Agrivoltaic Success

Credit: Tom Hickey

Adapted from Macknick, Jordan, *et al*. 2022

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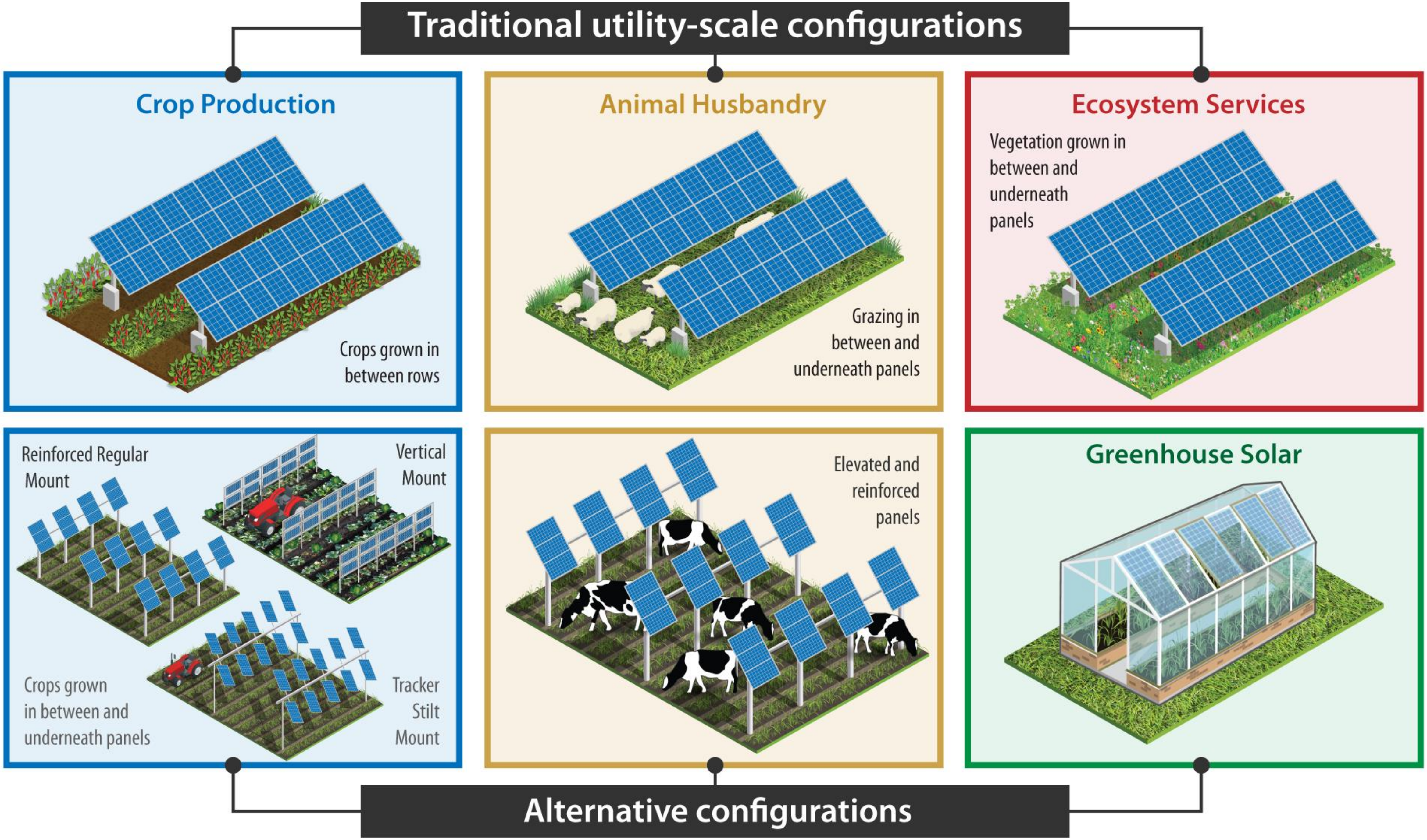
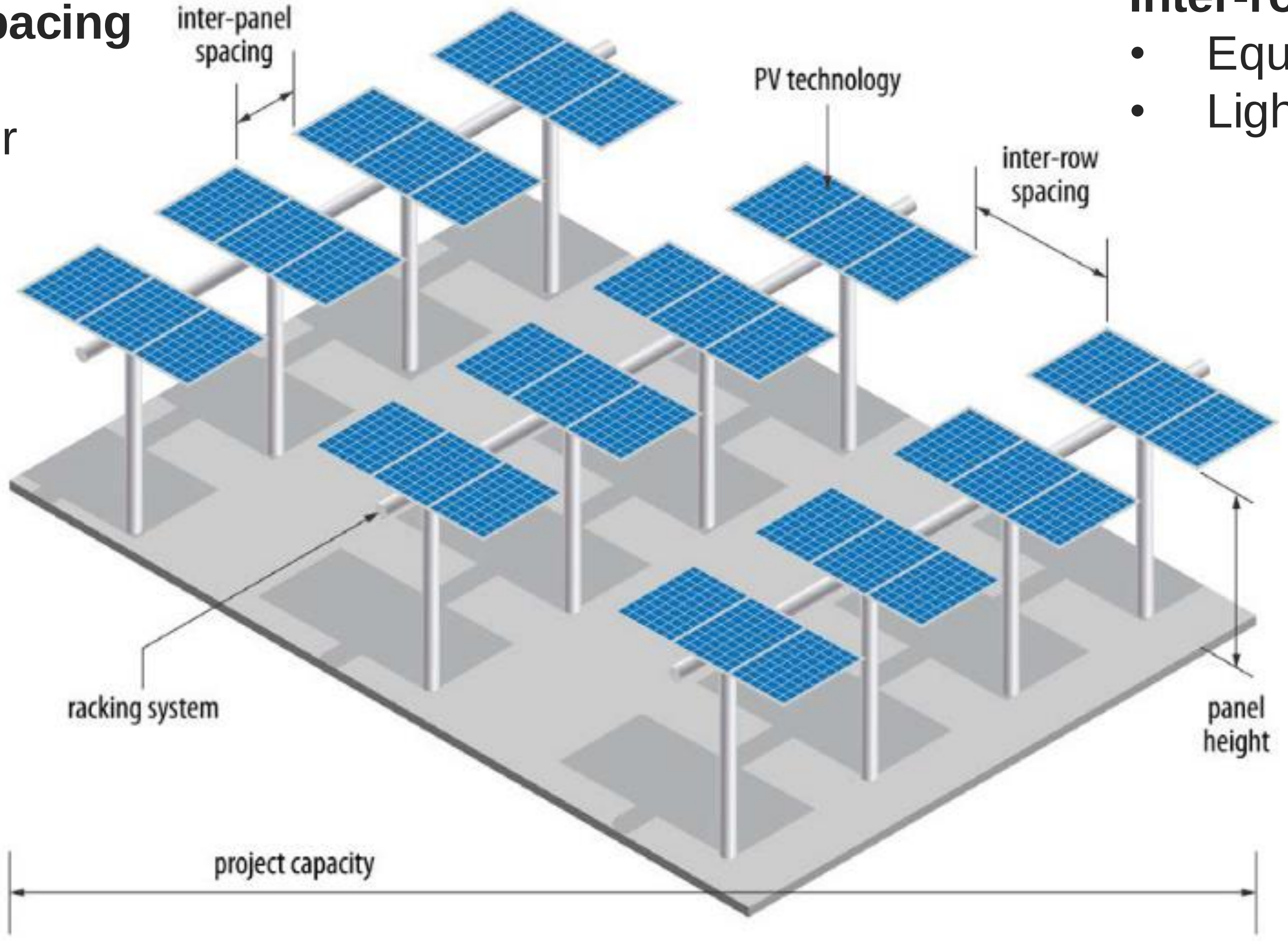


Traditional utility-scale configurations
Crop Production
Crops grown in between rows
Animal Husbandry
Grazing in between and underneath panels
Ecosystem Services
Vegetation grown in between and underneath panels
Reinforced Regular Mount
Vertical Mount
Crops grown in between and underneath panels
Tracker Stilt Mount
Elevated and reinforced panels
Greenhouse Solar
Alternative configurations

Changing Configurations for Agrivoltaics

Inter-panel spacing

- More light diffusion for crops



Inter-row spacing

- Equipment and labor access
- Light availability

Panel height

- Human and animal safety
- Equipment and labor access
- Light availability

Credit: Macknick, Jordan, *et al*. 2022

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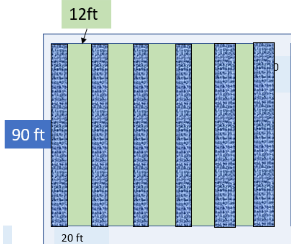
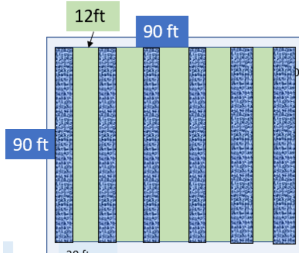
Configuration Tradeoffs

Energy-Focused ⟷ Farmer-Focused

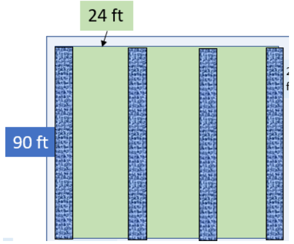
Utility Scale Height and Spacing
- Highest energy production and lowest cost
- Least ergonomic for farmers and lower compatibility with a range of agricultural equipment



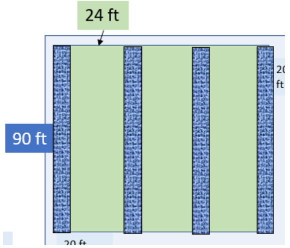
Elevated Panels, Traditional Row Spacing
- More ergonomic for hand labor
- Higher construction cost for same energy production as Traditional



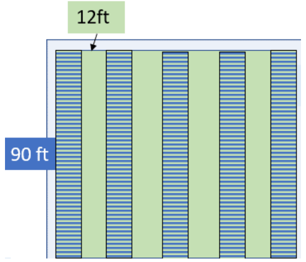
Utility Scale Height, Wide Spacing
- Allows for wider ag equipment and farming of more land
- Difficult for farmers to navigate around the field
- Less energy production per acre



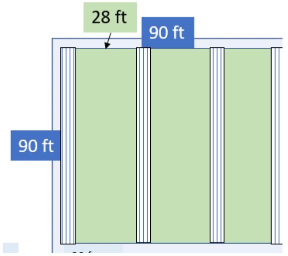
Elevated Panels, Wide Spacing
- Ergonomic for farmers, allows for wide ag equipment, and easier to navigate the field

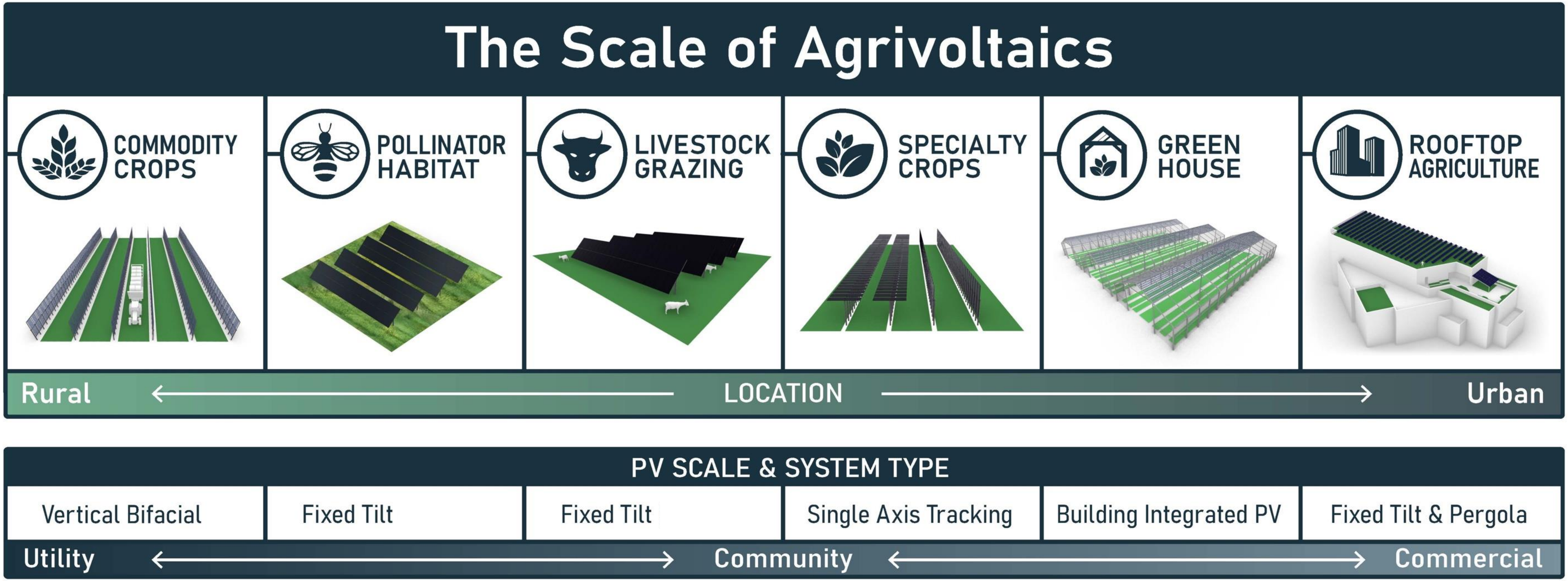


Elevated Panels, Interspaced Panels, Traditional Row Spacing
- Allows more sunlight to enter around/under panels
- Can plant directly under panels
- Does not allow for wide equipment (only farmer friendly for certain operations)



Vertical Bifacial, Wide Spacing
- Most ag equipment friendly/widest space between rows
- Largest tradeoff for energy production





Credit: Tom Hickey

Agrivoltaics has applications across rural and urban settings

Takeaways

- Agrivoltaics and ecovoltaics are being explored globally
- Applications are diverse – horticulture, grazing, bee-keeping, greenhouses, aquaculture
- Configurations are varied and not one-size fits all
- Novel and custom configurations are possible based on local agricultural needs and practices

Credit: Marrou 2019

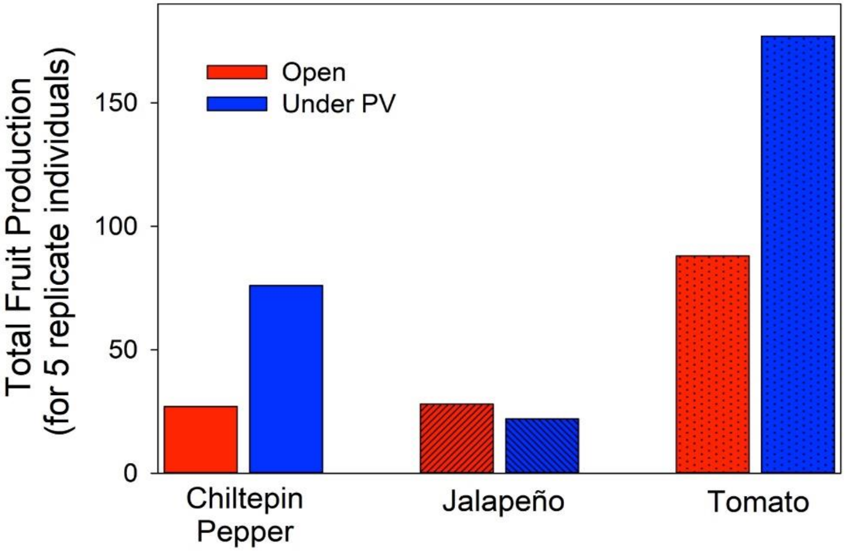
Credit: AgriSolar Clearinghouse

Credit: AgriSolar Clearinghouse

Credit: Weselek *et al*. 2019

Opportunities for Stakeholders

Potential Benefits: Yield and Water Use in an Arid Climate

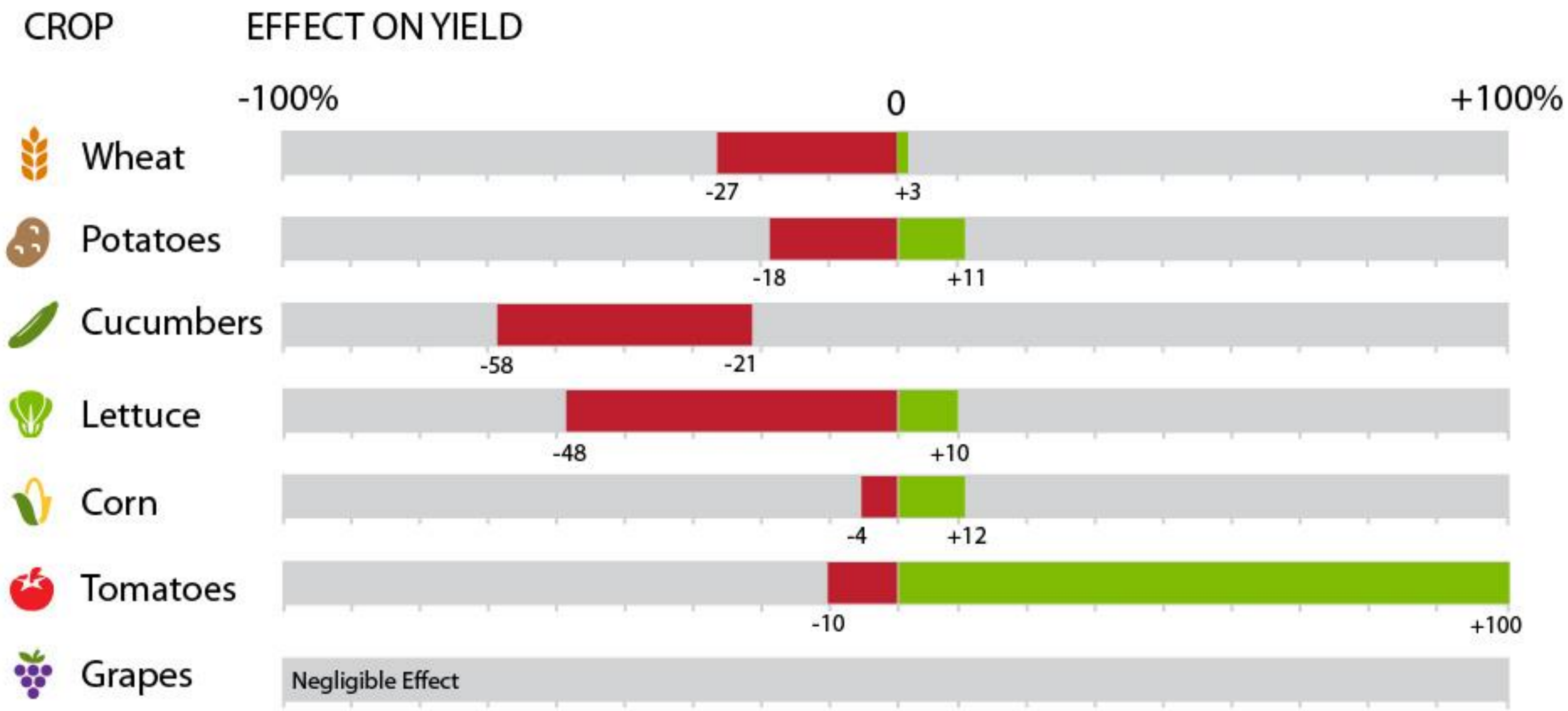


- **Energy Benefits**
  - Summertime average cooling from vegetation underneath panels: ~9^{o}C
  - Annual generation increase: ~2%
- **Food Benefits**
  - 3x yield for chiltepin peppers
  - 2x yield for tomatoes
  - Same yield for jalapeno peppers
- **Water Benefits**
  - Peppers need 50% less water
  - Tomatoes need 30% less water

University of Arizona Agrivoltaics system

- Elevated (10 ft) solar panels
- Barron-Gafford et al. (2019)
- https://www.barrongafford.org/agrivoltaics.html

Outcomes Vary by Crops and Cultivation Methods

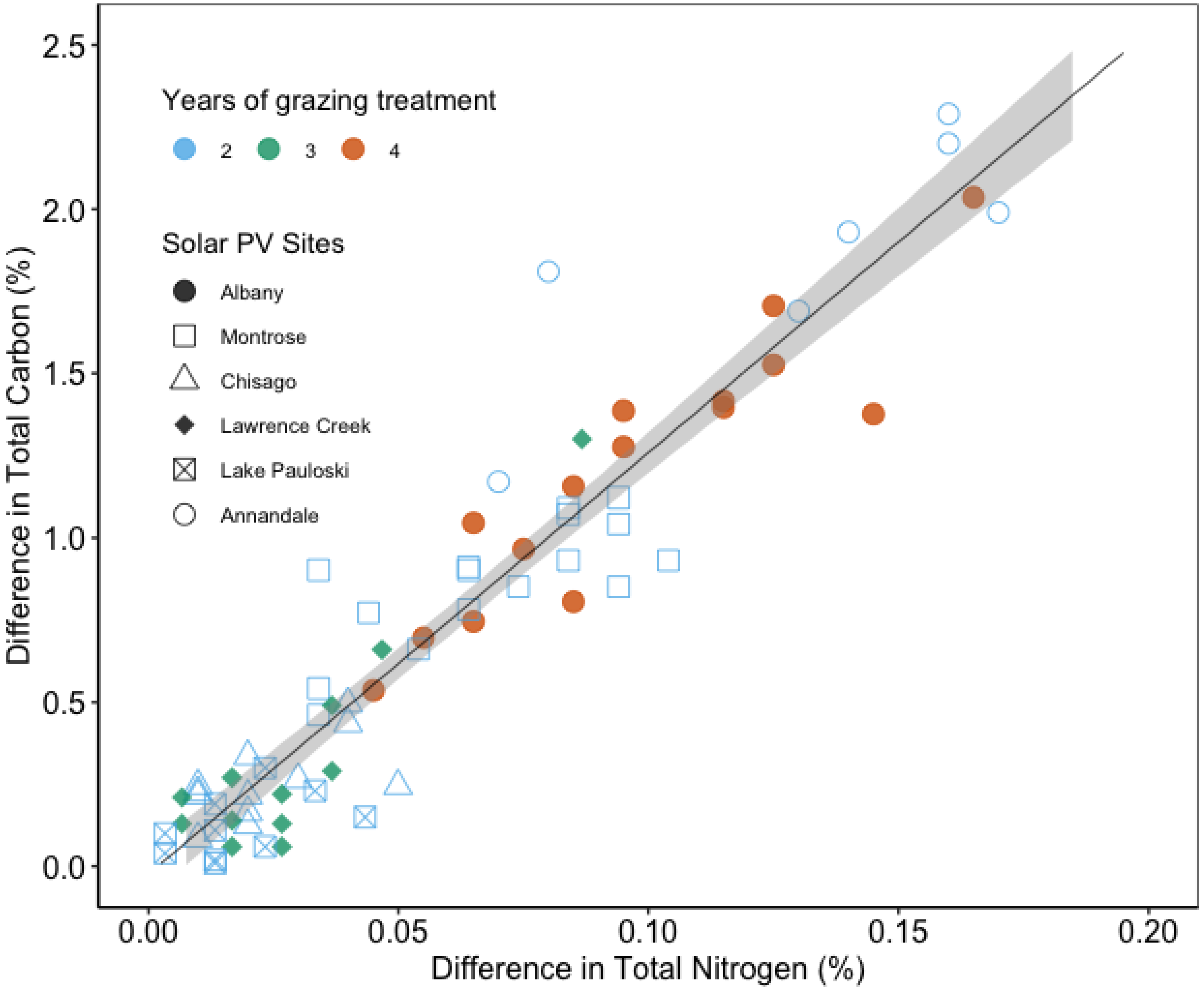


- Plant selection
- Cultivation methods
- Location within the array

*Example results based on **reported** yield outcomes in the literature (*not controlled for configuration or climate)

Macknick et al., 2022

Potential Benefit: Improved Soil Health from Grazing



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

- Potential to invest in long-term health and rejuvenation of agricultural land

Potential Benefit: Shade for Farmworkers and Livestock

Photo Credit: [AgriSolar Clearinghouse]

Photo Source: Colorado Agrivoltaic Learning Center

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Potential Benefits and Trade-offs

Potential Benefits	Potential Tradeoffs
• Decreased plant stress • Increased yields for certain crops • Lower irrigation requirements in certain climates • Improved forage quality in grazing systems • Improved soil health • Decreased land degradation • Biodiversity conservation • Increased crop marketability • Improved farmer and livestock health • Increased acceptance of solar • Decrease vegetation management costs	• Decreased yields for certain crops • Decreased land use for agricultural production • Decreased soil health or increased soil compaction • Delayed harvests • Uneven soil moisture distribution • Increased upfront investment costs

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

…and Concerns

Photo by Werner Slocum, NREL

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

Farmer Concerns	Community Concerns	Industry Concerns
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 infrastructure	Land type, aesthetic	Cost-benefit analysis uncertainties
Long-term planning, decommissioning	Distributional justice	Political feasibility

Collaboration is Critical for Success

- Balancing objectives
- Roles and responsibilities
- Ongoing communication
- Long-term agreements
- Stakeholder perspectives

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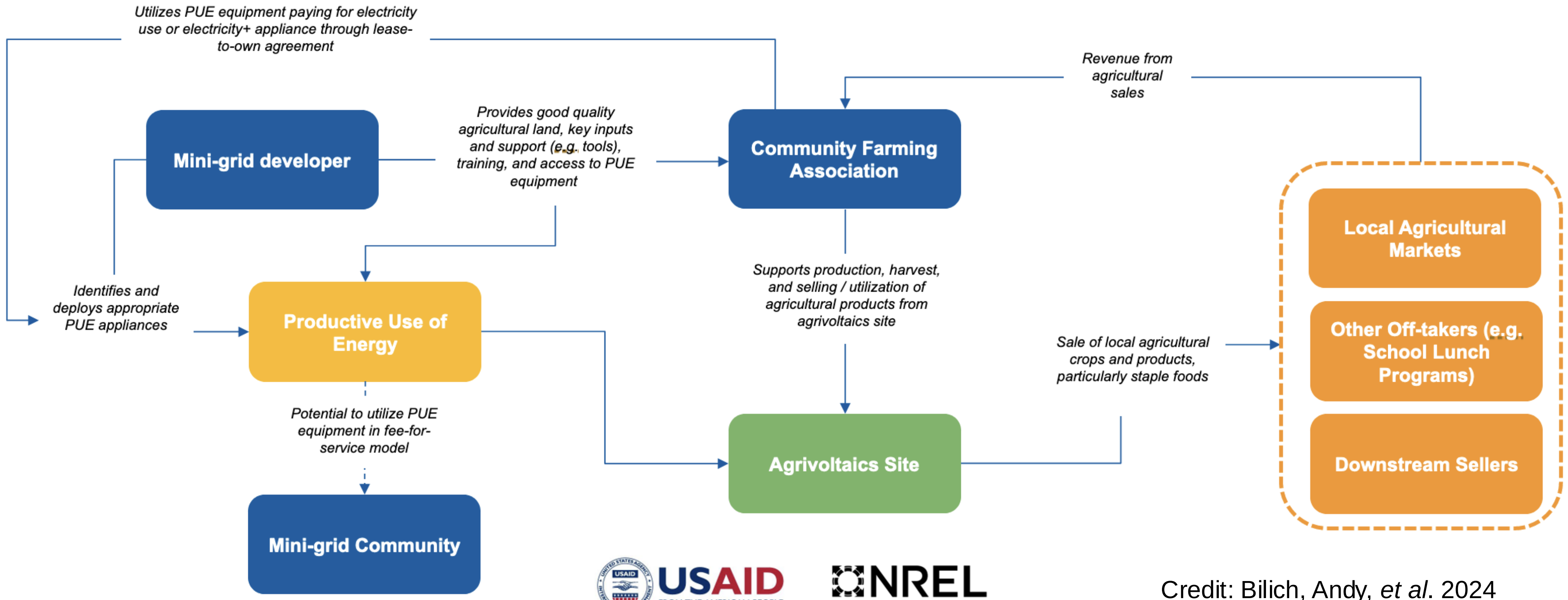
Multiple Potential Business and Partnership Models

- Farmer-owned projects
- Long-term (25-30 year) land leases
  - Solar owner/operator ↔ landowner
  - Landowner/solar owner ↔ tenant farmer
- Grazing operations and maintenance (O&M) contracts
  - Landowner/solar owner ↔ grazier
- Community association partnerships
  - Landowner/solar owner ↔ community farming association



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Credit: Bilich, Andy, *et al*. 2024

Key Considerations for Planning and Deployment

Is this a feasible location?

- Distance to transmission lines
- Local land-use and zoning policies
- Previous and current land use
- Proximity to agricultural markets
- Climate and water

Photo by Bruce Green, NREL 17516

Photo by Bryan Bechtold, NREL 77784

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Key Considerations for Planning and Deployment

***Compatibility**: Are the solar, agricultural, and partnership plans all compatible?*

Photo by Werner Slocum, NREL 64434

Consider:

- Farm equipment
- Solar infrastructure
- Farmer, grazer, and/or herder practices
- Sitewide Operations & Maintenance plans
- Yield, cost, and revenue impacts
- Farmer engagement in site design

Key Considerations for Planning and Deployment

Photo by Joe DelNero, NREL 68434

Do we have ***flexibility?***

- Ease of solar industry design accommodations
- Flexibility of farming crop and practice changes
- Back-up plans


Photo by Werner Slocum, NREL 69125

Photo by Werner Slocum, NREL 64493

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Takeaways

- Potential agricultural, sustainability, and financial benefits
- Benefits and trade-offs impact different stakeholders
- Need communication across stakeholders from design through operations
- *Compatibility* is key

Photo by Rob Davis, AgriSolar Clearinghouse

Learn More: Session 2

Agrivoltaics 101
July 23

Basics, history, and potential benefits

Agrivoltaics Groundwork
July 30

Collaboration and partnerships for success

Agrivoltaics Pathway
August 6

Steps and processes to develop a project

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Agrivoltaic Success Stories

Solar Shepherd: Massachusetts

Photo credit: AgriSolar Clearinghouse 2023

- 5-year-old grazing business by small, multi-generational family farm
- Partnerships with solar developers that own and operate the sites
- 100+ acres under solar grazing
  - Farmer accesses enough land for keep the farm sustainable
- Example site:
  - 15-acre site
  - 5 MW DC solar
  - Raised over 45 lambs to maturity so far

References: AgriSolar Clearinghouse 2023 and CBS 2023

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Joe Czajkowski Farm and Lakeside Organics: Massachusetts

- “Food first, then energy.”

- Existing 400-acre farm
  - 100 acres certified organic
  - Adds value by selling chopped and peeled produce
  - Sells to local schools, universities, grocery stores, and restaurants

- 2.2-acre (~0.9 hectare) site
- 445 kW DC array
  - Bifacial modules
  - N-S rows with ~6 m spacing

Photo courtesy of Jake Marley

USAID FROM THE AMERICAN PEOPLE — NREL Transforming ENERGY — HYPERION SYSTEMS Harvest the Sun!

Reference: Personal communication and Hyperion Systems 2023

Farmer-Focused Design

- Collaboration between Hyperion and farmer Joe
  - Followed state agrivoltaics program guidelines
- Generous row spacing
  - Accommodate existing equipment
  - Crop flexibility
- Farmable area
  - Everywhere except the posts
  - Considering perennial crops (rhubarb) under panel
  - No perimeter fence
- Farmland protection during construction:
  - No soil grading
  - No predrilling
  - No concrete

Photo courtesy of Jake Marley

Reference: Personal communication and Hyperion Systems 2023

Business and Management Model

- Solar owner/operator ↔ Landowner/farmer
- Hyperion – developer and builder
  - Additional value adds during solar construction
- Landowner leases land to Sunwealth
  - 2.5% annual escalator
- Sunwealth owns the solar power system
  - Revenue: Community solar subscriptions
  - Farm is one of the subscribers
    - 17.5% reduction in utility bills

Photo courtesy of Jake Marley

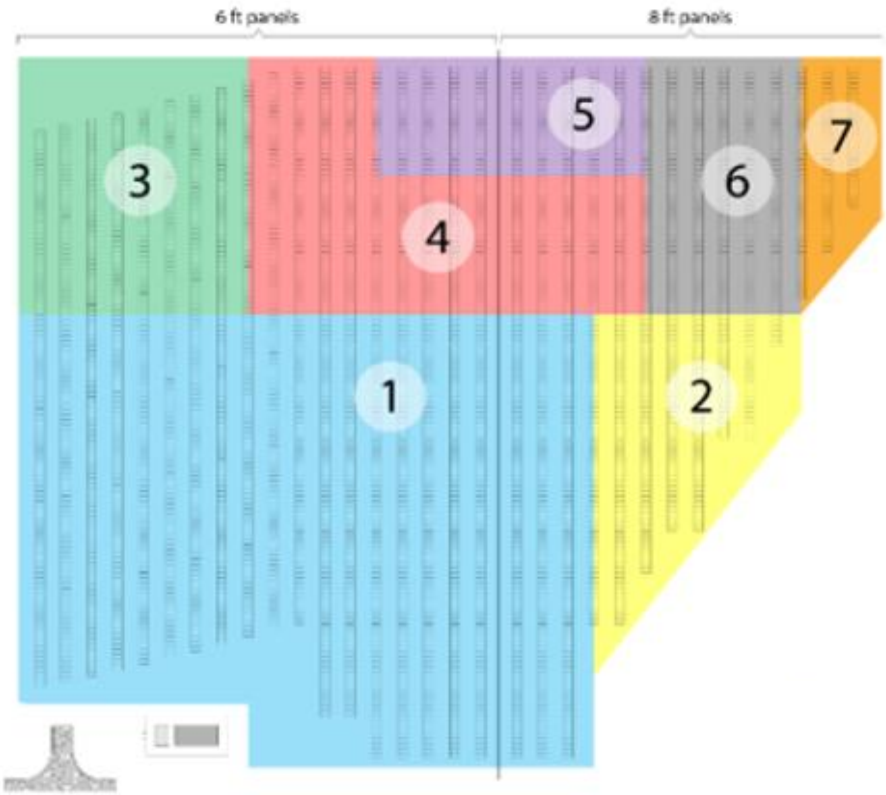
Reference: personal communication and Hyperion Systems 2023

Jack's Solar Garden: Longmont, Colorado

Photo Source: Sprout City Farms

- Currently largest commercial and research crop agrivoltaics site in the US
- 5-acre site (2 hectares)
- 1.2 MW array
    - 3,276 solar panels
    - Community solar program – provides electricity to ~300 homes in the area
- Vegetable production, pasture grass/grazing, pollinator habitat

Site Layout



Source: Sprout City Farms

1. Sprout City Farms: Production Farm
2. NREL: Pollinator Habitat
3. CSU: Ecosystem Services
4. University of Arizona: Agricultural Test Plot
5. CSU: Water Management Test Plot
6. NREL: Grassland and Nutrient Cycling
7. CALC: Educational Area

Perimeter Pollinator "Fence"


Photo by Werner Slocum, NREL 65561

- More than 1800 pollinator friendly plants, shrubs, and trees
- Planted in partnership with the Audubon Society

Jack's SOLAR GARDEN


Photo by Werner Slocum, NREL 65601

Photo by Werner Slocum, NREL 64500

Business and Management Model

- Farmer-owned model with farm entity, solar company, and non-profit

- Revenue from solar
  - **Energy production**: Community Solar Subscriptions
  - U.S. Tax Credits
  - U.S. Renewable Energy Credits (RECs)

- Upfront costs:
  - >90% from solar construction
  - < 10% for land and environmental surveys, legal fees, marketing and sales

- Monthly costs:
  - Salary, land lease, insurance, O&M, monthly loan payments

Photo by Werner Slocum, NREL 64492

Educational and Community Activities

Farm Dinners

School Tours

Public Tours

Solar Developer Workshops

Legislation Signings

Jack's SOLAR GARDEN

Colorado Agrivoltaic LEARNING CENTER

Takeaways

- Various partnership models are successfully deployed
- Agrivoltaics sites can be hubs for education, research, and community engagement, too
- “Upfront planning”
- “Perseverance”
- “Adaptability”

\- Jake Marley, Hyperion Systems

Photo by Werner Slocum, NREL 65569

Learn More: Session 3

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Poll: What topics are you most interested in learning about?

Q&A

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Additional Resources

- India Agrivoltaics Alliance (https://indiaagripv.org/)
  - Regional knowledge sharing and advocacy alliance
- Agrivoltaics in India website (https://www.agrivoltaics.in/) by NSEFI and IGEF
  - India agrivoltaics map, best practices, legal and policy, and case study reports
- American Solar Grazing Association (https://solargrazing.org/)
  - Industry association with sample contracts, example budgets, recommendations, and monthly webinars
- Agrisolar Clearinghouse (https://www.agrisolarclearinghouse.org/)
  - U.S information hub with Information Library of fact sheets
- NREL InSPIRE project (https://openei.org/wiki/InSPIRE)
  - Research data portal of agrivoltaics research worldwide (published in English), US agrivoltaics map
- AgriSolar website (https://agrisolareurope.org/) by SolarPower Europe
  - Industry group with best practice guidelines, Europe agrivoltaics map

Future Knowledge Series Sessions

Agrivoltaics 101
July 23

Basics, history, and potential benefits

Agrivoltaics Groundwork
July 30

Collaboration and partnerships for success

Agrivoltaics Pathway
August 6

Steps and processes to develop a project

Kate Doubleday

Model Engineer and Agrivoltaics Researcher

Jordan Macknick

Agrivoltaics Principal Investigator and Lead Energy-Water-Land Analyst

Brittany Staie

Agrivoltaics and Food-Water-Energy Nexus Researcher

Brian Mirletz

Energy Analyst and Software Engineer

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