Published in final edited form as:

Nat Sustain. 2023 July ; 6(7): 752–755. doi:10.1038/s41893-023-01134-4.

Revised estimates of racial and ethnic disparities in rooftop photovoltaic deployment in the United States

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Rooftop photovoltaic (PV) technology is an important component of sustainable energy transitions, but there is widespread concern about social inequalities in PV deployment. In a recent article, Sunter, Castellanos, and Kammen [1](SCK) find that black- and Hispanic-majority census tracts (i.e., neighborhoods) in the United States have, on average, much lower levels of rooftop PV deployment than white- and no-majority tracts. However, our re-analysis of comparable data identifies irregularities in SCK's reported procedures and results, generates substantively different estimates of ethnoracial disparities in PV deployment nationwide, and extends SCK's original analysis by examining how such disparities vary with the maturity of a state's PV market. Accurate accounts of ethnoracial disparities in PV deployment are necessary to develop interventions that effectively and equitably promote sustainable energy transitions.

As part of our own study of social disparities in PV deployment, we engaged SCK's original paper and developed a comparable dataset sourced from Google's Project Sunroof and the U.S. Census Bureau's American Community Survey (ACS) (see Supplementary Note 1: Availability of data and replication material). We noted an irregularity in SCK's reported results. Two of the figures (SCK's Figures 2b and 3b) report what appear to be implausibly low values for the outcome variable (tract-level state-normalized PV deployment). For example, while the mean of this variable is 1 by construction, the predicted deployment levels in SCK's Figure 3b fall below 1 across almost the entirety of the x-axis. This pattern suggests that a large share of tracts with above-state-average deployment does not inform the reported estimates. This may either reflect specific sample restrictions by SCK, which are not documented (see Supplementary Note 2: Analytic sample and methods), or the choice of a LOWESS estimator that systematically excludes observations that have high deployment levels (see Supplementary Note 3: Analytic procedures).

We re-construct the original analytic sample as closely as possible in the absence of the necessary details (see Supplementary Note 2: Analytic sample), yielding a sample of 34,869 tracts. Figure 1 (A-C) presents our replication of the estimated relationship between household income and rooftop PV installations by tract ethnoracial majority; and Figure 1 (D-F) shows the results for the relationship between homeownership and rooftop PV

Ethics Declaration

The authors declare no competing interests.

installations by tract ethnoracial majority (see Supplementary Note 3 for model details and Supplementary Note 7 for an alternative analysis using negative binomial regression). Our results reveal the expected distribution of the outcome variable (i.e., centered around 1), which supports our concern about the predictions generated by SCK and leads to significant differences between the absolute predictions in our model and SCK's. We therefore focus primarily on whether our conclusions about the relative disparities between types of tracts are consistent with the original paper.

Relative disparities are visualized in panels C and F of Figure 1, with no-majority tracts serving as the reference group. We confirm SCK's finding that white-majority tracts have the highest average levels of deployment. However, our conclusions about the relative deployment levels across other types of tracts often differ from those of SCK. First, we find that black-majority tracts have comparable deployment levels to no-majority tracts along most of the median income distribution, with a slight advantage at (empirically rare) high-income levels. This pattern translates into a 16% black-majority advantage on average (panel C), which contrasts with a deficit of 69% among black-majority tracts reported by SCK. Our estimates do indicate a deficit in adoption between black-majority and no-majority tracts when estimates are plotted against the renter-occupied rate. However, we find an average deficit for black-majority tracts of just 16% (panel F), compared to a deficit of 61% reported by SCK. We similarly find a smaller disparity between no-majority and Hispanic-majority tracts (18% deficit vs. 30% reported by SCK when plotted against median income [panel C] and 40% deficit vs. 45% reported by SCK when plotted against the renter-occupied rate [panel F]). Our PV deployment estimates for Hispanic-majority tracts are also lower than black-majority tracts (SCK find the opposite). Finally, and consistent with SCK's results, Asian-majority tracts have the lowest estimates of PV deployment at low levels of median income and these increase relative to all other groups as median income rises (panel C). Yet in our estimates, deployment levels for Asian-majority tracts never attain levels that are significantly higher than white- or no-majority tracts and are 24% lower than no-majority tracts on average (compared to 2% lower reported by SCK).

We also replicate SCK's analysis of PV seeding (i.e., the introduction of at least one PV unit in a tract) by calculating the percentage of each type of tract with and without existing rooftop PV installations. We provide full details of this analysis, and an extension of it, in the Supplementary Information (see Supplementary Note 4: Re-analysis and extension of PV seeding results). Here, however, we note only that the seeding disparities shrink significantly (and reverse in one case) after adjusting for median income, renter-occupied rate, and the state where the census tract is located.

Our analysis also goes beyond a replication of SCK. We extend the original analyses by fitting state-specific LOWESS models predicting state mean-normalized deployment as a function of census tract median income for each tract type. Attention to spatial heterogeneity within the United States is important given geographic differences in the extent and nature of racial inequality [2,3] and because overall rates of PV deployment vary greatly across states [4, 5]. Disparities in high-deployment states (e.g., California and Arizona) would be materially much more impactful than disparities in low-deployment states.

The five panels in Figure 2 present the results (for more details see Supplementary Note 5: Disparities in PV deployment by state). We observe considerable variation in deployment disparities across states, and these patterns appear to unfold systematically according to the level of deployment in each state. For example, black-majority census tracts have above-average estimates of deployment in Oklahoma, Michigan, Pennsylvania, Maryland, and Louisiana. None of these states have especially high overall levels of solar deployment. In contrast, white-majority tracts have above-average estimates of deployment in states with the greatest overall deployment levels: California, Florida, and Arizona. Notably, in two of these states (California and Florida), black-majority tracts have significantly lower-than-average deployment estimates. While our re-analyses do not support SCK's claims at the national level, they suggest that rooftop PV is indeed under-deployed in black-majority tracts within states where rooftop PV is most prevalent.

Overall, we fail to replicate SCK's reported findings. Our results differ in terms of both absolute deployment levels and relative disparities by tracts' ethnoracial majority. Importantly, our re-analysis does not rule out important ethnoracial disparities in solar deployment, and shows real disadvantages among black-majority tracts. White-majority tracts consistently have the highest deployment rates even after adjusting for median income and homeownership; Hispanic- and Asian-majority tracts have relatively low deployment; and black-majority tracts lag considerably behind white-majority tracts in states with well-developed solar markets. The deployment advantage of white-majority tracts, meanwhile, is driven almost exclusively by substantial advantages in several high-deployment states.

We hope that our attempt to correct and extend the empirical record can inform interventions that eliminate ethnoracial disparities in the deployment of rooftop PV and similar technologies. Our evidence of inter-state variation in ethnoracial disparities in deployment presents opportunities to identify factors that contribute to (or impede) equitable energy transitions, which future research should pursue. Future work should also address broader limitations to the Project Sunroof data used here and by SCK, which suffer from a sampling bias toward urban areas and require ecological inferences. As investments in sustainable energy increase in coming years, new efforts to collect and share data will be needed to guide its distribution in equitable ways.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

The authors thank Ethan Fosse for his valuable comments. Any remaining errors are the authors' alone. Thiede acknowledges the assistance provided by the Population Research Institute at Penn State University, which is supported by the Eunice Kennedy Shriver National Institute on Child Health and Human Development (P2CHD041025). Thiede was also supported by the USDA National Institute of Food and Agriculture Multistate Research Project #PEN04623 (Accession #1013257).

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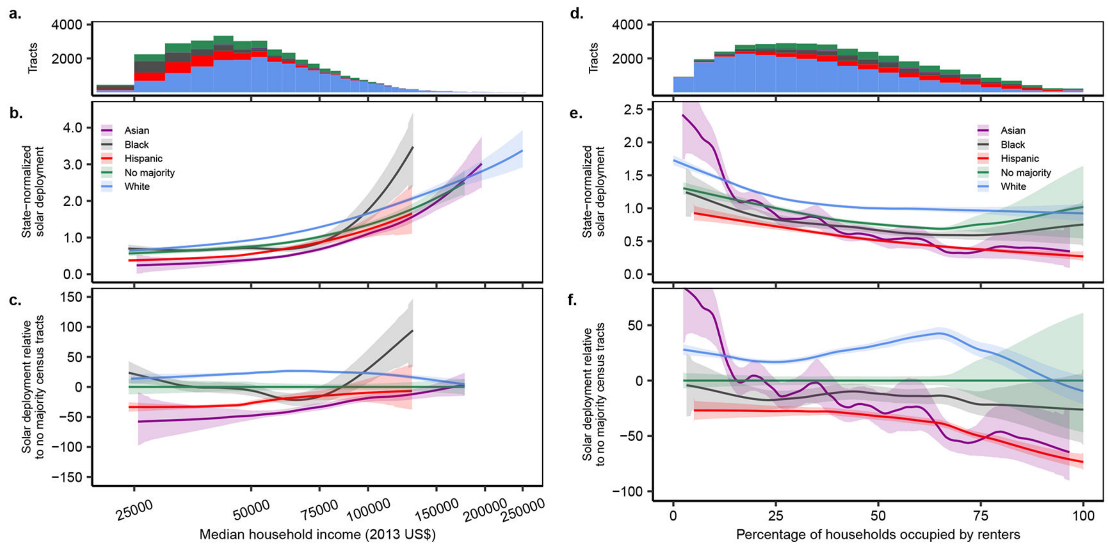

Figure 1. Relationships between household median income (panels a-c) and home ownership (panels d-f) and rooftop PV deployment by race and ethnicity.

Panels a and d display histograms of the distribution of census tracts across the median household income and renter-occupied percentage distributions, respectively. Panels **b and e** display rooftop PV deployment relative to the available rooftop PV potential and normalized by state as a function of the median household income (**b**) and as a function of the renter-occupied household percentage (**e**). Panels **c** and **f** display the same information as **b** and **e**, but the estimates are re-calculated relative to the rooftop PV adoption of no-majority census tracts. Each colour represents a majority race or ethnicity in the census tract. Dark continuous curves represent the results of the LOWESS method applied to all data in each ethnoracial majority group. Lighter shading represents the 90% Cis based on 1,000 bootstrap replications of each ethnoracial majority group.

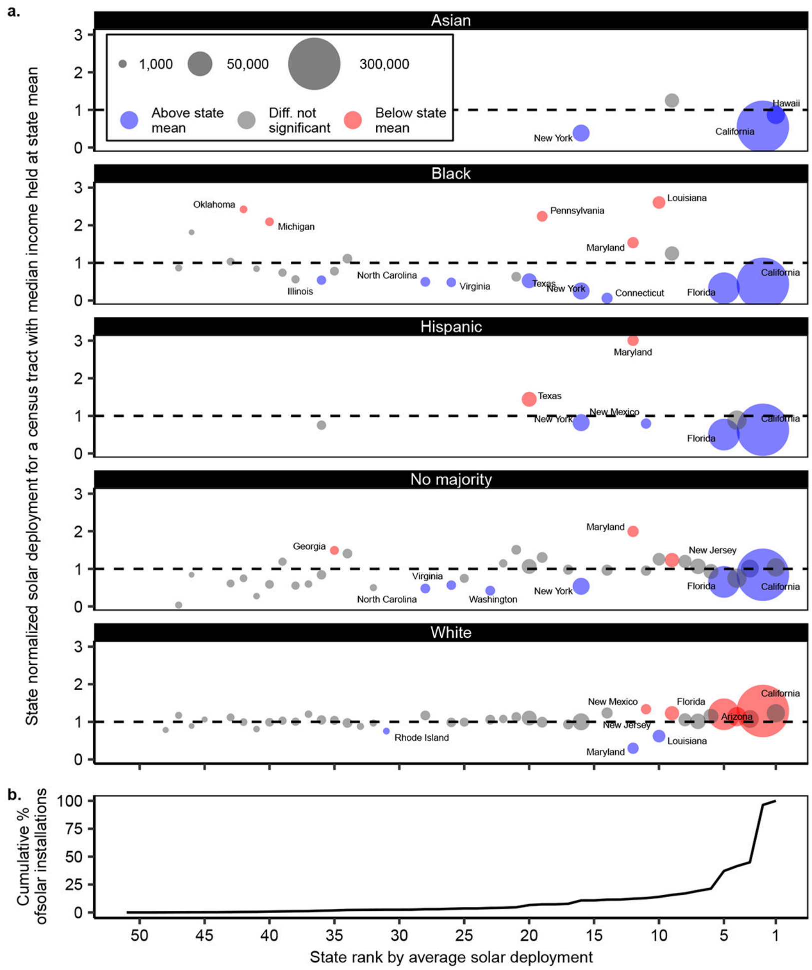

Figure 2. PV deployment estimates by race and ethnicity and by state arranged by state rank of average solar deployment.

a, Estimates of rooftop PV installations in a given state relative to the available rooftop PV potential and normalized by state as a function of the median household income for majority census tracts. Estimates are at the state's mean value of the median income variable. Estimates are arranged from left to right $\left(\frac{\sum SolarDeployment_{CT}}{CT_{state}}\right)$. Blue dots indicate estimates that are significantly below the state average and red dots indicate estimates that are significantly above the state average (based on 95% CIs). Dot size is proportional to the total number of solar installations in the state. The dashed line indicates the state average.

b, Cumulative percentage of all solar installations in the Project Sunroof sample across state rank of average solar deployment, from least to most.