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

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Session 3: Agrivoltaics Pathways

Brittany Staie and Brian Mirletz, National Renewable Energy Laboratory

SAREP Agrivoltaics Knowledge Series

August 6, 2024

Session 3 Agenda

Part 1:

Site Assessment for Planning an Agrivoltaics Project

- Farm Assessment
- Solar Panel System Design
- Crop Selection
- Environmental Impact, Sustainability, and Agritourism

Part 2:

Technical Parameters for Developing an Agrivoltaics Project

- PV Feasibility Study
- Technology and Equipment Selection
- Installation and Integration
- Monitoring and Maintenance
- Examples of Novel Agrivoltaic Technologies and Designs

Part 3:

Financial Planning Required for Deployment of an Agrivoltaics Project

- Financial Planning
- Risks and Mitigation Strategies
- Debt Equity Issues

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Part 1: Site Assessment for Planning an Agrivoltaics Project

Farm Assessment

- Site size, slope, and current land use
- Local climate conditions (temperature, irradiance, soil, humidity, precipitation)
- Availability of supplemental irrigation water
- Current and/or desired agricultural systems (e.g., crops/livestock/pollinator habitat)
- Agricultural equipment
- On-farm energy use
- Distance to nearest interconnection point (if transporting/selling energy to the grid)

Farmers harvest tomatoes at Jack's Solar Garden in Longmont, Colorado (Photo credit: Werner Slocum, NREL)

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Solar Panel System Design: Agricultural Compatibility

- Does the design
  - Allow for the maximum height of desired crops or livestock?
  - Provide enough sunlight to the crops below?
  - Allow for the safe integration of farmers, livestock, and/or agricultural equipment?
  - Maximize agricultural production or energy production?

Farmer drives tractor between solar panel rows at Jack's Solar Garden in Longmont, Colorado
(Photo credit: Werner Slocum, NREL)

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Fixed Tilt – Traditional and Elevated with Inter-Panel Spacing

Example of a south facing fixed-tilt solar array (Photo credit: Laura Beshilas, NREL)

Vegetables grow under solar panels at a test plot at the UMass Crop Animal Research and Education Center in South Deerfield, MA. (Photo credit: Dennis Schroeder, NREL)

Single-Axis Tracking - Standard Utility-Scale Height and Spacing: NREL's Research Site

Researchers plant crops at the Bifacial Agrivoltaics Research at NREL (BARN) site in Golden, Colorado (Photo credit: Werner Slocum, NREL)

Researchers harvest swiss chard at BARN agrivoltaics research site in Golden, Colorado (Photo credit: Joe DelNero, NREL)

Single-Axis Tracking - Standard Utility-Scale Spacing with Elevated Panels: Jack's Solar Garden

Farmers harvest beans underneath solar panels at Jack's Solar Garden in Longmont, Colorado (Photo credit: Werner Slocum, NREL)

Cows graze underneath solar panels at Jack's Solar Garden in Longmont, Colorado (Photo credit: Joe DelNero, NREL)

Vertical Bifacial or Agricultural PV “Fence”

Vertical bifacial agrivoltaic array used for cattle and sheep grazing (Photo credit: Brittany Staie, NREL)

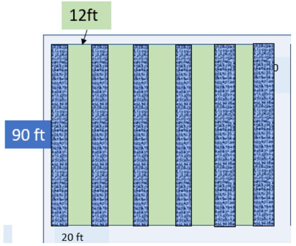
Farmer speaks about integrating cattle into their vertical bifacial array in the Netherlands (Photo credit: Brittany Staie, NREL)

Configuration Tradeoffs

Energy-Focused — Farmer-Focused

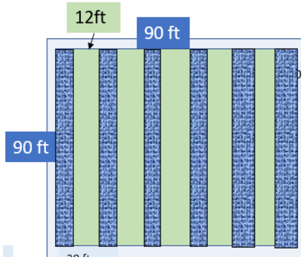
Utility Scale Height and Spacing

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



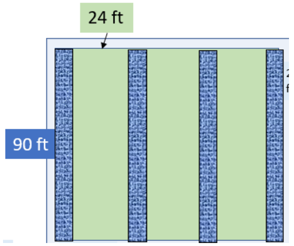
Elevated Panels, Traditional Row Spacing

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



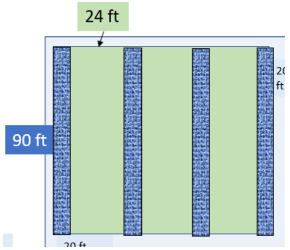
Utility Scale Height, Wide Spacing

- Allows for wider ag equipment and farming of more land
- Difficult for farmers to navigate around the field
- Less energy production per acre



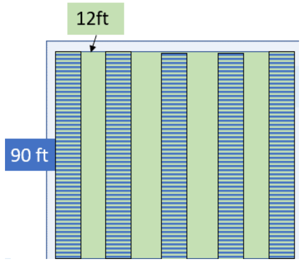
Elevated Panels, Wide Spacing

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



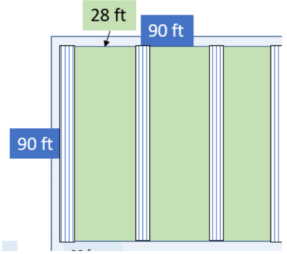
Elevated Panels, Interspaced Panels, Traditional Row Spacing

- 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

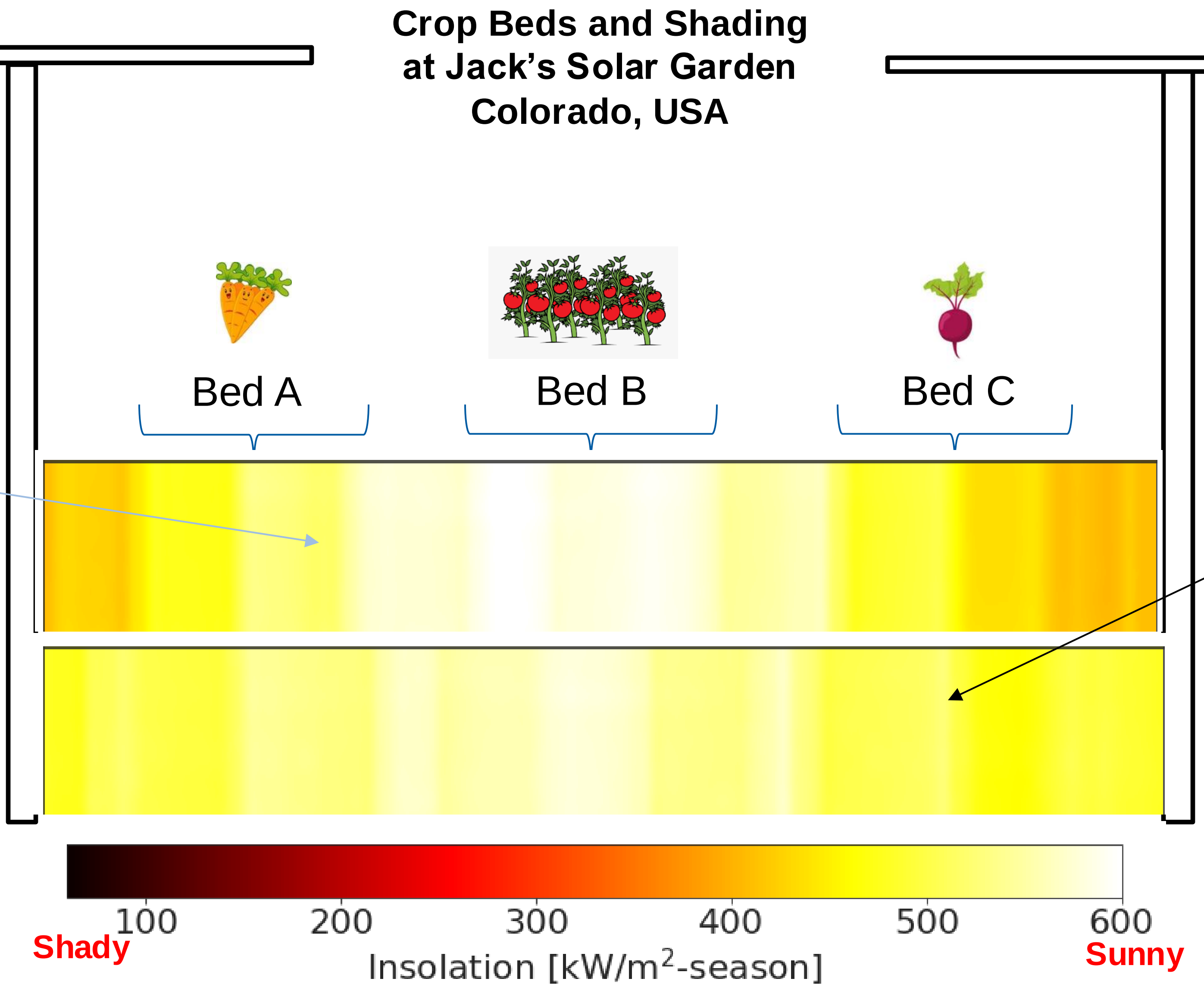


Design Considerations: Agrivoltaic Microclimate

Greens grow in the shade of the solar panels at Jack's Solar Garden in Longmont, Colorado
(Photo credit: Brittany Staie, NREL)

- Sunlight
- Soil Moisture
- Soil temperature
- Air temperature
- Humidity
- Wind speed

Agrivoltaic Microclimate - Sunlight



More variations in available sunlight in the **2 m** area, overall shadier

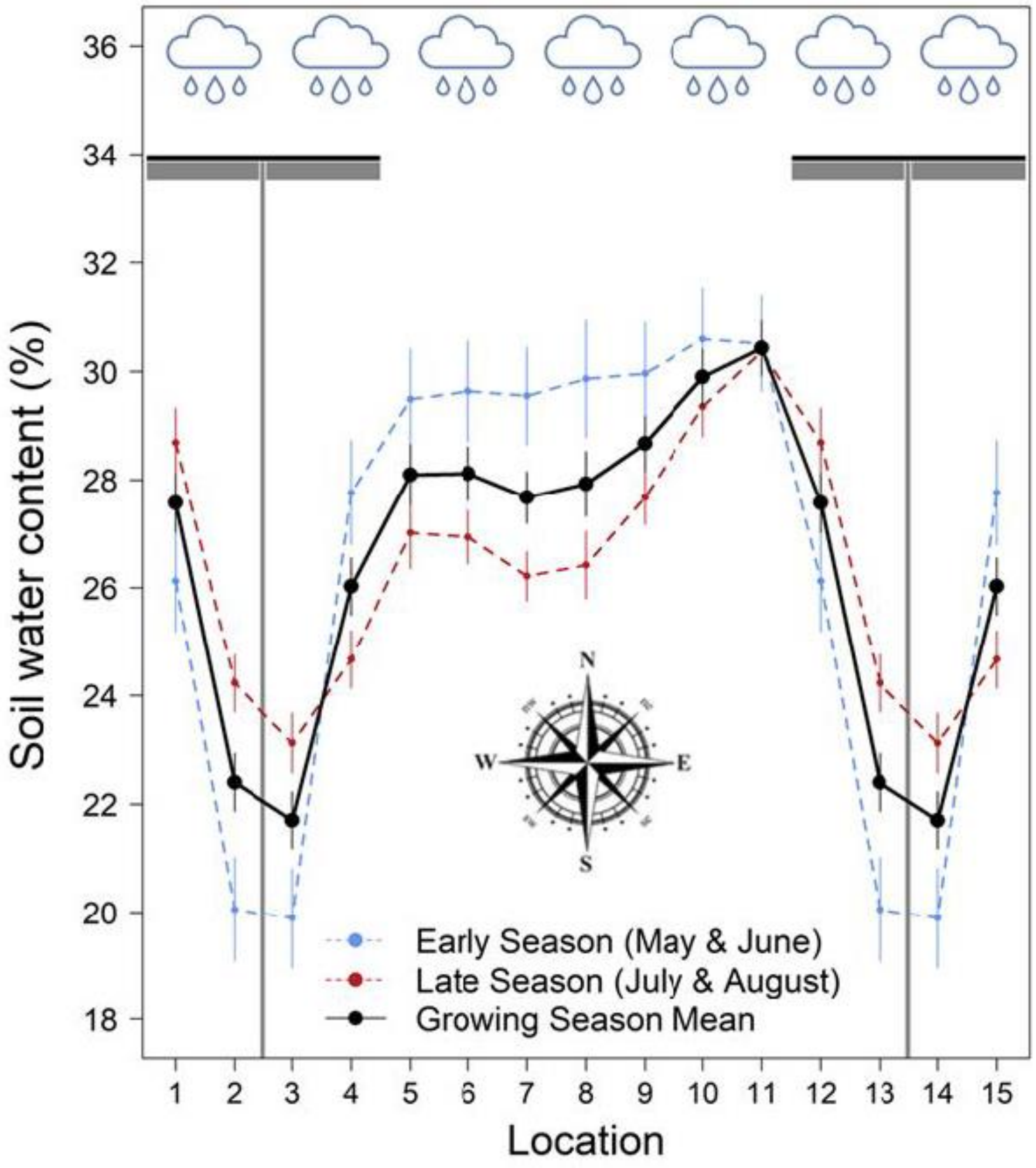
Bed A: 55-60% sun
Bed B: 65-70% sun
Bed C: 50-55% sun

Sunlight is more uniform in the **2.5 m** area, with a little more sunlight in the middle

Bed A: 57-62% sun
Bed B: 65-70% sun
Bed C: 55-60% sun

Agrivoltaic Microclimate - Water

- Agrivoltaic site in Colorado (Jack's Solar Garden)
- Seasonal soil moisture patterns under and between panels
- Panel configuration and tracking operations can affect runoff and dew
- Interplay of adjusted soil moisture, available sunlight, and temperature can affect vegetation performance



Sturchio et al., 2022

Water Management

Winter squash impacted by morning dew running off solar panels (Photo credit: Brittany Staie, NREL)

Potential Agrivoltaics Water Management Solutions

- Panel gutters/rain collection system
- Diversification – e.g., growing mushrooms along the panel edges
- Reduce agricultural production underneath panel edges

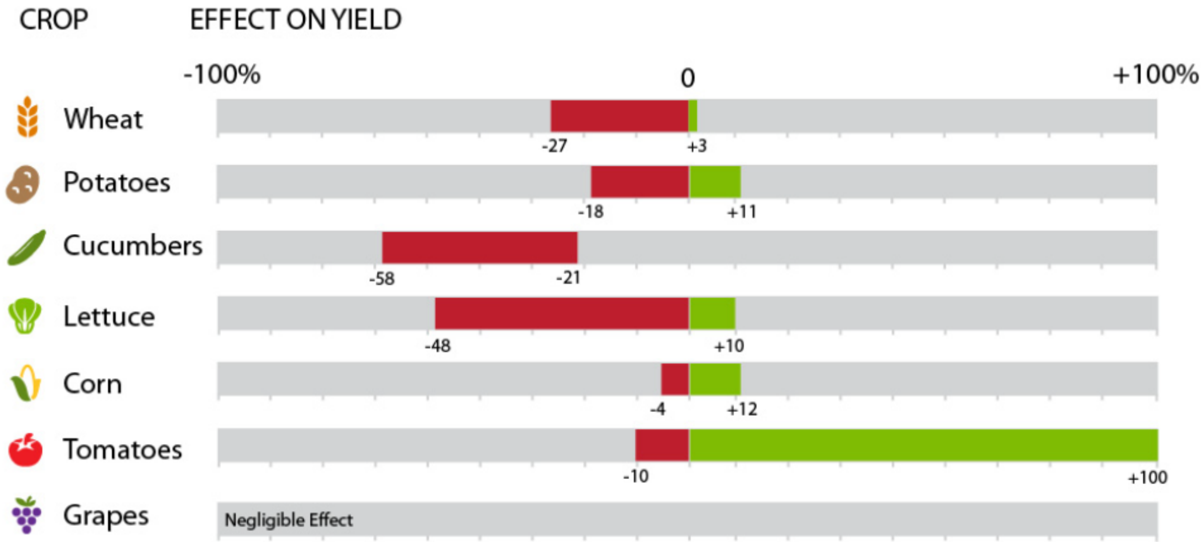
Crop Selection

- Shade tolerant vs. intolerant crops
- Preference for morning or afternoon sun
- Maturity heights of crops
- Trellising requirements
- Equipment and infrastructure needs

Shade Tolerant Crops			Shade Intolerant Crops
Full Shade	Moderate Light	Low light	
Alfalfa, arugula, Asian greens, broccoli, cassava, chard, collard greens, hog peanuts, kale, kohlrabi, lettuce, mustard greens, parsley, scallions, sorrel, spinach, sweet potatoes, taro, and yams	Beans, carrots, cauliflower, coriander, green peppers, and onions	Mushrooms	Cabbage, corn, cucumber, pumpkin, rice, tomato, turnip, and watermelon

Table adapted from [Al Mamun et al., 2022]

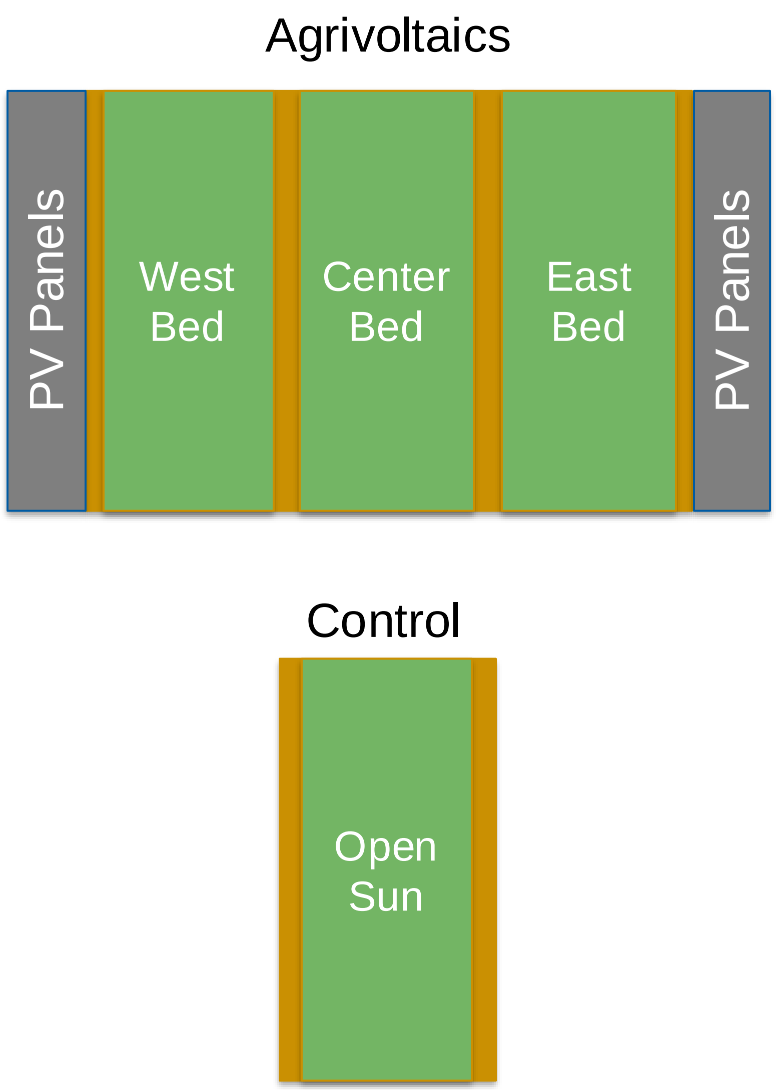
- Yield can be impacted by:
  - PV design and crop placement within the array
  - Sunlight and water availability
  - Crop variety
  - Soil health and ag management practices

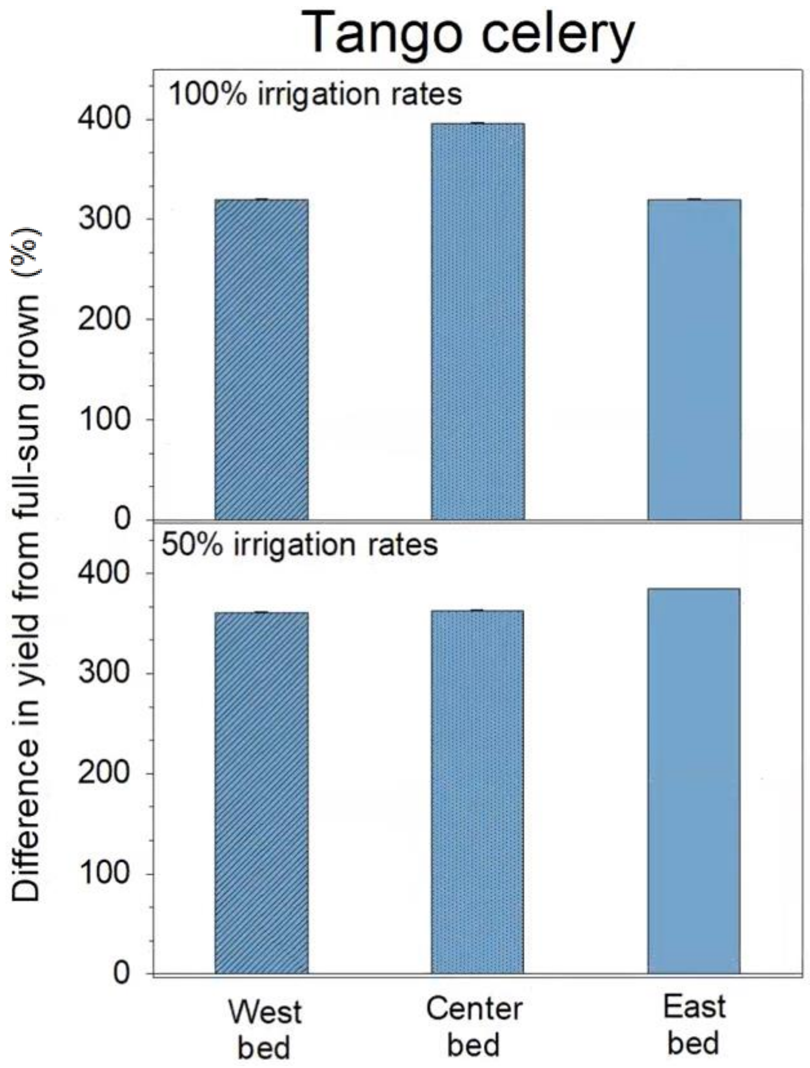


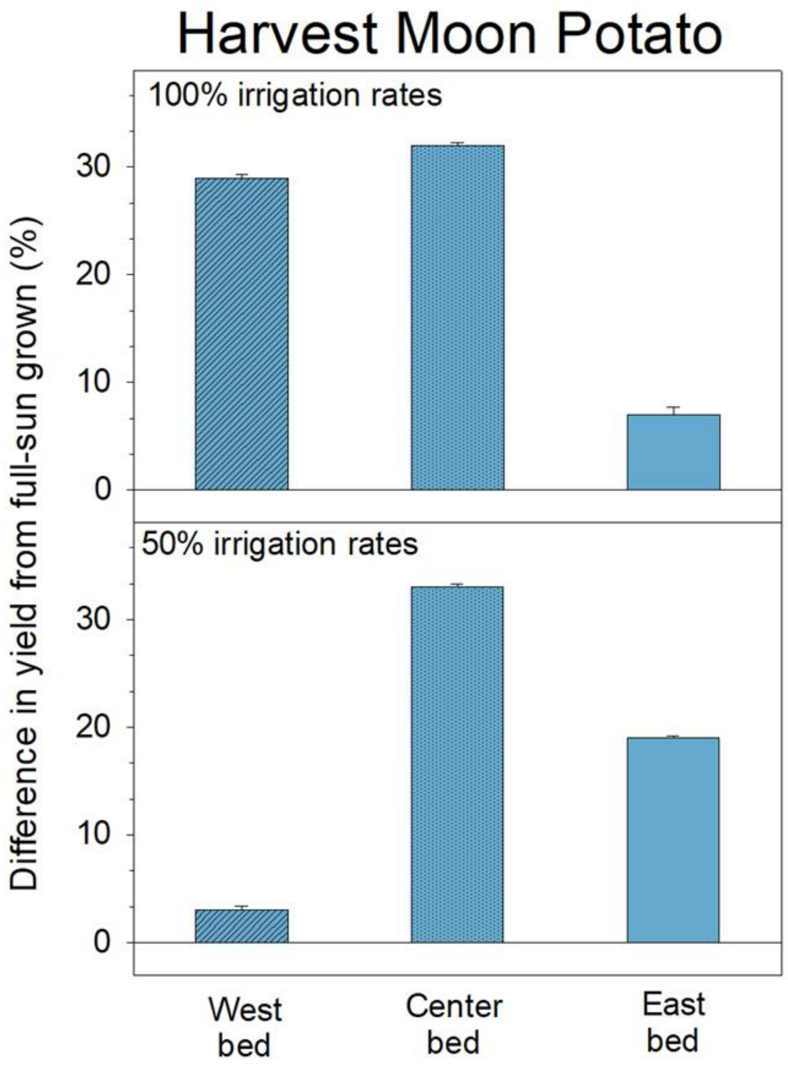
*Example results based on **reported** yield outcomes in the literature* (not controlled for configuration or climate)

Macknick et al., 2022

Crop Considerations: Results from Jack's Solar Garden

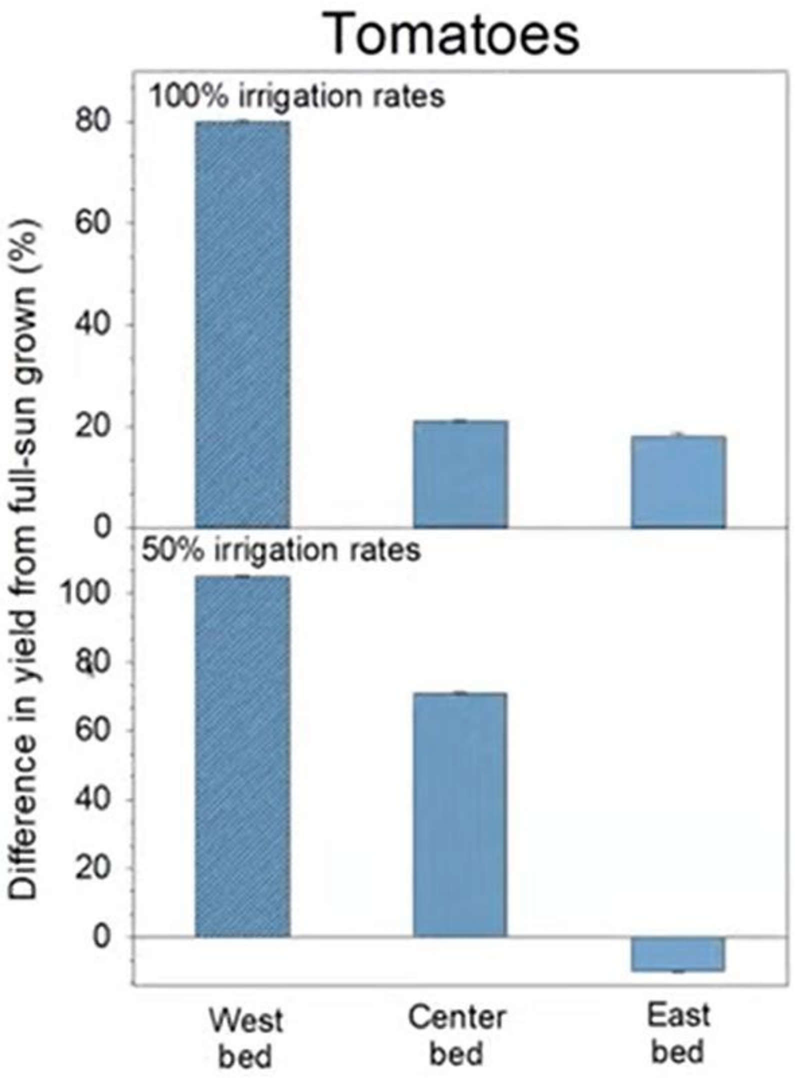


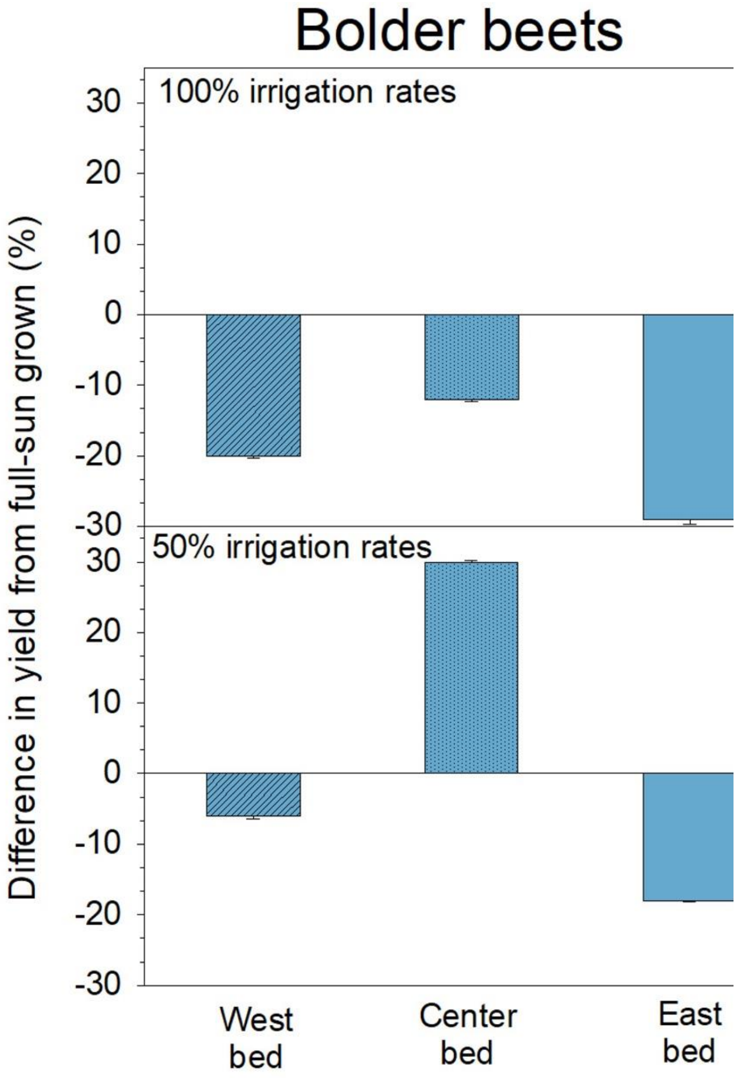


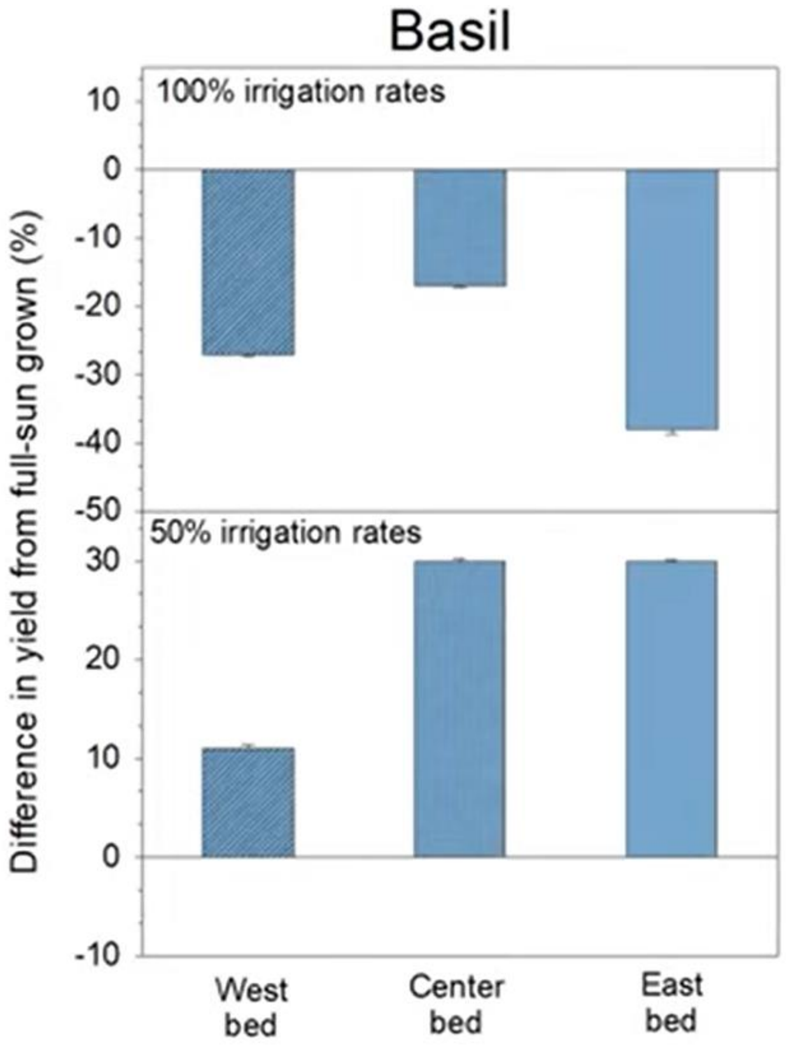


Data Source: University of Arizona

Crop Considerations: Results from Jack's Solar Garden







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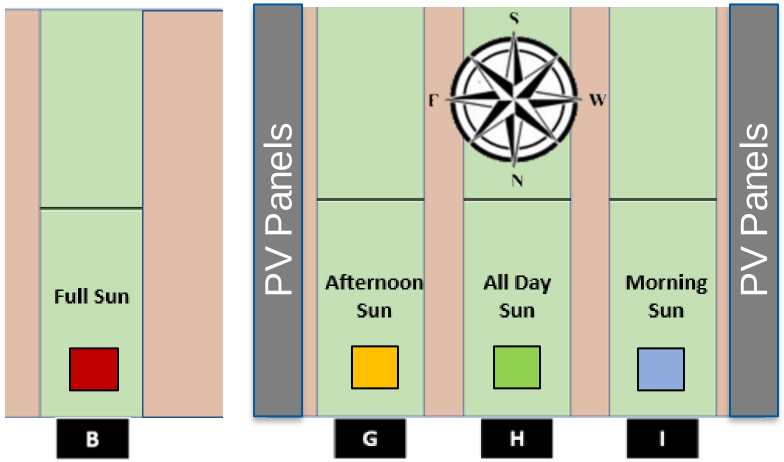
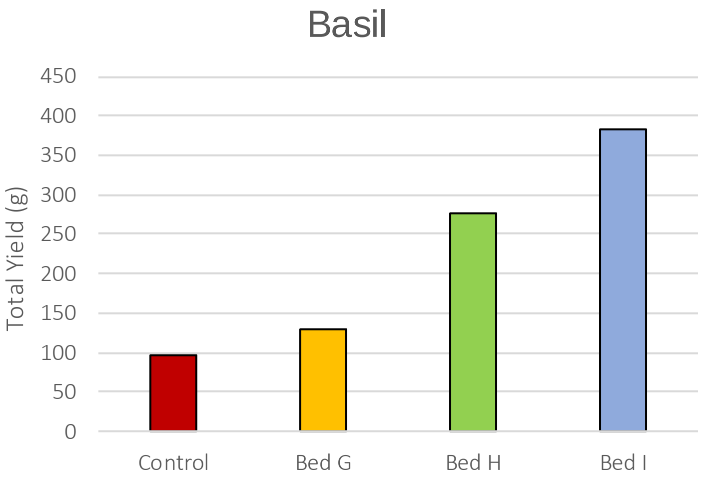
Crop Considerations: Bifacial Agrivoltaics Research at NREL (BARN)

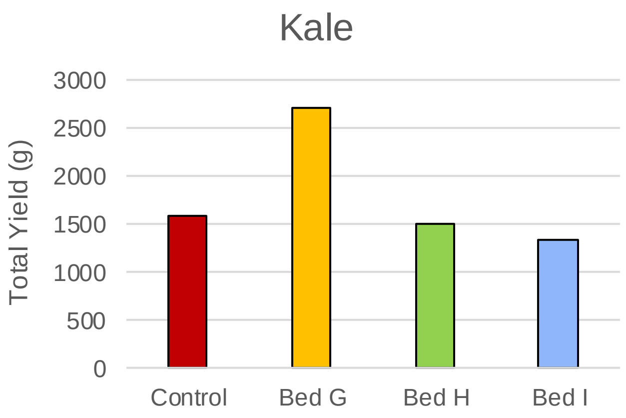


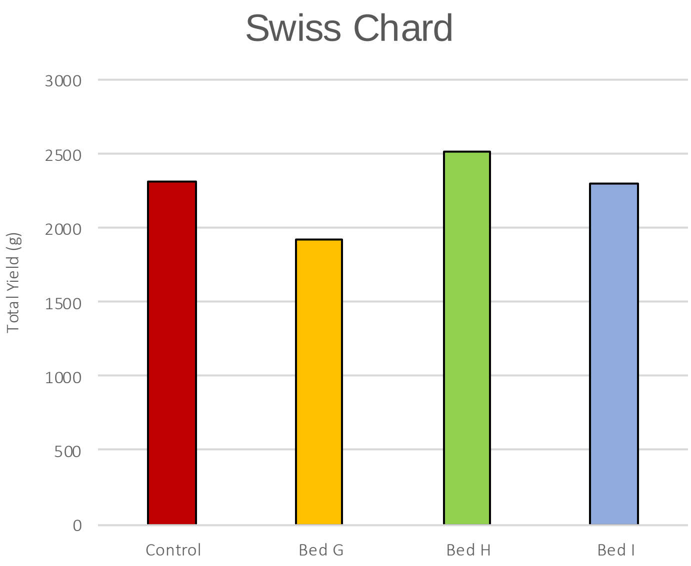
Control Plot

Agrivoltaics Plot

Researchers harvest swiss chard at the Bifacial Agrivoltaics Research at NREL site (Photo credit: Joe DelNero, NREL)







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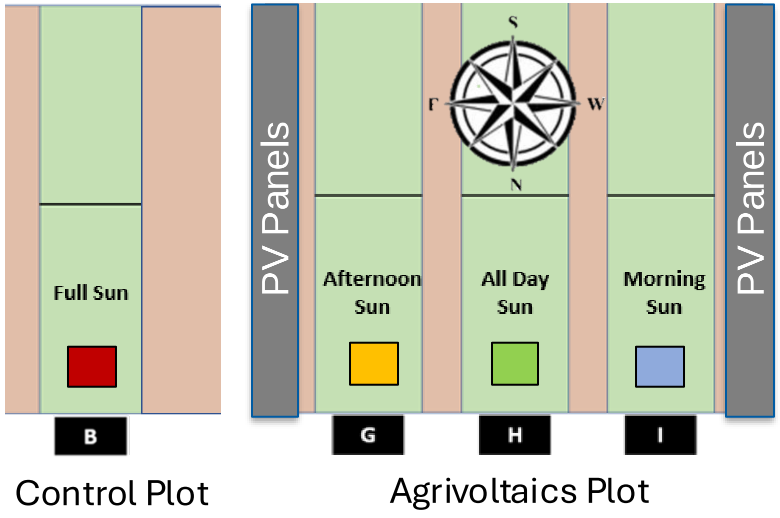
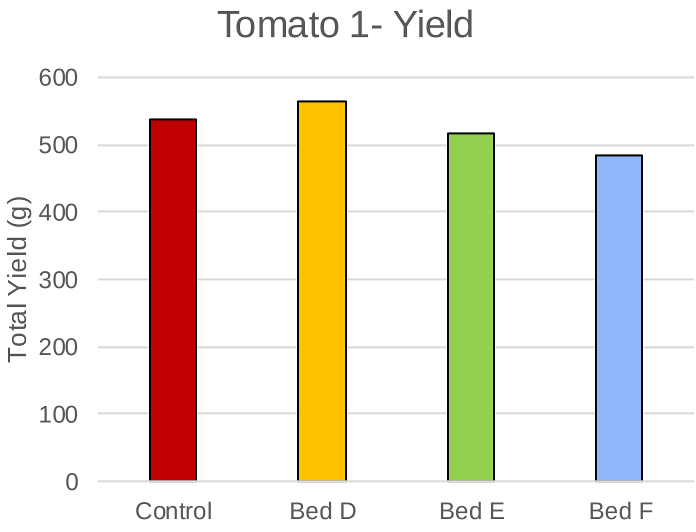
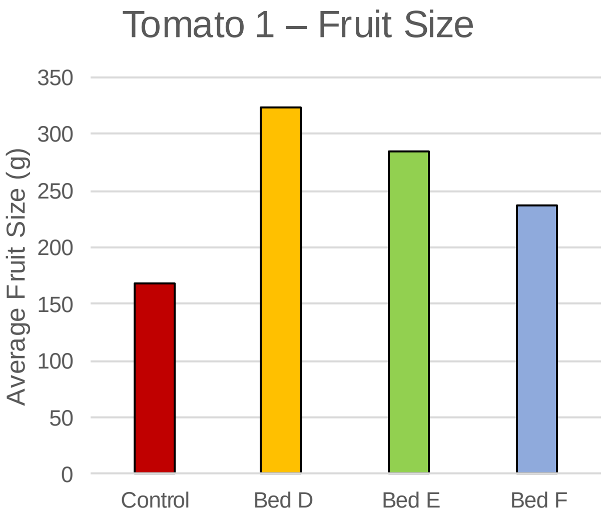
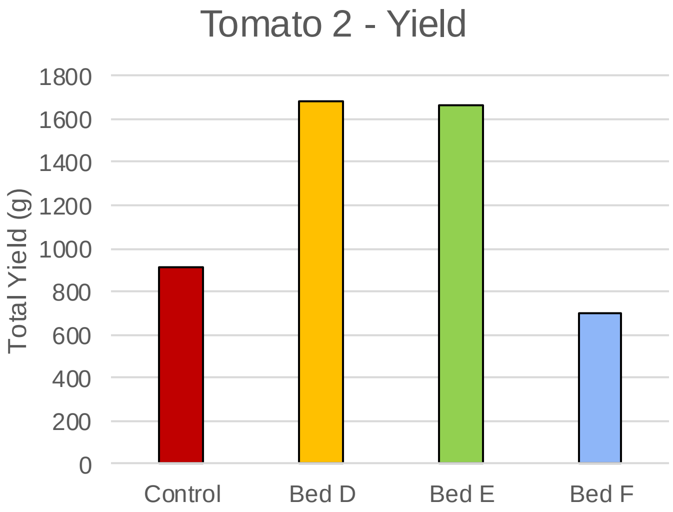
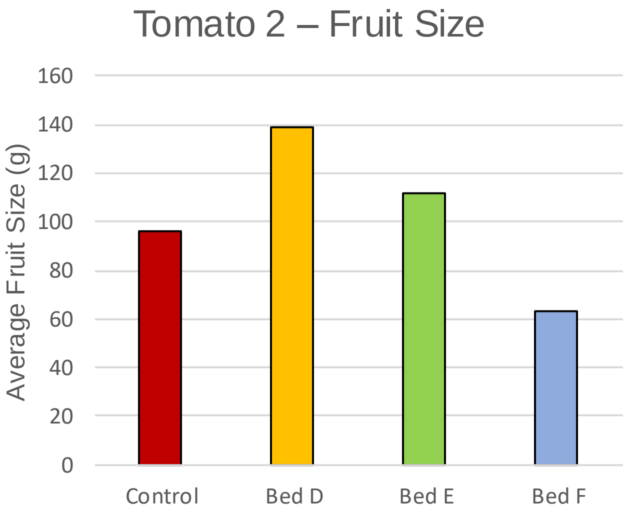


Tomatoes grow between solar panels (Photo credit: Werner Slocum, NREL)









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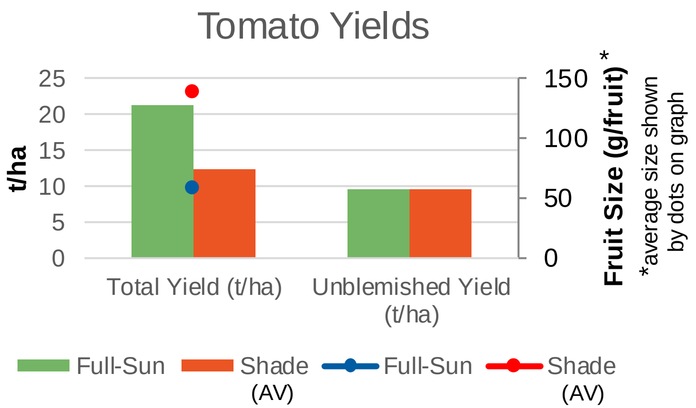
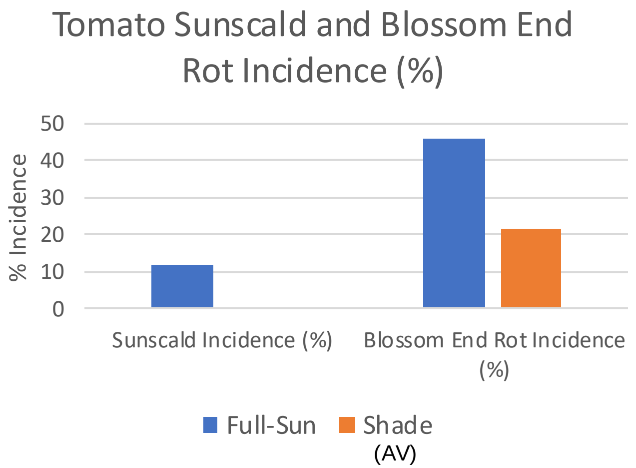
Crop Considerations: Oregon State University

- Dry farming techniques
- 20+ cultivars of tomatoes and potatoes
- Conventional utility-scale solar design
- Two beds of crops in between each row of panels
- Examining how agrivoltaics can reduce blossom end rot in tomatoes





Preliminary Results—Do Not Cite

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Crop Compatibility Summary

- Agrivoltaic designs should take into account compatibility of desired crops
- Agrivoltaics will create a microclimate that can impact locally compatible crops
  - Yield
  - Seasonality
  - Marketability
  - Taste
- Local demonstration sites will be the way to fully understand site specific agrivoltaic crop compatibility

Kohlrabi grows under solar panels (Photo credit: Brittany Staie, NREL)

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Environmental Impact and Sustainability

- Regenerative Agriculture in Agrivoltaic Systems
  - No till
  - Cover cropping
  - Diversified crop rotation
  - Organic amendments (e.g., compost)
  - Rotational grazing
- Irrigation reduction potential
- Biodiversity conservation with pollinator habitat
- Increased production of zero-carbon solar electricity

Farmer rakes compost at Jack's Solar Garden (Photo source: Bryan Bechtold, NREL)

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Agrivoltaics Agritourism Opportunities

Farm Dinners

Local Artist Showcases

Concerts

Fitness Classes

Legislation Signings

Photo Sources: Brittany Staie, NREL and Werner Slocum, NREL

Agrivoltaics Educational Opportunities

Public Tours

K-12 Tours

Art Classes

Science Classes

Solar Developer Workshops

Photo Sources: Werner Slocum, NREL and Gregory Cooper, NREL

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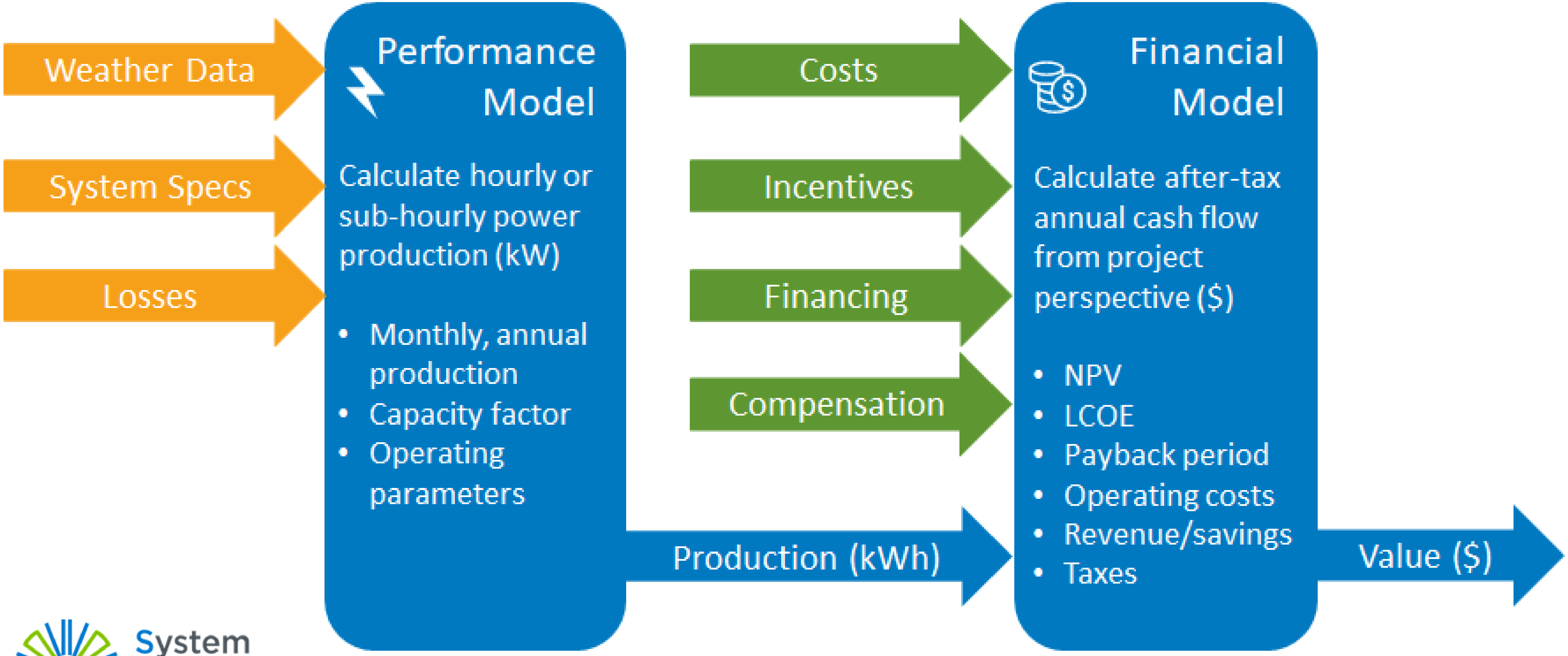
Part 2: Technical Parameters for Developing an Agrivoltaics Project

PV Feasibility Study



System Advisor Model

https://sam.nrel.gov/

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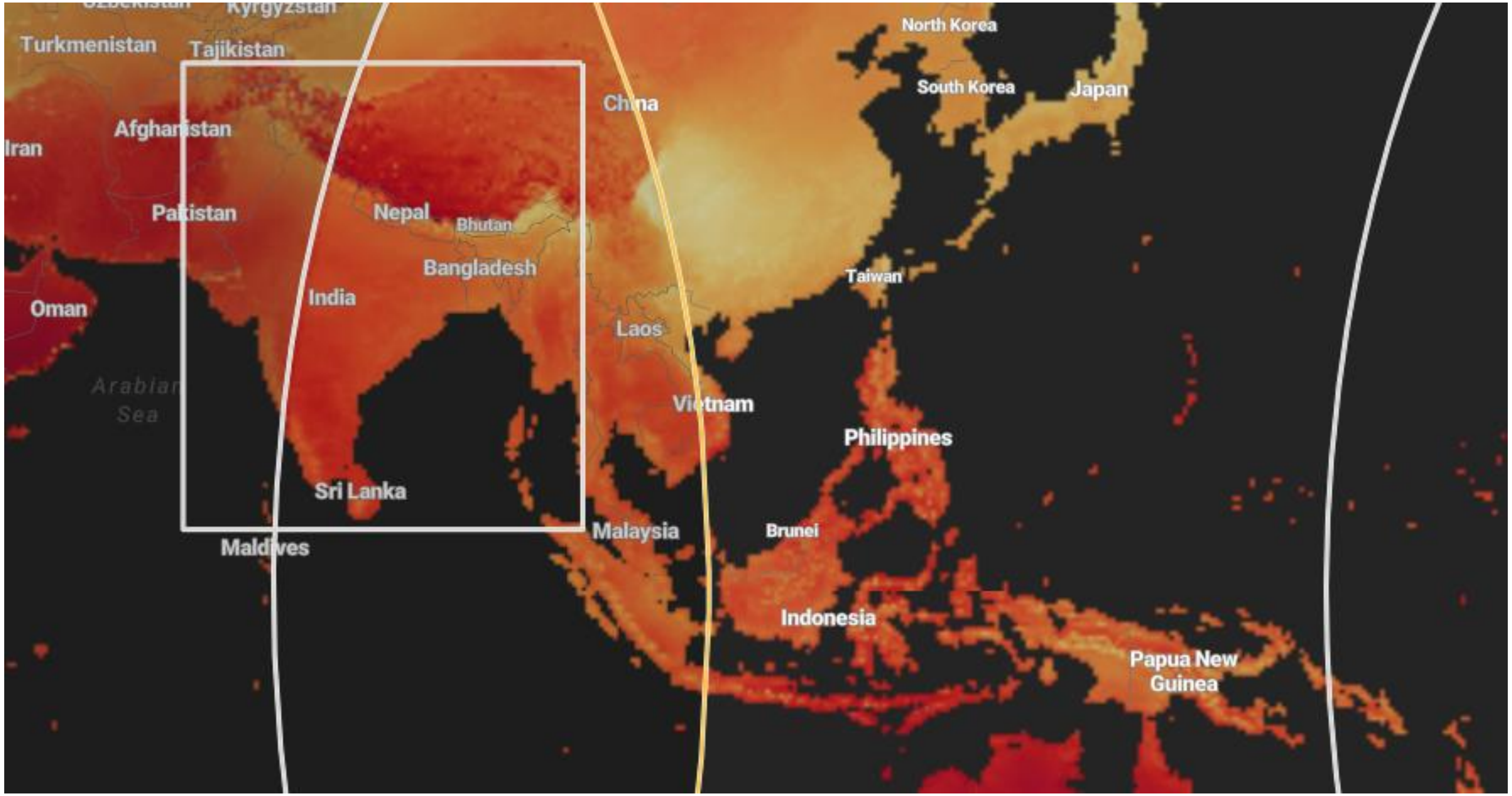
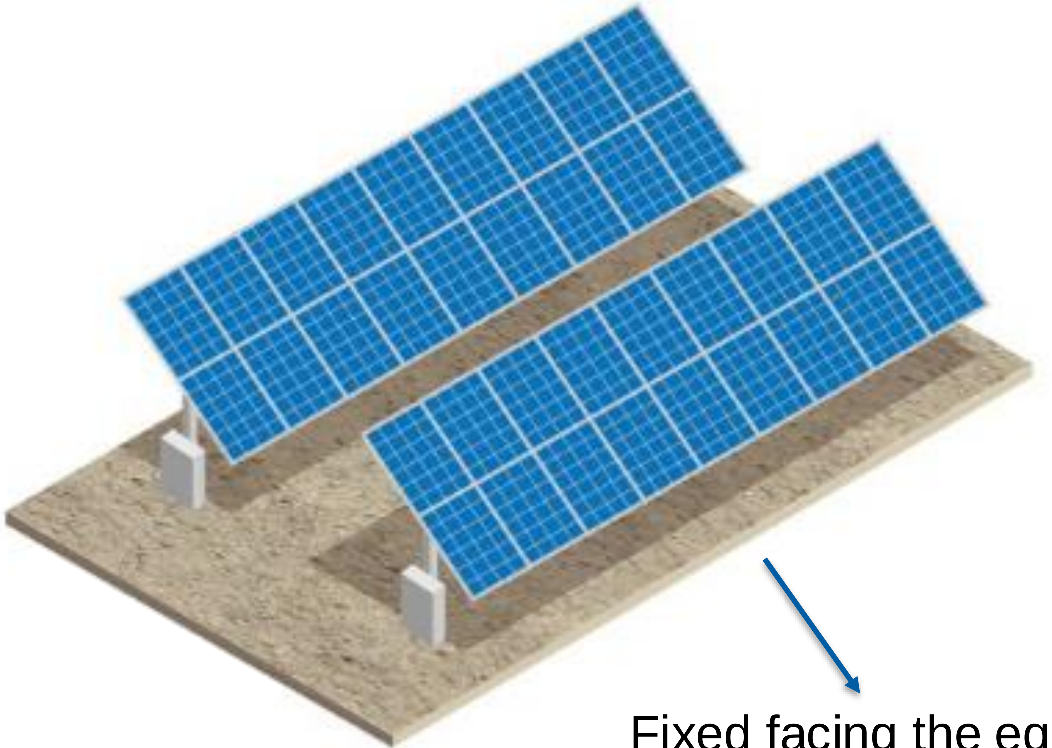
PV Feasibility Study: Data Availability



https://nsrdb.nrel.gov/

Racking Systems

Fixed-Tilt

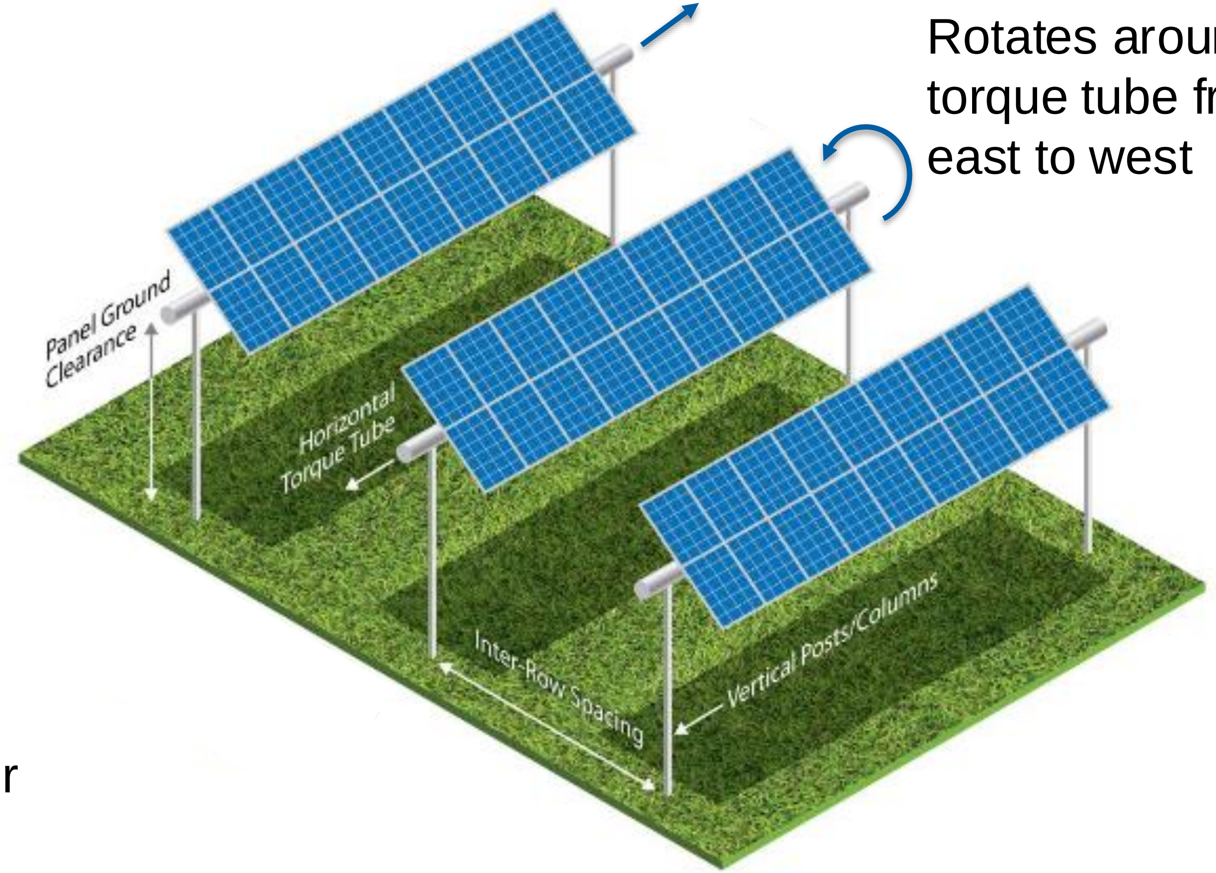


Fixed facing the equator

1-Axis racking

North

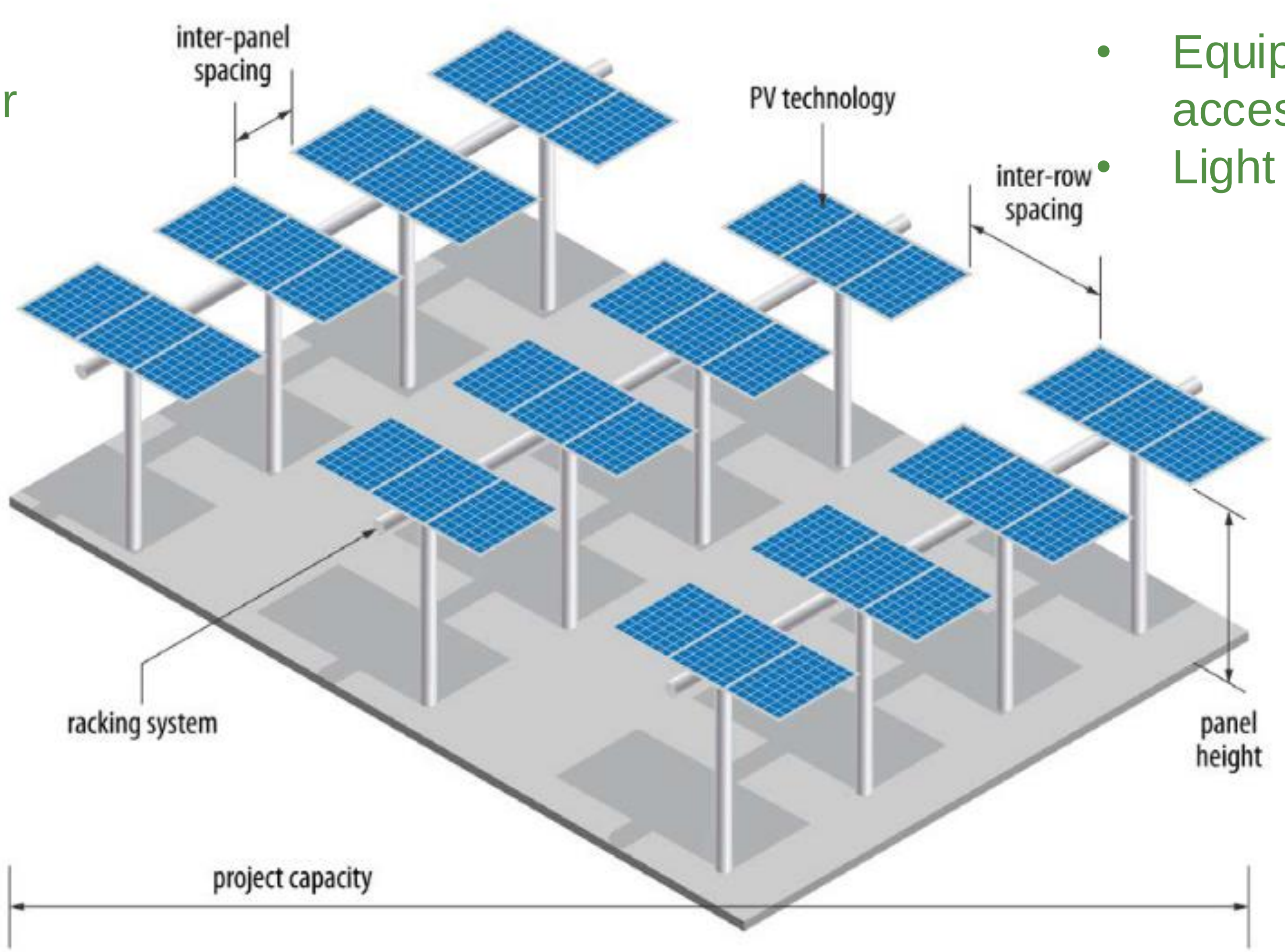
Rotates around torque tube from east to west



Kelsey Horowitz, Vignesh Ramasamy, Jordan Macknick and Robert Margolis. 2020. *Capital Costs for Multi-Land Use Photovoltaic Installations*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-77811 https://www.nrel.gov/docs/fy21osti/77811.pdf

Changing Configurations for Agrivoltaics

- More light diffusion for crops



- Equipment and labor access
- Light availability

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

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Macknick et al. 2022. 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

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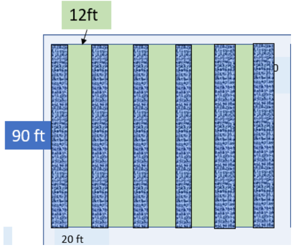
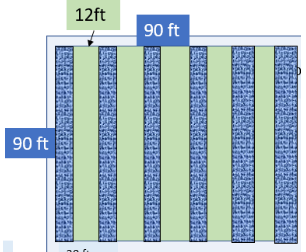
- Least ergonomic for farmers and lower compatibility with a range of agricultural equipment



Elevated Panels, Traditional Row Spacing

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



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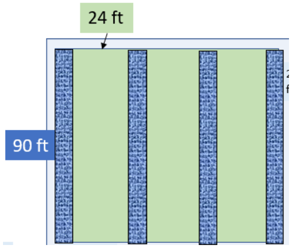

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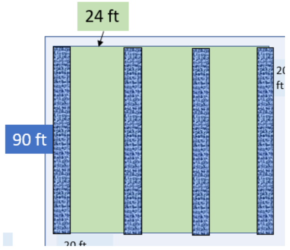

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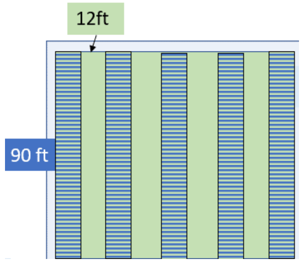

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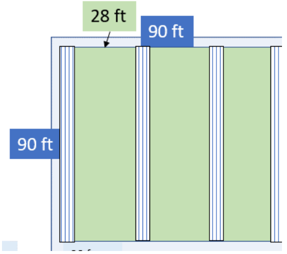
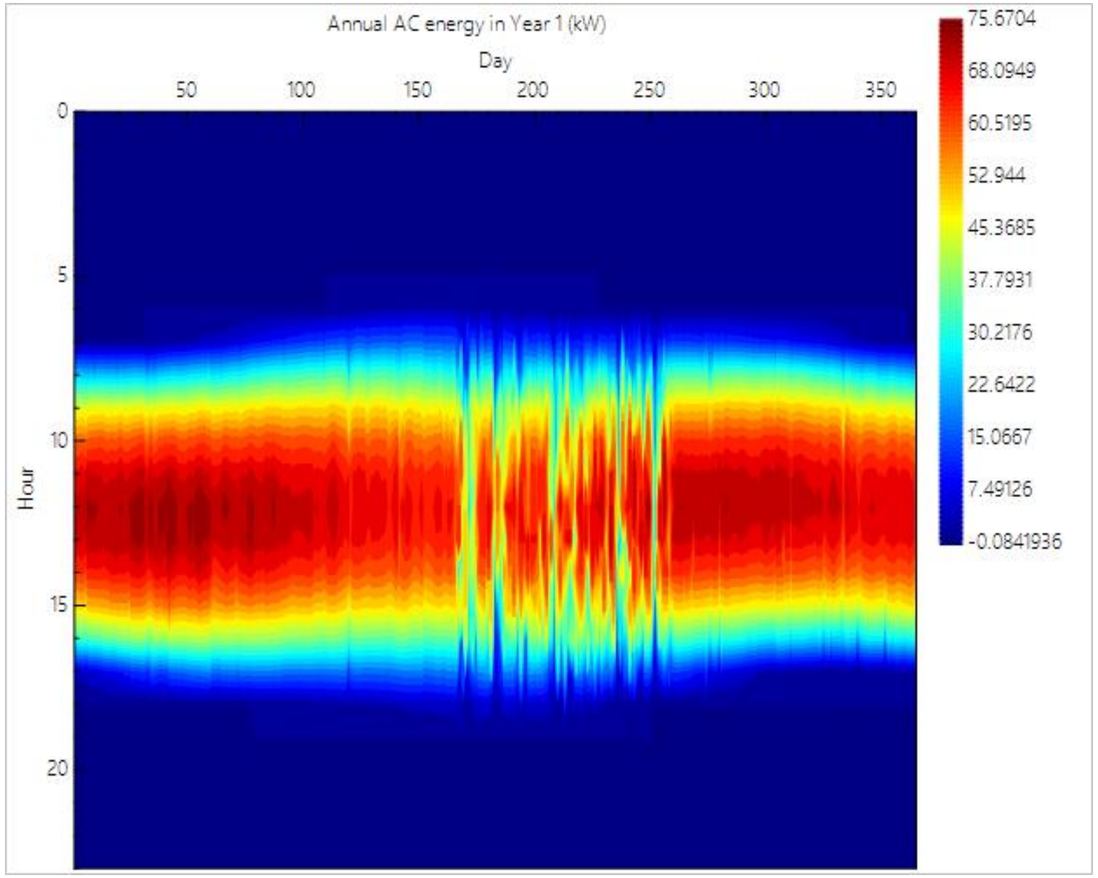
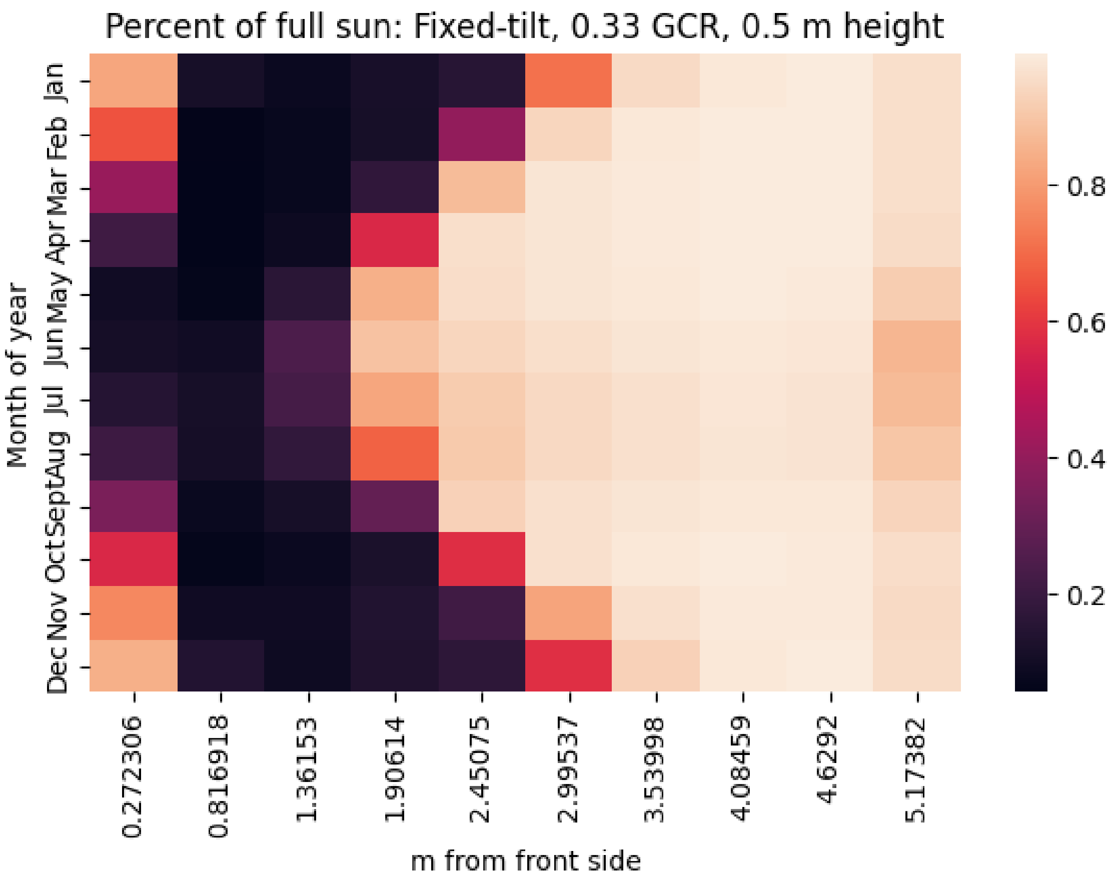


Case Study:

- Standard Design: 100 kW DC array
- Fixed at 22.3 deg, South facing
- Restrict other designs to approximate land area as traditional design (0.144 hectares)
- Compare energy production, space for equipment, available light

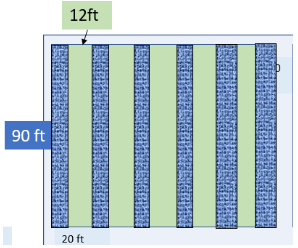


Standard Height and Spacing



South North

Parameter	Value
System Size	100 kW-dc
Annual Energy Production	170,761 kWh
Space between rows	3.65 meters
Height of Panels (front)	0.5 meters



System Advisor Model

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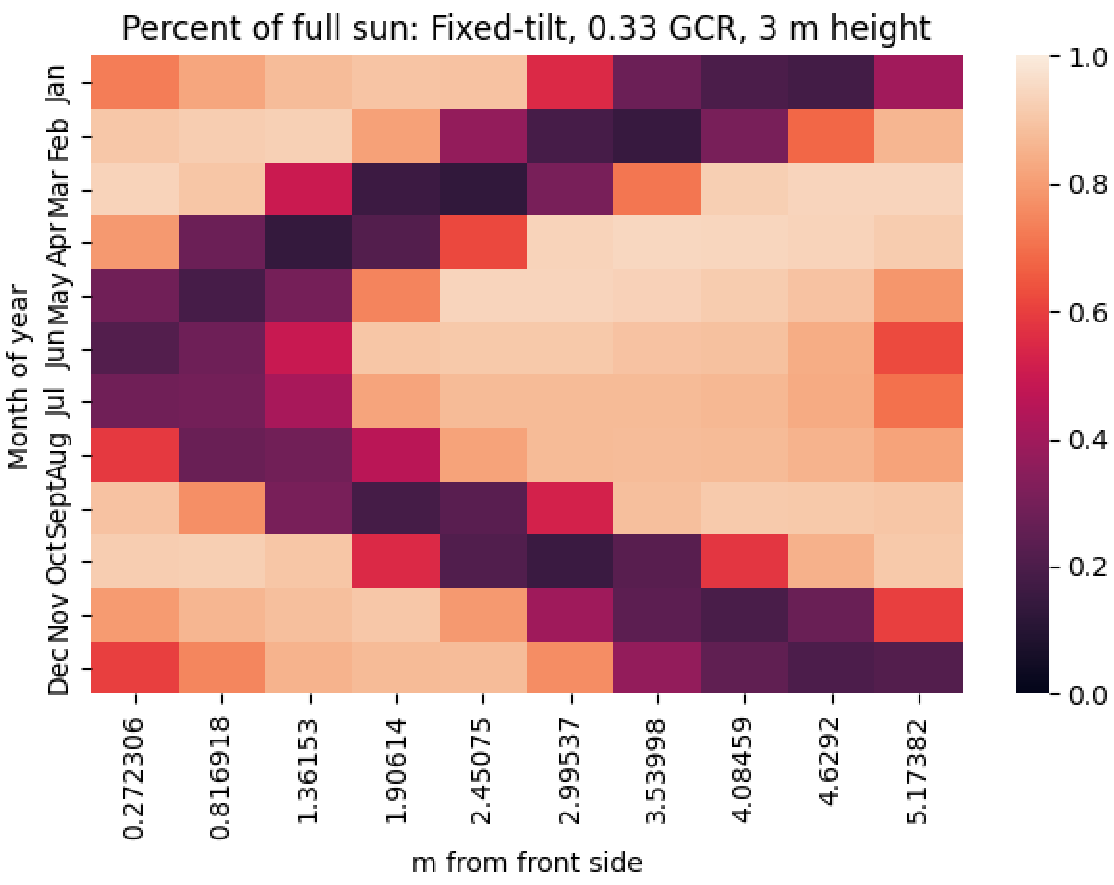
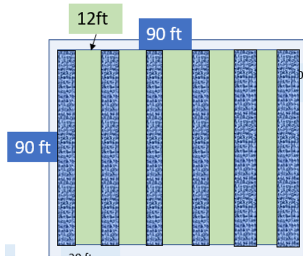
Elevated Panels, Standard Spacing

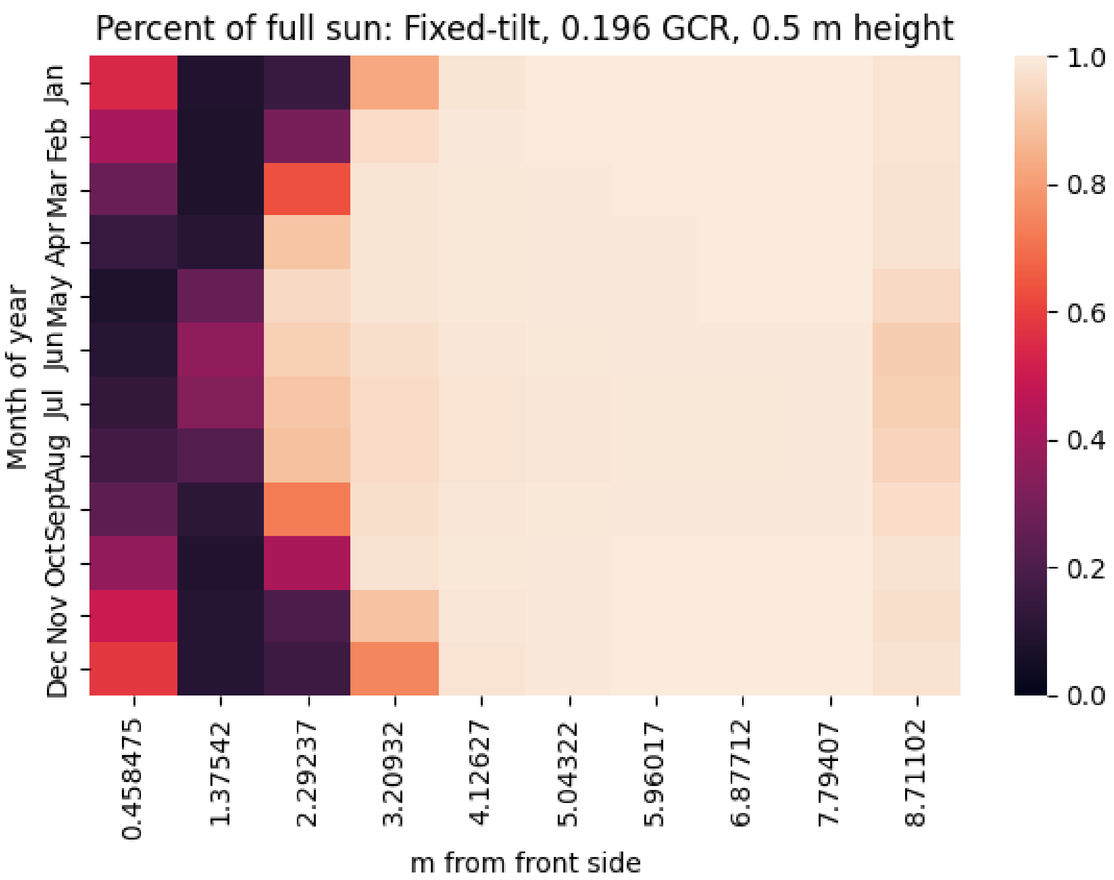


South North

Parameter	Value
System Size	100 kW-dc
Annual Energy Production	176,458 kWh
Space between rows	3.65 meters
Height of Panels (front)	3 meters



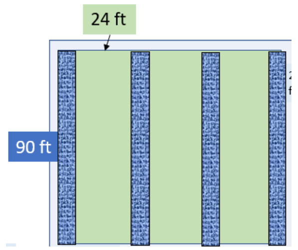
Standard Height, Wider Rows



South

North

Parameter	Value
System Size	48 kW-dc
Annual Energy Production	82,581 kWh
Space between rows	7.3 meters
Height of Panels (front)	0.5 meters



System Advisor Model

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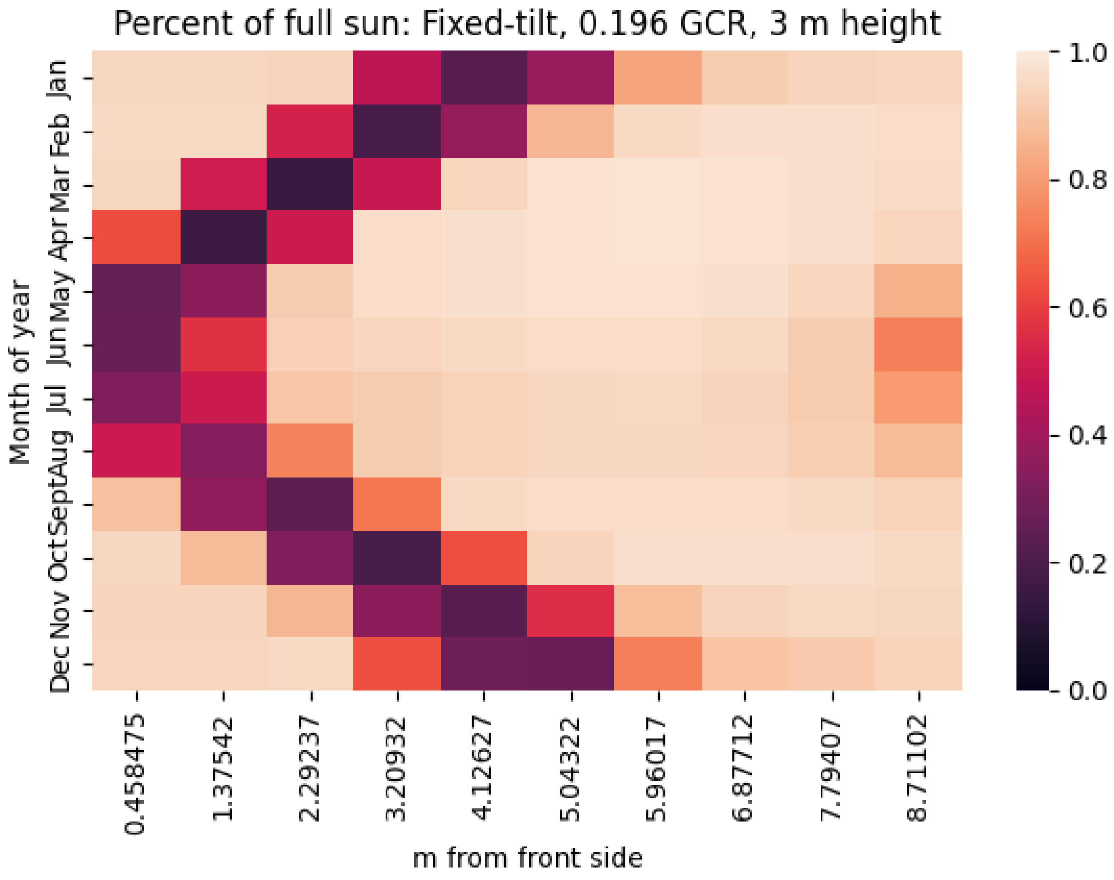
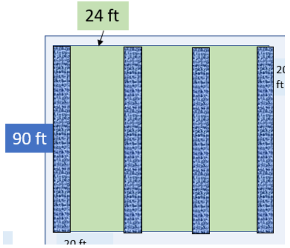
Elevated, Wider Rows



South

North

Parameter	Value
System Size	48 kW-dc
Annual Energy Production	86,290 kWh
Space between rows	7.3 meters
Height of Panels (front)	3 meters



System Advisor Model

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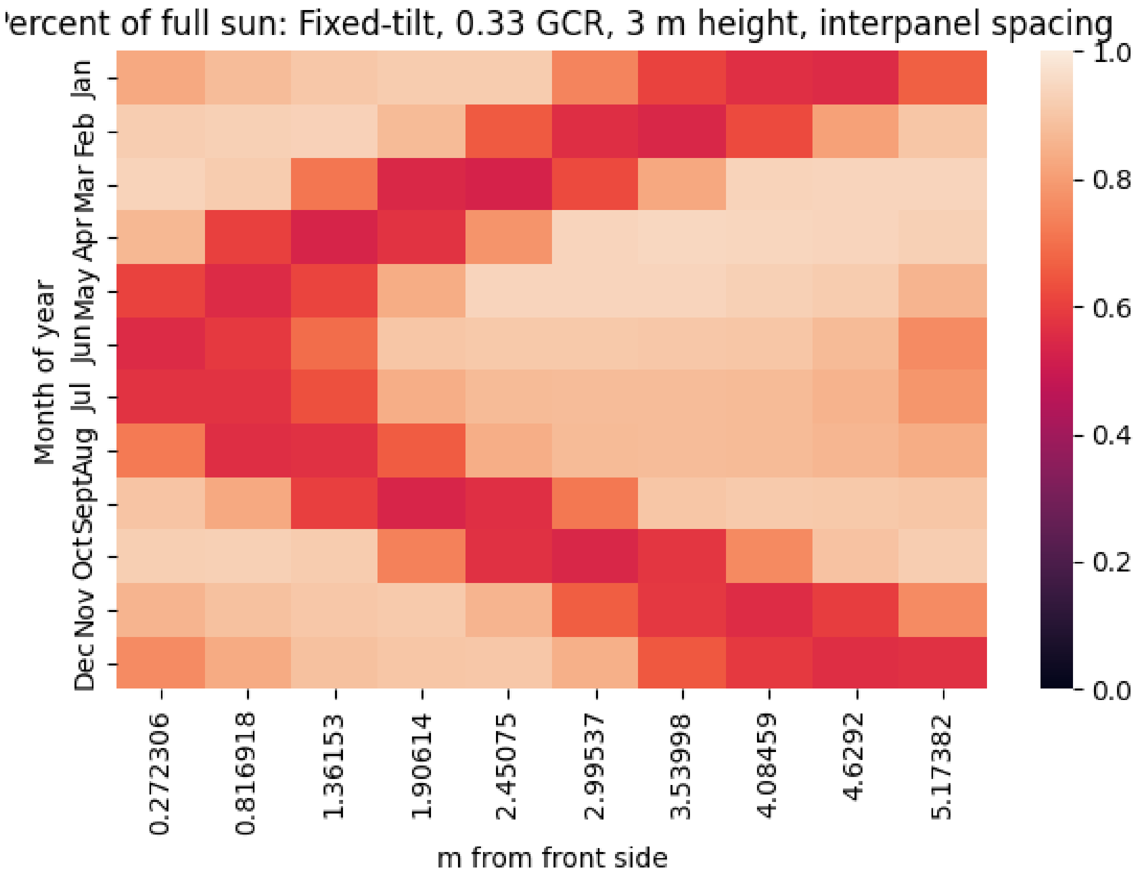
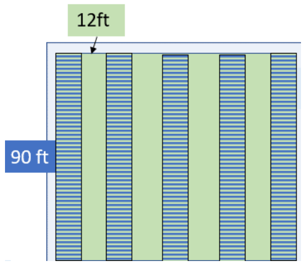
Elevated Panels, Inter-panel spacing



Parameter	Value
System Size	48 kW-dc
Annual Energy Production	86,487 kWh
Space between rows	3.65 meters
Height of Panels (front)	3 meters

South

North



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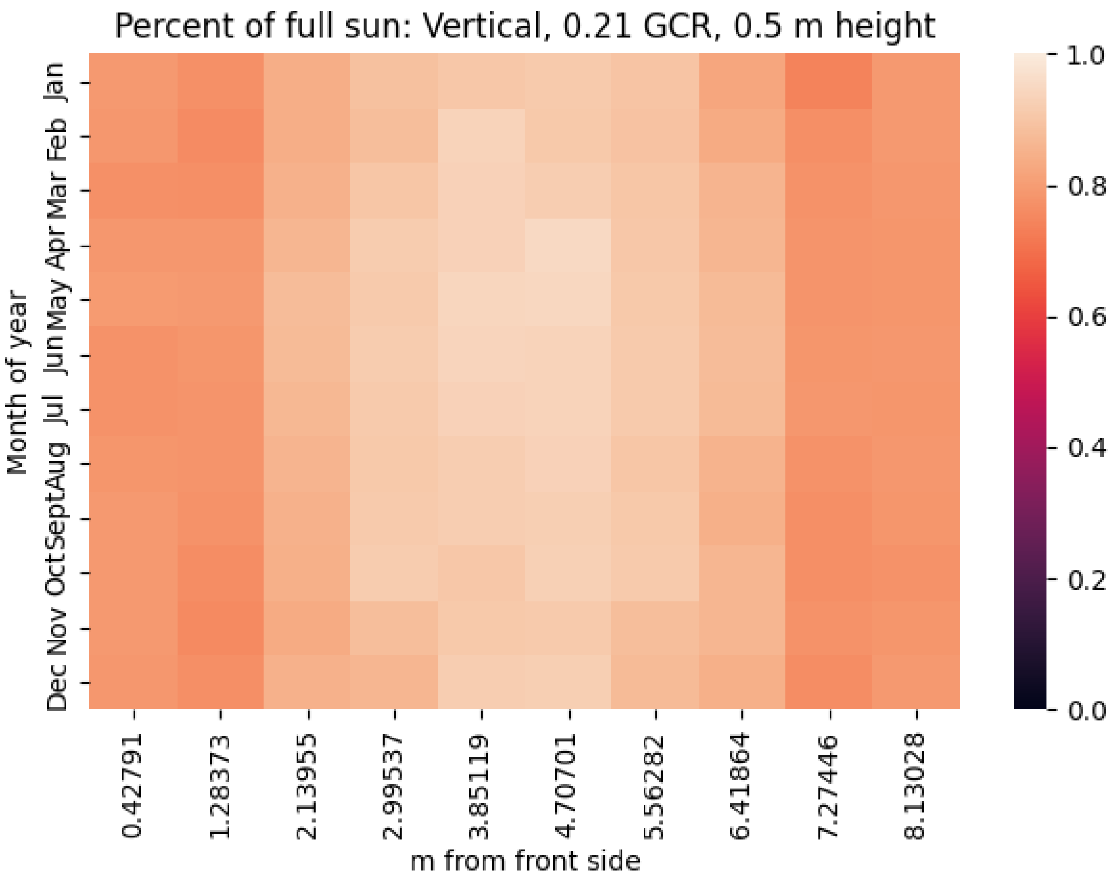
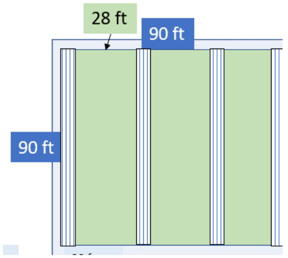
Vertical Bifacial

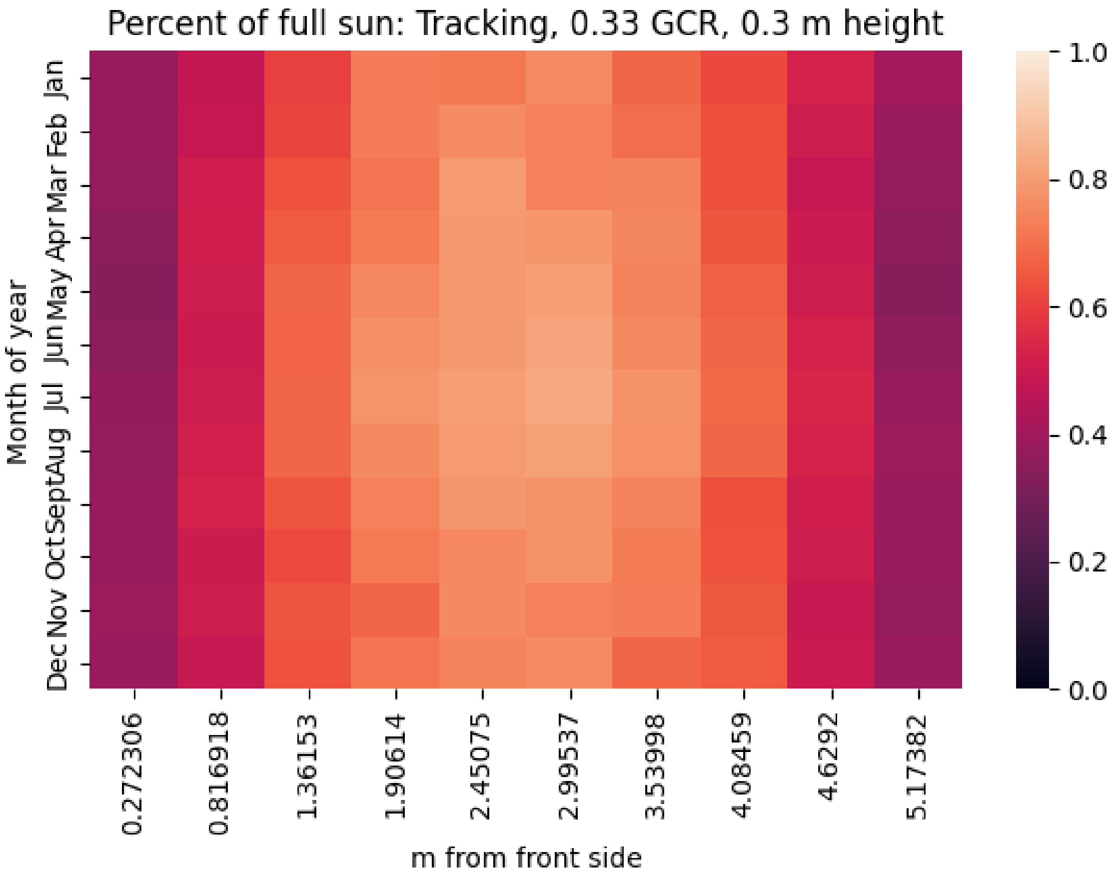


East West

Parameter	Value
System Size	64 kW-dc
Annual Energy Production	84,034 kWh
Space between rows	8.5 meters
Height of Panels (front)	0.5 meters



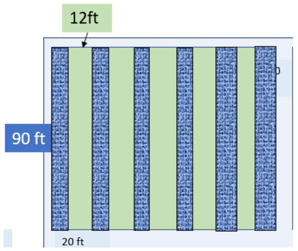
Standard Spacing: Tracking



East

West

Parameter	Value
System Size	100 kW-dc
Annual Energy Production	194,251 kWh
Space between rows	3.65 meters
Height of Panels (max tilt)	0.3 meters



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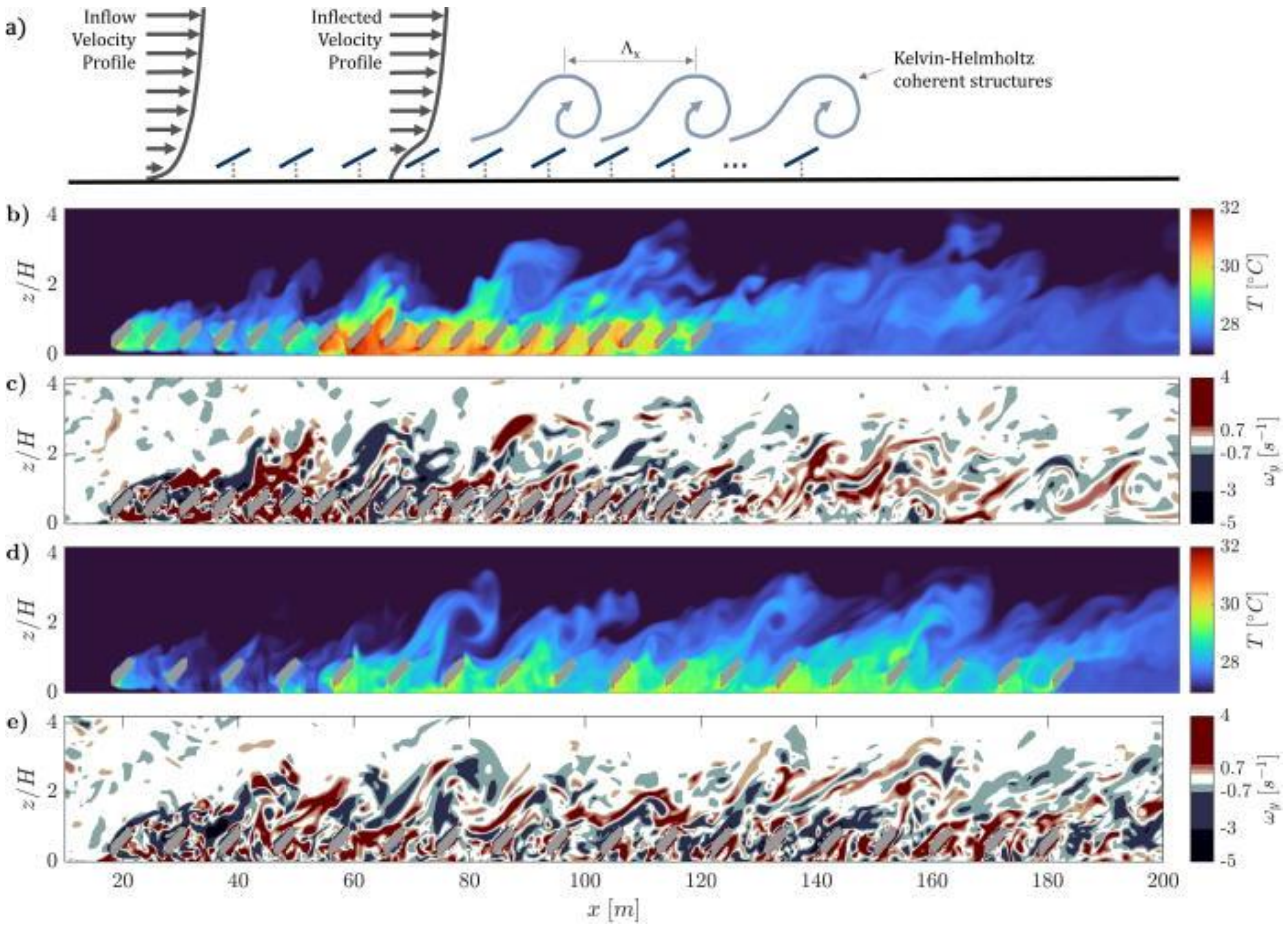
Configuration, Heat, and PV Performance

- Panels perform better at lower temperatures
- Interplay of panel temperature and crops depends on location
  - More arid: larger panel temperature decrease with irrigation
- Panel temperature also depends on PV configuration
  - Larger, tightly packed array with bare ground can create heat island
  - Wider row spacing decreases panel temperature



Stanislawski, Brooke J., et al. "Row spacing as a controller of solar module temperature and power output in solar farms." *Journal of Renewable and Sustainable Energy* 14.6 (2022).

Technology and Equipment Selection

- General PV Considerations
  - Wind and snow loads
  - Component reliability and warranty
  - Height of electrical equipment for flood risk
  - Panel & Inverter voltage compatibility
  - Planned use of the energy (local load or grid power)
  - Pairing with battery for resilience or energy shifting
- Additional Agrivoltaic Considerations
  - Potential additional shading from crops
  - Crop tracking needs

Tilling of the soil at a monofacial agrivoltaic array (Photo credit: Joe DelNero, NREL)

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Installation and Integration

- Farmland protection during construction:
  - No soil grading
  - No predrilling
  - No concrete
- Clearly marking where heavy machinery is allowed to operate
  - Training may be required to inform workforce why this is important
- Ensuring safety for humans and livestock
  - Wire management: tradeoffs with suspended versus buried wires

An example of overhead wire management at Jack's Solar Garden (Photo credit: Bryan Bechtold / NREL)

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Monitoring and Maintenance

- Farming/grazing staff on site provides additional opportunities to spot issues (stuck trackers)
- Climate and soiling:
  - Locations with infrequent rain and high particulate matter can accumulate soiling, resulting in solar production losses
    - Rain may be sufficient to clean
  - High pollen requires manual cleaning
- Agrivoltaics may mean water is available onsite to assist with cleaning
- Agrivoltaics may create additional soiling from farm equipment

Ongoing maintenance at an agrivoltaics array (Photo credit: Werner Slocum, NREL)

https://www.nrel.gov/pv/soiling.html

Bessa, João Gabriel, et al. "An Investigation on the Pollen-Induced Soiling Losses in Utility-Scale PV Plants." *IEEE Journal of Photovoltaics* (2023).

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Examples of Novel Agrivoltaic Technologies and Designs

- Novel racking systems
  - Tracker control software
  - "Anti-tracking" for an agricultural focused design
  - Up to a 180-degree rotation for washing panels
  - Shorter trackers (as low as 8 panels)
- Semi-transparent panels
  - Allows more sunlight to filter through the panels to the crops below
  - Increases range of compatible crops
- Gutter systems
  - Gutters can be used to fill cisterns to support redistribution of water for irrigation
- Canopy designs
  - Tall (~4.5 m) PV designs that can be placed over orchards and other tall crops
  - Allows for the integration of tall agricultural equipment
  - Can provide hail and frost protection

Elevated agrivoltaic system with gutters at Yeungnam University, South Korea (Photo source: Jordan Macknick, NREL)

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Part 3: Financial Planning Required for Deployment of an Agrivoltaics Project

Financial Planning

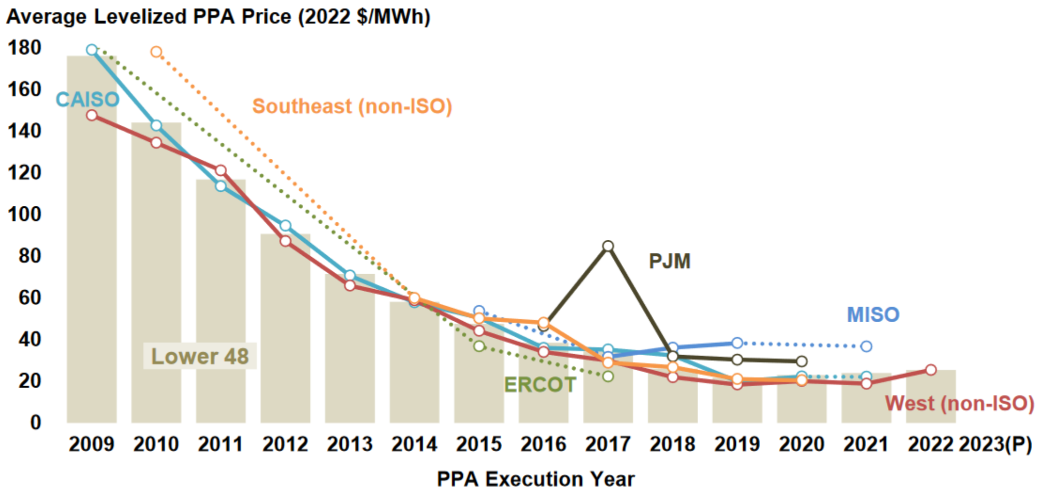
- Who owns the land?
- Who is doing the farming/grazing?
- Who will own the solar project?
- Different ownership/leasing models available depending on the answer to these.
  - Land can be leased to the solar company: lower risk but lower revenue for the landowner
  - Solar owner can contract with farmers/grazers or hire them directly
- Is there a sufficient return (or payback period) to the system owners?
- Is there enough revenue to cover any debt?
- Does the ownership model impact incentives?

- Case study: Silicon Ranch Snipesville Solar Ranch:
  - Snipesville, Georgia, USA
  - 300 MWac
  - 1600+ sheep
  - 8 agricultural workers directly employed by solar company

  https://www.siliconranch.com/stories/replicating-agrivoltaics-in-a-big-way

Who is buying the energy?

- Behind the meter (offset load):
  - Energy used on-farm or nearby
  - Net metering allowed in some jurisdictions
  - May limit size of the array
    - Typically, not allowed to produce more than annual load pre-install
- Front of meter (sell to grid):
  - Long term power purchase agreement helpful for receiving financing
  - Community solar subscriptions can increase revenue relative to wholesale market

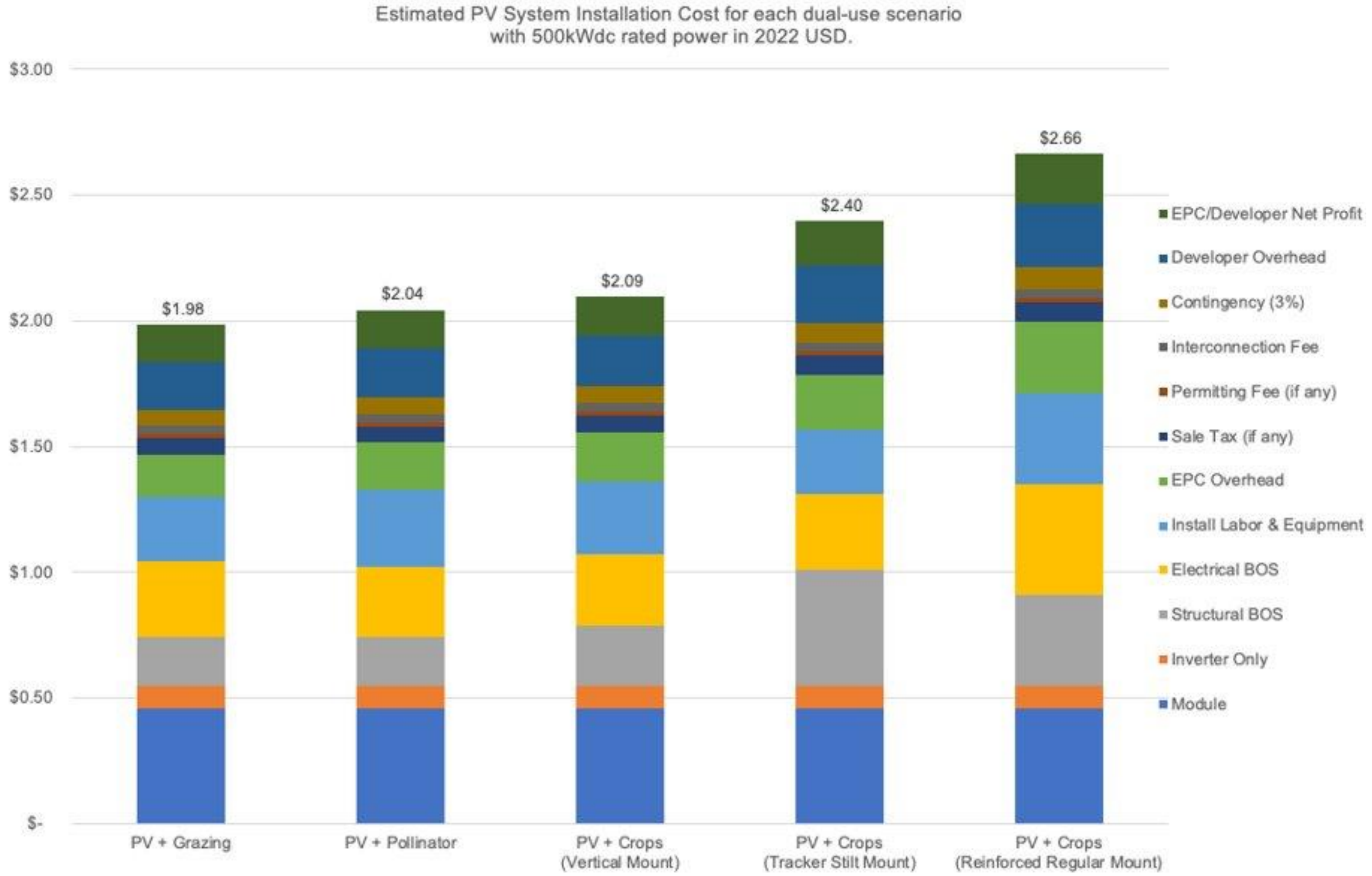


Bolinger, Mark, et al. "Utility-Scale Solar, 2023 Edition: Empirical Trends in Deployment, Technology, Cost, Performance, PPA Pricing, and Value in the United States." (2023).

Cost Factors to Consider for Agrivoltaics

Capital Cost Considerations

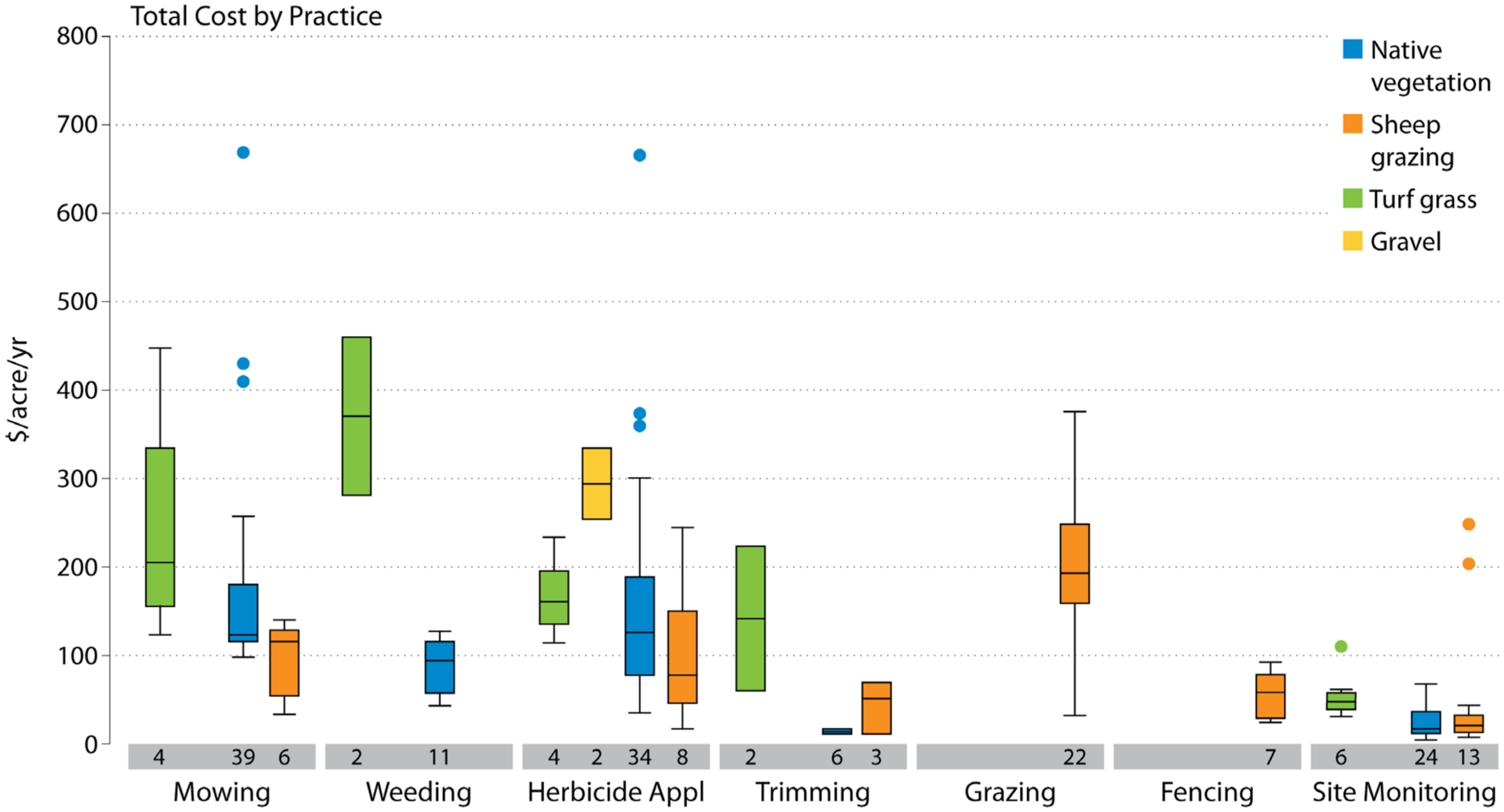
- Module type and equipment
- Panel height
- Racking/Tracking system
- Land acquisition costs
- Installation labor costs
- Site preparation costs



Kelsey Horowitz, Vignesh Ramasamy, Jordan Macknick and Robert Margolis. 2020. *Capital Costs for Multi-Land Use Photovoltaic Installations*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-77811 https://www.nrel.gov/docs/fy21osti/77811.pdf

Results are for 500-kW systems. Results can vary at lower and higher installed capacities

O&M Cost Analysis for Utility-Scale PV



Key Notes

- Survey of >100 different PV sites across multiple years
- Specific activities needed can vary from site to site
- Costs can change each year due to vegetation evolution

McCall, J.; Macdonald, J.; Burton, R.; Macknick, J. Vegetation Management Cost and Maintenance Implications of Different Ground Covers at Utility-Scale Solar Sites. *Sustainability* **2023**, *15*, 5895. https://doi.org/10.3390/su15075895

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Risks and Mitigation Strategies: Physical

- Physical risks:
  - Hail: some mitigation with stowing panels at a steep angle
    - Panels can protect crops from small hail
  - Fires: site design (underground wires, fireproof enclosures), defensible space
  - Floods: Raise equipment
  - Storms: fixed tilt systems can tolerate higher winds, other hardening techniques available
  - Agrivoltaics interaction between people, livestock, and the equipment: mitigate with design and training

Farmer drives tractor underneath solar panels at Jack’s Solar Garden (Photo credit: Werner Slocum, NREL)

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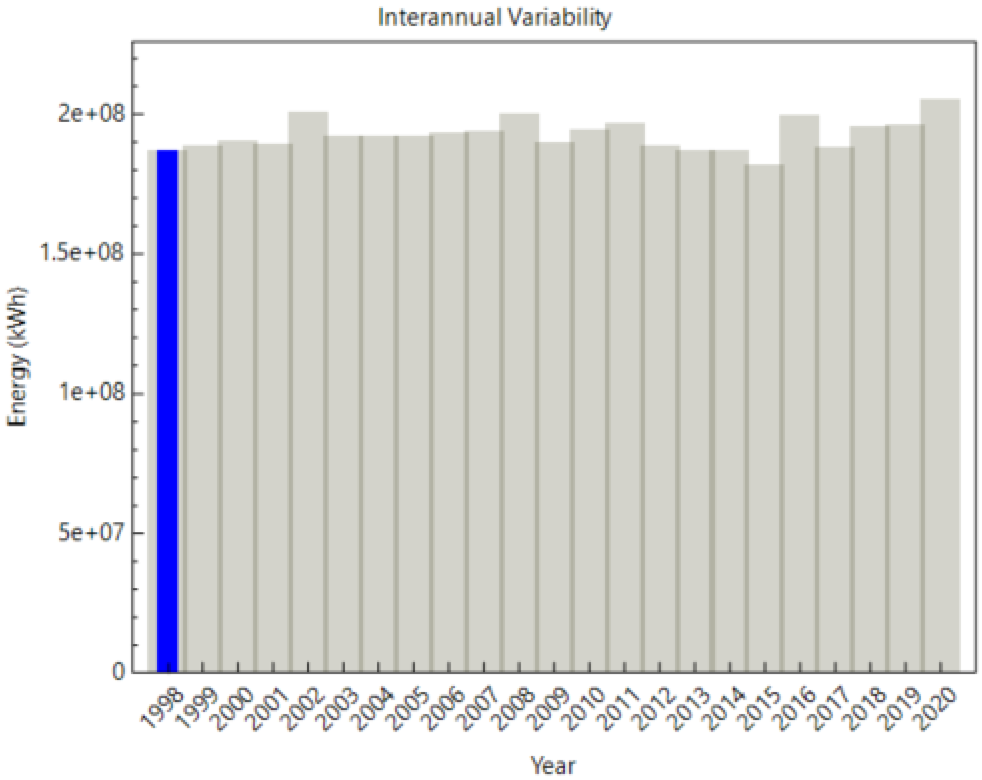
Risks and Mitigation Strategies: Performance

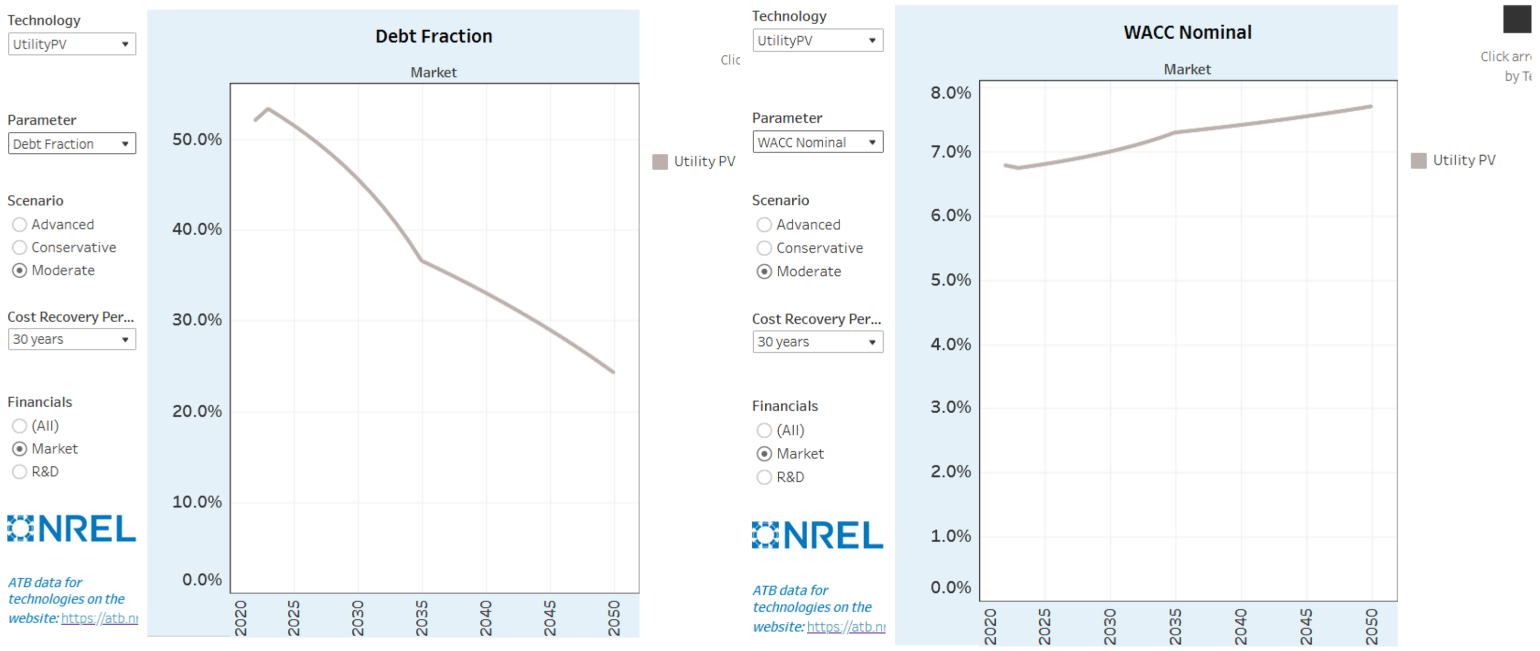
- Performance risks:
  - Interannual variability
    - Planning to meet debt in worst year
    - Understanding typical meteorological year versus specific year data
  - Component outages
    - Improved monitoring to quickly address issues
    - Planning reserve accounts or warranties for component replacements (panels last longer than inverters)



Interannual variability for a simulated 100 MW-dc system in Lakewood, Colorado

Debt Equity Issues

- Equity typically requires a higher return than debt interest
- Debt requires stronger guarantee of revenue
  - Modeling the uncertainty associated with the project
  - (in the US) unlikely obtain debt based on tax credits
- Unclear if or how crop revenue enters into these agreements



As debt fraction decreases over time (based on anticipated US tax structures), WACC increases over time (source: https://atb.nrel.gov/electricity/2024/financial_cases_&_methods)

Thank you! Questions?

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Brian Mirletz: Brian.Mirletz@nrel.gov

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