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

Mark Bolinger and Greta Bolinger

***Abstract*—The rapid deployment of large numbers of utility-scale photovoltaic (PV) plants in the United States, combined with heightened expectations of future deployment, has raised concerns about land requirements and associated land-use impacts. Yet our understanding of the land requirements of utility-scale PV plants is outdated and depends in large part on a study published nearly a decade ago, while the utility-scale sector was still young. We provide updated estimates of utility-scale PVs power and energy densities based on empirical analysis of more than 90% of all utility-scale PV plants built in the United States through 2019. We use ArcGIS to draw polygons around satellite imagery of each plant within our sample and to calculate the area occupied by each polygon. When combined with plant metadata, these polygon areas allow us to calculate power (MW/acre) and energy (MWh/acre) density for each plant in the sample, and to analyze density trends over time, by fixed-tilt versus tracking plants, and by plant latitude and site irradiance. We find that the median power density increased by 52% for fixed-tilt plants and 43% for tracking plants from 2011 to 2019, while the median energy density increased by 33% for fixed-tilt and 25% for tracking plants over the same period. Those relying on the earlier benchmarks published nearly a decade ago are, thus, significantly overstating the land requirements of utility-scale PV.**

***Index Terms*—Energy density, land requirements, land-use impacts, photovoltaics (PVs), power density.**

I. Introduction

UTILITY-SCALE photovoltaic (PV) plants—defined here to include any ground-mounted plant larger than 5 MW_{AC} of capacity—have quickly become the backbone of the solar industry in the United States. The first two utility-scale PV plants in the United States came online as recently as late 2007, but within just five years (by 2012), utility-scale PV had become the largest sector of the overall solar market (bigger than either the residential or commercial and industrial sectors), and by 2020, it contributed more than half of all solar generation in the United States [1]. This rapid growth is widely expected to continue, as utility-scale PV is projected to play a major role in transitioning the United States toward a lower carbon future [2].

Unlike rooftop PV systems, which have limited or no land-use impacts by virtue of being mounted on existing structures, utility-scale PV plants are, by definition, sited on the ground and in the landscape and, therefore, occupy space that could, in most instances, be used for alternative purposes. As such, concern about the land requirements and land-use impacts of utility-scale PV have grown, as deployment has accelerated and as decarbonization plans routinely call for an unprecedented expansion of the sector [2], [3]. This concern has spurred productive research into areas such as "agrivoltaics" [4], which holds promise for mitigating the impacts of an expanding utility-scale PV sector on the availability and use of arable land in particular, by combining energy and food production.

Beyond potential land-use impacts, the amount of land required to build a utility-scale PV plant is also an important cost consideration. The cost of most components of a utility-scale PV plant (e.g., modules, inverters, and tracking systems) will tend to decline with greater deployment due to technology- or manufacturing-related learning [5]. In contrast, the cost of the land on which to build the plant is more likely to *increase* with greater deployment because—as Will Rogers and/or Mark Twain once famously quipped—land is the one thing that "they are not making any more of." For utility-scale PV to live up to its potential as a key decarbonization tool, minimizing costs—including land costs—must be a high priority.

While there are potentially other ways (such as agrivoltaics) to limit the land-use impacts of utility-scale PV, the primary, if not the only, way to mitigate the inevitability of rising land costs is to minimize the amount of land needed to generate each MWh of solar energy. In other words, increasing the power (MW/acre) and energy (MWh/acre) density of utility-scale PV can at least partially offset the higher land costs likely to be incurred going forward, while also helping to mitigate any associated land-use impacts.

Despite the increasing importance of land requirements from both a land-use and cost perspective, estimates of utility-scale PVs power and energy density are woefully outdated. The last major study of utility-scale PVs power and energy density in the United States (from Ong *et al.* [6]) is now almost a decade out of date, yet is still routinely cited on matters pertaining to land requirements and land use—despite the rapid evolution of the industry in the years since its publication. For example, the National Renewable Energy Laboratory's web page titled "Land Use by System Technology" [7] still reflects densities from Ong

Manuscript received October 18, 2021; revised November 22, 2021; accepted December 13, 2021. Date of publication January 10, 2022; date of current version February 19, 2022. This work was supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Office under Contract DE-AC02-05CH11231. *(Corresponding author: Mark Bolinger.)*

Mark Bolinger is with the Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA (e-mail: mabolinger@lbl.gov).

Greta Bolinger is with Bowdoin College, Brunswick, ME 04011 USA (e-mail: gbolinge@bowdoin.edu).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/JPHOTOV.2021.3136805.

Digital Object Identifier 10.1109/JPHOTOV.2021.3136805

et al. [6]. Despite including "observation based" within its title, a study published in 2018 [8] simply applies observed plant capacities to the power densities estimated by Ong *et al.* [6] to arrive at land requirements (i.e., only the capacities, and not the land areas, were "observed" in this case). Another 2018 study [9] is simply a review and meta-analysis of earlier studies, including Ong *et al.* [6], and therefore, does not add new information. A 2020 comparison of the land requirements of geothermal power to that of other forms of generation [10] refers back to Ong *et al.* [6] for its solar estimates. Another 2020 study [11] questions the viability of high-penetration wind and solar scenarios based in large part on land-use impacts, relying on estimates from both Ong *et al.* [6] and [8], which itself depends on Ong *et al.* [6], as well as another early study that takes a similar approach to Ong *et al.* [6] but with a more limited focus on California [12]. A highly publicized 2021 study of land requirements under various decarbonization scenarios modeled by Princeton University [13] relies on Ong *et al.* [6], [7], and [9] for its solar estimates. Finally, Kowalczyk [3] discusses the rising tension between using land for solar versus crop production, yet again referencing outdated data from Ong *et al.* [6] to provide an indication of solar's land requirements in 2021. In short, the estimates of utility-scale PVs land requirements found within the literature have become rather inbred, with most estimates ultimately linking back Ong *et al.* [6], even if only indirectly (e.g., through secondary citations that themselves depend on Ong *et al.* [6]).

Despite its status as the go-to reference for utility-scale PV power and energy density estimates, Ong *et al.* [6] suffers from several limitations, such as follows.

1) A small sample size that includes plants that were still in development and had not yet been built (given that the sector was still young at the time).
2) Potential over-representation of fixed-tilt plants (as single-axis tracking had not yet become dominant).
3) Use of inconsistent and potentially conflicting data sources (e.g., a combination of permit filings, developer interviews, and satellite imagery).
4) Expressing power density in ac rather than dc capacity terms (even though land requirements are a direct function of the dc capacity of the array and are only loosely tied to the ac capacity of the inverters).

The most significant limitation of Ong *et al.* [6], however, is simply that it is now almost a decade out of date. The intervening years have seen profound changes to the utility-scale PV sector, such as a significant increase in module power density (driven by improved conversion efficiency), higher dc:ac ratios, an almost complete shift to single-axis tracking, and—very recently—the introduction of bifacial and larger format modules (none of which are reflected in our analysis to any significant degree, given that our plant sample only runs through 2019). These changes, combined with the growing importance of land requirements and land-use issues as deployment continues at a rapid pace, mean that it is long past time for an update.

This article provides a much-needed update to estimates of utility-scale PVs land requirements, expressed via the metrics of power and energy density. We find that both power and energy density have increased significantly since the period examined by Ong *et al.* [6]. Specifically, the median power density (MW_{DC}/acre) increased by 52% (fixed tilt) and 43% (tracking) from 2011 to 2019, while the median energy density (MWh/year/acre) increased by 33% for fixed tilt and 25% for tracking over the same period. Three of these four percentage increases are even larger when compared with estimates from Ong *et al.* [6] rather than to our own 2011 data. Analysts, modelers, planners, regulators, and policymakers still relying on the benchmarks laid out by Ong *et al.* [6] nearly a decade ago are, thus, significantly overstating the land requirements of utility-scale PV.

II. Methods

A. Sample

We began by mining Berkeley Lab's *Utility-Scale Solar* dataset [1] to establish the universe of operational utility-scale PV plants in the United States through the end of 2019 and to pull key metadata for each plant in that universe. Key metadata includes each plant's commercial operation date (COD), centroid coordinates (latitude and longitude), capacity (in both dc and ac terms), module type (crystalline silicon versus thin film) and wattage, mount type (fixed-tilt versus single-axis tracking), and annual energy production, as well as the long-term average annual global horizontal irradiance (GHI) at each plant site (sourced from NRELs solar resource data[1]). Berkeley Lab compiles these metadata from a variety of sources, typically starting with key databases from the U.S. Energy Information Administration (e.g., EIA-860 and EIA-923) and supplemented by other sources from the Federal Energy Regulatory Commission (e.g., Form 556, Form 1, and Electric Quarterly Reports), by web-scraping trade press articles, by direct verification through satellite imagery (e.g., for plant coordinates and mount type), and, where necessary, by direct communication with plant developers or owners. The result is a carefully compiled, cross-checked, and curated database that provides the most complete and accurate publicly available record of utility-scale PV plants larger than 5 MW_{AC} in the United States.

We then used the latitude and longitude of plant centroids to locate each plant within satellite imagery obtained from Maxar/DigitalGlobe and identify its boundaries. In most cases, plant boundaries are obvious as there are no contiguous or even nearby plants. In some cases, however, multiple plants are located within the immediate area, often right next to one another, making it difficult to distinguish where one plant ends and the next begins. In these less-obvious cases, we relied on other means to discern one plant from another. First, we squared the visual image with our knowledge of each plant's metadata, such as module type and fixed tilt versus tracking, as each of these choices results in obvious visual differences. In addition, we looked back at earlier imagery of the same location to see when each plant first appeared in the imagery and then squared that against our COD data. In some cases, developer websites had aerial pictures of their projects that helped with identification. In the end, however, there were still some plants within the

[1][Online]. Available: https://www.nrel.gov/gis/solar-resource-maps.html

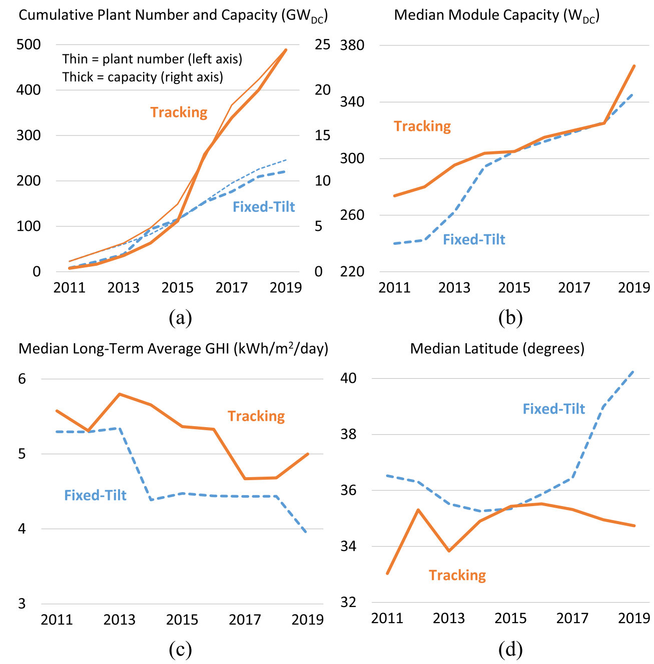

Fig. 1. Temporal trends in plant sample, 2011–2019.

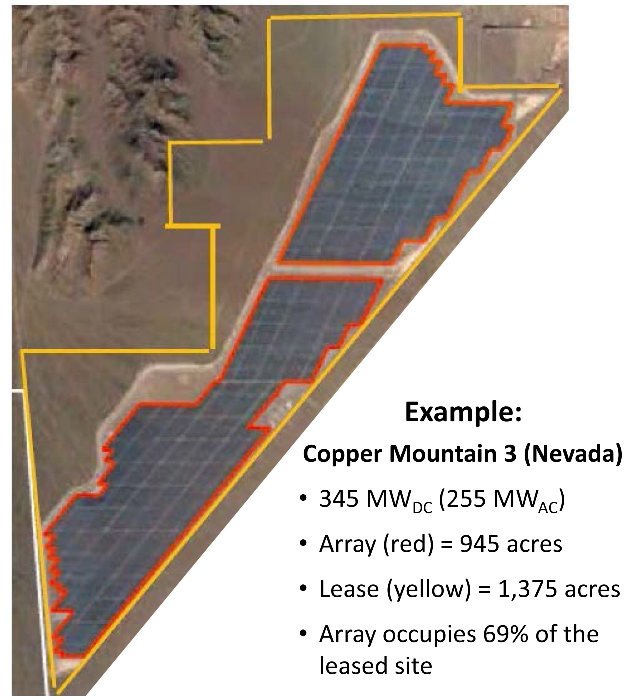

Fig. 2. Comparison of direct array and total site areas.

total universe whose boundaries we were unable to identify with precision—we excluded these plants from our sample.

Our sample ended up with 736 plants totaling 35 482 MW$_{DC}$ (27 001 MW$_{AC}$) that came online from 2007 to 2019 across 38 (of 50) states. This sample includes 92% of the total universe of utility-scale PV plants in the United States that achieved commercial operations from 2007 to 2019 [1]. However, because of a very limited buildout (and, hence, sample size) in the first few years of the sector from 2007 to 2010, our analysis focuses on the period from 2011 to 2019. Fig. 1 graphs temporal trends in our sample over this period in terms of the cumulative plant count and capacity, median module capacity, median site quality (in terms of the long-term average GHI at each plant site), and median latitude, in each case broken out by fixed-tilt versus tracking plants. Panel (a) of Fig. 1 shows that there were roughly twice as many tracking plants (and roughly twice as much tracking capacity) as fixed-tilt at the end of 2019; this disparity has developed entirely since 2015 when the two were still roughly equal and reflects the declining cost and increasing reliability of single-axis tracking [1]. Panel (b) shows an increase in module capacity (which is a function of module efficiency and directly affects both power and energy density), and that prior to 2015, tracking plants tended to use higher-powered modules than fixed-tilt plants as a way to get the most out of the then-much-higher cost of trackers. Panel (c) shows the migration of both fixed-tilt and tracking plants to lower irradiance areas of the United States (though with tracking plants regularly sited at higher irradiance locations than fixed-tilt plants) as the up-front cost of utility-scale PV has declined, enabling it to compete even in areas with poorer solar resources. Finally, panel (d) shows that, since 2014, fixed-tilt plants have increasingly been relegated to higher latitude sites, where the use of single-axis tracking does not make as much sense.

B. *Estimating Area and Densities*

Once certain of the boundaries of the 736 individual plants in our sample, we used ArcGIS to draw polygons around each plant and calculate its area. In doing so, we elected to limit the polygons to the area directly occupied by the PV arrays (plus any inverter pads or other related electrical equipment that falls outside of the array footprint), rather than attempting to include the total area of the leased or owned land parcel. This decision was driven by two factors. First, boundaries of the total leased or owned parcel are most often not discernible from satellite imagery, while the boundaries of the PV array are obvious. Second, the relationship between the direct array area and the total leased or owned area can vary considerably from plant to plant, depending on local site conditions (e.g., the extent to which sites include wetlands that cannot be developed), which limits the information content of the total leased or owned area.

For example, Fig. 2 illustrates the difference between the array area and the total site area for the 345 MW$_{DC}$ (255 MW$_{AC}$) Copper Mountain 3 project in Nevada. While the array boundaries (denoted by the red polygons) are obvious within the image, the total site boundaries are invisible. Only after obtaining data from the local municipality [14], which is the lessor, were we able to sketch in the yellow polygon that approximates the total leasehold or site boundaries. Moreover, there is no logical relationship between the shape or size of the direct array area, which covers 945 acres, and the total leased area, which is 1375 acres. In other words, the fact that the array occupies 69% of the total site, in this case, provides little or no information content, as that ratio could potentially range from something less than 69% (at a particularly problematic site) to near 100% (at a flat rectangular site that can be fully developed). Only the area directly occupied by the array (and including associated nearby equipment, such

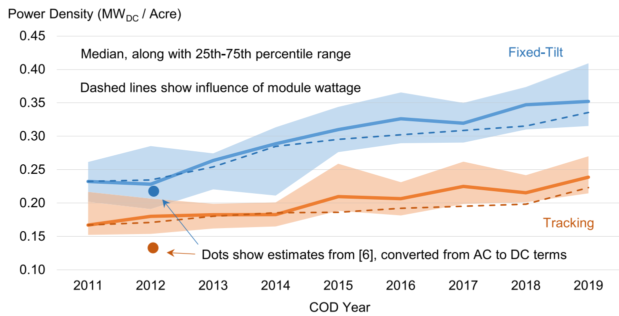

Fig. 3. Utility-scale PV power density over time.

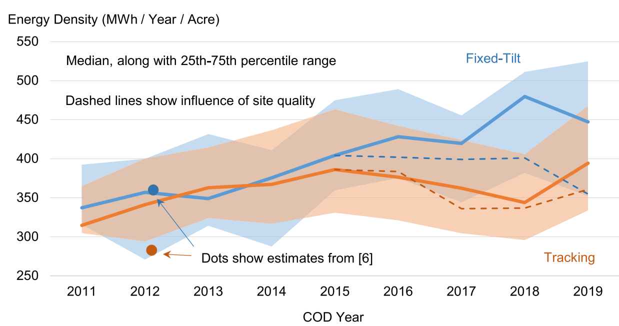

Fig. 4. Utility-scale PV energy density over time.

as inverter pads) provides usable information about power and energy density—as such, that is our focus. Readers hoping to use our numbers to estimate power and energy density on a total site basis can simply derate our numbers accordingly, based on local site conditions (e.g., if only 75% of a site is buildable, simply multiply our density estimates based on direct array area by 75% to get an estimate of density on a total site basis).

The next step in our methodology is to calculate the area occupied by each plant's PV array (or arrays, as shown in Fig. 2). We do this within ArcGIS, measuring the area within each polygon using the Albers equal area conic projection, which is well suited for comparing areas within the continental United States. Given our U.S. focus, we express all areas in units of acres. The final step is to calculate the power and energy density of each plant, expressing them in MW_{DC}/acre and MWh/year/acre, respectively (where each plant's MWh/year represents the annual average across as many full calendar years of operations as exist for each plant). Readers can invert power and energy density if instead interested in land intensity.

III. Results

Utility-scale PVs power and energy densities have both increased significantly since the sector's early days more than a decade ago—and since the last comprehensive review [6]. In 2019, median power densities were 52% higher for fixed-tilt plants and 43% higher for tracking plants than in 2011 (see Fig. 3), and were 62% and 78% higher, respectively, than commonly used estimates from Ong *et al*. [6]. Median energy densities, meanwhile, rose 33% for fixed-tilt plants and 25% for tracking plants over this same period (see Fig. 4), and were 25% and 38% higher, respectively, than estimates from Ong *et al*. [6].

A. Power Density (MW_{DC}/Acre)

The higher power densities of fixed-tilt relative to tracking plants across all years, as shown in Fig. 3, reflect differences in typical ground coverage ratios, which measure how tightly the modules are packed onto the site (specifically, what portion of the ground underlying the array would be covered if the modules were laid flat). Although ground coverage ratios vary from site to site, depending on terrain and other factors, they typically range from 0.40 to 0.50 for fixed-tilt plants versus 0.25–0.40 for tracking plants [15], [16]. This difference between the two plant types reflects different layouts (i.e., fixed-tilt modules typically laid out in east–west rows tilted south, and tracking modules typically laid out in north–south rows that track east-to-west), as well as tracking plants' need for greater row spacing to avoid self-shading as modules track the sun throughout the day. All else equal, a higher ground coverage ratio translates directly into a higher power density.

The improvement in power density over time for both fixed-tilt and tracking plants has been driven in large part by the increase in module wattage shown earlier in Fig. 2(b), which reflects the increase in module efficiency over this period. The dashed lines in Fig. 3 show the same median module wattage trends as shown in Fig. 2(b), but in this case indexed to the median 2011 power densities for both fixed-tilt and tracking plants. For both types of plants, the correlation of median module wattage with median power density over time is strong, explaining not only most of the general increase in power density over time but also why power density appears to have increased more for fixed-tilt than for tracking plants over this period. Specifically, because tracking plants typically used higher-powered modules in the early years (to wring as much value as possible out of the cost of the tracker), they have not benefited as much in terms of power density from the increase in module wattage over time.

The fact that the median power densities in Fig. 3 ultimately exceed the indexed median module wattage trend lines suggests that other drivers have also contributed to higher power densities over time. For tracking plants, these include "backtracking" algorithms that enable tighter row spacing by limiting the tracker range of motion in the mornings and evenings to reduce self-shading and—more recently—independent row tracking across the array to optimize spacing and production even further [17]. Fixed-tilt plants have benefited from more-efficient racking configurations and plant layouts, driven in part by improved modeling software (which has also benefitted tracking plants).

B. Energy Density (MWh/Acre)

While fixed-tilt plants have higher power densities than tracking plants (see Fig. 3), energy density (see Fig. 4) is more of a toss-up due to tracking plants' greater generation per unit capacity (i.e., greater MWh/MW). Moreover, time trends in energy density are more nuanced, reflecting the tension between increasing power densities (as seen in Fig. 3) and declining site quality [as shown in Fig. 1(c)]. Fig. 4 shows that from 2011 to 2015, fixed-tilt and tracking plants exhibited similar energy densities, both in terms of medians and 25th–75th percentile ranges. Post 2015, however, the expansion of tracking plants in particular to less-sunny parts of the country caused energy

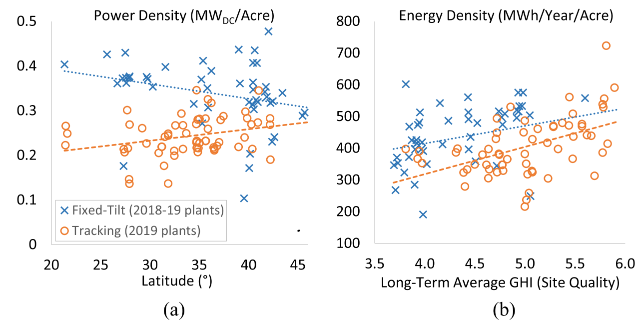

Fig. 5. Power and energy density of recent plants as a function of latitude and site quality.

densities to diverge among tracking and fixed-tilt plants. The influence of site quality can be seen in the dashed lines, which show post-2015 trends in the median long-term average GHI at each site, indexed to 2015 energy densities, for both fixed-tilt and tracking plants.

C. *Beyond the Median*

Some of the apparent variation around the median power and energy densities shown in Figs. 3 and 4 (via the 25th–75th percentile ranges) are attributable to differences in site latitude, which can affect ground coverage ratios—especially for fixed-tilt plants that need to space rows farther apart at higher latitudes in order to avoid self-shading. Variation in energy density also reflects differences in the strength of the solar resource at each site. Fig. 5 attempts to tease out these relationships, focusing on the most recent fixed-tilt and tracking plants in our sample.

Although there is considerable spread, Fig. 5(a) shows power density declining with latitude for fixed-tilt plants, as expected, while tracking plants appear to see a slight *increase* in power density at higher latitudes. This latter result could be explained by the north–south axes and zero-degree tilt of most single-axis tracking plants, which largely eliminates the self-shading concerns that fixed-tilt plants face (with their east–west axes and south-facing tilted modules). In fact, the lower sun angle at higher latitudes could even *reduce* self-shading at tracking plants in the mornings and evenings, potentially enabling them to increase their ground coverage ratios and, hence, power densities [16]. Consistent with Fig. 1(d), Fig. 5(a) also shows a greater preponderance of fixed-tilt plants at higher latitudes and tracking plants at lower latitudes.

Energy density is a function of both power density and the quality of the solar resource at each site. Although there is, once again, considerable spread, Fig. 5(b) shows energy density increasing with site quality (in terms of the long-term average irradiance at the site) for both fixed-tilt and tracking plants, as one would expect. Consistent with Fig. 1(c), Fig. 5(b) also shows a greater preponderance of fixed-tilt plants at lower irradiance sites and tracking plants at higher irradiance sites.

Site topography could also be driving some of the variation around the medians in Figs. 3 and 4 that is unexplained in Fig. 5. Our area measurements based on satellite imagery do not account for the impact—either positive or negative—that underlying terrain may have on power and energy density. In general, utility-scale PV plant sites tend to be flat (or, if not flat originally, are graded to be so), and tracker manufacturers have become more adept over time at accommodating uneven terrain (e.g., through independent row movement and advanced backtracking algorithms), but topography can nevertheless still influence densities. Incorporating site topography, as well as underlying land-use impacts, is an area ripe for future work.

D. *International Comparison*

Our study is focused exclusively on the United States. Although we have little reason to suspect different results or trends in other countries, our methodology is readily transferable, allowing us to spot check our density results overseas. We do this by identifying a handful of utility-scale PV plants in each of Chile, Australia, and Europe, all of which are of similar distances from the equator as the plants in our U.S. sample. These overseas plants have CODs spanning the full duration of our analysis period and represent a mix of fixed-tilt (mostly in Europe) and tracking plants (mostly in Chile and Australia). We took the same approach to drawing polygons and calculating areas as we did in the U.S. and then crosschecked the resulting power densities against our U.S. results (we do not have good enough data on annual generation for these overseas plants to calculate energy densities). As expected, the power densities of all overseas plants that we looked at fall within the range of what we see in the U.S. for the specific mount type and COD year, suggesting that our results are broadly applicable, at least for plants at similar latitudes.

IV. Conclusion

Based on empirical observations drawn from a large, nearly complete sample of utility-scale PV plants built in the United States through 2019, we find that both power and energy density have increased significantly over the past decade. Modelers and analysts, policymakers and regulators, and others who continue to rely on outdated benchmarks from the *last* comprehensive U.S.-based assessment of power and energy density conducted nearly a decade ago [6] will, therefore, significantly overstate the land requirements, and by extension perhaps also the land-use impacts, of utility-scale PV.

Updated benchmarks as of 2019 established by this study are as follows.

1) *Power density:* 0.35 MW_{DC}/acre (0.87 MW_{DC}/hectare) for fixed-tilt and 0.24 MW_{DC}/acre (0.59 MW_{DC}/hectare) for tracking plants.
2) *Energy density:* 447 MWh/year/acre (1.10 GWh/year/hectare) for fixed-tilt and 394 MWh/year/acre (0.97 GWh/year/hectare) for tracking plants.

While these are nationwide, median benchmarks, our study also illuminates how the latitude of and irradiance at each plant site can cause individual plant densities to diverge from the medians, and how one might adjust the median benchmarks to account for that divergence. In addition, we improve upon past studies in the following ways:

1) By presenting time series data that reveal trends in power and energy density over time (rather than providing just a current snapshot);

2) By delineating between fixed-tilt and tracking plants;
3) By specifying that our power density benchmarks are denominated in dc (rather than ac) capacity and that we are considering only the direct area occupied by the PV arrays.

Finally, although we believe dc capacity to be more relevant than ac capacity when expressing power density (given that ac capacity depends more on the capacity of the inverters than on the area occupied by the dc array), we do have the ability to express power density in ac capacity terms as well, given that we know the dc:ac ratio of each plant. We present those numbers here—0.28 MW_{AC}/acre (0.69 MW_{AC}/hectare) for fixed-tilt and 0.18 MW_{AC}/acre (0.45 MW_{AC}/hectare) for tracking plants—solely for the purpose of comparison against the densities of other utility-scale generation sources, which are typically expressed in ac terms.

Looking ahead, we see two clear paths for suggested future extensions of this work. First, regularly updating the sample, through 2020 and then successive future years, will ensure that these power and energy density benchmarks never become as stale as they were prior to this update. Second, and related, 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 both power and energy density. As our current analysis only runs through 2019, none of these up-and-coming module innovations had yet infiltrated our plant sample to any significant degree, but such modules (particularly bifacial) have been more widely deployed at plants that have come online post 2019, and will be seen with increasing frequency in the years ahead.

Acknowledgment

The authors would like to thank S. Fujita of Lawrence Berkeley National Laboratory for assistance with ArcGIS, and A. Qusaibaty and Z. Eldredge of the Solar Energy Technologies Office, as well as two anonymous reviewers, for their helpful comments on an earlier draft. The views expressed in this article do not necessarily represent the views of the United States Department of Energy or the United States Government. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States 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 United States Government purposes.

References

[1] M. Bolinger, J. Seel, D. Robson, and C. Warner, "Utility-scale solar data update: 2020 edition," Lawrence Berkeley Nat. Lab., Berkeley, CA, USA, 2020. [Online]. Available: https://emp.lbl.gov/01014p8790ublications/utility-scale-solar-data-update-2020
[2] "Solar futures study," U.S. Dept. Energy, Washington, DC, USA, Sep. 2021. [Online]. Available: https://www.energy.gov/eere/solar/solar-futures-study
[3] A. Kowalczyk, "Can solar developers and farmers find common ground?," Canary Media, Aug.–Dec. 2021. [Online]. Available: https://www.canarymedia.com/articles/solar/can-solar-developers-and-farmers-find-common-ground
[4] E. H. Adeh, S. P. Good, M. Calaf, and C. W. Higgins, "Solar PV power potential is greatest over croplands," *Sci. Rep.*, vol. 9, 2019, Art. no. 11442. [Online]. Available: https://doi.org/10.1038/s41598-019-47803-3
[5] M. Junginger and A. Louwen, Eds., *Technological Learning in the Transition to a Low-Carbon Energy System*. New York, NY, USA: Elsevier, 2019.
[6] S. Ong, C. Campbell, P. Denholm, R. Margolis, and G. Heath, "Land-use requirements for solar power plants in the United States," Nat. Renewable Energy Lab., Golden, CO, USA, Tech. Rep. NREL/TP-6A20-56290, Jun. 2013. [Online]. Available: https://www.nrel.gov/docs/fy13osti/56290.pdf
[7] "Land use by system technology," Nat. Renewable Energy Lab., Golden, CO, USA, 2021. [Online]. Available: https://www.nrel.gov/analysis/tech-size.html
[8] L. M. Miller and D. W. Keith, "Observation-based solar and wind power capacity factors and power densities," *Environ. Res. Lett.*, vol. 13, no. 10, 2018, Art. no. 104008.
[9] J. van Zalk and P. Behrens, "The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S.," *Energy Policy*, vol. 123, pp. 83–91, Dec. 2018. [Online]. Available: https://doi.org/10.1016/j.enpol.2018.08.023
[10] J. R. Cruce, J. Cook, and T. Larsen, "Streamlining energy sprawl: Assessment of geothermal impacts on public lands," *Geothermal Resour. Council Trans.*, vol. 44, pp. 1049–1065, 2020.
[11] P. J. Saunders, "Land use requirements of solar and wind power: Understanding a decade of academic research," Energy Innov. Reform Project, Arlington, VA, USA, 2020. [Online]. Available: https://www.innovationreform.org/2020/10/12/land-use-requirements-of-solar-and-wind-power-understanding-a-decade-of-academic-research/
[12] R. R. Hernandez, M. K. Hoffacker, and C. B. Field, "Land-use efficiency of big solar," *Environ. Sci. Technol.*, vol. 48, pp. 1315–1323, 2014, doi: 10.1021/es4043726.
[13] D. Merrill, "The U.S. will need a lot of land for a zero-carbon economy," Bloomberg, New York, NY, USA, Jun. 2021. [Online]. Available: https://www.bloomberg.com/graphics/2021-energy-land-use-economy/
[14] City of Boulder City Finance Department, "Turning land into revenues: Understanding solar lease revenues," Boulder City, NV, USA, Aug. 25, 2020. [Online]. Available: https://www.bcnv.org/DocumentCenter/View/8182/Energy-Revenues-Brochure-FY20
[15] D. Smith, "Sunny-side up (and down): How feasible are bifacial trackers?," Sol Syst., Washington, DC, USA, Jun. 22, 2018. [Online]. Available: https://www.solsystems.com/sunny-side-up-and-down/
[16] S. Smith, "Solar tracker site design: How to maximize energy production while maintaining the lowest cost of ownership," Solvida Energy Group, Berkeley, CA, USA, Oct. 2017.
[17] A. Daly and V. Abbaraju, "Optimizing your energy yield: Truecapture smart control technology boosts energy production and financial returns," NEXTracker, Fremont, CA USA, Jun. 2018.