Sustainably Co-locating Agricultural And Photovoltaic Electricity Systems (SCAPES)

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Dr. Mwebaze works on iSEE's Sustainably Colocating Agricultural and Photovoltaic Electricity Systems (SCAPES) project, studying the economic balance between agricultural and photovoltaic systems. SCAPES is a new project funded by the U.S. Department of Agriculture, at $10M over four years.

Dr. Mwebaze holds a master's and Ph.D. in Agricultural Economics

SCAPES

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University of Illinois, Urbana-Champaign

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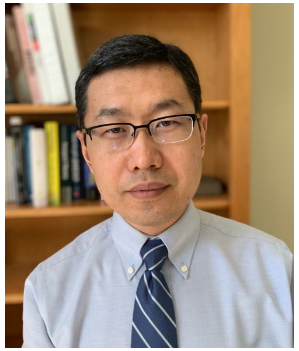
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Motivations for this research

- Agrivoltaics (AV) considered a promising strategy for reducing the competition for land with solar energy by
  - Allowing dual use of land
  - Potentially increasing crop yield under extreme heat and precipitation
  - Preserving soil moisture
  - Producing higher value use for land
  - Diversifying returns to land
- Costs and Benefits yet to be quantified in the case of row crops in the Midwest
  - Specific requirements in terms of panel height and spacing to allow
    - Conventional farm equipment
    - Row crops: soybeans and corn
  - Effects of shade on row crop yields yet to be analyzed

Source: Solar Farm 2.0

Relevant research questions

- AV at field scale: Implications compared to Photovoltaics (PV) or crops alone
  - For productivity of land: measured by Land Equivalent Ratio
  - For land requirement compared to PV or crop production for producing a given amount of electricity and bushels
  - For profits per acre for PV developer and for farmer individually and jointly
- At regional scale: Considering spatial heterogeneity
  - What are the arable land requirements for meeting regional targets for solar energy using PV vs AV?
  - What the optimal locations for PV and AV?
  - What is the extent of crop production displacement with PV vs AV?
- Farmer and PV developer level willingness to adopt AV
  - Incentives for adoption of AV
  - Conditions and types of decision makers

Integrated Interdisciplinary Modeling for Spatially Explicit Economic Analysis

1. Spatially varying solar radiation- NREL's Rev Model
2. Spatially varying availability of land – USDA's CDL data/Kaiyu Guan
3. Agronomic aspects of AV configuration at field scale – DK Lee
4. Crop modeling of effects of shading on crop yields at large scale- Kaiyu Guan's group
5. Solar engineering modeling of effects of shading on crop yields at field scale – Nenad Miljkovic's group
6. Economic analysis of Levelized Cost of PV/AV generation and crop production at field and regional scales – Economic Modeling Team and NREL's SAM model

Economics of AV for solar developer:

- If solar developer and farmer each cares only about their individual profits and each manages their portion of the field
  - Developer pays rent for non-cropped portion of the field; farmer manages vegetation cover on non-cropped portion of the field
- Solar developer assumed to adopt AV with a given space-height configuration if the
  - Profit per acre from PV ≤ Profit per acre from AV
  - Adoption of AV involves
    - Higher CAPEX per acre due to raising panel height
    - Lower vegetation management cost; partial field rental payment
  - Transmission cost with PV vs AV:
    - Density and capacity of transmission network
    - Large scale AV will spread PV thinly over space
    - Raise transmission cost and be limited by transmission capacity
- Loss in profits with AV compared to PV represents the subsidy needed: Investment tax credit, production tax credit

Farmer adoption of AV:

- Farmer adopts AV if
  - Profit per acre from AV ≥ Profit from leasing land for PV alone ≥ Profit per acre from crops alone
  - With AV:
    - Higher rent on leased portion of the field to PV production
    - Yield effect on the cultivated portion of the field due to partial shading which could be positive, negative or zero
    - Loss of land underneath panels that cannot be farmed
- Loss in profits with AV vs PV for farmer will be the subsidy needed for the farmer to adopt AV: Conservation program payment

Profit Sharing by developer and farmer

- If landowner is PV producer and crop producer, they will adopt AV if

Profit from solar under AV+ Profit from crops under AV

≥

Profit from PV + Profit from crop production

- Solar producer may be worse off but if farmer is substantially better off with AV such that they are better off together then AV will be adopted.

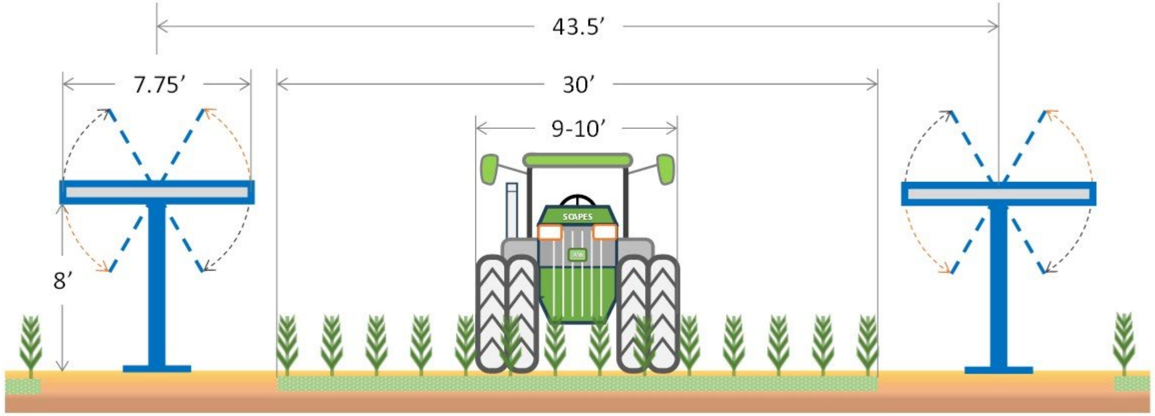
Parameters of PV generation alone and crops alone

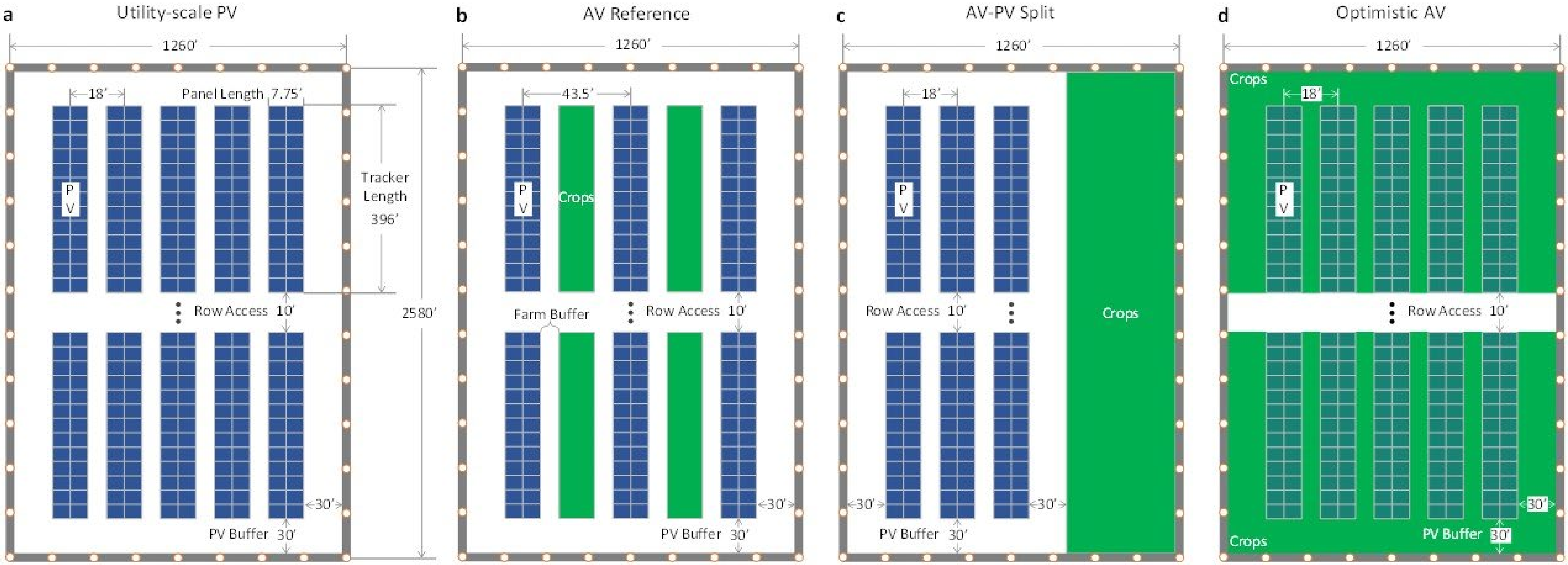
- Solar (PV Reference) returns:
  - Utility scale PV has 18 feet between panels
  - 4 feet tall panels
  - CAPEX is $1.15 per Watt
  - 80 acre field has a capacity of 26 MW and produces 43GWH per year
  - Land lease is $1000 per acre
  - Assume a $75.5 per MWh PPA price and a $6.6 per MWh REC value,
  - Annualized net returns for developer are **$3380** per acre per year
- Crop (Ag alone) returns:
  - Corn or Soybean farmer with 80 acres earns about **$600** per acre per year
    - Would prefer to earn more by leasing land to solar developer ($1000 per acre per year)

*Costs, yields, and returns are calculated for Champaign County, Illinois

Design of agrivoltaics (AV Reference) at field scale

- **Panel height:**
  - PV standard is 4 feet, AV may be raised to 8 (AV Reference), or 12 feet
- **Spacing between panels:**
  - Standard is 18 feet
  - 30 feet for conventional field equipment to operate
  - Loss of 4 feet (panel width and buffer) directly below the panels with no cropping
- **Loss of land:**
  - Buffer area at field ends for turning farm equipment
  - 57% cropped acres
  - 10% more land per MW than PV alone
- **Capital Expenditure (CAPEX):**
  - CAPEX for AV is \$2.66/W dc (8 feet, AV Reference) and \$3.06/W dc (12 feet) compared to \$1.15/W dc for PV alone



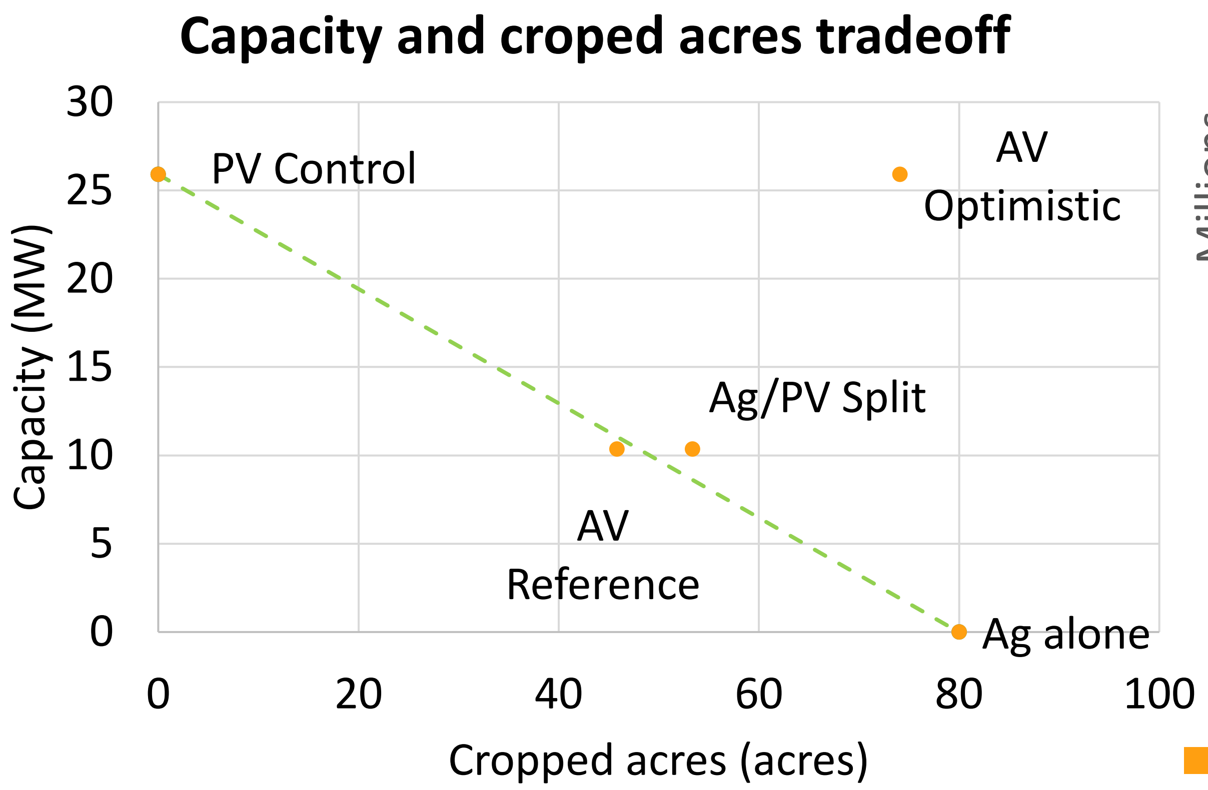


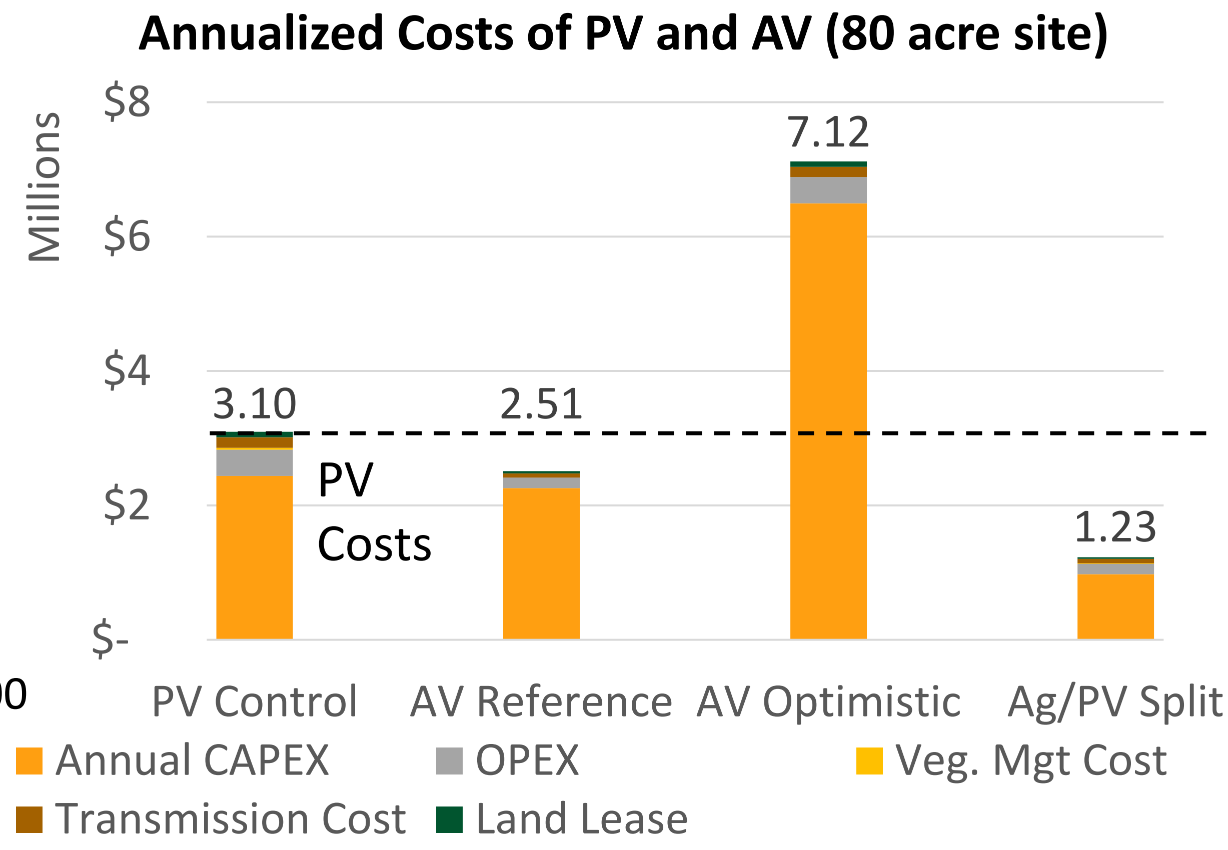
a
Utility-scale PV
1260'
18'
Panel Length 7.75'
Tracker Length 396'
P V
Row Access 10'
2580'
30'
PV Buffer 30'
b
AV Reference
1260'
43.5'
P V
Crops
Farm Buffer
Row Access 10'
30'
PV Buffer 30'
c
AV-PV Split
1260'
18'
P V
Row Access 10'
Crops
30'
30'
PV Buffer 30'
d
Optimistic AV
1260'
Crops
18'
P V
Row Access 10'
30'
Crops
PV Buffer 30'

Alternative designs

- **AV Optimistic**
  - 12 feet panel height, farming under panels
  - 93% cropped
  - Utility level MW capacity
- **Ag-PV split**
  - 63% cropped
  - 78% land area per MW dc compared to AV Ref.
  - Some additional crops can be planted in perimeter around solar array (green).

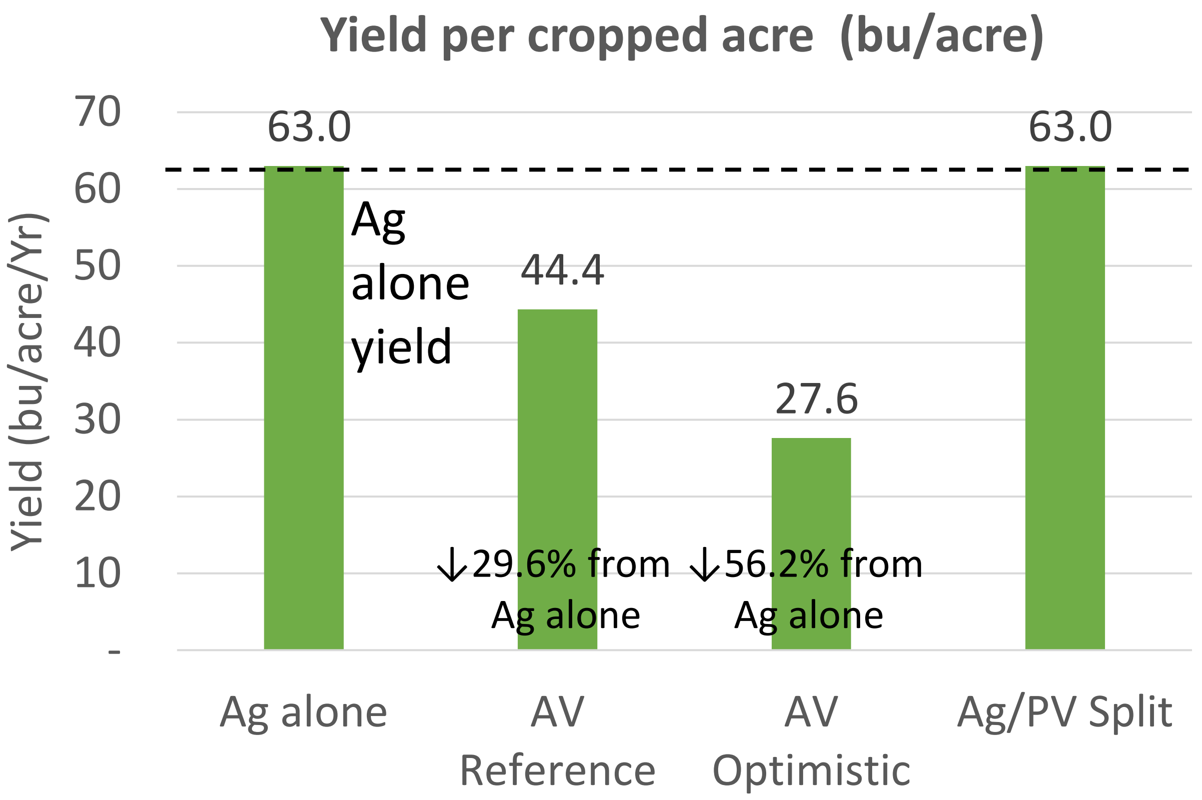
Comparing alternative configurations of AV systems

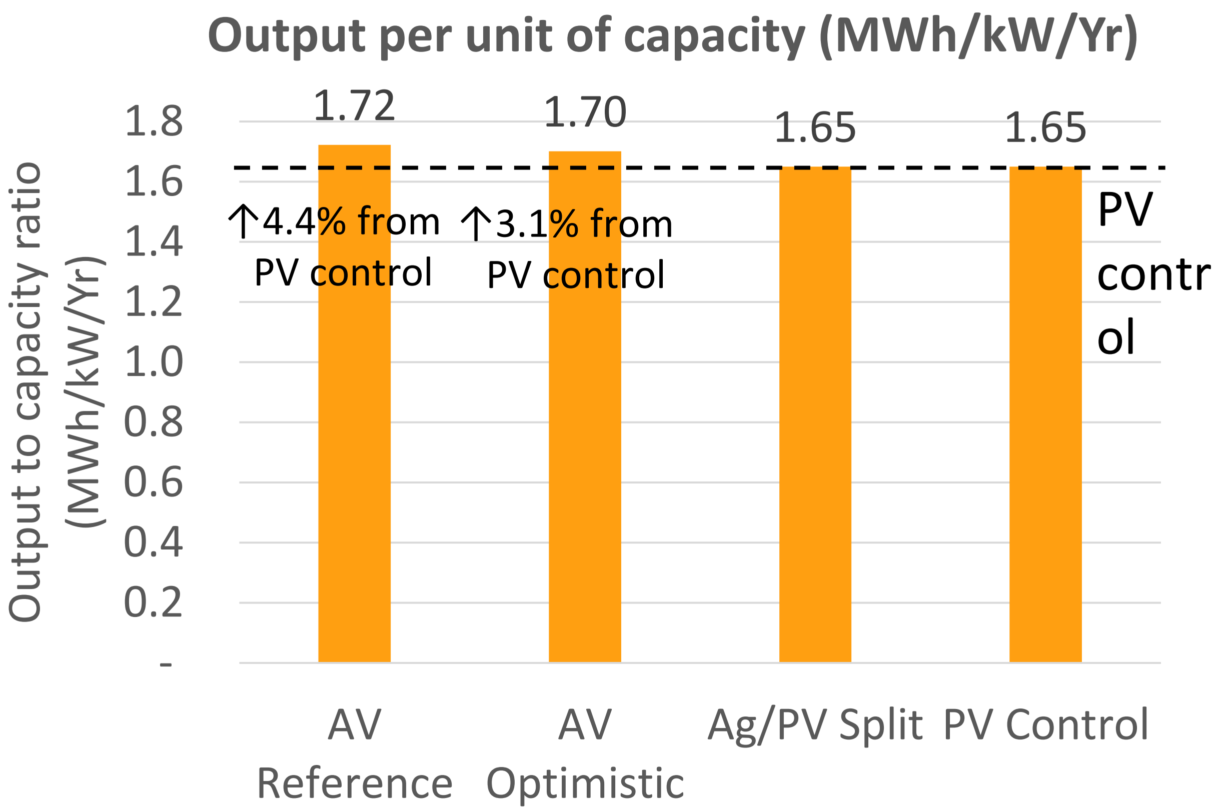




- AV Optimistic has the same energy capacity as PV but at 2.3 times the cost
- AV Reference has the same energy capacity as Ag/PV Split but at 2 times the cost
- AV Optimistic has almost similar cropped acres to Ag alone

Effect of AV on crop yield and energy generation





- Crop yield per cropped acre in AV scenarios is significantly lower (by 30% and 56% in AV reference and AV Optimistic) than in scenarios under Ag alone due to shading.
- Energy generation (MWh/yr per installed kW) in AV scenarios is slightly higher (by 4.4% and 3.1% in AV reference and AV Optimistic) than in scenarios under PV Control due improved power generating conditions (elevation, reflection, moisture, etc.).

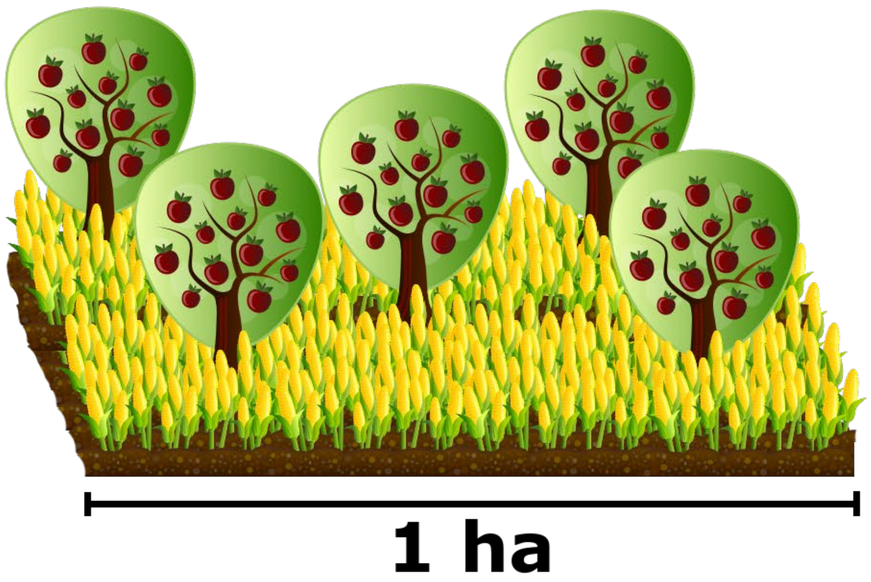
Land Equivalent Ratio: Greater than 1 implies increase in overall productivity of land

Sole yields:

Grain: 5t/ha
Fruit: 15t/ha

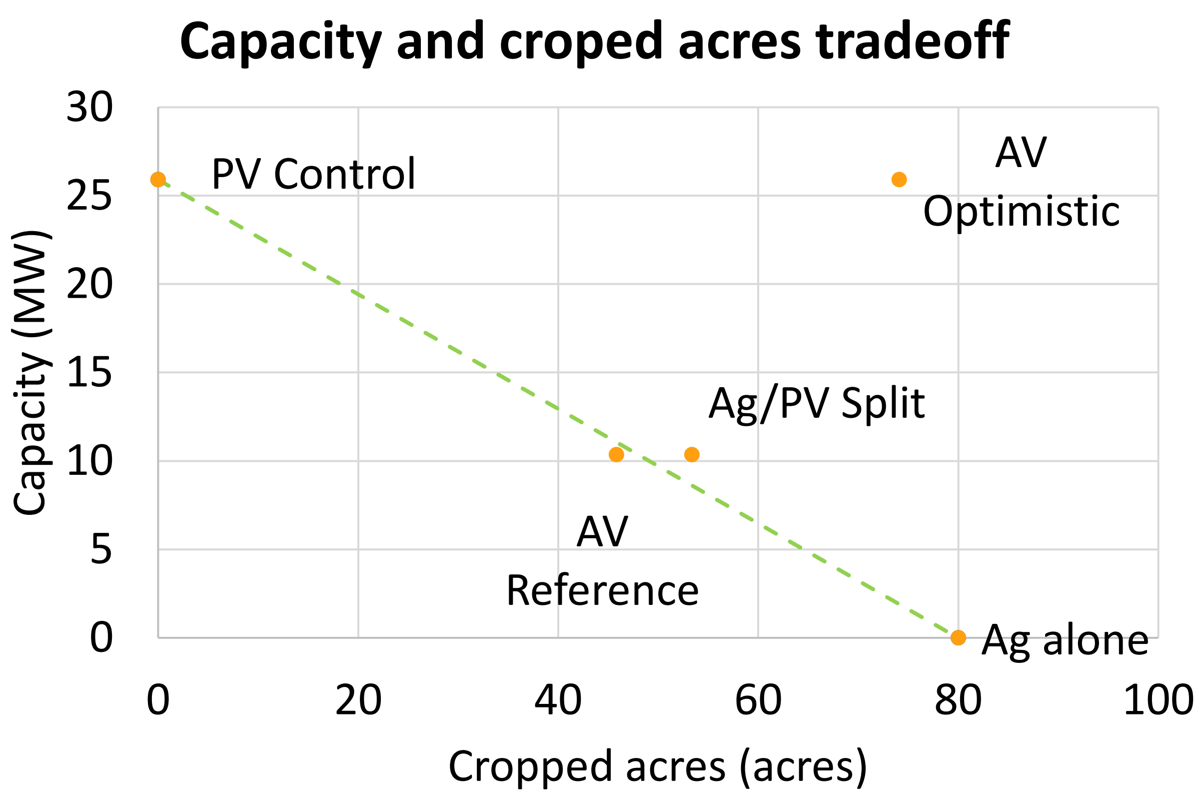
LER =1 if only grain is planted or only fruit trees are planted

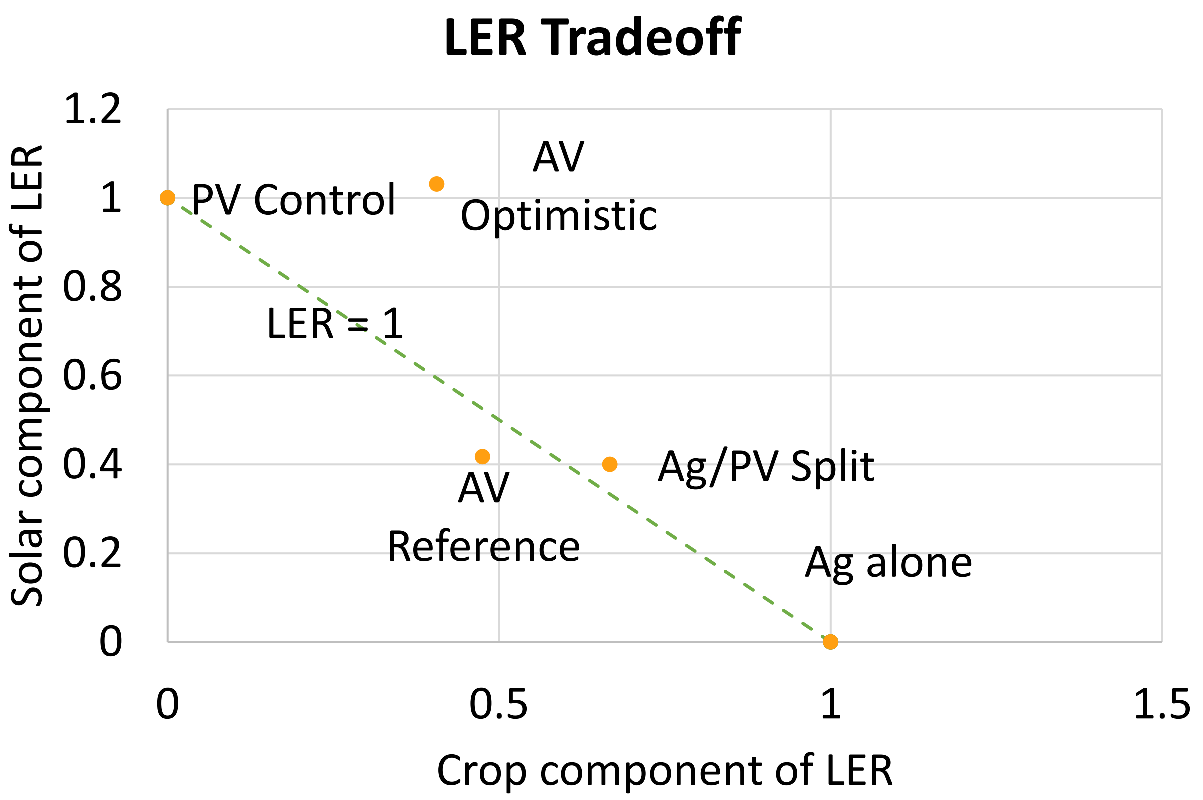
Intercropped:
Grain: 4t/ha
Fruit: 9t/ha



$$\text{LER} = \frac{4t/ha}{5t/ha} + \frac{9t/ha}{15t/ha}$$
$$= 0.8 + 0.6$$
$$= 1.4$$

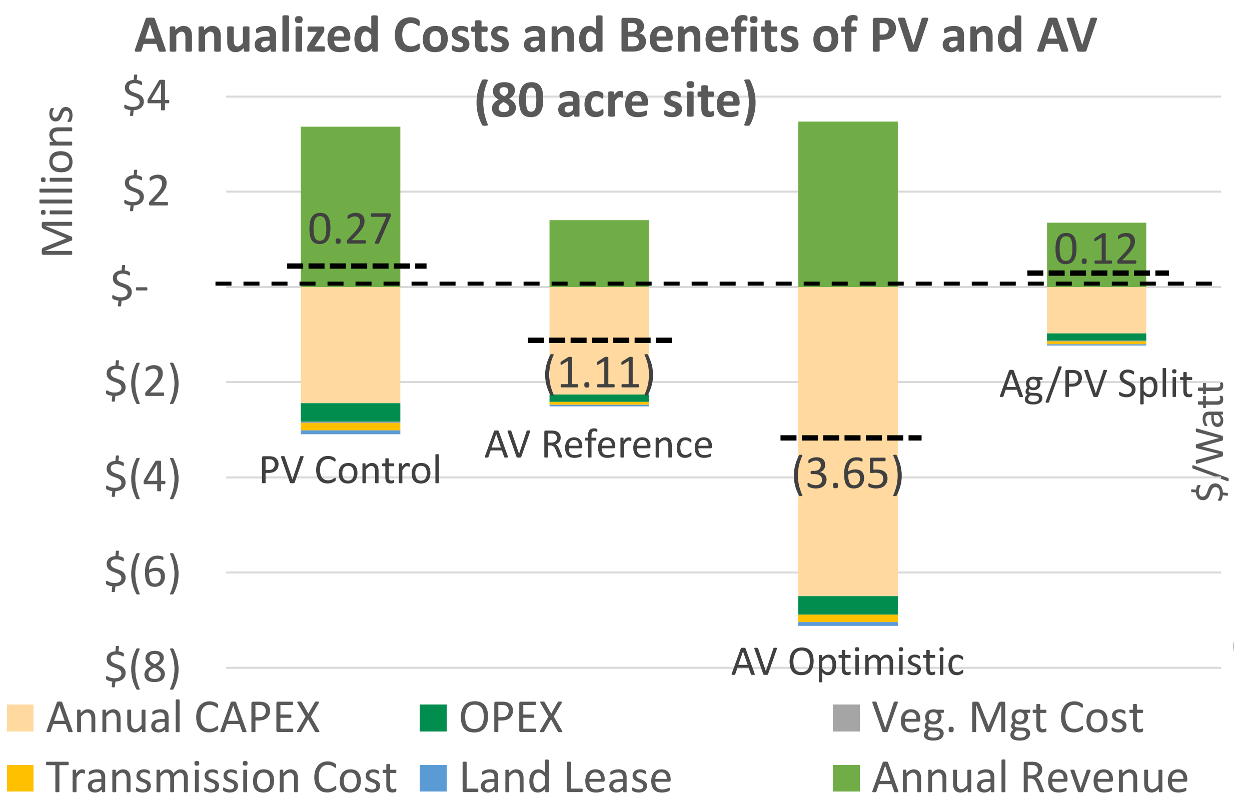
Comparing alternative configurations of AV systems

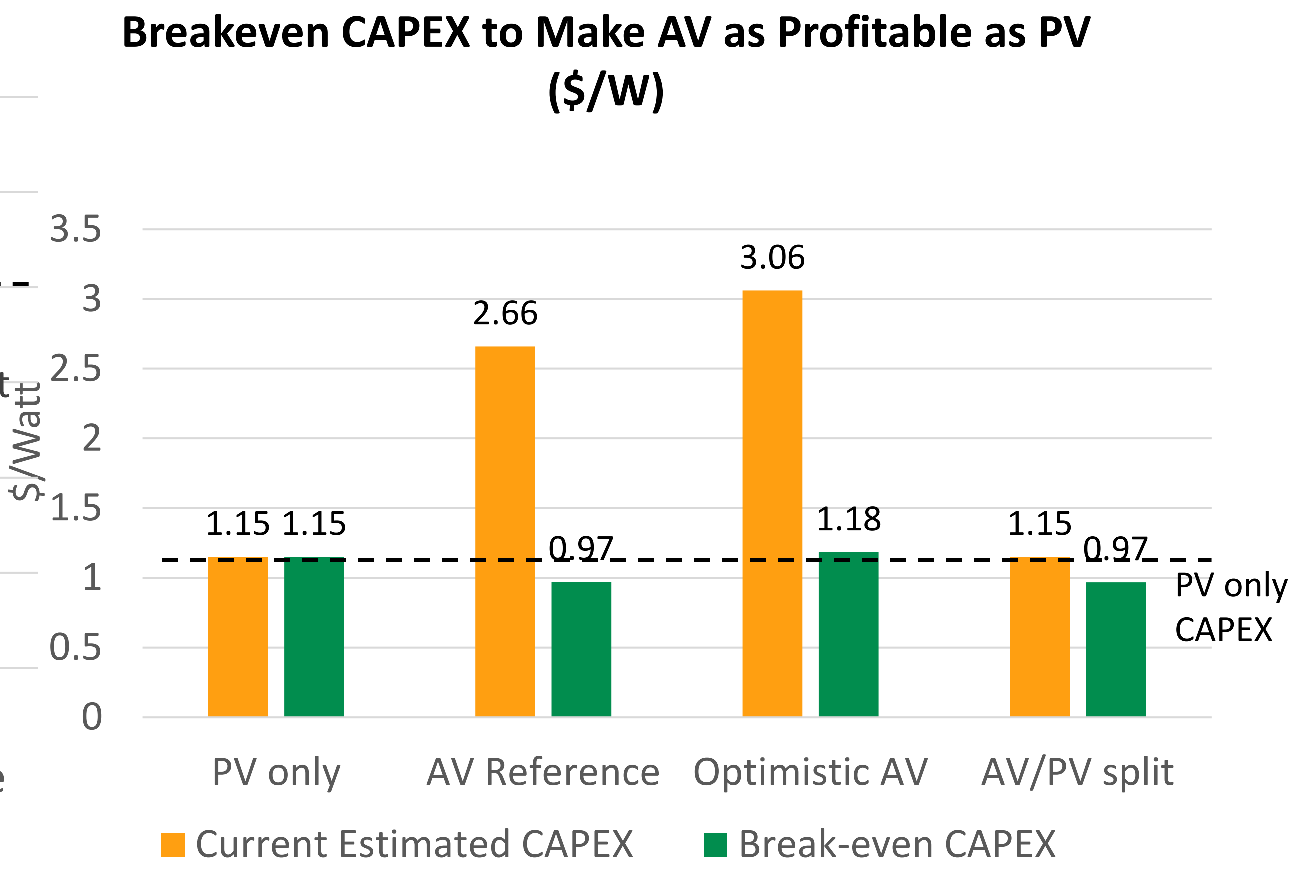




- LER shows the adjusted productivity of each scenario.
- AV Optimistic and AV Reference both have reduced yields and increased solar generating potential.

Profitability of AV

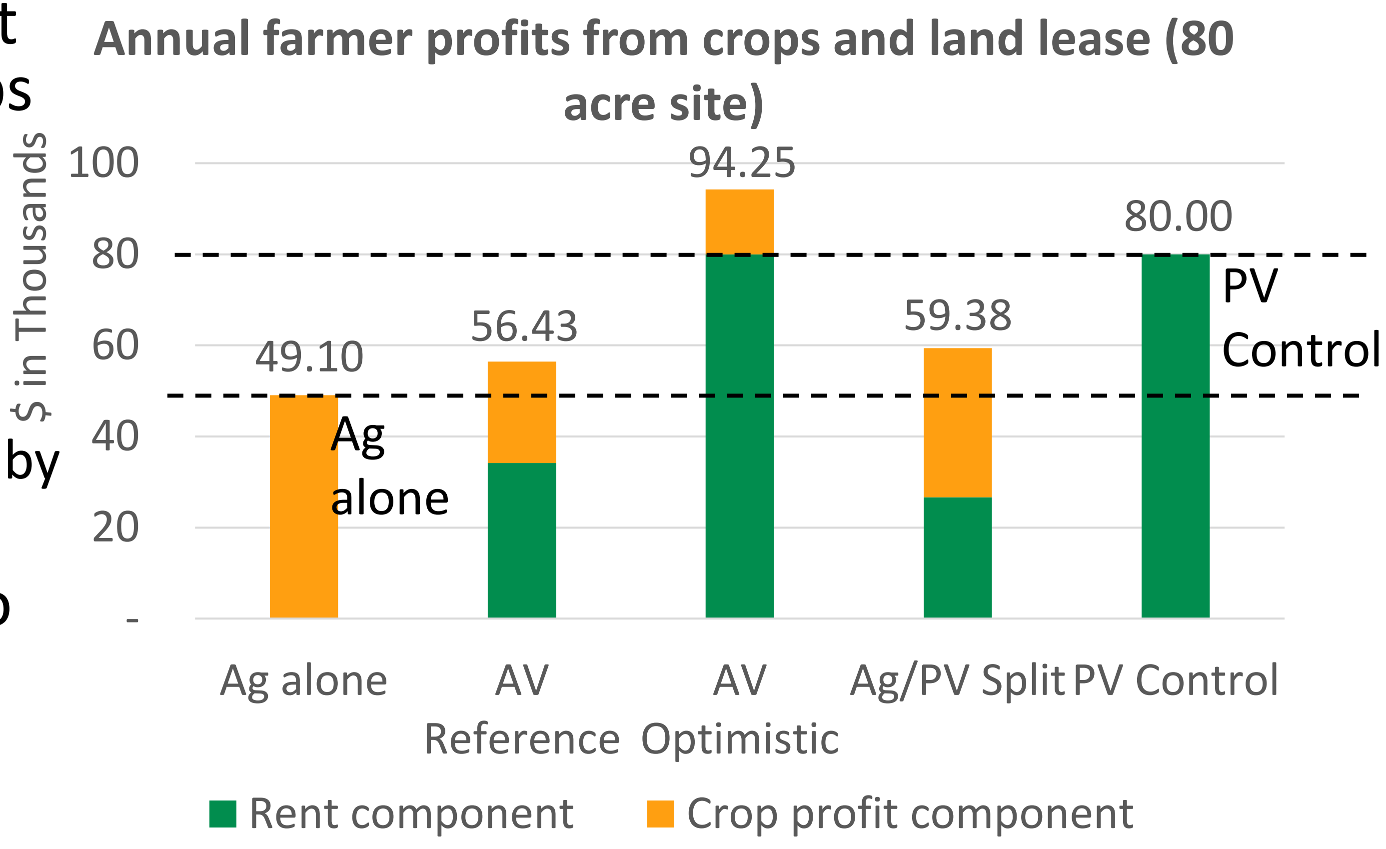




- Ag/PV split profitable compared to AV reference but less than PV alone: Subsidy to utility needed for AV Optimistic design $3.7 M (for 80 acre field)
- To achieve same profits per acre as PV, CAPEX would need to be significantly lower than current estimates and even 15% lower than that of PV alone

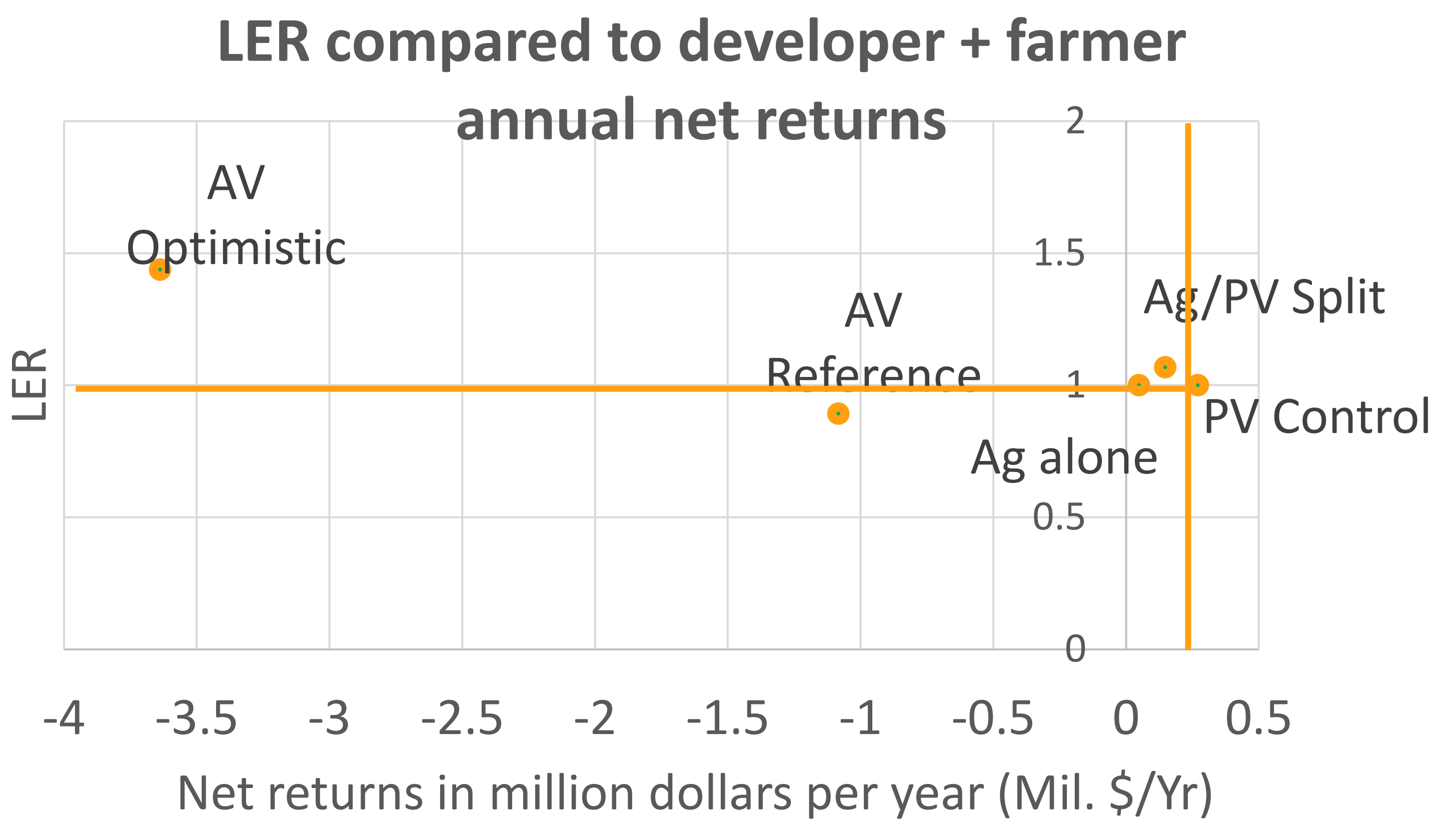
Farmer returns from crops, AV and PV

- Profits from leasing land to PV is about $30K more annually compared to crops alone
- Profits from AV greater than crop production alone for farmer
  - But less than that from PV alone
  - Ag/PV split is preferable to AV Reference by farmers also
- AV Optimistic is close in profitability to that of leasing land to PV alone for farmer.
- Dilemma with AV: The most profitable option for AV from the farmer's perspective is least preferable from the solar developer's perspective

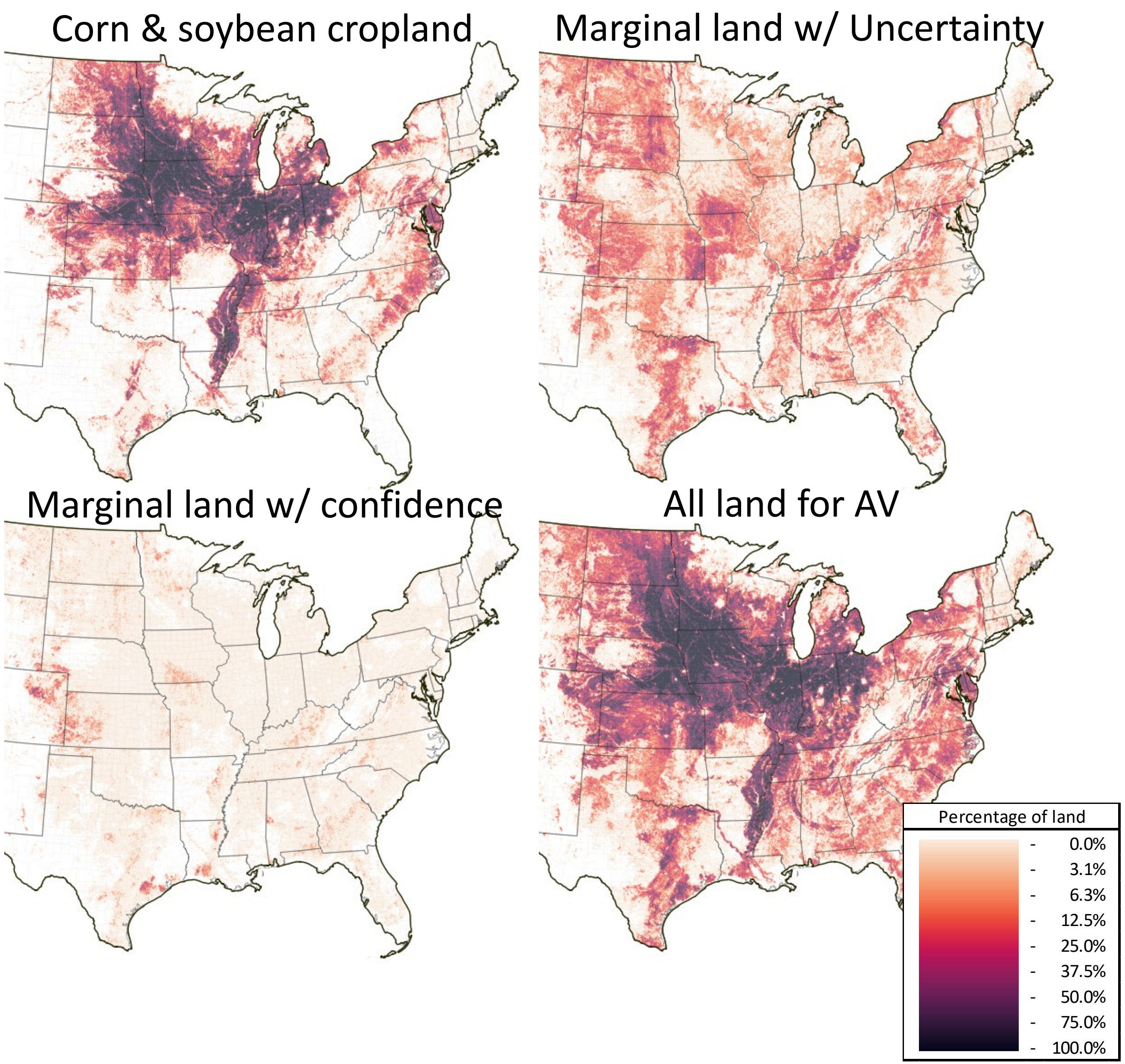


Net returns from solar and crops on land

- AV scenarios may result in higher LER, but may have lower LER in some instances.
- AV scenarios tend to cost significantly more than Ag alone, PV Reference, or Split.



Land requirements for PV and AV

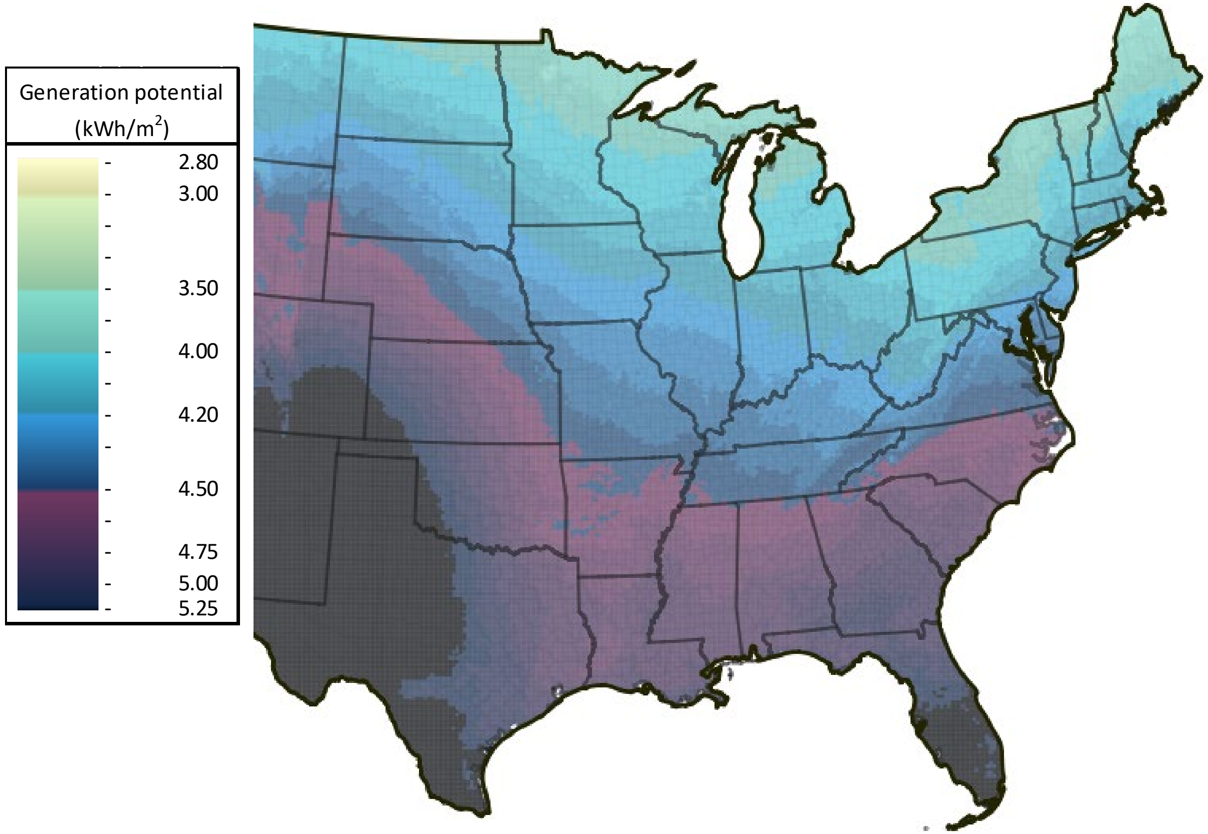


Objective:

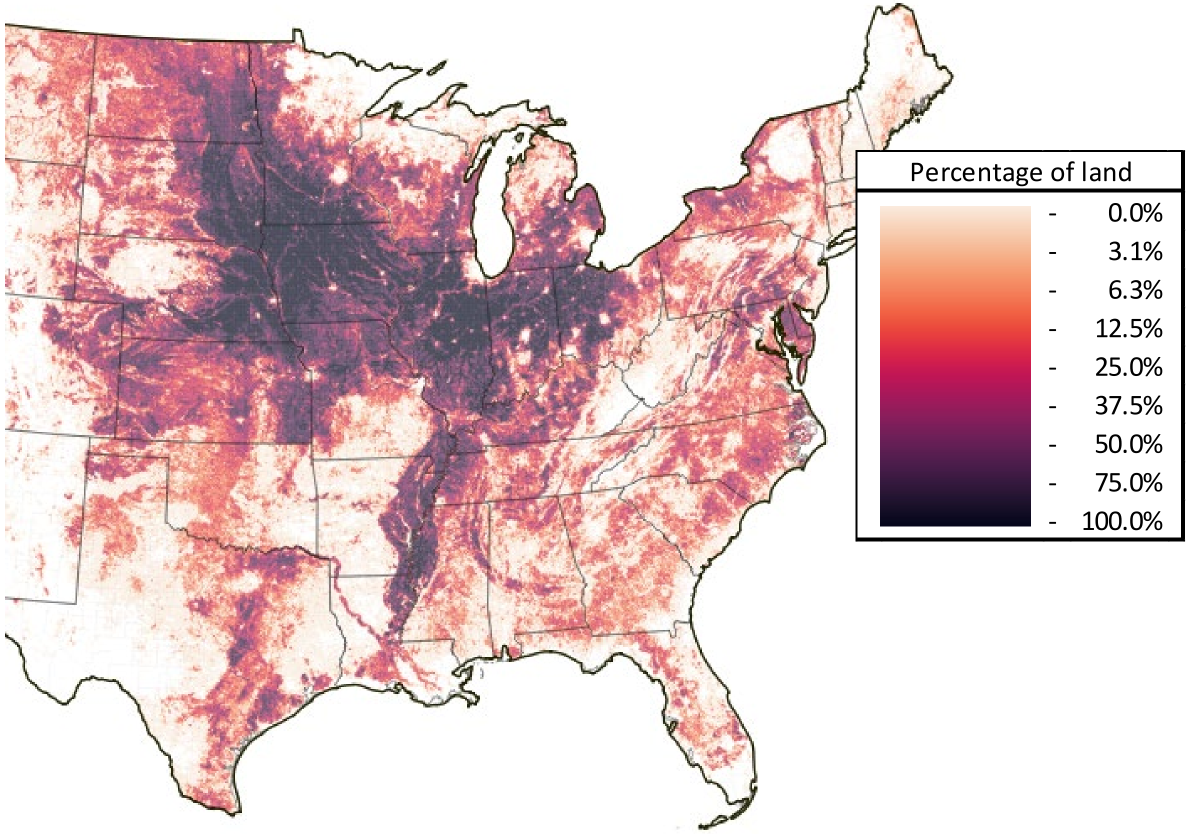
- Analyze the land use requirements of meeting solar energy targets of:
  - ■ 0.225 TW ac by 2025
  - ● 0.55 TW ac by 2030
  - ◆ 1.0 TW ac by 2035
  - ★ 1.6 TW ac by 2050
- For cropland and marginal land conversion to solar farms
- Region considered: cropland (corn and soybean) and idle marginal lands in Eastern Interconnect (MRO, RFC, SPP, SERC, SWER)
- Extent of competition between crop production and solar energy
- Trade-off between solar farm income and crop farm income

Summary	**Mil Hectares**
Cropland	769
Marginal Land with Confidence	36
Marginal land with Uncertainty	247
Total usable land	1051

Maps of solar potential for AV

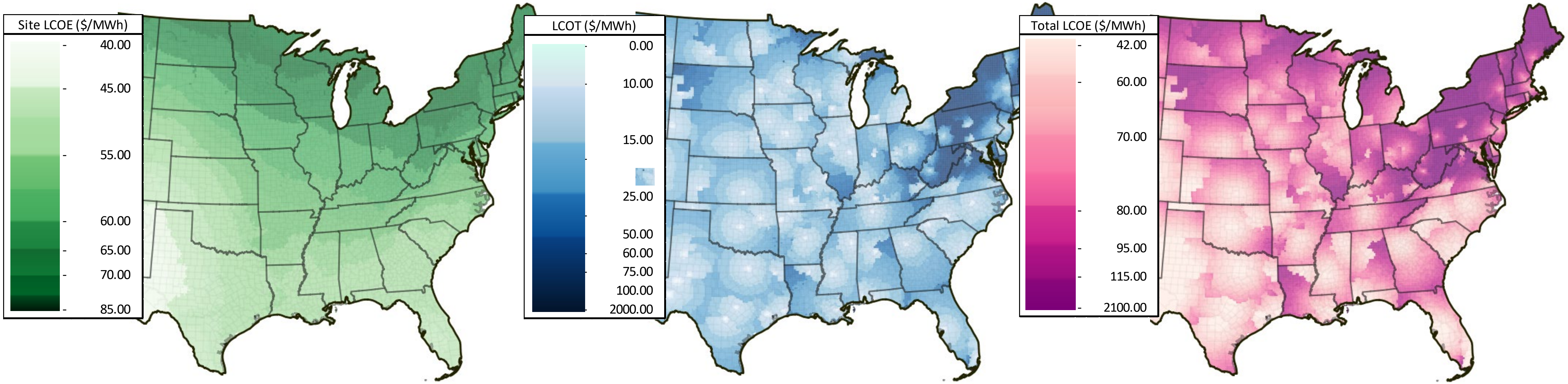


Solar generation potential (kWh/m2)



Cropland and marginal land availability (%/Acre)

Maps of Site-LCOE, LOCT, and Total LCOE for utility solar



Site LCOE ($/MWh)

LCOT (Transmission) ($/MWh)

Total LCOE ($/MWh)

Higher site costs due to less generation potential in the Northeast

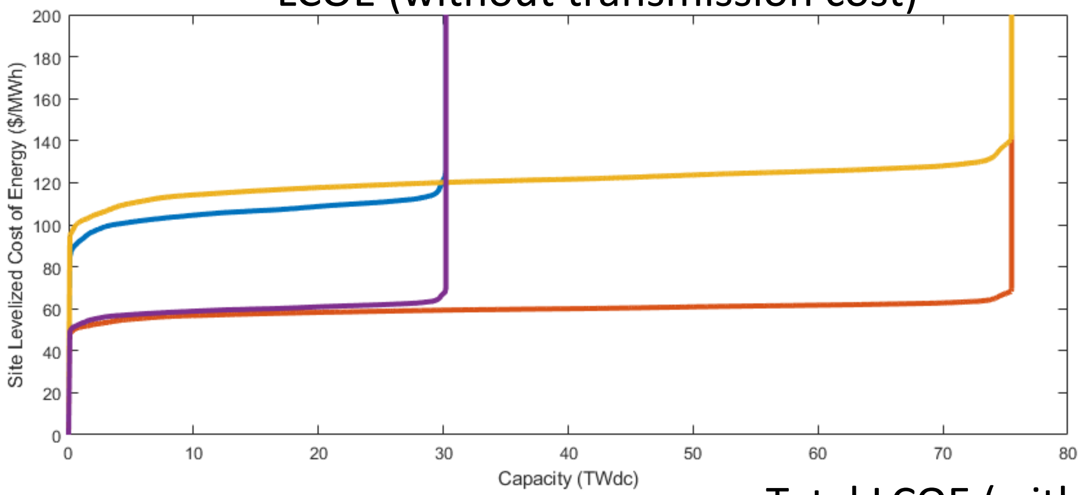
Higher transmission costs further from transmission lines

Pockets of low cost regions

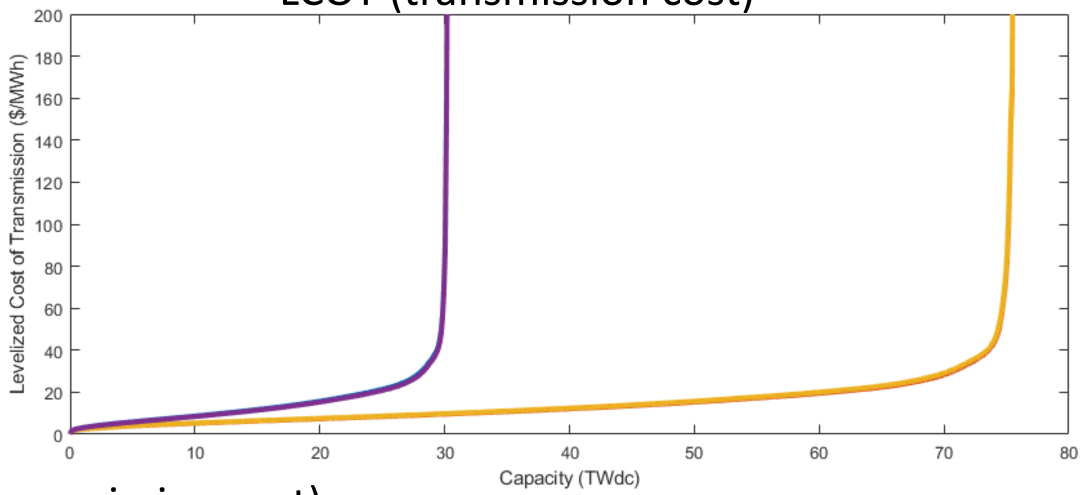
Supply curves

Coverage area = Corn + Soybean + Idle Marginal land
in eastern interconnect (MRO, RFC, SPP, SERC, SWER)

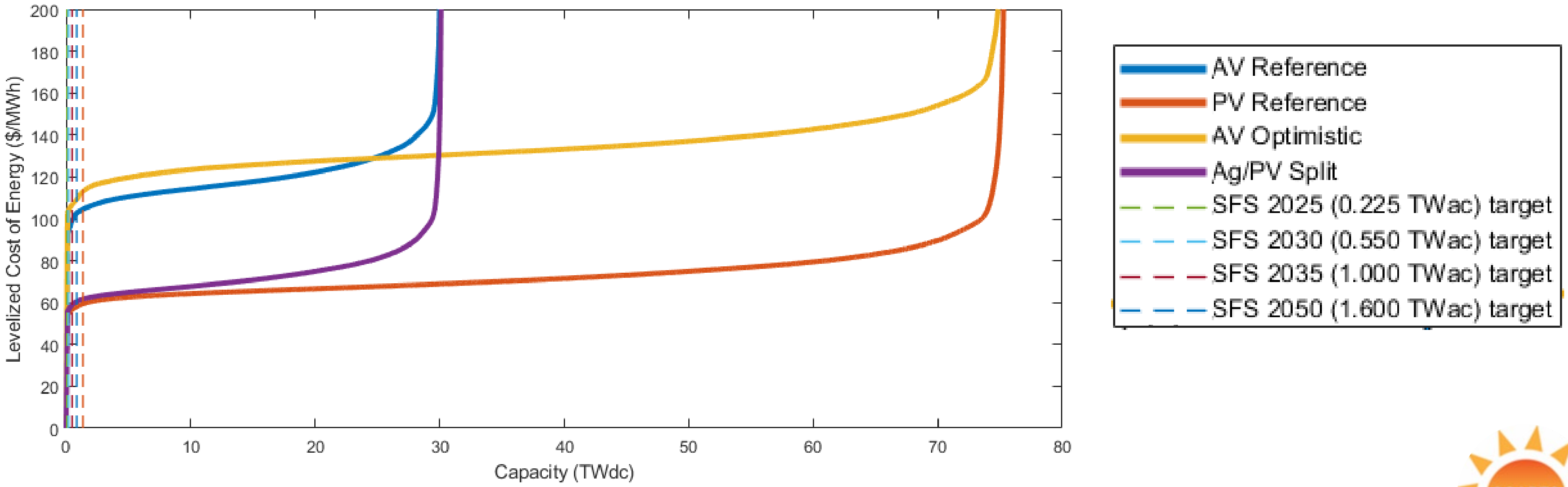
LCOE (without transmission cost)



LCOT (transmission cost)

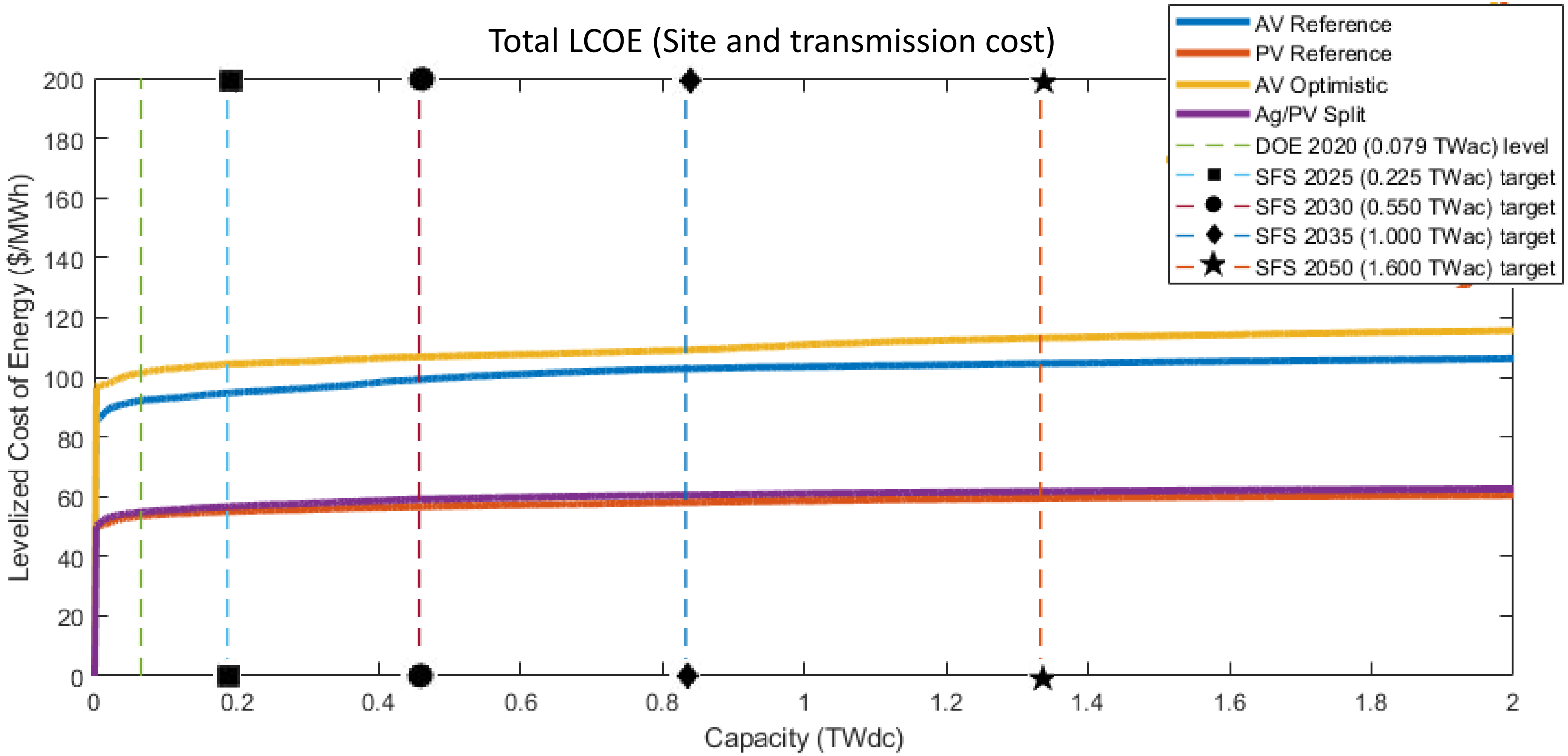


Total LCOE (with transmission cost)



AV scenarios cost more for generation and transmission and have lower cumulative capacity and cost more per MW
Land availability isn't a capacity constraint for Solar Futures Study targets

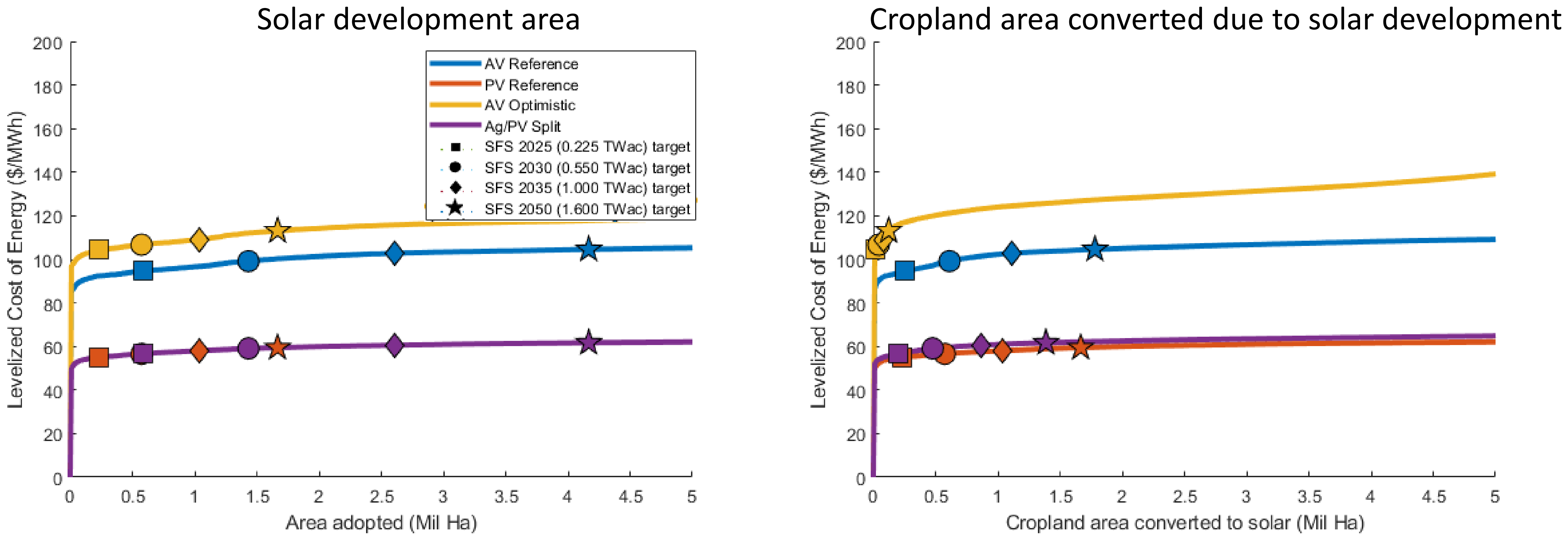
Supply curves



Solar Futures Study targets for 2025, 2030, 2035, and 2050 can potentially be met at the lowest cost by PV and the highest cost by AV Optimistic

Land usage and cropland converted under PV and AV adoption

Coverage area = Corn + Soybean + Unused Marginal land in eastern interconnect (MRO, RFC, SPP, SERC, SWER)



- Solar SFS Target for 2050 can be met by 4.25 million hectares of which 1.75 million hectares is cropland
- AV Ref and Ag/PV will require most land to meet Solar Futures Study targets and AV Optimistic and PV reference the lowest
- Most cropland is lost when adopting solar through AV reference, whereas the least cropland is lost via the AV Optimistic scenario
- More cropland is used through AV ref than PV ref when meeting SFS targets
- Least land is converted to solar under AV Optimistic, however yield on this land is significantly lower

Land usage and cropland converted under PV and AV adoption

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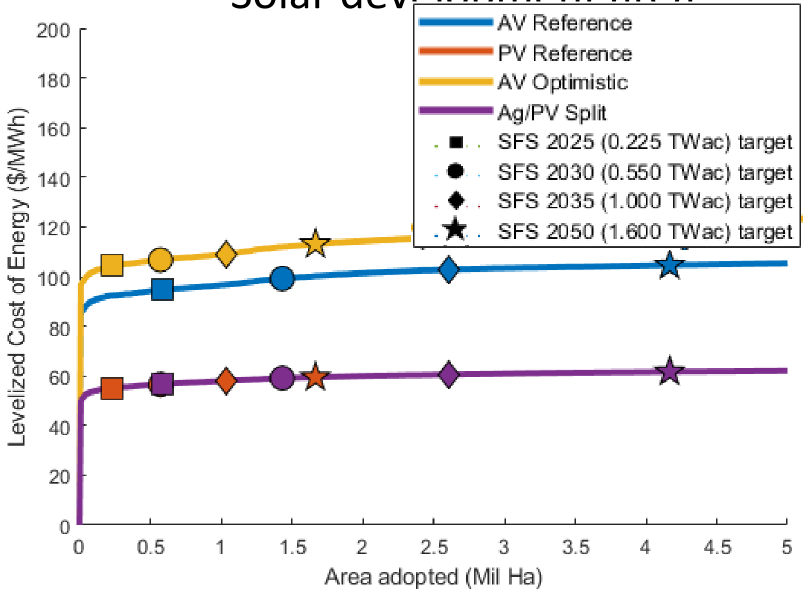
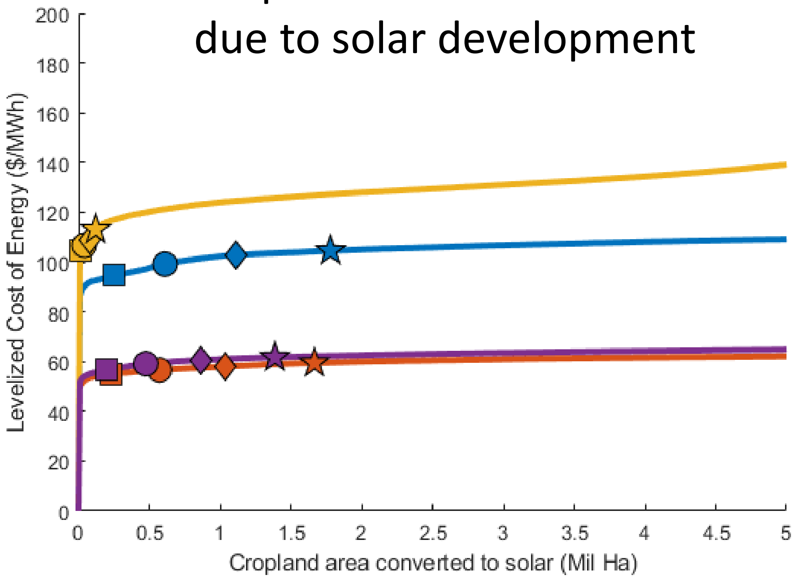
in eastern interconnect (MRO, RFC, SPP, SERC, SWER)

Solar development area



Cropland area converted due to solar development



Solar model	Solar adopted (Mil. Ha)			
	SFS Target			
	225 GW	550 GW	1 TW	1.6 TW
AV reference	0.59	1.43	2.60	4.17
PV reference	0.23	0.57	1.04	1.67
AV Optimistic	0.23	0.57	1.04	1.67
Ag/PV split	0.59	1.43	2.60	4.17

Solar model	Cropland converted (Mil. Ha)			
	SFS Target			
	225 GW	550 GW	1 TW	1.6 TW
AV reference	0.25	0.61	1.11	1.78
PV reference	0.23	0.57	1.04	1.67
AV Optimistic	0.02	0.04	0.08	0.12
Ag/PV split	0.20	0.48	0.87	1.39

- Solar SFS Target for 2050 can be met by 4.25 million hectares of which 1.75 million hectares is cropland
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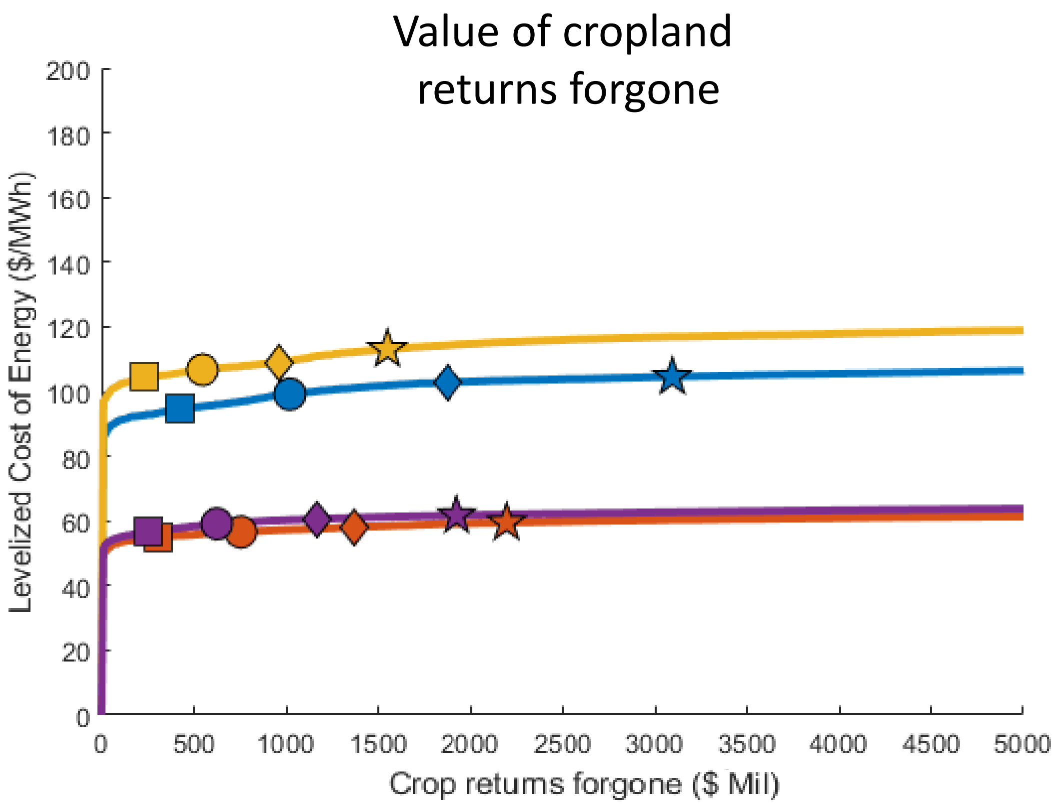
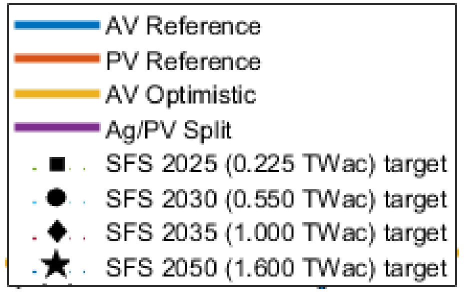
Cropland returns forgone by conversion of land to solar

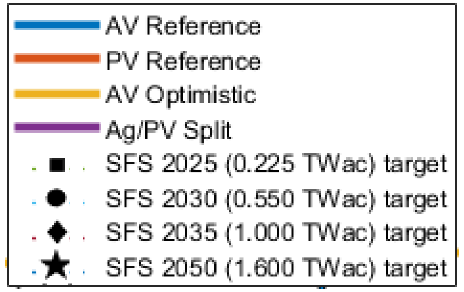




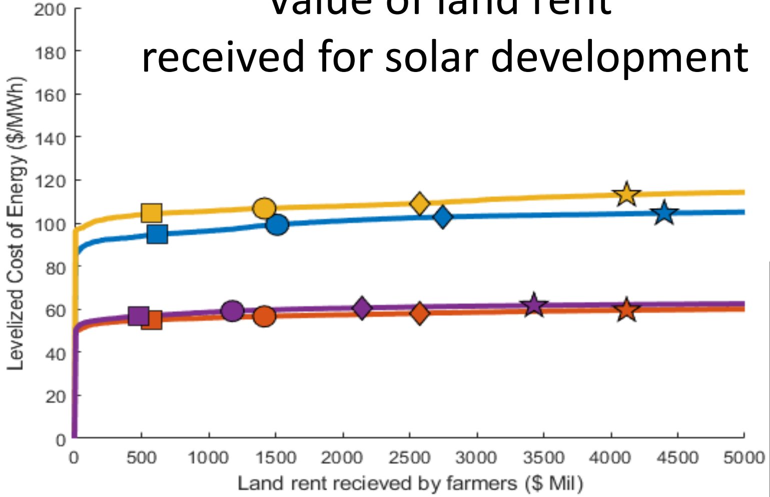
Solar model	**Returns forgone (Mil. $)**			
	SFS Target			
	225 GW	550 GW	1 TW	1.6 TW
AV reference	429.3	1021.1	1874.0	3094.2
PV reference	301.8	755.3	1366.0	2196.6
AV Optimistic	234.3	546.7	961.3	1550.2
Ag/PV split	257.6	624.9	1164.4	1925.8

- $ 2.2 Billion value of cropland returns will be forgone annually to meet solar targets in 2050 under PV only
- $ 3.1 Billion value of cropland returns will be forgone annually to meet solar targets in 2050 under AV reference
- $ 1.5 Billion value of cropland returns will be forgone annually to meet solar targets in 2050 AV Optimistic
- $ 1.9 Billion value of cropland returns will be forgone annually to meet solar targets in 2050 under a split Ag/PV setup

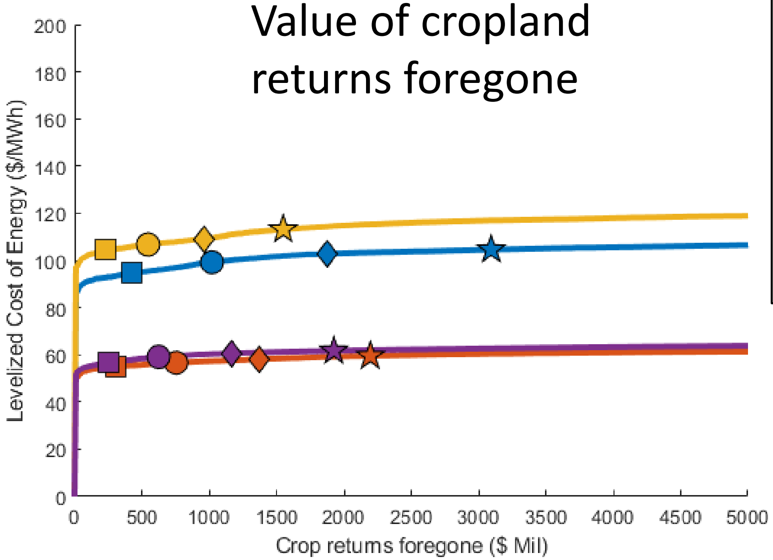
Farmer returns under PV and AV adoption



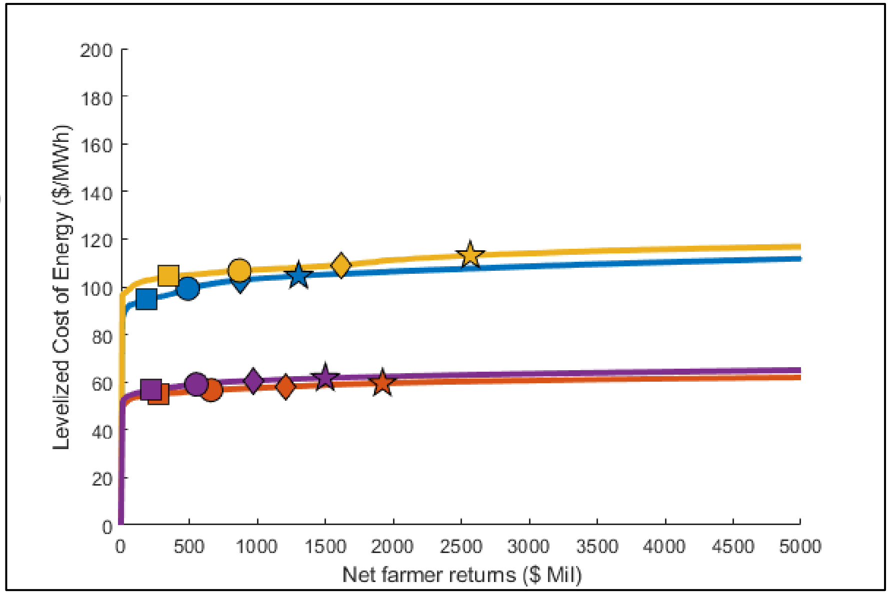
Value of land rent received for solar development



Value of cropland returns foregone



Net additional value to farmers due to solar development



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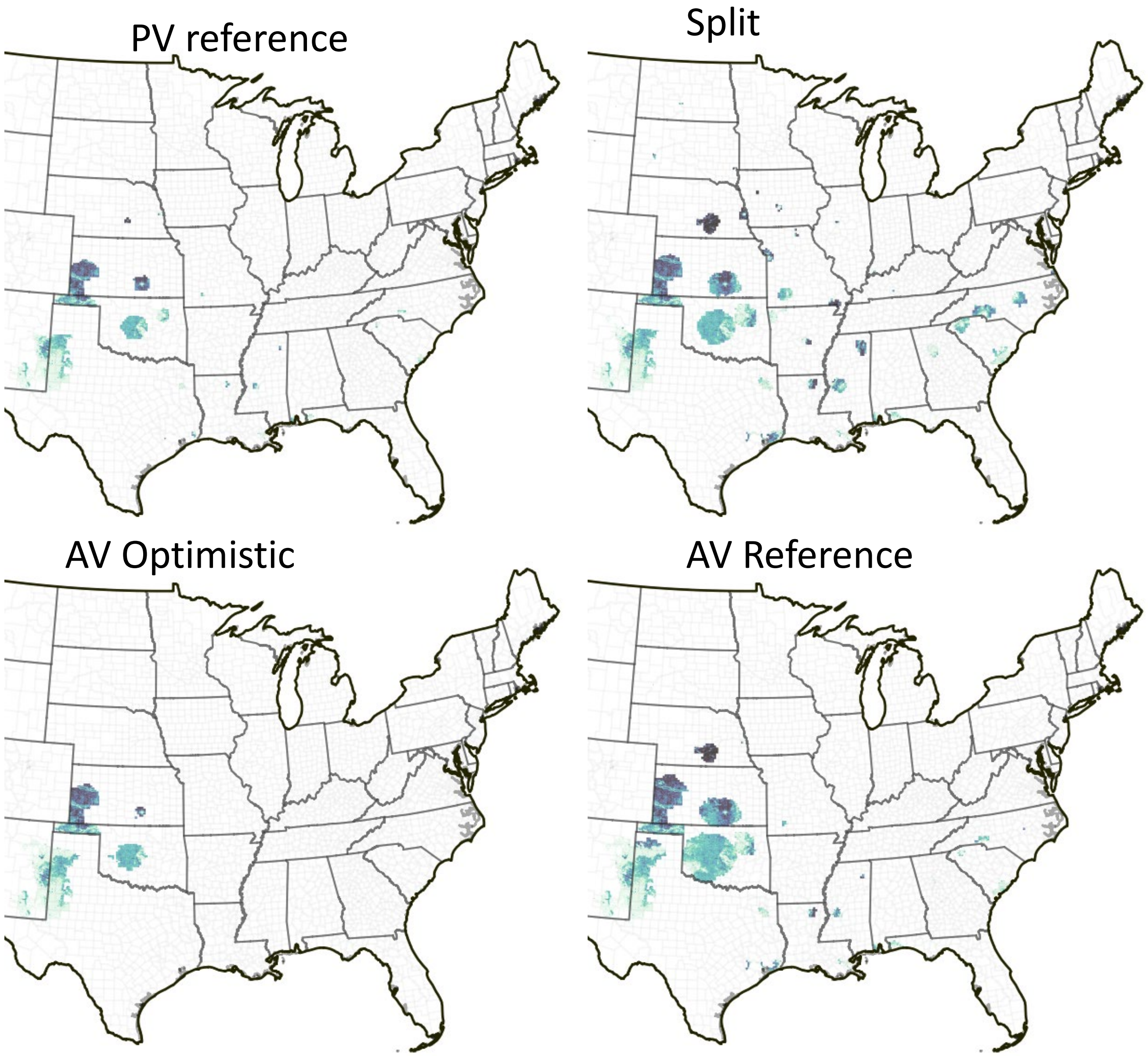
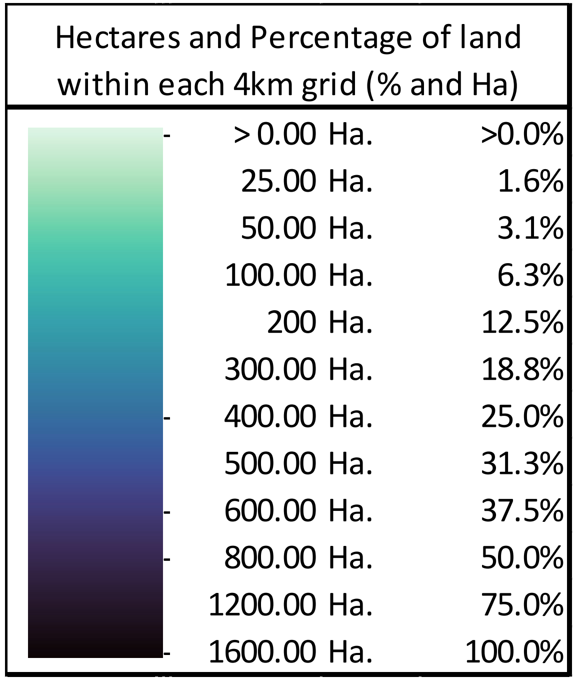
Solar model	Additional rent collected (Mil. $)			
	SFS Target			
	225 GW	550 GW	1 TW	1.6 TW
AV reference	619.4	1512.5	2750.0	4399.6
PV reference	580.1	1416.8	2575.9	4118.7
AV Optimistic	580.2	1416.8	2575.2	4118.9
Ag/PV split	482.1	1178.5	2142.2	3427.6

Solar model	Additional net returns (Mil. $)			
	SFS Target			
	225 GW	550 GW	1 TW	1.6 TW
AV reference	190.2	491.3	875.9	1305.3
PV reference	278.2	661.5	1209.9	1922.1
AV Optimistic	345.9	870.1	1613.9	2568.7
Ag/PV split	224.5	553.6	977.8	1501.8

Land usage under PV and AV adoption

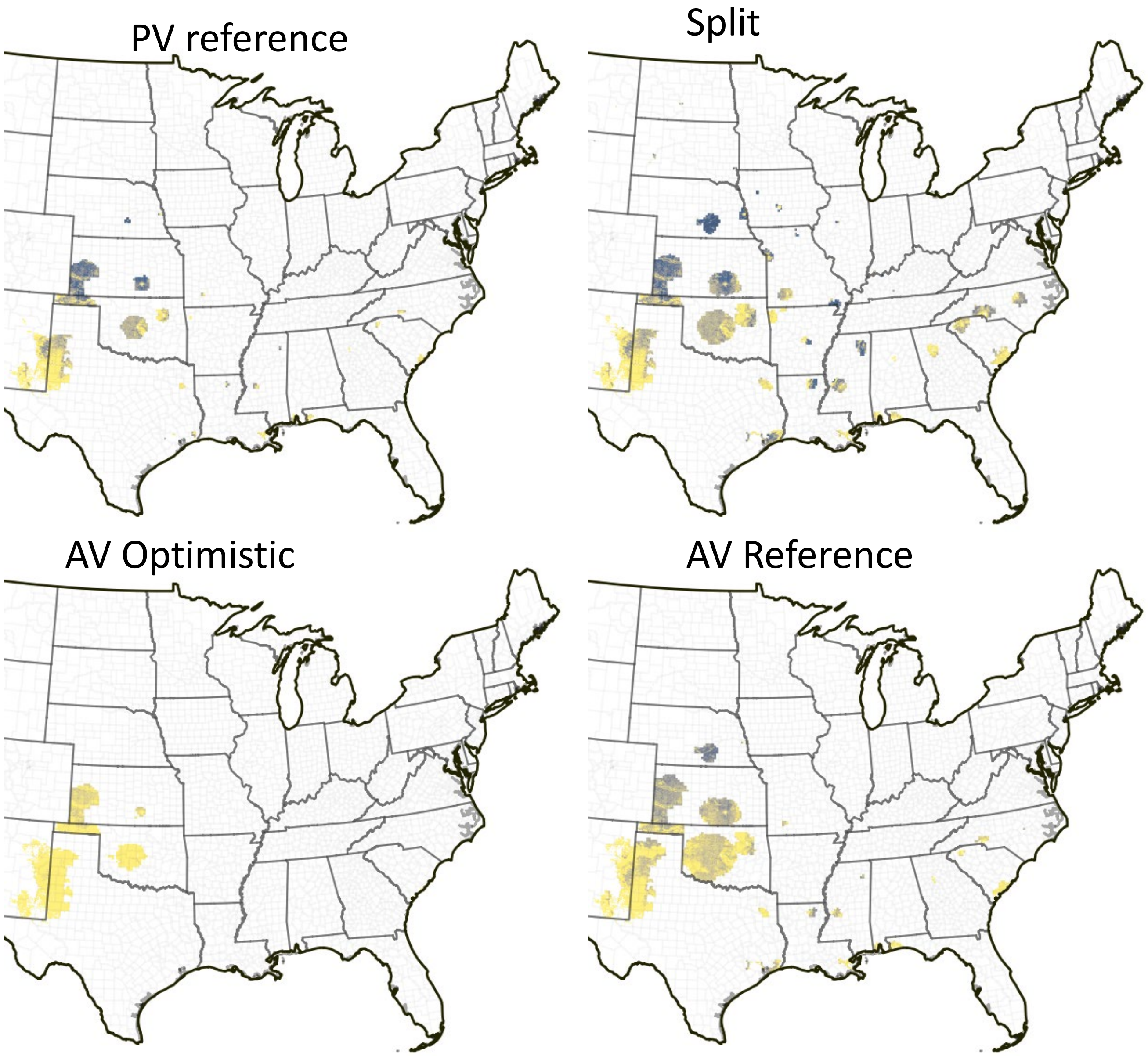


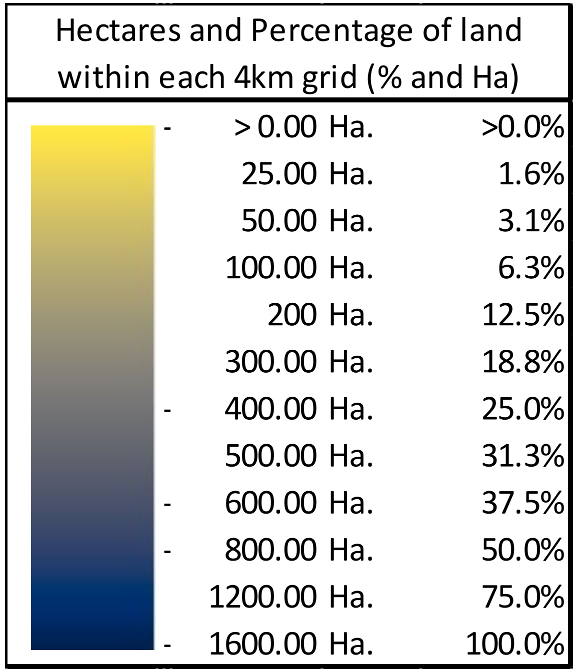


PV and AV Optimistic do not need much land, so developers adopt in the southwest where site LCOE is lowest

Split is cheaper (less elastic in supply) in terms of Total LCOE relative to Reference – so developers choose regions where TLOCE is lowest in Ref, and choose locations with lowest LCOT in Split

Cropland forgone under PV and AV adoption





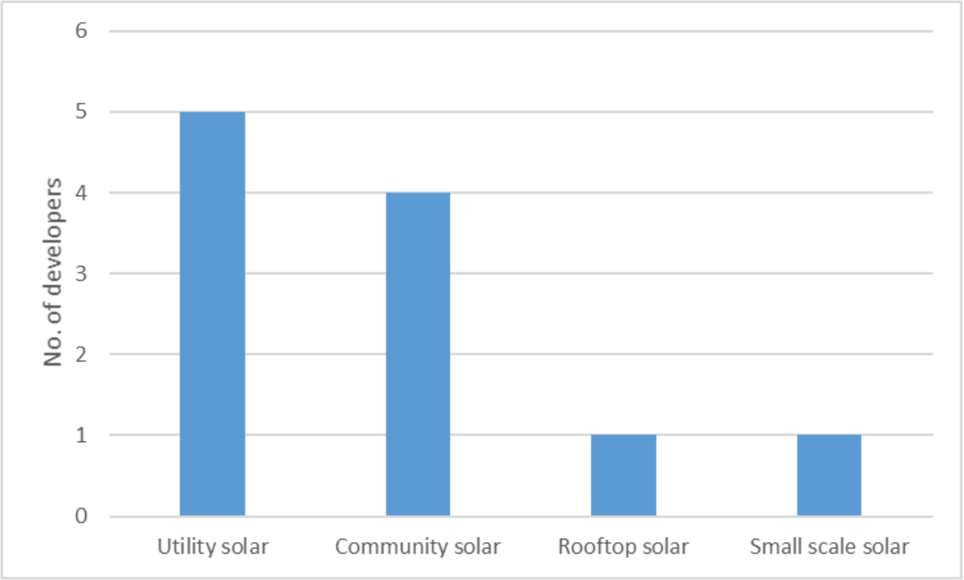
PV reference and AV Optimistic have similar adoption regions, however the impact on cropland is significantly lower.

AV reference has the largest impact on land use but this use is spread out.

Survey of solar energy developers

- The need for off-the-shelf AV technology and lower costs are important drivers.
- Government regulations, community requirements, or other mandatory requirements to do AV are needed.
- Concerns about liabilities and insurance when allowing farmers to plant crops near solar panels- the question is, who will provide that insurance for AV farms?
- Community opposition occurs for various myths, beliefs and NIMBY attitudes, not just legitimate food production concerns.
- Farmers will have to manage their portion and solar developers their portion
  - “We would like to focus on making electrons” – SCAPES: Solar Developer Focus group participant
- AV may not lower land costs for solar since it also adds to the requirement for more land.

“What type of solar technology are you doing?”



Source: SCAPES Focus Group, Dec. 2022

Perspectives from farmer focus groups

"We're producers, we like to produce something, it is hard to see our land just go to solar panels."
SCAPES: Farmer focus group participant

Interests

- Overall interest in the idea of agrivoltaics (a new concept for most)
- Agrivoltaics incorporating livestock and non-productive acres
- A business structure that would include an energy revenue sharing agreement with the landowner/operator, dual revenue streams
- Agrivoltaics can enable some conversion to solar while preserving the way of life for farmers

Concerns

- The lifespan of solar panels, decommissioning, and their impact on future farmland productivity
- The current row crop equipment size is incompatible with a panel-dense solar farm layout.
- Community opposition to solar developers purchasing land in their communities and the percentage of farmers who might be interested in such an opportunity
- Farmers cannot set up utility-scale solar independently- they need a partnership with the solar industry.

Source: https://www.nytimes.com/

Survey questionnaire in preparation

Original Plan to conduct a choice experiment

Solar Developers Survey

AAA

Features of Solar energy generation system:

Agrivoltaic Land Area: Share of land for agricultural crop production out of the total land area leased for the project.

Agrivoltaic Incentive is **is the additional incentive provided by the government (in cents per kilowatt hour (kWh)) for** electricity **produced from an agrivoltaic project** as compared to a solar alone project.

Time of Approval: Total **number of months** taken from project planning to breaking ground for construction of solar development.

Upfront Installation Cost is capital expenditure cost **(CAPEX)** to build the solar project.

Vegetation Management Cost: Cost related to **vegetation management** (mowing, herbicide treatment, brush removal, etc.) on the solar farm. This does not include electrical O&M activates.

Please indicate your preference by **checking only one of the boxes (☒) below** the two columns "Utility Scale Agrivoltiacs System" and "Photovoltaics Only System".

Scenario 1: Select one between the given Agrivoltiacs system or Photovoltaics Only System:

Utility Scale Agrivoltaic System	Photovoltaics Only System
Agrivoltaic land area: 30% agricultural land for solar panels Agrivoltaics incentive: 5 Cents/kWh Time for approval: 30% less than current time Upfront installation cost: 40% more than current CAPEX Vegetation management cost: 60% less than current cost	Current Photovoltaics System
☐	☐

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Revised Plan to have a Stated Preference Survey

Section A: Your preference for future solar projects:

*Suppose an AV system requires a spacing of 42 ft. between panel supports and a PV panel height of **8 ft.** above the ground to allow farming activity between the panels and it will reduce vegetation management costs by **20%** and decrease time for project approval by **20%**.*

1. Would your company be willing to pay a CAPEX of **$2.66/W** for this AV system?

[*The price varies randomly across the sample:* ***$1.15/W, $1.50/W, $2.00/W, $2.66/W, & $4.00/W.***]

Yes→Go to Q2	☐
No→Go to Q2/Q3	☐

Example of a Choice Experiment (CE) survey question format presented to solar developer focus group (July 12, 2023)

Key preliminary insights

- Utility scale Agrivoltaics with corn and soybeans unlikely to be profitable compared to PV under current climate conditions and land availability
    - Could be appealing with high valued crops where return to land is comparable to that of solar generation
    - For non-economic reasons – mitigating community opposition, optimal site locations, reputation and image of utility, regulatory requirements
    - With large payments for land preservation in agriculture and even then an Ag/PV split model would be preferable to an interspersed model

- Agrivoltaics likely to be appealing to farmers who interested in preserving a life-style instead of leasing land to solar farming
    - In arid, moisture stressed environments
    - Or with short crops/vegetables that can be grown under panels without requiring major changes due to equipment

- LER greater than one is a misleading metric
    - Value greater than 1 does not imply higher profitability of Agrivoltaics or lower land requirements to obtain similar amount of crops or solar

SCAPES