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Impact of siting ordinances on land availability for wind and solar development

In the format provided by the authors and unedited

Supplemental Tables

Supplemental Table 1. Summary of wind ordinance requirements for various ordinance types based on the ordinances surveyed in 2018 and 2022.

Ordinance	2018	2022	Fixed Setback Count	Tip-height Setback Count	Rotor Setback Count	Mean Value (All years)
Total	**275**	**1,828**	**362**	**775**	**29**	**N/A**
Structure Setback	88	375	235	134	5	433m
Road Setback	61	355	49	293	12	225m
Property Line Setback	4	346	63	253	29	270m
Sound Restriction	50	219	N/A	N/A	N/A	52 dBA
Transmission Setback	42	183	14	167	2	212m
Height Limit	12	92	N/A	N/A	N/A	126m
Water Setback	6	66	60	6	0	756m
Railroad Setback	9	60	3	56	1	220m
Moratorium or Ban	3	54	N/A	N/A	N/A	N/A
Tower Density Limit	0	34	N/A	N/A	N/A	N/A
Minimum Lot Size	0	18	N/A	N/A	N/A	50 acres
Shadow Flicker Limit	0	13	N/A	N/A	N/A	18 hours/year
Other	0	13	N/A	N/A	N/A	N/A

Supplemental Table 2. Summary of solar ordinance requirements for various ordinance types based on the ordinances surveyed in 2022.

Ordinance	Value Type	Mean Value	Count
Total	N/A	N/A	839
Property Line	Meters	23.1	234
Height	Meters	6.7	190
Roads	Meters	52.9	142
Structures	Meters	93.5	136
Minimum Lot Size	Acres	17.0	50
Sound	dBA	52.4	36
Maximum Lot Size	Acres	642.5	14
Water	Meters	65.7	11
Maximum Lot Coverage	Percentage	54.4	8
Maximum Project Size	Acres	2833.5	8
Density	Meters	2212.5	4
Moratorium Banned	N/A	NaN	4
Density	Percentage	3.0	1
Railroads	Meters	61.0	1

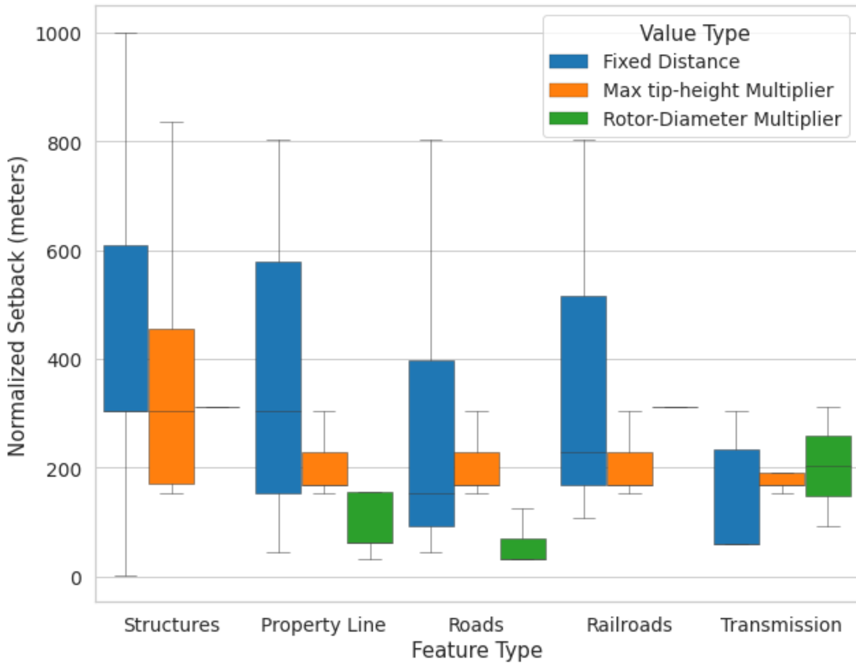
Supplemental Table 3. Data used for performing spatial modeling.

Dataset	Description	Data Source
Property boundaries (Parcels)	LightBox Parcel database.	HIFLD Licensed Data 2022
Road network	HERE Street Roads from Homeland Security Infrastructure Database (HSIP).	HERE Transportation Data 2022
Building footprints	Microsoft Maps created open-source building footprints datasets in United States based on satellite imagery. We removed structures with areas <50m^2 and >5,000m^2 to focus on residential dwellings (Huang et al. 2020).	https://www.microsoft.com/en-us/maps/building-footprints
State/county boundaries	The datasets were download from the Census Bureau's MAF/TIGER geographic database.	https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html

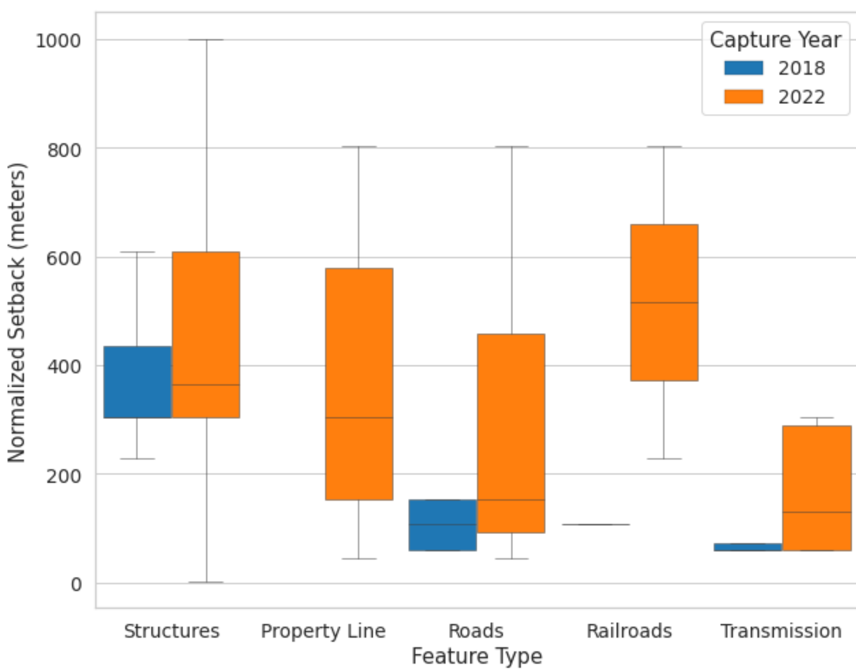
Water, Woody/Herbaceous Wetlands	National Land Cover Database raster values = [11, 90, 95].	https://www.usgs.gov/centers/eros/science/national-land-cover-database
Railroads	Railroad line vectors from Homeland Security Infrastructure Database (HSIP). Lines were buffered by 15-meters to represent the typical rail line width.	https://hifld-geoplatform.hub.arcgis.com/
Transmission Right-of-way	Electric transmission data from Homeland Security Database (HSIP). Right-of-way widths were applied based on voltage. >345 kV: 27-meters 345 kV: 23-meters 230 kV: 18-meters 115 kV: 15-meters <=60 kV: 11-meters	https://hifld-geoplatform.hub.arcgis.com/
Urbanized boundaries	U.S. Census Bureau urbanized boundaries 2018.	https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html
Bureau of Land Management Areas of Critical Environmental Concern	A designated area that requires special management attention to protect important and relevant values. If a nominated area meets the criteria, an interdisciplinary planning team develops potential management options and incorporates the proposed ACEC into a draft land use plan. The types of activities allowed within an ACEC depend on the resource and natural value the area is designated to protect.	https://landscape.blm.gov/geoportal/catalog/main/portal.page
National Forest Service Inventoried Roadless Areas	This dataset is the official data for the 2001 Roadless Area Conservation Rule (36 CFR 294, Subpart B). It contains the Inventoried Roadless Areas (IRAs) designated by the 2001 Roadless Area Conservation Rule and used in the associated Final Environmental Impact Statement.	https://data.fs.usda.gov/geodata/edw/datasets.php?xmlKeyword=roadless
National Conservation Easement Database	Private land conservation easements. A conservation easement is a legal agreement between a landowner and an eligible organization that restricts the activities that may take place on a property in order to protect the land's conservation values. Each easement's restrictions are tailored to the particular property, to the interests of the	https://www.conservationeasement.us/

	individual owner, and to the policies and purposes of the easement holder. Also known as conservation servitudes and conservation restrictions, conservation easements are recorded as deed restrictions, and the restrictions apply to all future owners of the land.	
American Farm Trust Conservation Easements	The Protected Agricultural Lands Database (PALD) is a first-of-its-kind comprehensive national inventory of spatial data about protected agricultural lands. It contains boundaries of easements that permanently protect private farmland and ranchland in the U.S. as well as important information about each site.	https://farmlandinfo.org/statistics/pald/
Protected Areas Database (PAD-US)	The USGS Protected Areas Database of the United States (PAD-US) is the nation's inventory of protected areas, including public land and voluntarily provided private protected areas, identified as an A-16 National Geospatial Data Asset in the Cadastre Theme.	https://www.usgs.gov/programs/gap-analysis-project/science/pad-us-data-download
Mountainous Landforms	Classified landform regions using the national elevation dataset (NED) as a function of local relief, slope and profile consistent with the methods employed by Karagulle et al. (2017). In our classification, we differentiate between several major types of landform including tablelands, hills, mountains, plains and flat areas.	Karagulle, Deniz, Charlie Frye, Roger Sayre, Sean Breyer, Peter Aniello, Randy Vaughan, et al. 2017. "Modeling Global Hammond Landform Regions from 250-m Elevation Data." Transactions in GIS 21 (5): 1040–60. https://doi.org/10.1111/tgis.12265.
Elevation (>9,000 ft.)	Elevation greater than 9,000 feet is excluded from development.	Jarvis, A., E. Guevara, H.I. Reuter, and A.D. Nelson. 2008. "Hole-Filled SRTM for the Globe: Version 4: Data Grid." Presented at the CGIAR Consortium for Spatial Information.

Supplemental Figures

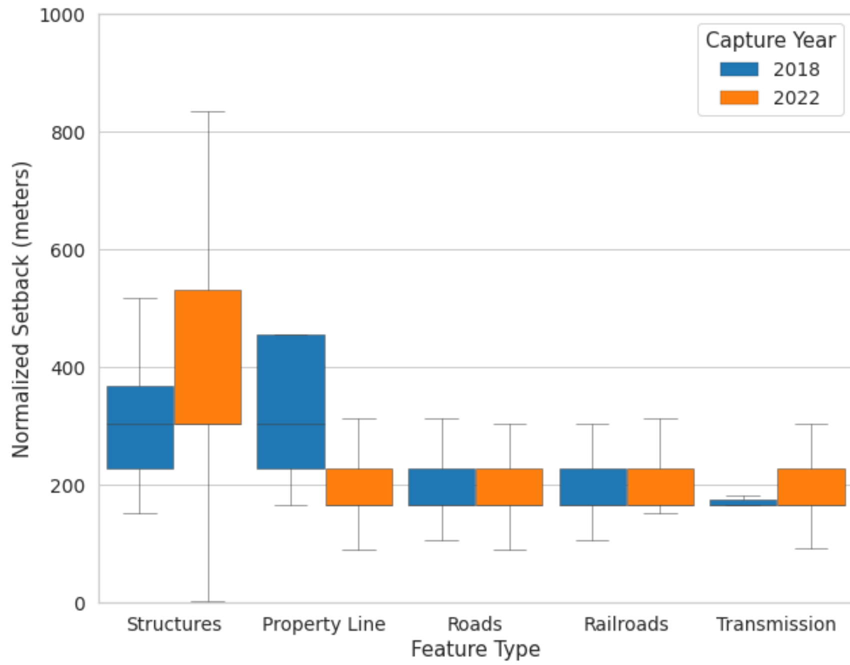


*Supplemental Figure 1. Fixed distance setbacks are typically have the largest setback as compared to tip-height or rotor-based setbacks. In these box plots the rectangles represent the interquartile range (IQR), the lines represent the median, the whiskers extend to Q1-1.5*IQR and Q3+1.5*IQR, outliers have been suppressed in the images. Structures fixed distance n: 233, max tip-height multiplier n: 134, rotor-diameter multiplier n: 5; Property Line fixed distance n: 63, max tip-height multiplier n: 258, rotor-diameter multiplier n: 29; Roads fixed distance n: 50, max tip-height multiplier n: 285, rotor-diameter multiplier n: 12; Railroads fixed distance n: 3, max tip-height multiplier n: 57, rotor-diameter multiplier n: 1; Transmission fixed distance n: 14, max tip-height multiplier n: 163, rotor-diameter multiplier n: 2.*

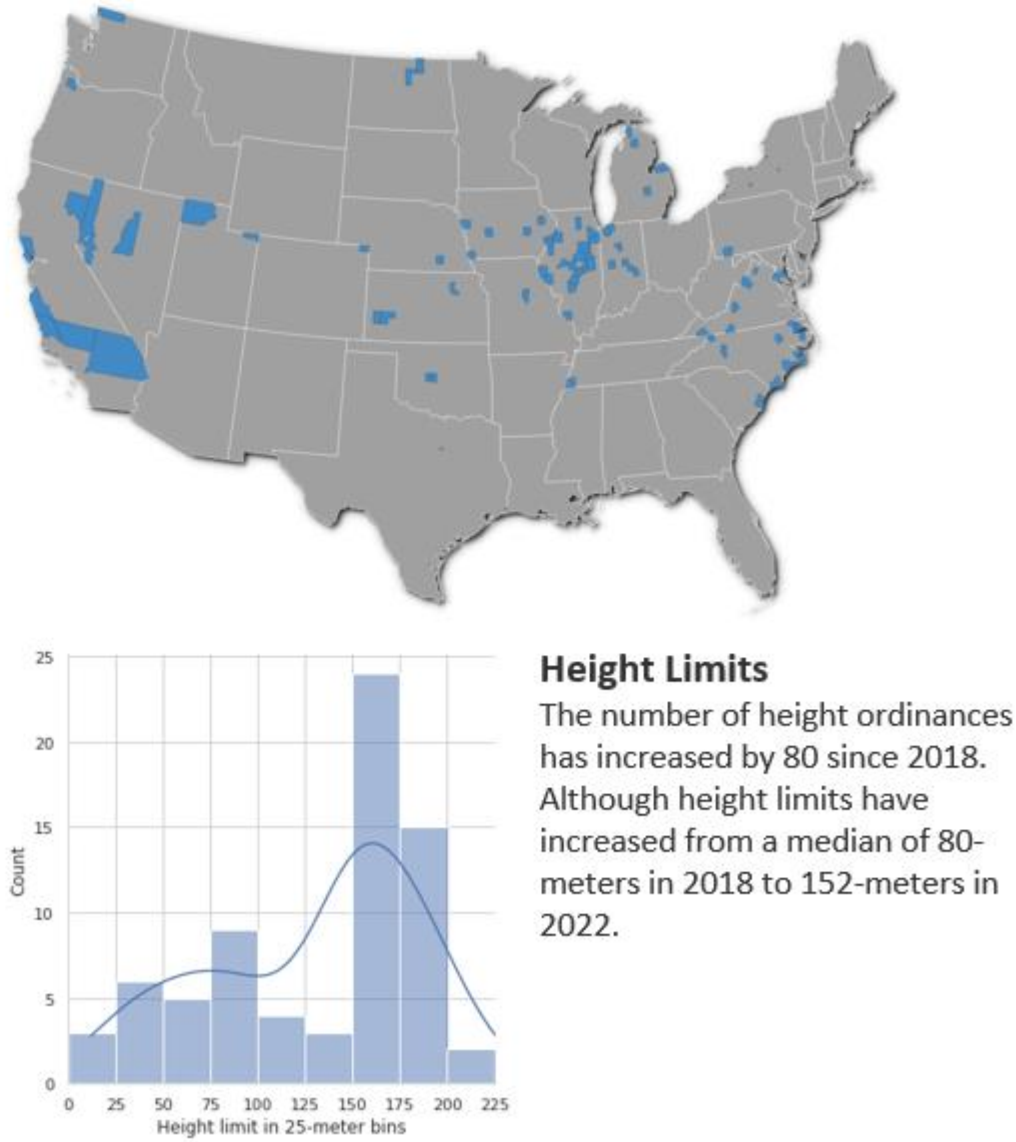


*Supplemental Figure 2. Fixed distance setbacks have increased from 2018 to 2022 for all feature types. In these box plots the rectangles represent the interquartile range (IQR), the lines represent the median, the whiskers extend to Q1-1.5*IQR and*

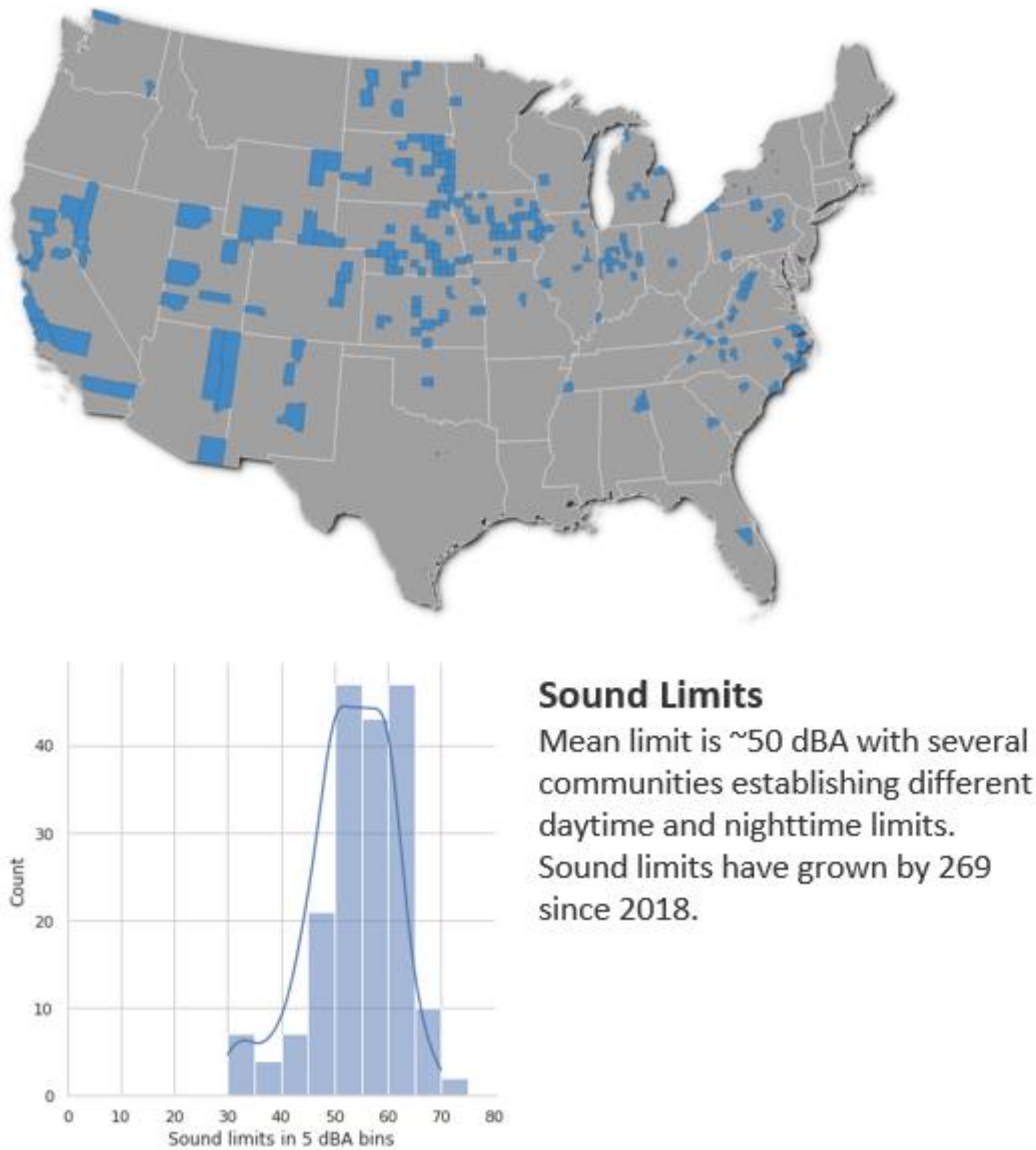
*Q3+1.5*IQR, outliers have been suppressed in the images. Structures 2018 n: 40, 2022 n: 193; Property Line 2018 n: 0, 2022 n: 63; Roads 2018 n: 9, 2022 n: 41; Railroads 2018 n: 1, 2022 n: 2; Transmission 2018 n: 4, 2022 n: 10.*



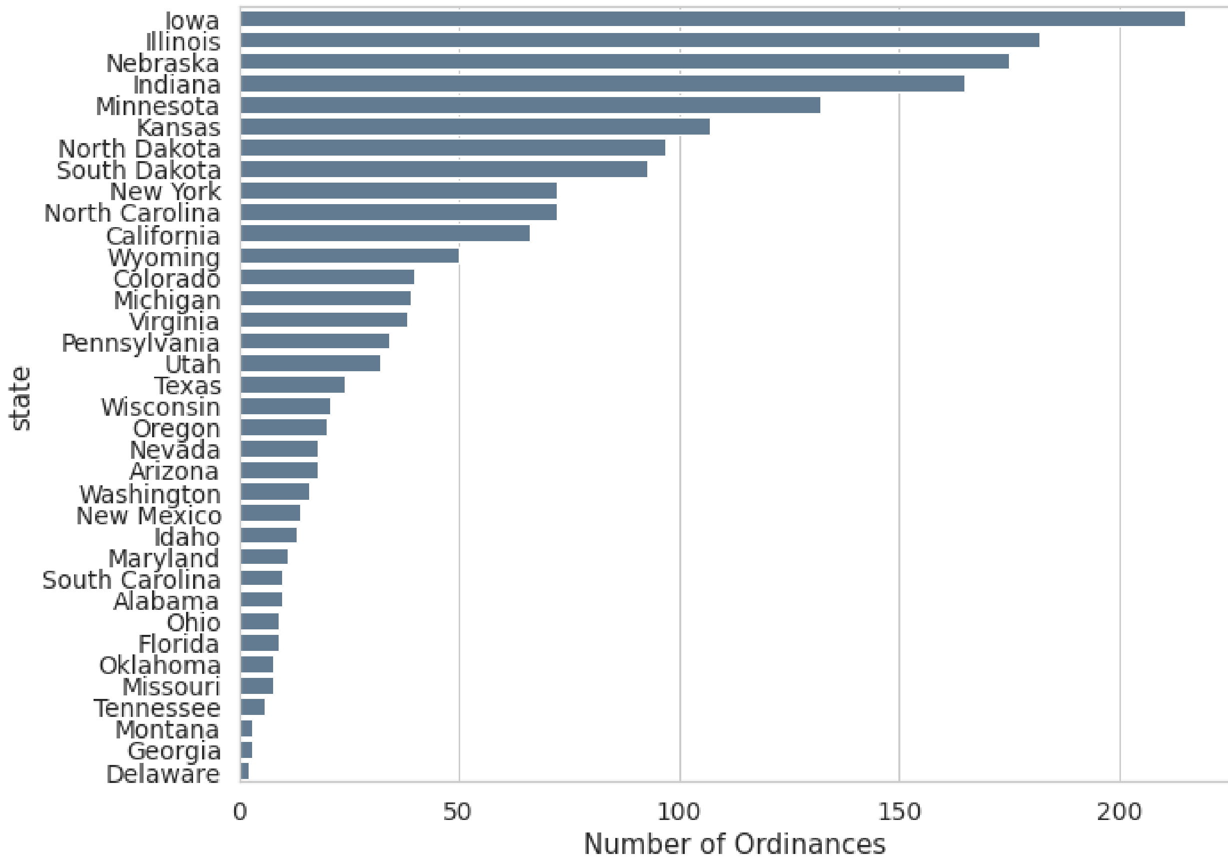
*Supplemental Figure 3. Tip-height multipliers have increased from 2018 to 2022 for structures, decreased for property lines, and stayed relatively the same for other features. In these box plots the rectangles represent the interquartile range (IQR), the lines represent the median, the whiskers extend to Q1-1.5*IQR and Q3+1.5*IQR, outliers have been suppressed in the images. Structures 2018 n: 84, 2022 n: 288; Property Line 2018 n: 5, 2022 n: 345; Roads 2018 n: 56, 2022 n: 291; Railroads 2018 n: 9, 2022 n: 52; Transmission 2018 n: 39, 2022 n: 140.*



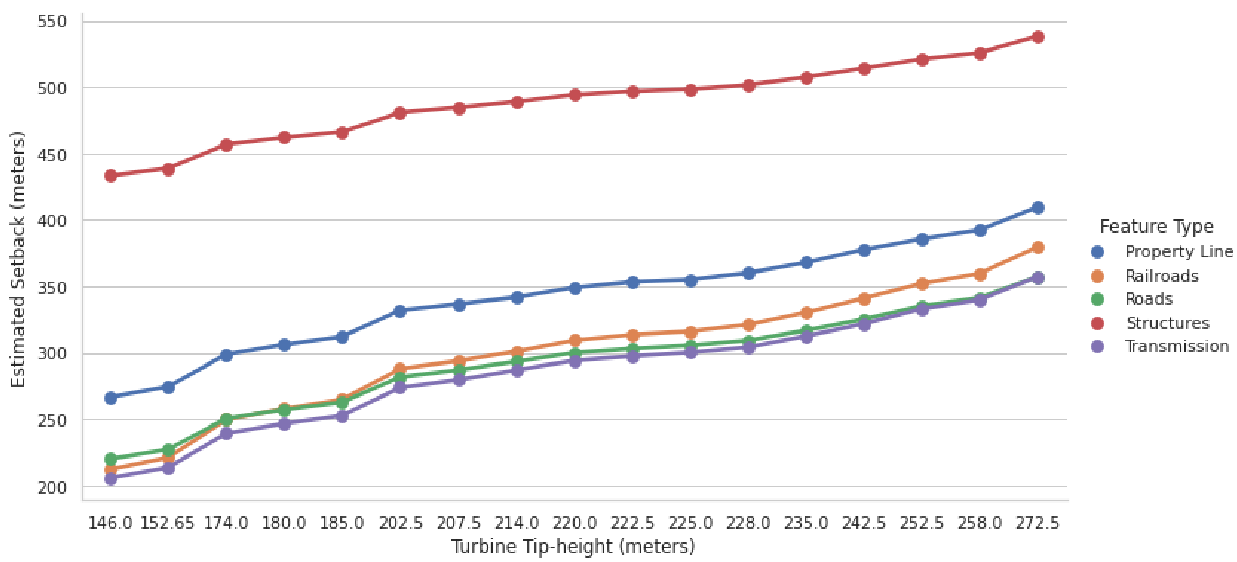
Supplemental Figure 4. Counties that include height limits, with the distribution shows in the lower figure.



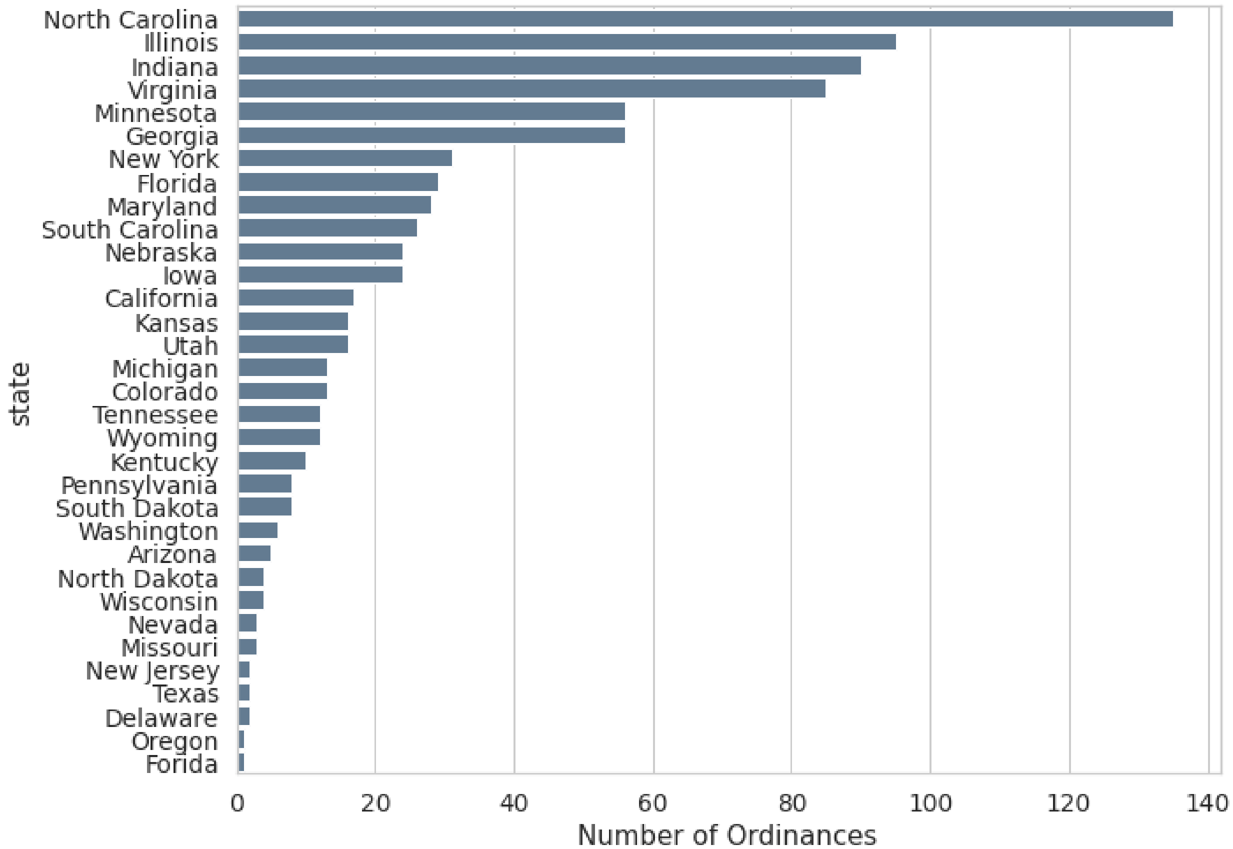
Supplemental Figure 5. Counties that include sound limits, with the distribution shown in the lower figure.



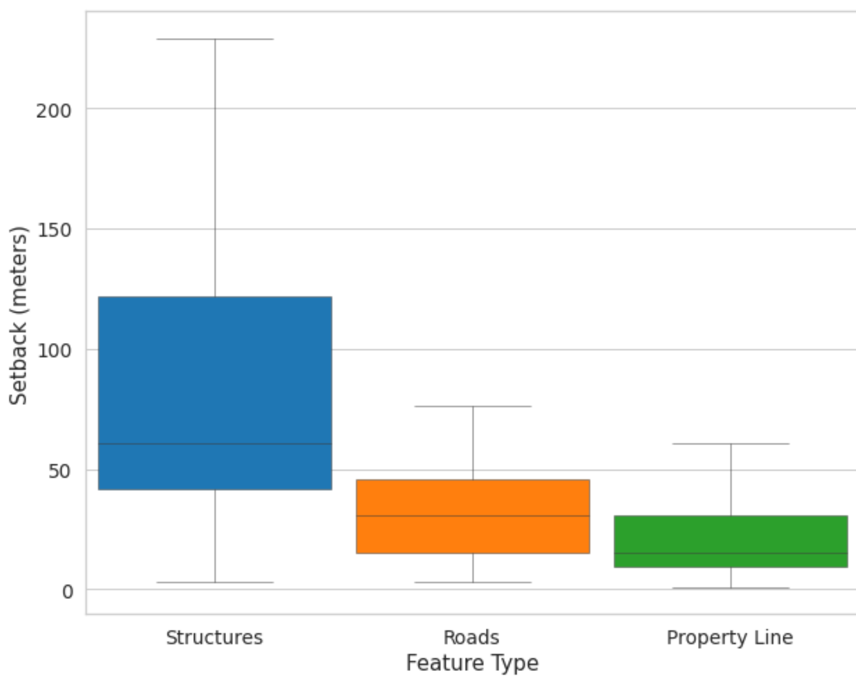
Supplemental Figure 6. Number of wind ordinances by states in 2022.



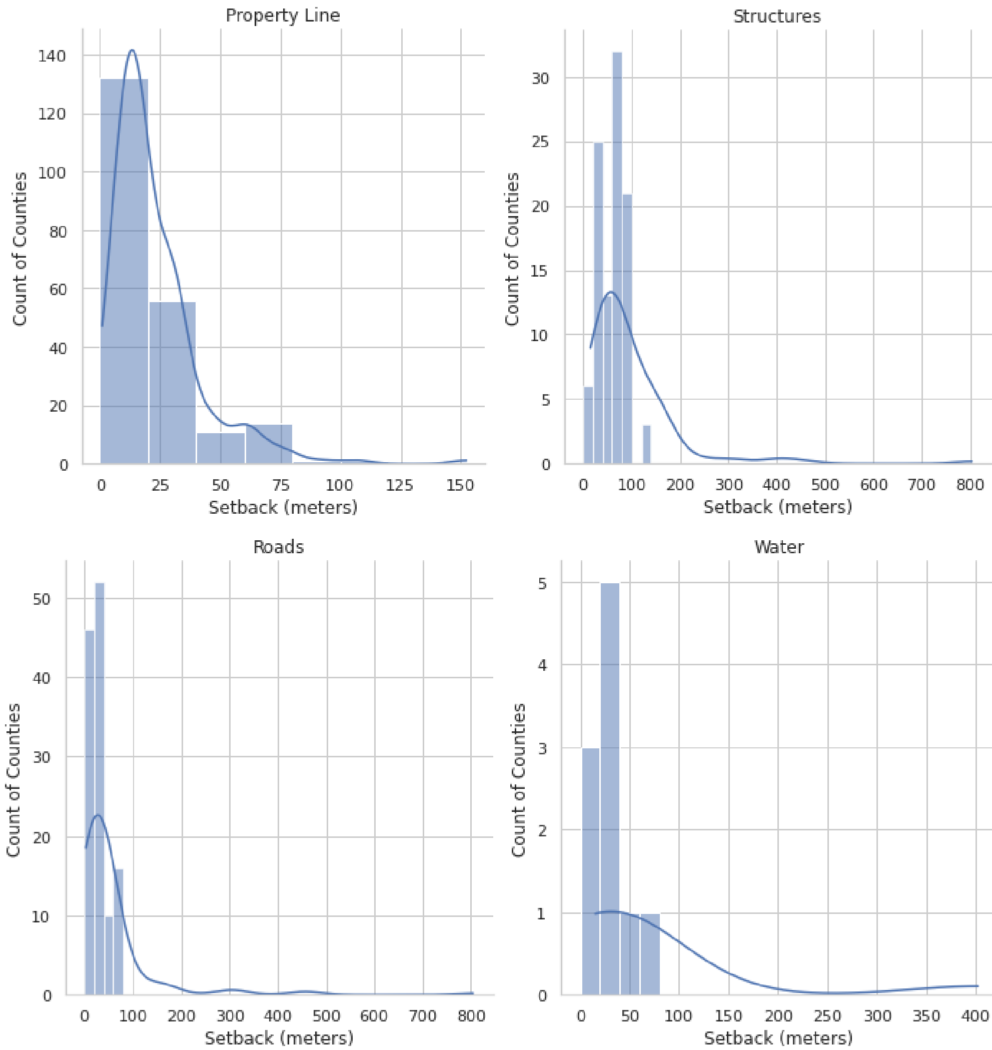
Supplemental Figure 7. Relationship between turbine size and the estimated setback. Larger turbines will have a greater setback due to setbacks being tied to tip height.



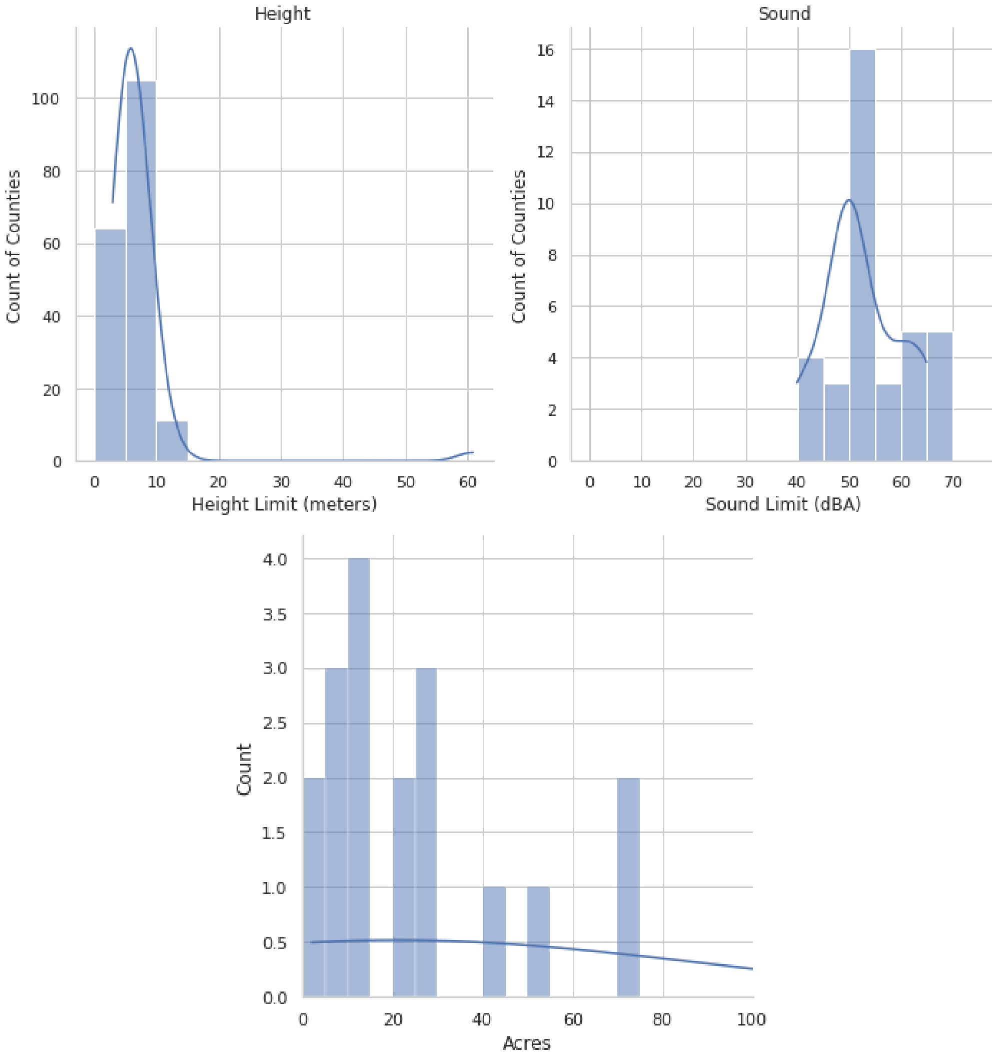
Supplemental Figure 8. The number of solar ordinances by state.



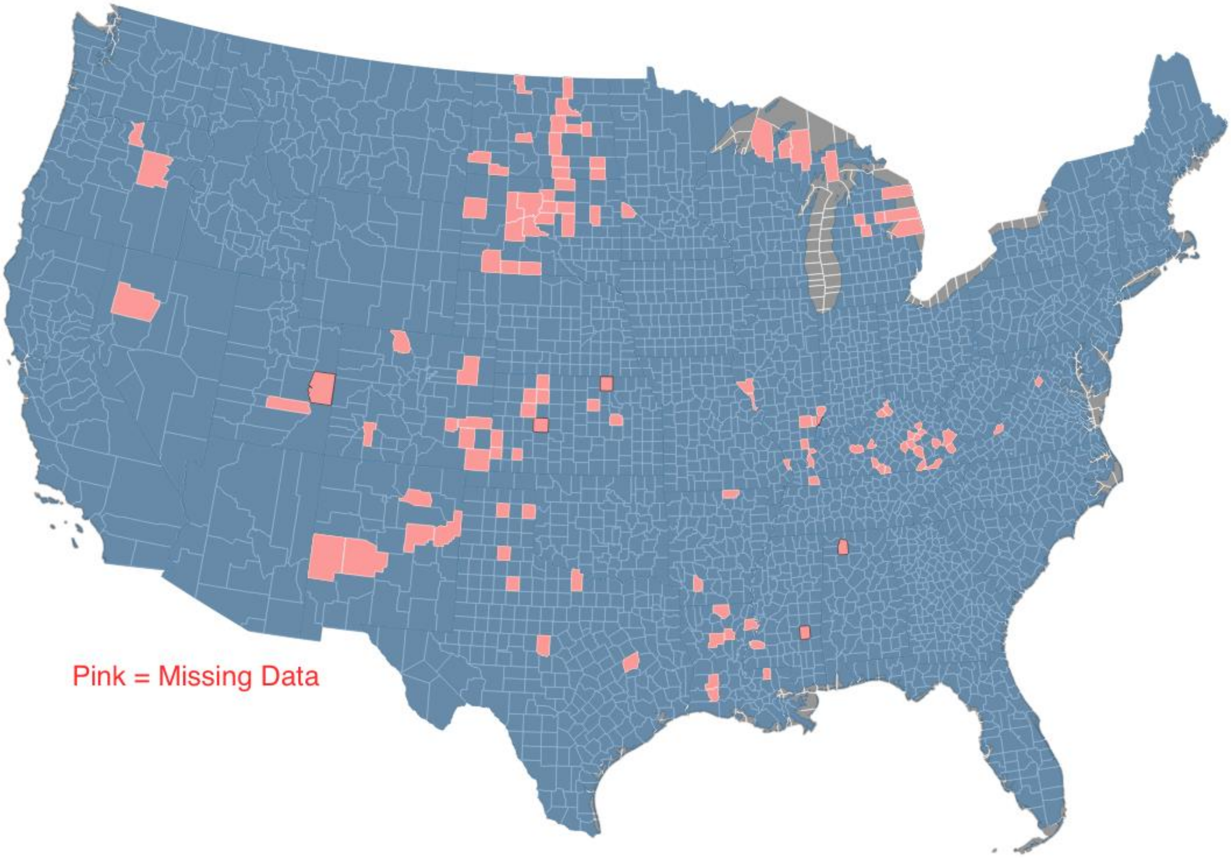
*Supplemental Figure 9. Setbacks by feature type for solar. In these box plots the rectangles represent the interquartile range (IQR), the lines represent the median, the whiskers extend to Q1-1.5*IQR and Q3+1.5*IQR, outliers have been suppressed in the images. Structures n: 136; Roads n: 141; Property Line n: 233.*



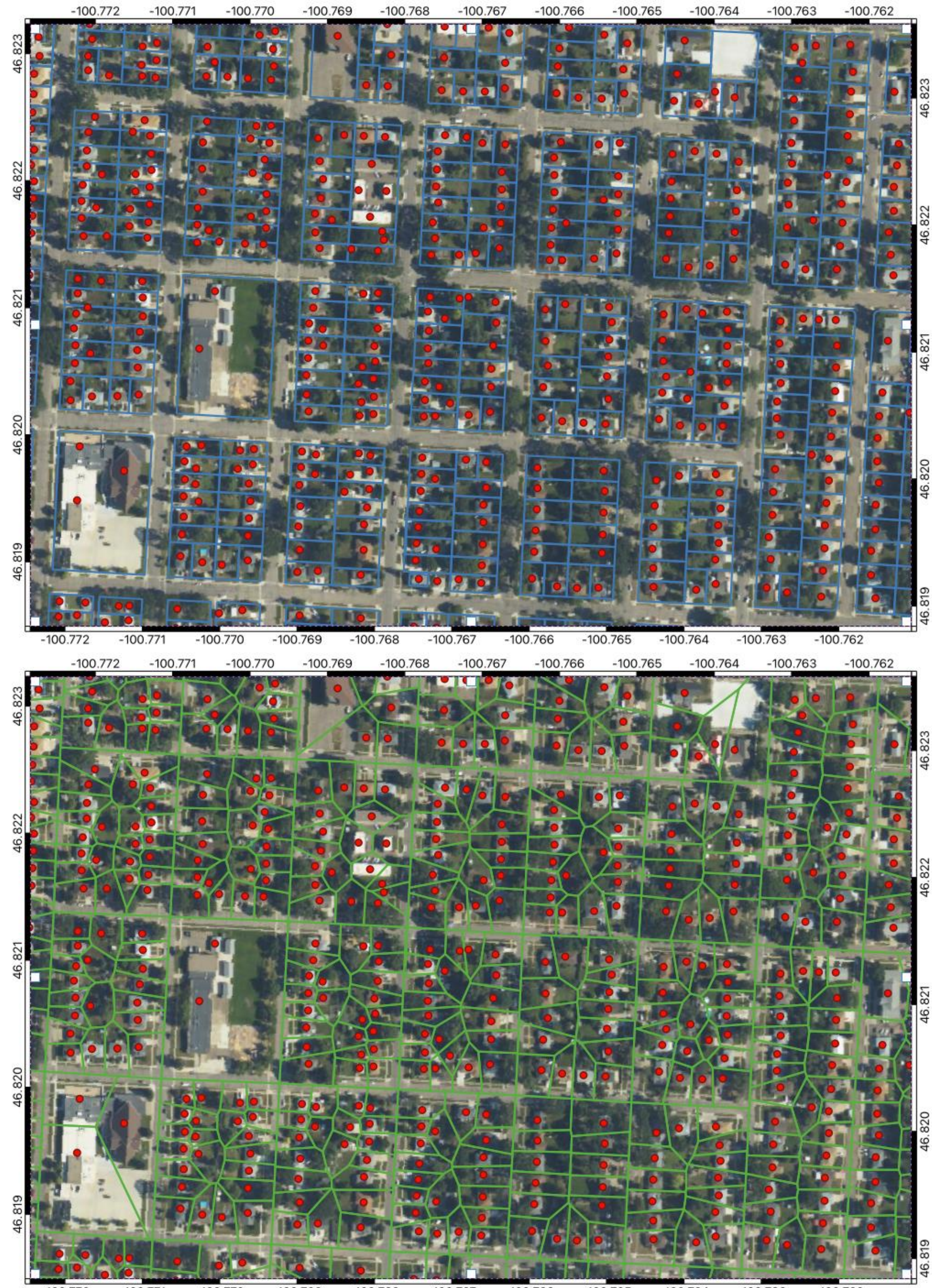
Supplemental Figure 10. Distribution of ordinance setback requirements for solar PV for property lines, structures, roads, and water setbacks.



Supplemental Figure 11. Distribution of ordinance requirements for solar PV for height, sound, and minimum lot size.

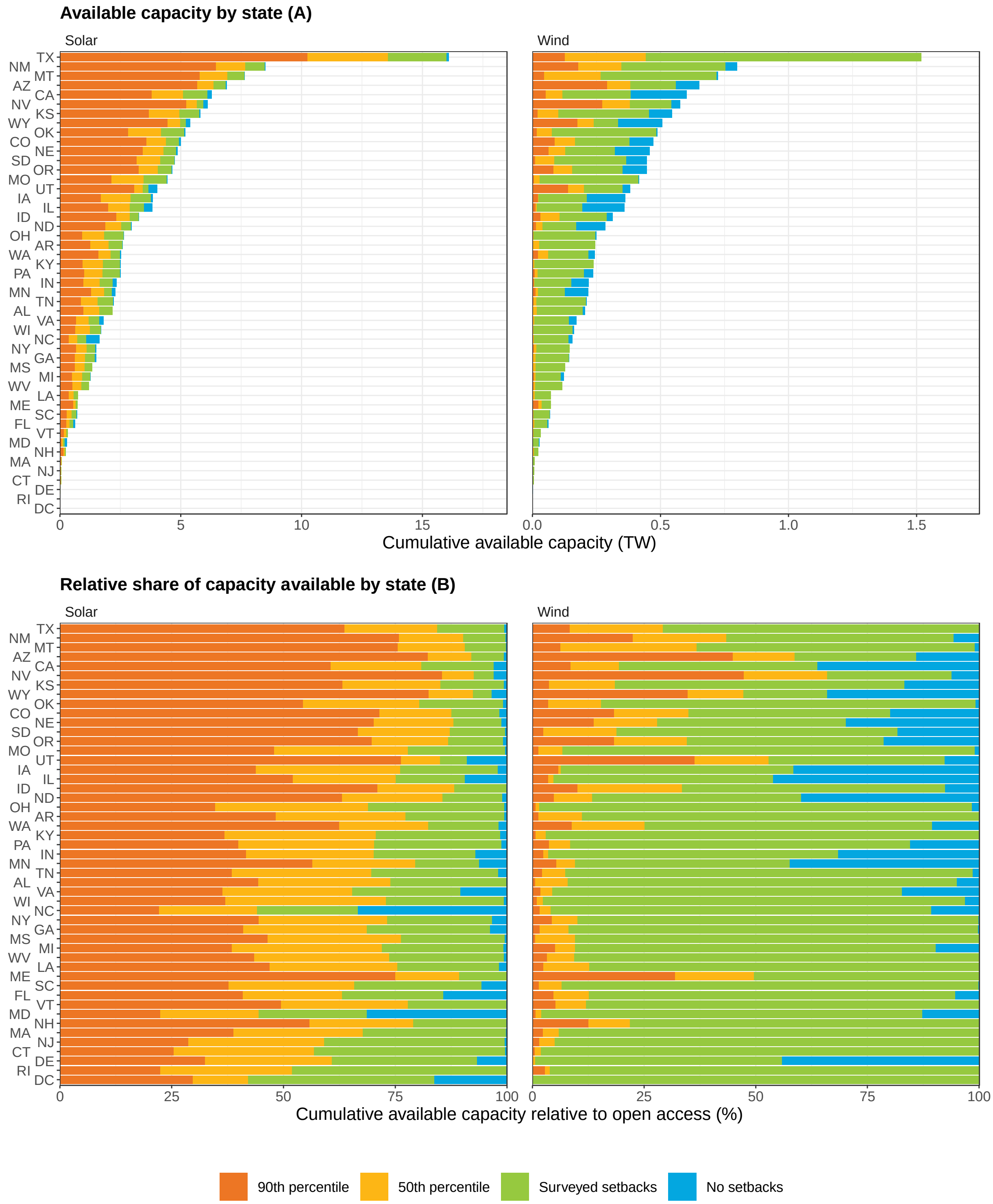


Supplemental Figure 12. Coverage of property boundaries in our county datasets. Counties in pink do not have property boundary data.

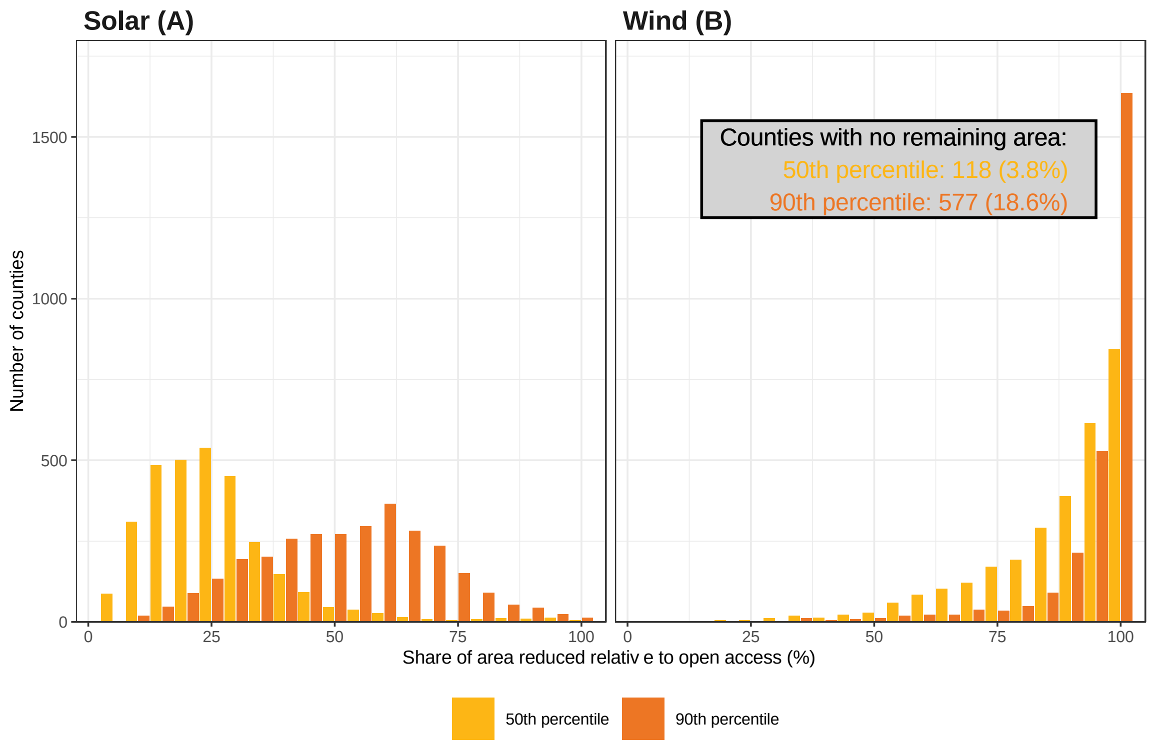


Supplemental Figure 13. Actual parcels for an urban area (top, using blue lines) versus modeled parcels (bottom, using green lines) for a representative location.

Supplemental Figure 14. Actual parcels for a rural area (top, using blue lines) versus modeled parcels (bottom, using green lines) for a representative location.



Supplemental Figure 15. Absolute solar and wind resource capacity (A) and relative resource (B) by state. The bottom plot (B) shows the share relative to the No Ordinances case. The Surveyed setbacks case includes only the setbacks in the ordinances surveyed as a reference point for what has been captured in the surveyed ordinances.



Supplemental Figure 16. Distribution of area reduced by county for solar (A) and wind (B). The share reduced is relative to the No Ordinances case. For reference, there are approximately 3,000 counties in the U.S.

Supplemental Notes

Supplemental Note 1: Parcel Simulation Details

Property boundaries (parcels) are important setbacks might limit solar siting. Unfortunately, data of parcels are missing in some counties, though there is a good coverage across the contiguous United States (see Supplemental Figure 12). Therefore, we developed a workflow to simulate the parcels in these missing counties and validated the methodology. The workflow was derived from empirical observations that the road network highly aligns with parcels boundaries spatially and that each house in a high-density residential zone (HDRZ) is likely to own one parcel while parcels in a low-density residential zone (LDRZ) are likely to be equal in size. As a result, parcels within a HDRZ and a LDRZ were simulated independently, and both modeling processes used the road network to constrain the locations and arrangement of parcels. The data used for this workflow are detailed in SI Table 2 including existing property boundaries, road network, building footprints and state/county boundaries. The workflow comprises five steps.

Step 1: Divide a missing county into HDRZ and LDRZ. We first extracted the centroid (point) from each building footprint (BF) polygon. Then we grouped the points into HDRZ-BFs and LDRZ-BFs by leveraging the DBSCAN algorithm[1] which is a density-based clustering algorithm to group the points in space into high-density (more spatial neighbors) and low-density regions. The algorithm requires two key parameters, the minimum number of points forming a dense region and the maximum distance between two points considered as neighborhoods, which were set to 20 and 240m, respectively. We further transformed the road network (polylines) into polygons (RP) and overlaid them with the grouped points to separate the HDRZ-RPs from the LDRZ-RPs.

Step 2: Simulate the property parcels within a HDRZ. An HDRZ-RP was divided into multiple simulated parcels based on the Voronoi algorithm[2] using HDRZ-BFs within this polygon.

Step 3: Simulate the property parcels within a LDRZ. We first estimated the average size of LDRZ parcels of neighboring non-missing counties. For each LDRZ-RP in a missing county, we split it into several square-like polygons of the average size inferred from neighboring counties if the size of a LDRZ-RP is larger than the average size. Please note that there may be an offcut polygon remained in the result because irregular shape of LDRZ-RP and its size may be not the exactly an integral multiple of the average size of parcels. Please refer to https://github.com/jonnyhuck/RFCL-PolygonDivider for the details of this splitting algorithm.
Step 4: Post-processing. The simulated parcels in steps 2 and 3 were merged to form the parcels in a missing county. Water bodies, especially those big lakes and rivers, are unlikely to own parcels of averaged size. Therefore, we used the water polygons transformed from the national land cover dataset (NLCD)[3] to update the simulated parcels, where the size of a water body for updating was estimated from the neighboring non-missing counties.

Step 5: Validation and application. The workflow was tested using those non-missing counties in the State of North Dakota. We compared the buffered area using 30 meters as a parameter between simulated parcels and ground truth parcels. The overall accuracy achieved 94.7%. We applied this workflow to each missing county from Supplemental Figure 12. Example locations are shown in Supplemental Figure 13 for an urban region and Supplemental Figure 14 for a rural region.

Supplemental References

1. Ester, M., Kriegel, H.-P., Sander, J. & Xu, X. A density-based algorithm for discovering clusters in large spatial databases with noise. in *Proceedings of the Second International Conference on Knowledge Discovery and Data Mining* 226–231 (AAAI Press, 1996).

3. Huang, X., Wang, C., Li, Z., Ning, H. A 100 m population grid in CONUS by disaggregating census data with open-source Microsoft building footprints. Big Earth Data 5, 112-33.

2. Reem, D. An Algorithm for Computing Voronoi Diagrams of General Generators in General Normed Spaces. in *2009 Sixth International Symposium on Voronoi Diagrams* 144–152 (2009). doi:10.1109/ISVD.2009.23.

3. Wickham, J., Stehman, S. V., Sorenson, D. G., Gass, L. & Dewitz, J. A. Thematic accuracy assessment of the NLCD 2016 land cover for the conterminous United States. *Remote Sensing of Environment* **257**, 112357 (2021).