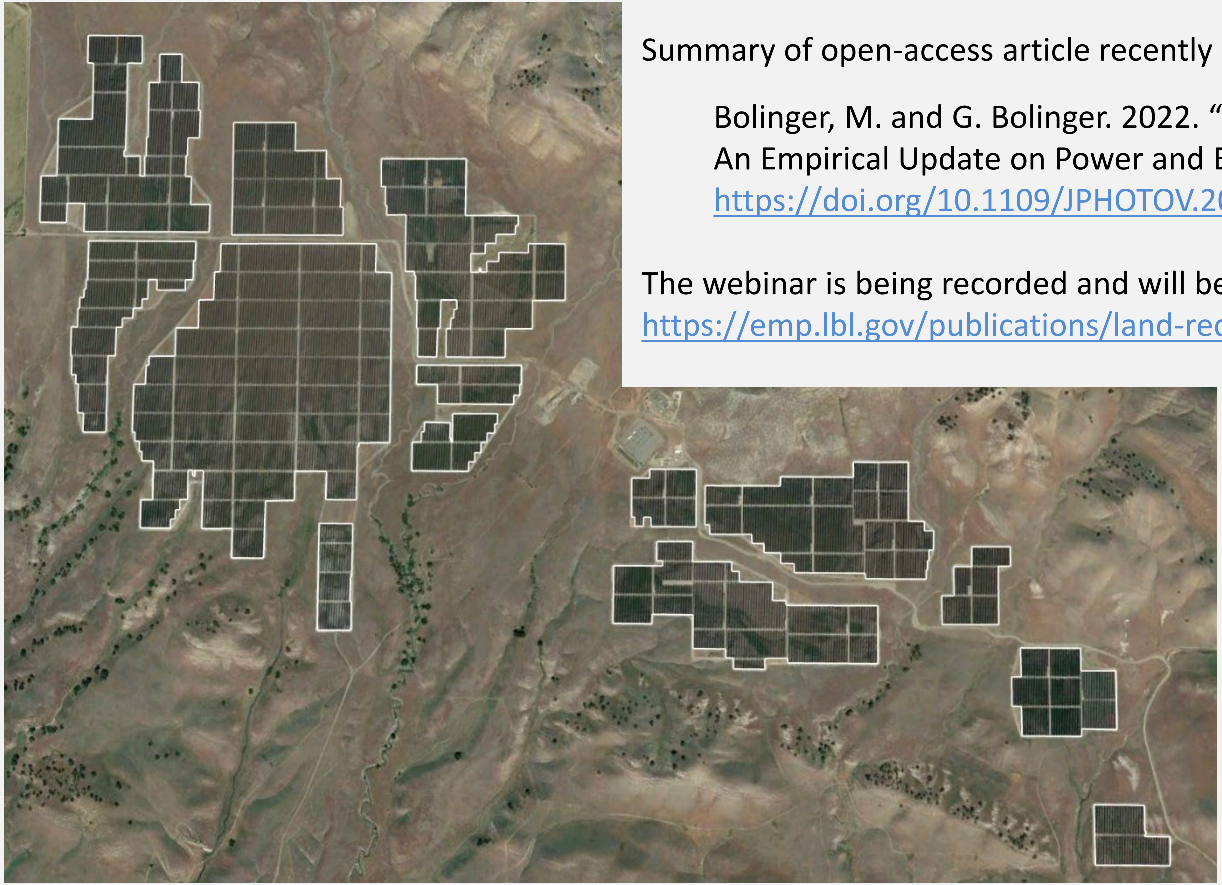
# Land Requirements for Utility-Scale PV: An Empirical Update on Power and Energy Density



Summary of open-access article recently published in the *IEEE Journal of Photovoltaics*:

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The webinar is being recorded and will be posted at:
https://emp.lbl.gov/publications/land-requirements-utility-scale-pv

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# Why power (MW/acre) and energy (MWh/acre) density matter

- Decarbonizing the power sector (and the broader economy) will require massive amounts of solar
- The amount of land occupied by utility-scale PV plants has grown significantly, and will continue to—raising valid concerns around land requirements and land-use impacts (such as taking farmland out of production)
- The amount of land required to build a utility-scale PV plant is also an important cost consideration, and unlike other PV plant costs (e.g., for modules and inverters), land costs—which are a component of LCOE—will likely NOT decline with greater deployment
  - Land costs are more likely to INCREASE as the sector expands and competition for good sites heats up
  - "Buy land. They ain't making any more of it."—Will Rogers and/or Mark Twain
- While there are potentially other ways (such as "agrivoltaics") to mitigate the negative land-use impacts of utility-scale PV, the primary way to mitigate the inevitability of rising land costs is to minimize the amount of land needed to generate each MWh of solar energy
  - ***Increasing utility-scale PV's power (MW/acre) and energy (MWh/acre) density can help reduce land costs*** **and** ***land-use impacts***

# Why we need updated density estimates

- The last comprehensive review of (semi-)empirical data on solar's power and energy density was an NREL paper published in June 2013 (with data through mid-2012), and ***much has changed since then***
  - Ong et al. June 2013. "Land-Use Requirements for Solar Power Plants in the United States." NREL/TP-6A20-56290
- Nearly a decade later, NREL's 2013 report is still often referenced and cited for power and energy density, despite a few shortcomings:
  - **Small sample size:** The utility-scale PV sector was still young back in 2012, and relatively few of the projects in NREL's sample had actually been built yet
  - **Inconsistent data sources:** To boost sample size, NREL relied on a combination of permit filings, developer interviews, and satellite data—perhaps introducing data that does not reflect what was ultimately built
  - **AC instead of DC:** NREL's power density is expressed in AC terms ($MW_{AC}$/acre), even though density is largely a function of DC capacity (i.e., the array's DC rating rather than the inverters' AC rating)
  - **Out of date:** Pre-2013 data misses all of the subsequent advances in terms of module capacity, plant design, single-axis tracking, etc.
- With utility-scale PV density and land-use issues becoming increasingly important, and given all the progress made over the past decade, ***it is high time for an update***

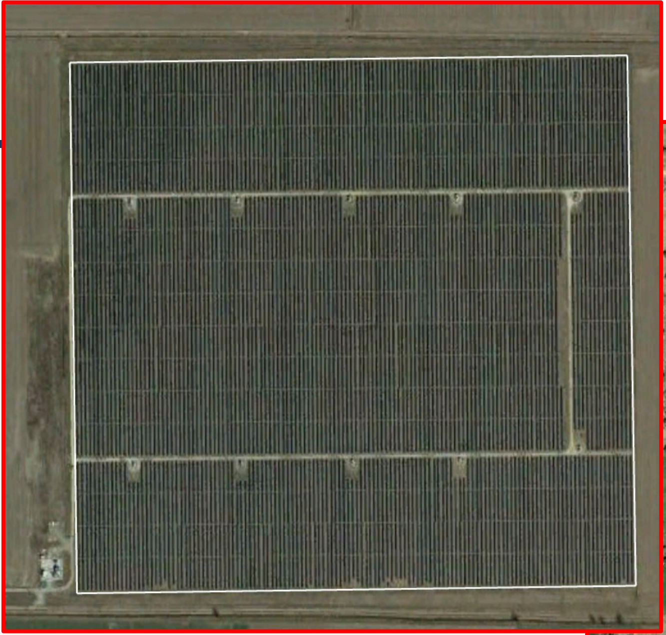
# What we did

1) We used plant-level data—such as lat/long coordinates, capacity (DC and AC), capacity factor, and fixed-tilt versus tracking—collected for our “Utility-Scale Solar” report series (utilityscalesolar.lbl.gov) to establish the universe of ground-mounted PV plants >5 $MW_{AC}$

2) We used ArcGIS to draw polygons around satellite imagery (from Google Earth and Maxar/Digital Globe) of each plant’s PV array(s) and to calculate the polygons’ acreage

3) We calculated power ($MW_{DC}$/acre) and energy (MWh/year/acre) density for each PV plant, and then analyzed geospatial and temporal trends

# Some examples…



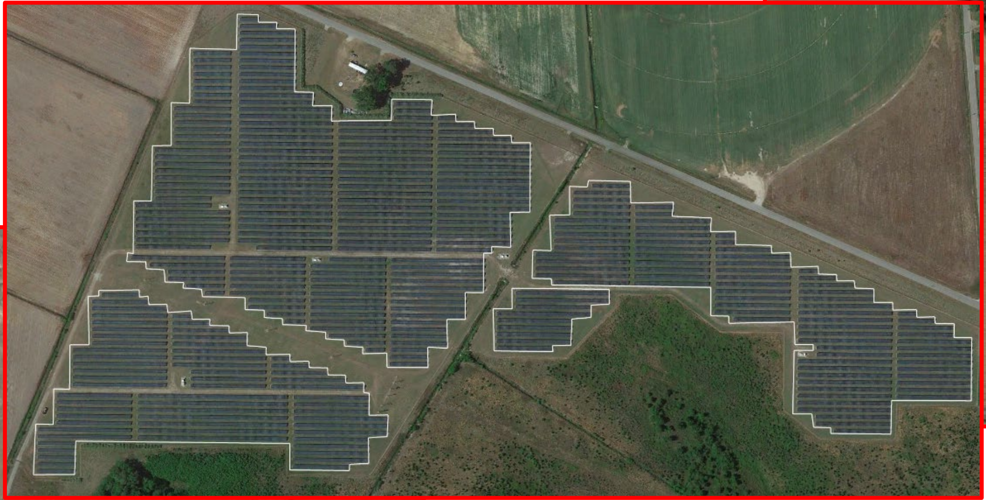
29 $MW_{DC}$ (OH)

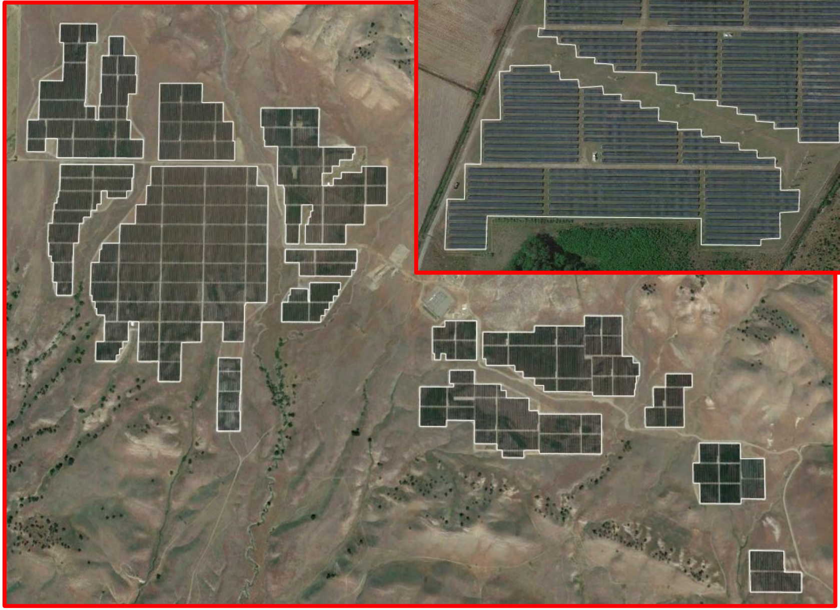
14 $MW_{DC}$ (OR)

11 $MW_{DC}$ (MD)

# A few more examples…

14 $MW_{DC}$ (SC)

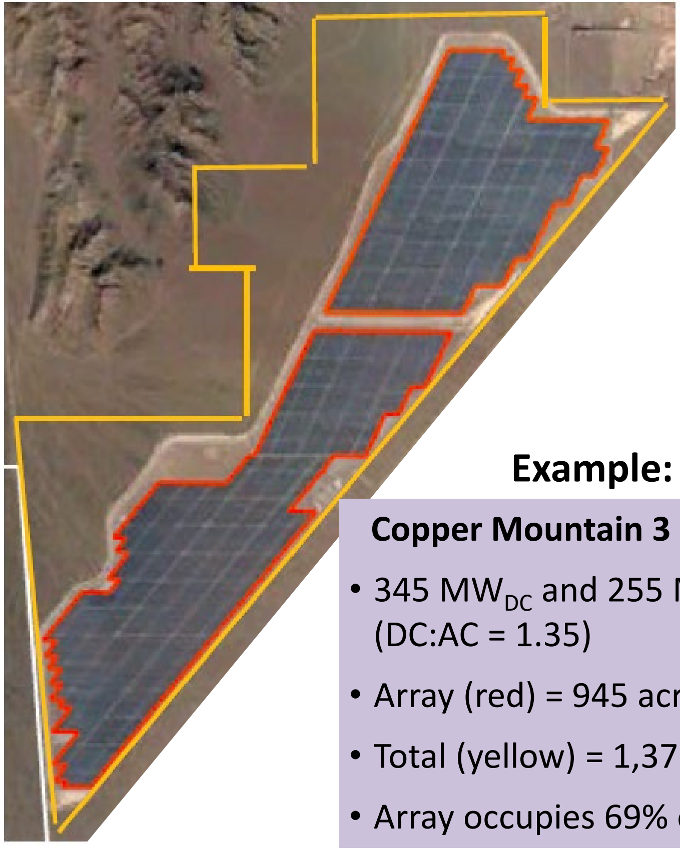




10 $MW_{DC}$ (OH)

173 $MW_{DC}$ (CA)

# We focus on the area occupied by the arrays, rather than the total site area



**Example:**

**Copper Mountain 3 (Nevada)**

- 345 $MW_{DC}$ and 255 $MW_{AC}$ (DC:AC = 1.35)
- Array (red) = 945 acres
- Total (yellow) = 1,375 acres
- Array occupies 69% of the site

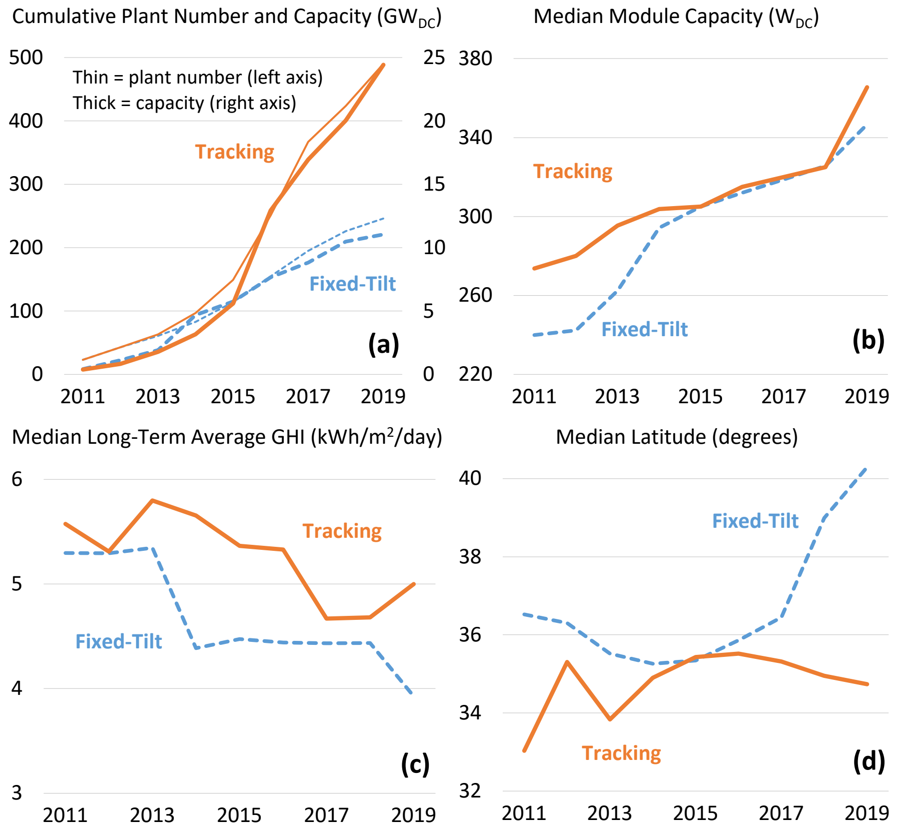
- Our polygons focus on the area directly occupied by the arrays (and any associated nearby equipment, such as inverter pads) – **NOT** on the total leased or owned area of the site
  - ➢ The total leased/owned area is often not apparent from satellite imagery (in the example on the left, the yellow lease boundaries—obtained from municipal data—are not at all obvious from imagery)
  - ➢ The relationship between the direct/array area and the total leased/owned area may vary considerably from site to site, depending on local site conditions (e.g., if a site includes wetland areas that can't be disturbed)
  - ➢ Therefore, only the direct/array area provides usable information about power and energy density
- Users can de-rate our numbers to suit their own local conditions—e.g., if only 75% of your site is buildable, just multiply our numbers by 75%

# Overview of our sample—in numbers

| | All Plants | | | | | | Fixed-Tilt Plants | | | | | | Single-Axis Tracking Plants | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | # of | Sum | | | Median | | # of | Sum | | | Median | | # of | Sum | | | Median | |
| COD | Plants | $MW_{DC}$ | $MW_{AC}$ | DC:AC | LT GHI | Latitude | Plants | $MW_{DC}$ | $MW_{AC}$ | DC:AC | LT GHI | Latitude | Plants | $MW_{DC}$ | $MW_{AC}$ | DC:AC | LT GHI | Latitude |
| 2007 | 1 | 14 | 12 | 1.17 | 5.6 | 36.3 | 0 | 0 | 0 | | | | 1 | 14 | 12 | 1.17 | 5.6 | 36.3 |
| 2008 | 1 | 12 | 10 | 1.21 | 5.7 | 35.8 | 1 | 12 | 10 | 1.21 | 5.7 | 35.8 | 0 | 0 | 0 | | | |
| 2009 | 2 | 53 | 46 | 1.15 | 5.4 | 30.5 | 1 | 25 | 21 | 1.20 | 5.7 | 33.6 | 1 | 28 | 25 | 1.10 | 5.0 | 27.3 |
| 2010 | 9 | 174 | 144 | 1.20 | 4.7 | 35.8 | 6 | 121 | 100 | 1.22 | 4.8 | 33.1 | 3 | 53 | 45 | 1.18 | 4.5 | 37.7 |
| 2011 | 33 | 549 | 461 | 1.19 | 5.4 | 36.0 | 15 | 261 | 215 | 1.21 | 5.3 | 36.5 | 18 | 288 | 247 | 1.17 | 5.6 | 33.0 |
| 2012 | 40 | 1,155 | 909 | 1.27 | 5.3 | 35.7 | 20 | 703 | 546 | 1.29 | 5.3 | 36.3 | 20 | 452 | 363 | 1.24 | 5.3 | 35.3 |
| 2013 | 38 | 1,754 | 1,344 | 1.31 | 5.6 | 34.8 | 18 | 800 | 607 | 1.32 | 5.3 | 35.5 | 20 | 954 | 736 | 1.30 | 5.8 | 33.8 |
| 2014 | 56 | 4,139 | 3,188 | 1.30 | 5.5 | 35.1 | 22 | 2,759 | 2,120 | 1.30 | 4.4 | 35.3 | 34 | 1,380 | 1,068 | 1.29 | 5.7 | 34.9 |
| 2015 | 83 | 3,494 | 2,681 | 1.30 | 5.3 | 35.4 | 31 | 1,070 | 803 | 1.33 | 4.5 | 35.3 | 52 | 2,424 | 1,877 | 1.29 | 5.4 | 35.4 |
| 2016 | 143 | 9,252 | 7,065 | 1.31 | 5.1 | 35.8 | 41 | 1,919 | 1,432 | 1.34 | 4.4 | 35.9 | 102 | 7,333 | 5,633 | 1.30 | 5.3 | 35.5 |
| 2017 | 156 | 5,179 | 3,883 | 1.33 | 4.6 | 35.8 | 40 | 1,150 | 849 | 1.35 | 4.4 | 36.4 | 116 | 4,029 | 3,033 | 1.33 | 4.7 | 35.3 |
| 2018 | 88 | 4,733 | 3,445 | 1.37 | 4.6 | 35.3 | 31 | 1,655 | 1,143 | 1.45 | 4.4 | 39.0 | 57 | 3,078 | 2,301 | 1.34 | 4.7 | 34.9 |
| 2019 | 86 | 4,973 | 3,813 | 1.30 | 4.7 | 35.3 | 20 | 566 | 394 | 1.44 | 3.9 | 40.3 | 66 | 4,406 | 3,419 | 1.29 | 5.0 | 34.7 |
| **Total** | **736** | **35,482** | **27,001** | **1.31** | | | **246** | **11,042** | **8,241** | **1.34** | | | **490** | **24,440** | **18,760** | **1.30** | | |

- Our sample consists of 736 plants totaling 35.5 $GW_{DC}$ (27.0 $GW_{AC}$) that came online from 2007-2019 across 38 (of 50) states
- This sample includes 92% of all utility-scale (i.e., ground-mounted and >5 $MW_{AC}$) PV plants that came online over this 13-year period
- However, due to a very limited buildout (and, hence, sample size) in the first few years of the sector from 2007-2010, our analysis focuses on the period from 2011-2019

# Overview of our sample—in graphs




a) At the end of 2019, there were roughly twice as many tracking plants, and roughly twice as much tracking capacity, as fixed-tilt

- ➢ This disparity has developed entirely since 2015
- ➢ Reflects the declining cost and increasing reliability of single-axis tracking

b) Module capacity, which is a function of module efficiency, has increased significantly since 2011

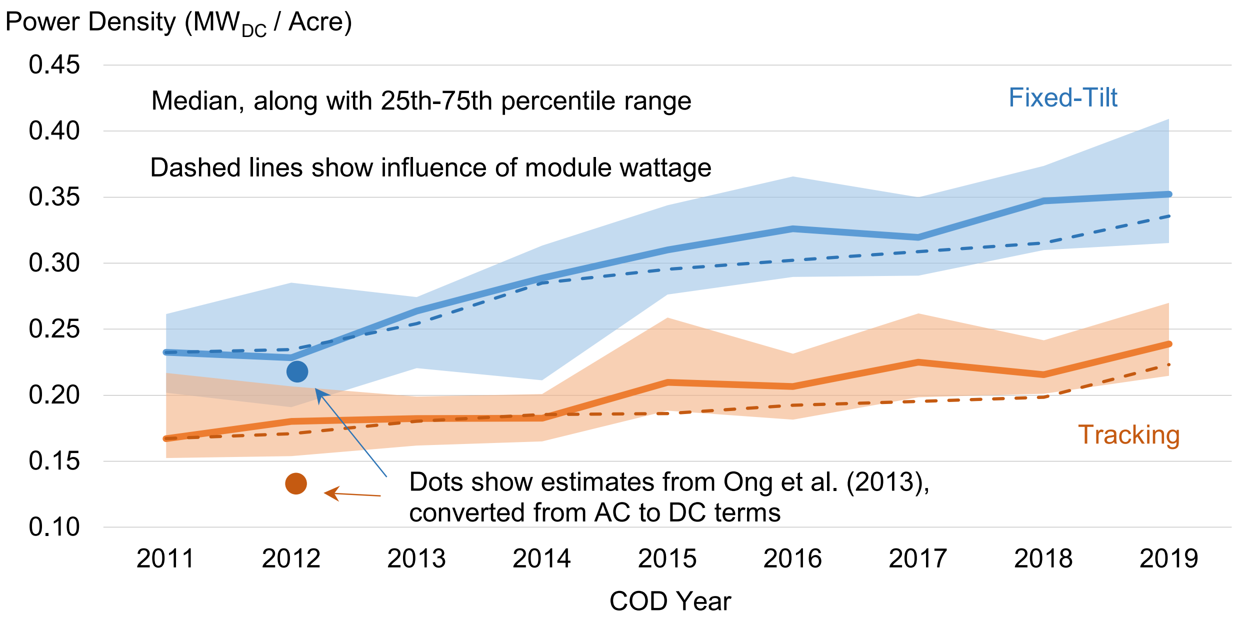
- ➢ Prior to 2015, tracking plants tended to use higher-powered modules than fixed-tilt plants, to get the most out of the then-much-higher cost of trackers

c) Both fixed-tilt and tracking plants have migrated to lower-irradiance areas of the U.S. over time, as the up-front cost of utility-scale PV has declined, enabling it to compete even in areas with less insolation

- ➢ That said, tracking plants are regularly sited at higher-irradiance locations than fixed-tilt plants

d) Since 2014, fixed-tilt plants have increasingly been relegated to higher-latitude sites, where use of single-axis tracking does not make as much sense

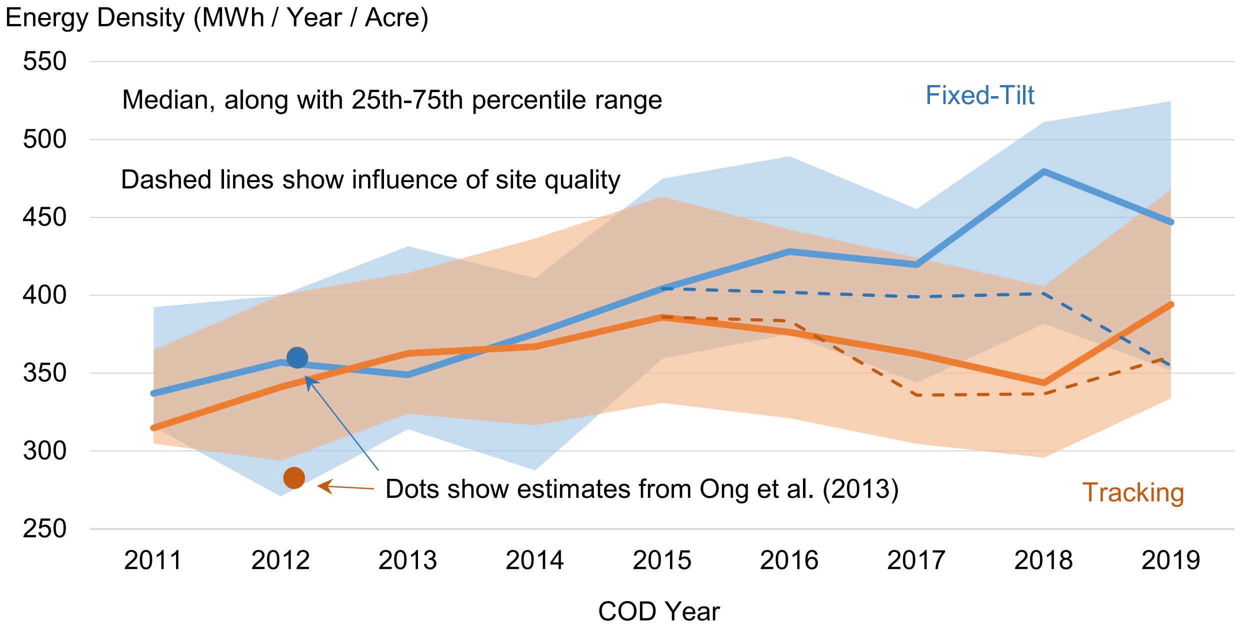
# Power density ($MW_{DC}$/Acre) has steadily increased over time




- Fixed-tilt's higher power density reflects its higher ground coverage ratio (GCR)
  - ➢ ~0.40-0.50 GCR for fixed-tilt versus ~0.25-0.40 GCR for tracking
  - ➢ Less concern about self-shading with fixed-tilt drives higher GCR
- **In 2019, median power densities were 52% higher than in 2011 for fixed-tilt plants, and 43% higher for single-axis tracking plants**

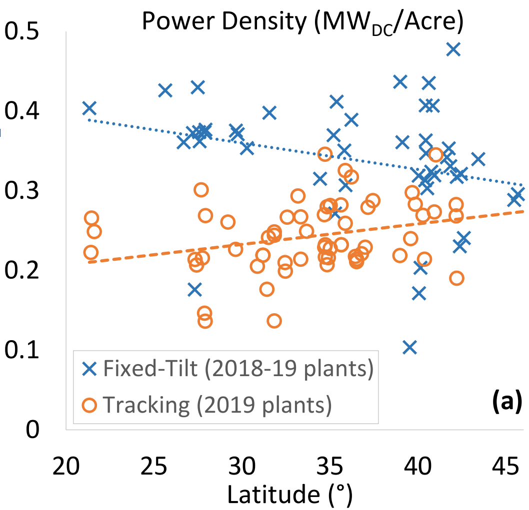
- Respective trends in power density mostly (but not only) reflect respective trends in module capacity
  - ➢ The thin dashed lines, indexed to 2011 median densities, show trends in median module capacity for fixed-tilt and tracking plants
  - ➢ Early tracking plants used higher-power modules than fixed-tilt plants as a way to get the most out of the then-much-higher cost of trackers, and so have not gained as much density as have fixed-tilt plants from the increase in module wattage over time
- Other improvements include backtracking, independent row movement, improved fixed racking and modeling software

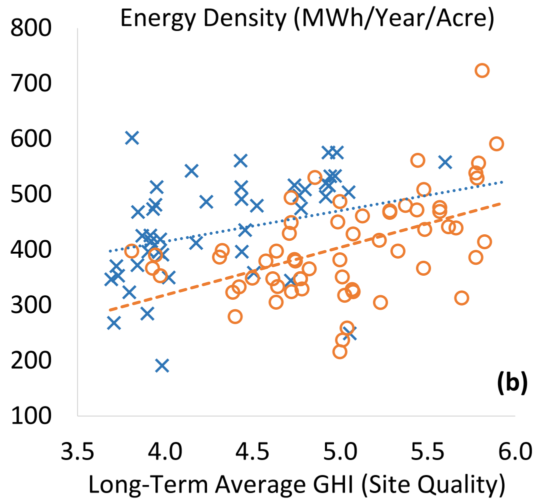
# Energy density (MWh/Acre) has also improved, but depends on site quality




- While fixed-tilt has higher power density than tracking (see prior slide), energy density was largely a toss-up until post-2015 divergence (driven by expansion of tracking to less-sunny sites—see bottom bullet)
- **In 2019, median energy densities were 33% higher than in 2011 for fixed-tilt plants, and 25% higher for single-axis tracking plants**

- The thin dashed lines, indexed to 2015 median densities, are an attempt to show the influence of site resource quality (long-term average insolation at each site) on the post-2015 divergence of fixed-tilt and tracking energy densities
  - ➢ Fixed-tilt energy density continued to move higher post-2015, as median site quality held steady (until 2019 reversal)
  - ➢ Tracking energy density has languished since 2015, due to declining site quality (until 2019 reversal)




# Site latitude and site quality (average irradiance) influence densities

a) Power density declines at higher latitudes for fixed-tilt plants (blue x's), as lower GCRs are required to avoid self-shading, but trends for tracking plants (orange circles) are less obvious/intuitive

- A tracking plant's north/south axes (tracking east to west) make latitude not as much of a consideration in terms of shading…in fact, graph (a) suggests that power density for tracking plants may even *improve* slightly at higher latitudes—perhaps because a lower sun angle reduces self-shading, thereby enabling a slightly higher GCR?
- Graph (a) shows a greater preponderance of fixed-tilt plants at higher latitudes and tracking plants at lower latitudes (makes sense)

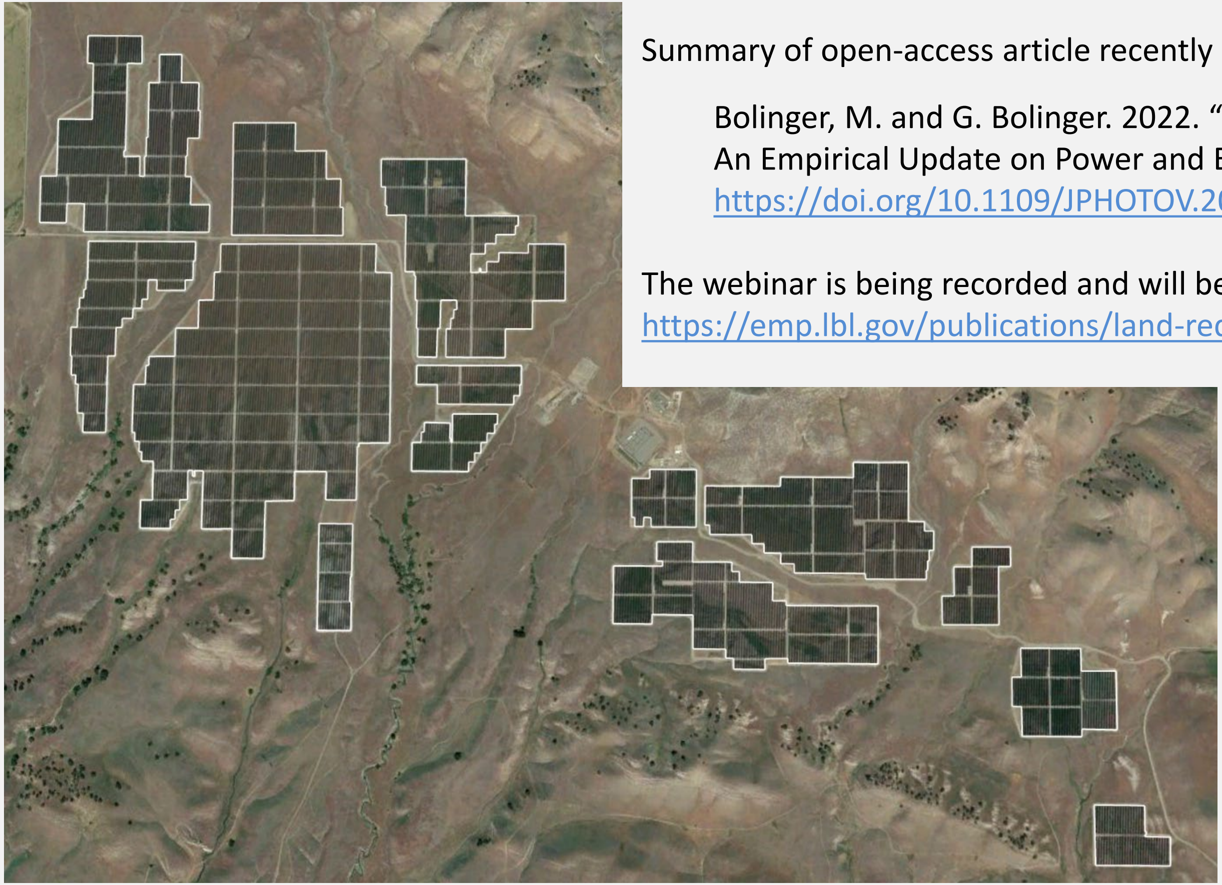
b) Energy density increases at higher-insolation sites, for both fixed-tilt and tracking plants (intuitive)

- Graph (b) shows a greater preponderance of fixed-tilt plants at lower-irradiance sites and tracking plants at higher-irradiance sites (makes sense)

# Conclusions and Next Steps

- Our density estimates for the early years more or less agree with NREL's 2013 report—at least for fixed-tilt
  - ➢ But we're farther apart for single-axis tracking—perhaps because there were fewer tracking systems back then (small NREL sample?)
- Since then, both power and energy density have increased significantly—power more so than energy
  - ➢ Median power density ($MW_{DC}$/acre) increased by 52% (fixed-tilt) and 43% (tracking) from 2011 through 2019
  - ➢ Median energy density (MWh/year/acre) increased by 33% (fixed-tilt) and 25% (tracking) from 2011 through 2019
- **Updated reference densities for 2019:**
  - ➢ **Power density: 0.35 $MW_{DC}$/acre (2.8 acres/$MW_{DC}$) for fixed-tilt and 0.24 $MW_{DC}$/acre (4.2 acres/$MW_{DC}$) for tracking**
  - ➢ **Energy density: 447 MWh/acre (2.2 acres/GWh) for fixed-tilt and 394 MWh/acre (2.5 acres/GWh) for tracking**
  - ➢ **These are median values—there is obviously a range around the median, depending on latitude, site resource quality, etc.**
- Next steps:
  - ➢ Regularly update the analysis so that power and energy density benchmarks never get as stale as they were prior to this update
  - ➢ Future updates should pay particular attention to new plants using bifacial modules as well as larger-format modules—each of which could have a significant impact on densities. As our current analysis only runs through 2019, neither of these up-and-coming module innovations had yet infiltrated our plant sample to any significant degree.

# Questions?



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