Profitability of agrivoltaics

SCAPES Economics Meeting

Paul Mwebaze, Madhu Khanna, Fahd Majeed, University of Illinois Urbana Champaign
Ruiqing Miao, Auburn University
James McCall, Jordan Macknick, NREL

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Goal

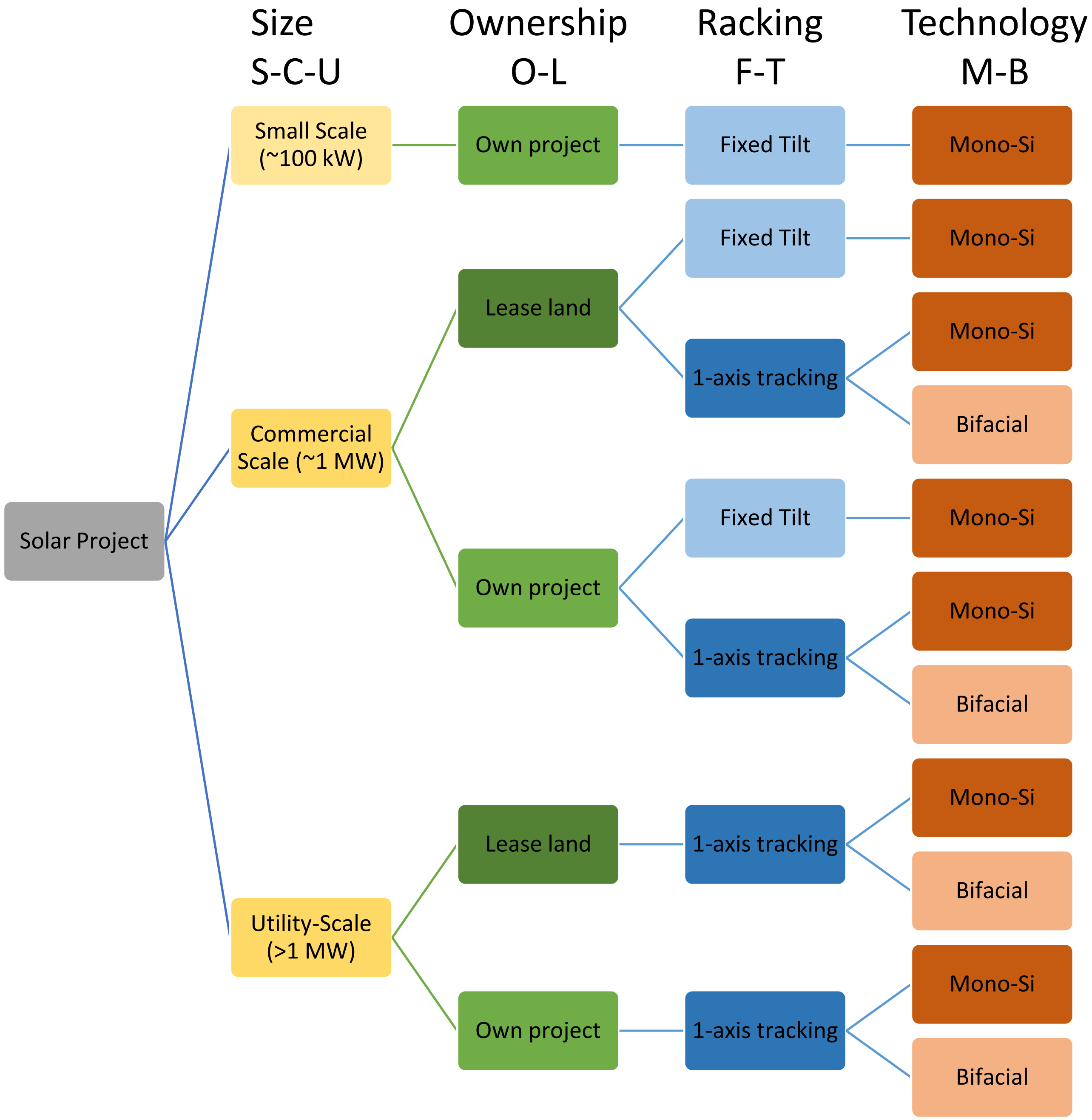
- To examine the optimal configuration and design of Agrivoltaics across various regions in the US and its implications for farm income and risk and for market and climate feedbacks on the agricultural and electricity sectors.

- To conduct a survey of farmers and solar developers to examine the technology, economic and behavioral factors that will influence the provision and adoption of Agrivoltaics.

Current work

- Developed framework for spatially varying profitability for three options
  - Crop only
  - Solar only option
  - Combined crop and solar option

- Techno-economic analysis collaboration with NREL
  - System Advisor Model (SAM)
  - Renewable energy potential model (reV)



Scenario List

- Each scenario represents a combination of Size+Ownership+Racking+Technology
- *E.g.,* C-O-F-M or U-L-T-B

- *11 total scenarios (can potentially reduce to 7)*

Metrics/output

- Energy
  - KWh/year
  - KWh/kW
  - KWh/acre (or hectare)

- Economic
  - Capital costs
  - Annual cashflow
  - NPV
  - IRR
  - Payback period
  - Levelized cost of energy (LCOE)

Converting Watts to Kilowatt-Hours

- A kilowatt-hour, expressed as kWh or kW·h, is a measure of energy that is equivalent to 1,000 watts of power for a 1-hour time period.
- To convert watts to kilowatt-hours, we multiply the power in watts by the number of hours, and divide by 1,000.
- Formula to calculate kWh:

$$kWh = \frac{(watts * hours)}{1000} \tag{1}$$

Calculating the solar energy output of a PV system

- The global formula to estimate the electricity output of a PV system:

$$kWh = A * r * H * PR \tag{2}$$

  - kWh = Energy output (kWh/year)
  - A = Total Estimated Area (m2)
  - r = solar panel yield or efficiency (%) [e.g. 15.6%]
  - H = Annual average solar radiation on panels (shadings not included)
    - Between 200 kWh/m2.y (Norway) and 2600 kWh/m2.y (Saudi Arabia)
  - PR = Performance ratio, coefficient for losses
    - Range between 0.5 and 0.9, default value = 0.75

Levelized cost of electricity (LCOE)

- The LCOE is a measure of the average net present cost of electricity generation for a plant over its lifetime.

- LCOE method (Schindele et al., 2020; Agostini et al., 2021):

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} A_t * (1+r)^{-t}}{\sum_{t=1}^{n} M_{t,el} * (1+r)^{-t}}$$

  - I_0 is capital cost (CAPEX)
  - A_t is operating cost (OPEX) in year t
  - r is the discount rate
  - $M_{t,el}$ is electricity production in year t

Framework for AV profitability

$$E[\pi_C] = P_C Y_C - (Y_C VC_C + FC_C) \qquad (3)$$

$$E[\pi_{PV}] = (P_S + REC - LCOE_{PV}) * kWh_{PV} \qquad (4)$$

where:

- π_C is annualized expected profit of the crop only option per unit of land ($/acre);
- π_{PV} is annualized expected profit of the solar only option per unit of land ($/acre);
- P_C is crop price ($/bushels);
- P_S is price of electricity from the solar PV ($/kWh);
- Y_C is crop yield from a monocropping system (bushels/acre);
- kWh_{PV} is energy output from the PV only system (kWh/year);
- VC and FC are variable cost ($/bushels) and fixed cost ($/acre).
- REC is solar renewable energy credit ($/kWh); $LCOE_{PV}$ is levelized cost of solar electricity ($/kWh)

Framework for AV profitability (Cont.)

$$E[\pi_{AV}] = \underbrace{x_{ij}(P_S + REC - LCOE_{AV}) * kWh_{AV}}_{\text{Solar energy profit}} + \underbrace{(1 - x_{ij})(P_C * Y_{AV} - C_C)}_{\text{cropland profit}} \quad (5)$$

$$E[\pi_{AV}] - E[\pi_{PV}]$$
$$= x_{ij} P_S kWh_{AV} + (1 - x_{ij}) P_C Y_{AV} - (VC_{PV} + VC_C) - (FC_{PV} + FC_C)$$
$$- P_S kWh_{PV}$$
$$= P_S (x_{ij} kWh_{AV} - kWh_{PV}) + (1 - x_{ij}) P_C Y_{AV} - \Delta VC - \Delta FC$$
$$(6)$$

- π_{AV} is annualized expected profit of AV per unit of land ($/acre);
- kWh_{AV} is energy output from AV system per unit of land (kWh/year)
- x_{ij} is the land area allocated under solar panels (%)

Framework for AV profitability (Cont.)

$$LER = (1 - x_{ij})\left(\frac{Y_{crop\ AV}}{Y_{monocrop}}\right) + \left(\frac{Y_{electricity\ AV}}{Y_{electricity\ PV}}\right)$$

$$= \left(\frac{(1-x_{ij}) * \delta_C * Y_{monocrop}}{Y_{monocrop}}\right) + \left(\frac{(x_{ij}) * Y_{electricity\ PV}}{Y_{electricity\ PV}}\right)$$

$$= (1 - x_{ij})\delta_C + x_{ij} \quad (7)$$

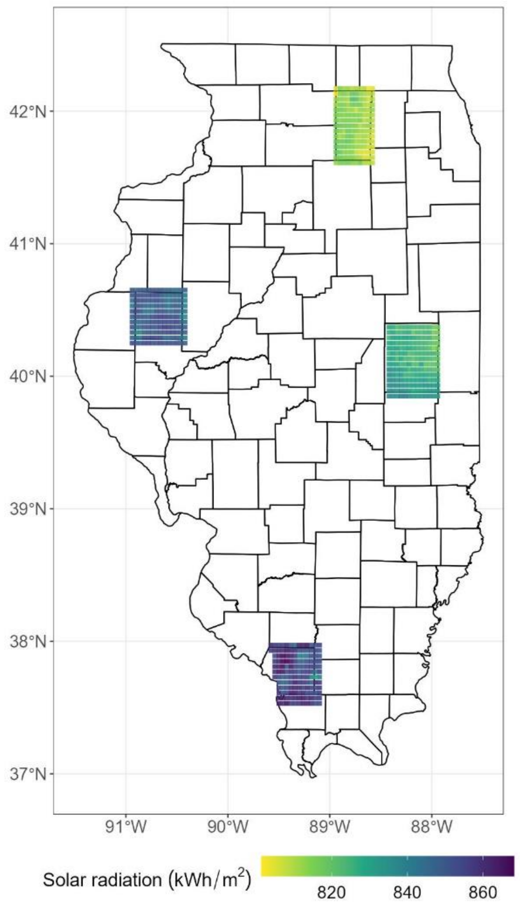
- The land equivalent ratio (LER) indicates the net impact of AV systems on the efficiency of land use
- Y is yield.
- For simplicity, it is assumed that yield in AV is proportional to that of mono-cropping and PV systems.
- δ_C is the impact on crop yield from the shading due to the solar panels

Conditions for AV profitability

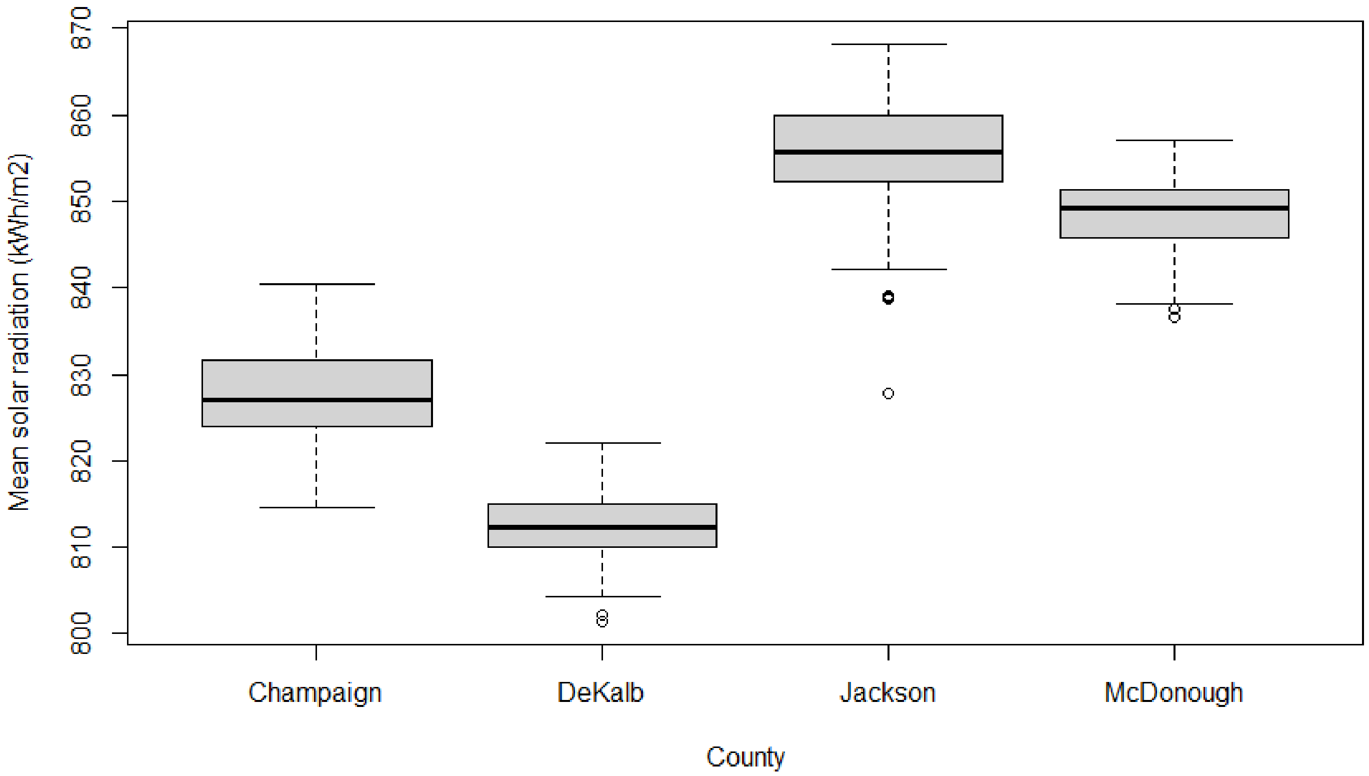
$$\underbrace{E[\pi_{AV}] - E[\pi_{PV}] = P_S\left(x_{ij}kWh_{AV} - kWh_{PV}\right)}_{\text{Solar energy profit}} + \underbrace{\left(1 - x_{ij}\right)P_C\left(\frac{LER - x_{ij}}{(1 - x_{ij})}\right)Y_{AV}}_{\text{cropland profit}} \underbrace{- \Delta VC - \Delta FC}_{\text{costs}} \tag{8}$$

- Adoption if $\mathrm{E}[\pi_{AV}] - E[\pi_{PV}] > 0$
- The difference in solar profit is negative ($kWh_{AV} < kWh_{PV}$).
- Solar energy production will occur on less land under AV scenario ($x_{ij} < 1$).
- Costs are higher for AV compared to PV option
- Additional crop production can be positive or negative, depending on the shading effect on crop yield and changes in production costs.
- Adoption potential of AV increases with higher yields, crop prices and LER

Variability in the solar resource

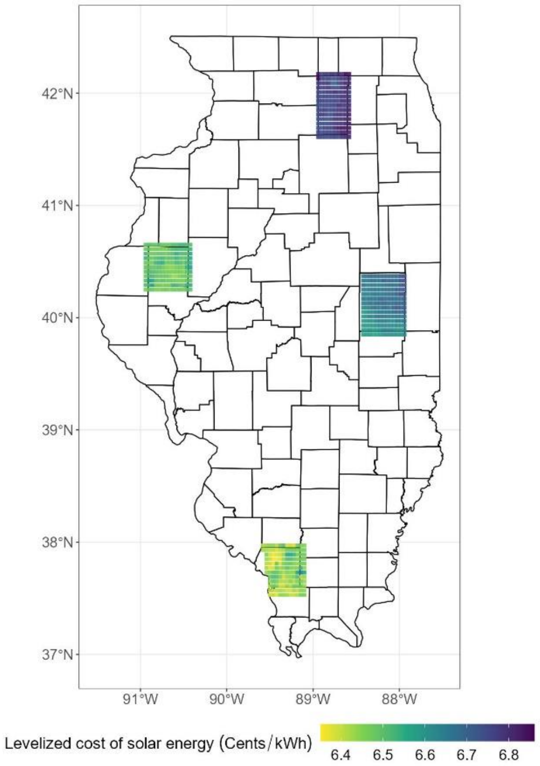


Distribution of the solar resource



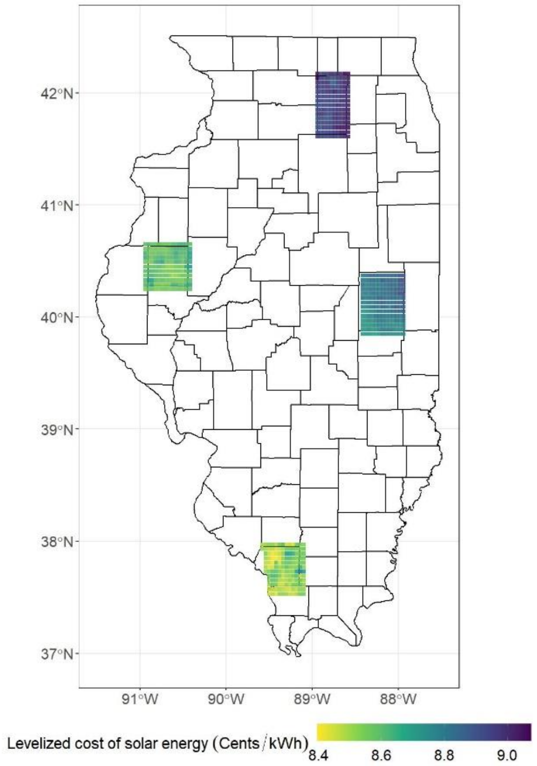
Spatially varying LCOE (scenario: C-O-T-B)

Solar only



Mean LCOE for PV= 6.60 cents/kWh

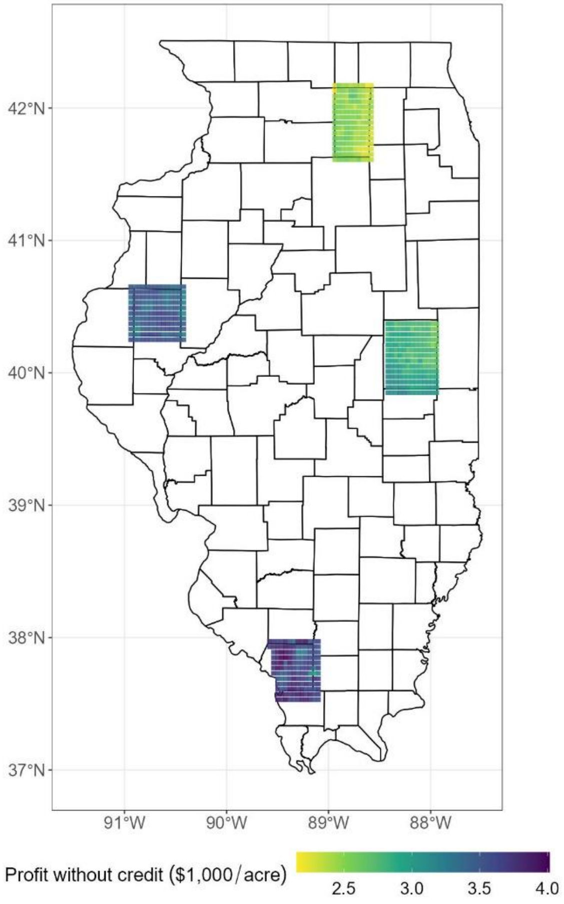
AV with 75% area under solar panels



Mean LCOE for AV= 8.72 cents/kWh

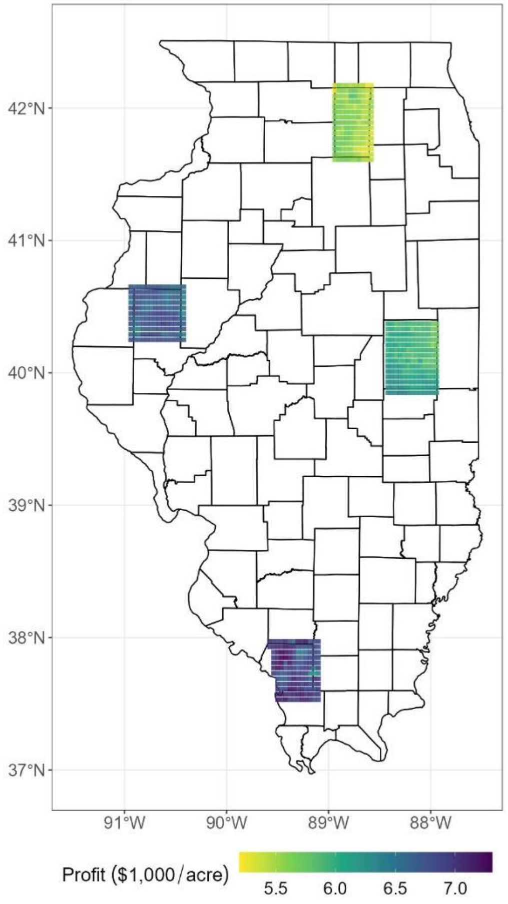
Profitability of solar only (scenario: C-O-T-B)

REC=$0/MWh



Average profit ~$3,098/acre

REC= $6.6/MWh



Average profit ~$6,267/acre

Next steps

- Spatial variability in crop profitability
  - Variability of yields and profits over 30 years
- Spatial variability in solar profits
  - Adding data on land leasing rates from solar developers
  - Adding transmission costs
  - Renewable energy potential (reV) model
- Spatial variability in AV profitability
  - Key assumptions about costs
  - Yield assumptions for AV
    - Crop types
- Draft manuscript on AV profitability

- Choice experiment (CE) survey to examine farmer and solar developer preferences

- Conference presentation at “Third Society for Benefit-Cost Analysis: European Conference, Paris, 2022”, Nov 3-4, 2022