NREL

Technoeconomic Analysis of changing PV System Layout and Convection Heat Transfer

Matthew Prilliman[1], Sarah Smith[3], Brooke Stanislawski[1], Marc Calaf[2], Raúl Bayoán Cal[3], Tim Silverman[1], Janine Keith[1]

[1]National Renewable Energy Laboratory, Golden, CO, 80401, USA; [2]University of Utah, Salt Lake City, UT, 84112
[3]Portland State University, Portland, OR, 97201

Abstract

This work includes analysis of potential economic improvements for PV systems for changing system parameters such as ground coverage ratio that alter the convective cooling consideration on PV modules through a newly proposed convective curve fit. Accounting for the spatial layout of the system in the convection heat transfer calculations allows for more accuracy in convective cooling load and subsequent module temperature calculations. The changing heat transfer considerations can be shown to improve system LCOE along with improved incident irradiance from increased row spacing despite the additional system costs incurred with increased module spacing. State-level analyses show that the impact of decreasing system GCR is greatest for climates with cold average annual ambient temperatures and moderate to high average annual wind speeds. Further waterfall analysis of changing system parameters reveals that the changing heat transfer dynamics have a non-negligible impact on system LCOE when compared to the changes in incident irradiance that serve as the primary driver of annual energy performance changes.

Introduction

- PV module heat transfer models do not account for changing convective cooling flow for changes in PV array layout
- Accounting for array layout in convection heat transfer calculations can affect module temperature and subsequent conversion efficiency
- Convection flow is affected by array spacing, tilt, clearance height, etc.

Heat Transfer

- Lacunarity: value representing spatial arrangements of modules
- Lacunarity takes panel height, tilt, GCR, etc. into account in calculation
- Nusselt number Nu_H correlation used to calculate convective heat transfer coefficient h:

$$Nu_H = \frac{hL_H}{k_{air}} = aRe^m Pr^n + b$$

$$Re = \frac{u_\infty L_{sc}}{\nu}$$

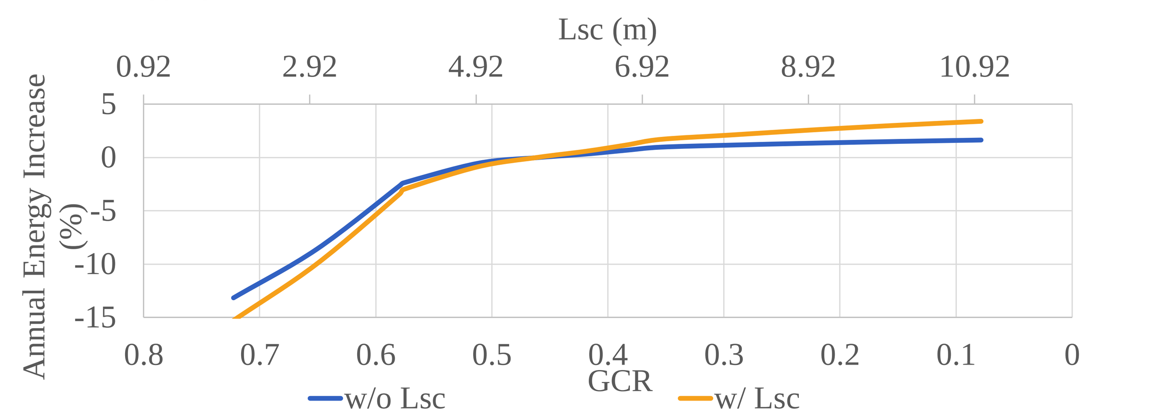
- L_H : array canopy height (m)
- k_{air} : thermal conductivity of air (W/mK)
- L_{sc} : lacunarity length scale (m)
- u_∞ : wind speed (m/s), ν : kinematic viscosity (m²/s)
- a = 0.090125, b = 1.8617, m = 1/5, n = 1/12

Case Study

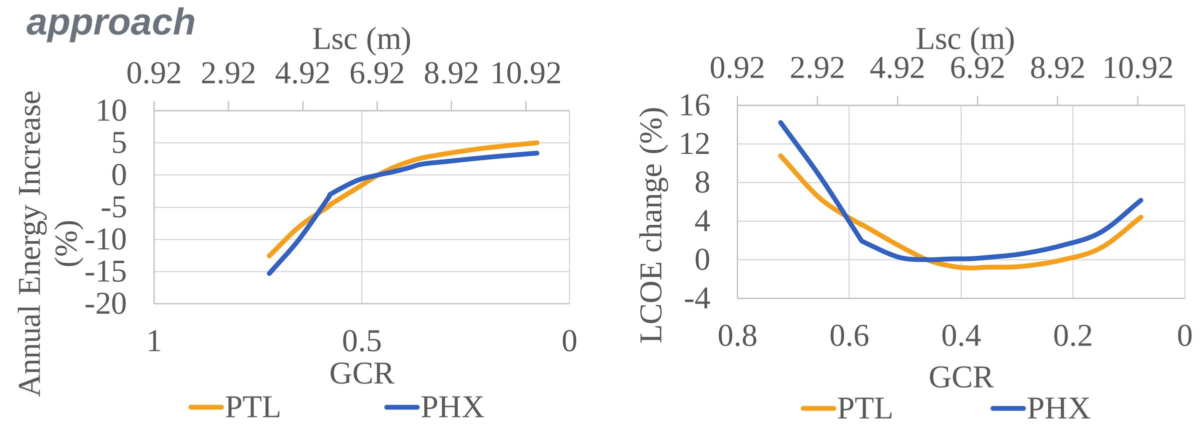
- Technoeconomic analysis was performed using the System Advisor Model (SAM)
- SAM: detailed PV system calculations with detailed cash flow financial calculations
- Parametric analysis of changing GCR and tilt, linked to L_H (m) values, system costs
- 1 MW system, 0.93 AC:DC Ratio
- Proposed convection heat transfer correlation used in place of conventional flat plate convection assumptions
- Wiring costs linked to GCR based on CAPEX sensitivity studies [2]
- Changing GCR requires changes in costs, DC wiring losses, land lease annual costs for different fixed tilt angles

LCOE Comparisons

- Energy gains increase for greater spacing, cooling flow
- LCOE inflection at point where increased costs outweigh energy gains



Normalized annual energy increase of lacunarity convection heat transfer approach vs. conventional flat-plate convection approach



Normalized annual energy (left) and LCOE (right) for Phoenix, AZ and Portland, OR systems

Tabular LCOE and Energy results for changing system GCR

Lsc (m)	GCR	System Costs ($/Wdc)	Land area (acres)	Annual Energy per Module (kWh/yr)	LCOE (cents/kWh)
2.00	0.72	0.16	1.78	527.71	3.30
3.00	0.65	0.17	1.98	560.63	3.13
4.00	0.58	0.19	2.22	601.52	2.95
4.28	0.58	0.20	2.23	604.16	2.94
4.83	0.51	0.21	2.51	617.46	2.89
5.54	0.46	0.22	2.79	622.93	2.89
6.10	0.42	0.23	3.07	626.53	2.89
6.68	0.38	0.24	3.35	630.19	2.89
7.34	0.35	0.25	3.63	633.49	2.89
8.00	0.29	0.26	4.39	636.07	2.90
9.00	0.22	0.28	5.81	639.09	2.93
10.00	0.15	0.30	8.59	641.73	2.97
11.00	0.08	0.32	16.44	644.03	3.06

U.S. States Heatmaps

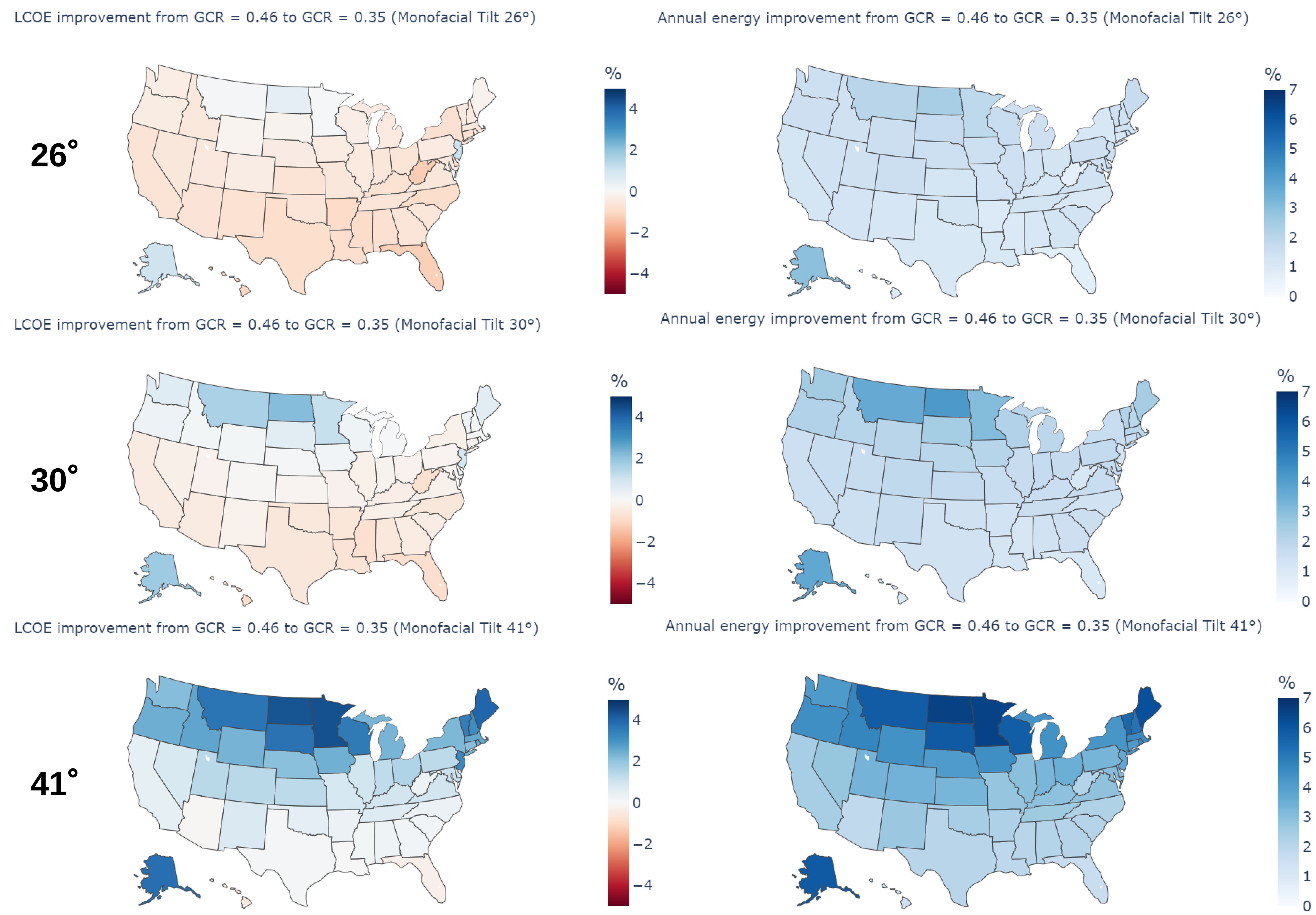
- Analysis of changing system GCR from 0.46 to 0.35 was performed for each U.S. state capitol at tilt angles of 26, 30, 41 degrees
- Systems were evaluated with monofacial panels with fixed tilt angles
- Cost increases, land lease costs, 0.2% DC wiring loss increase for decreased GCR

Takeaways

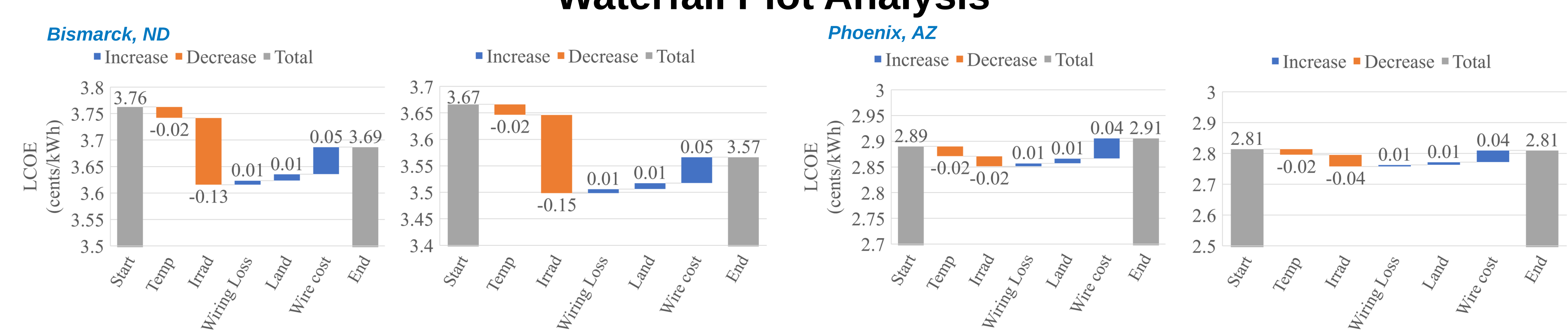
- **LCOE improves for decreasing GCR despite cost increases for several states**
- **Moving away from latitude tilt can have performance improvements due to improved convection heat transfer**
- **Waterfall analysis shows heat transfer effects are non-negligible component of LCOE improvements**

Changing LCOE with decreased GCR

Energy Increases with decreased GCR



Waterfall Plot Analysis



Waterfall analysis of modeling factors for LCOE for monofacial (left) and bifacial (right) systems at 30° fixed tilt angle

References

- Prilliman, Matthew, Sarah Smith, Brooke Stanislawski, Marc Calaf, Raul Bayoan Cal, Tim Silverman, and Janine Keith. Improvement in PV Plant LCOE from Convection Heat Transfer Changes from Altered Plant Layout (2022). 2022 IEEE PVSC. Preprint.
- B. J. Stanislawski, "Influence of spatial arrangement of solar farms in convective cooling and module temperature," Ph.D. dissertation, University of Utah, 2021, to be published.
- R. Scott, H. Kadum, G. Salmaso, M. Calaf, and R. B. Cal, "A lacunarity based index for spatial heterogeneity," Earth and Space Science Open Archive, p. 16, 2022. [Online]. Available: https://doi.org/10.1002/essoar.10510827.1
- S. Smith, B. Stanislawski, B. Eng, N. Ali, T. Silverman, M. Calaf, and R. Cal, "Viewing convection as a solar farm phenomenon broadens modern power predictions for solar photovoltaics," J. Renew. Sustain. Energy, Under Review, 2022.
- K. Horowitz, V. Ramasamy, J. Macknick, and R. Margolis, "Capital costs for dual-use photovoltaic installations: 2020 benchmark for ground-mounted pv systems with pollinator-friendly vegetation, grazing, and crops," National Renewable Energy Laboratory, Golden, Colorado, Tech. Rep., March 2018. [Online]. Available: https://www.nrel.gov/docs/fy21osti/77811.pdf.

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number DE-EE0008168. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

PV Performance Modeling and Monitoring Workshop
Salt Lake City, Utah
8/23/2022 – 8/24/2022
NREL/PO-7A40-83655