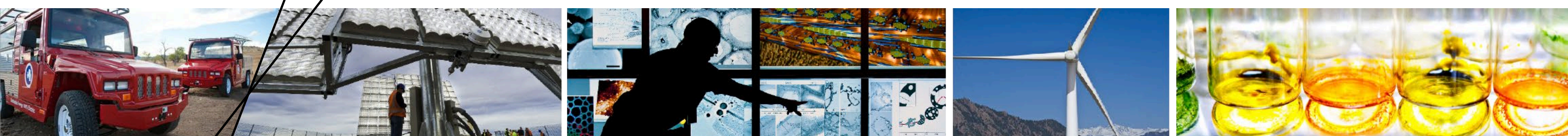
NATIONAL RENEWABLE ENERGY LABORATORY

Rooftop Solar Photovoltaic Technical Potential in the United States



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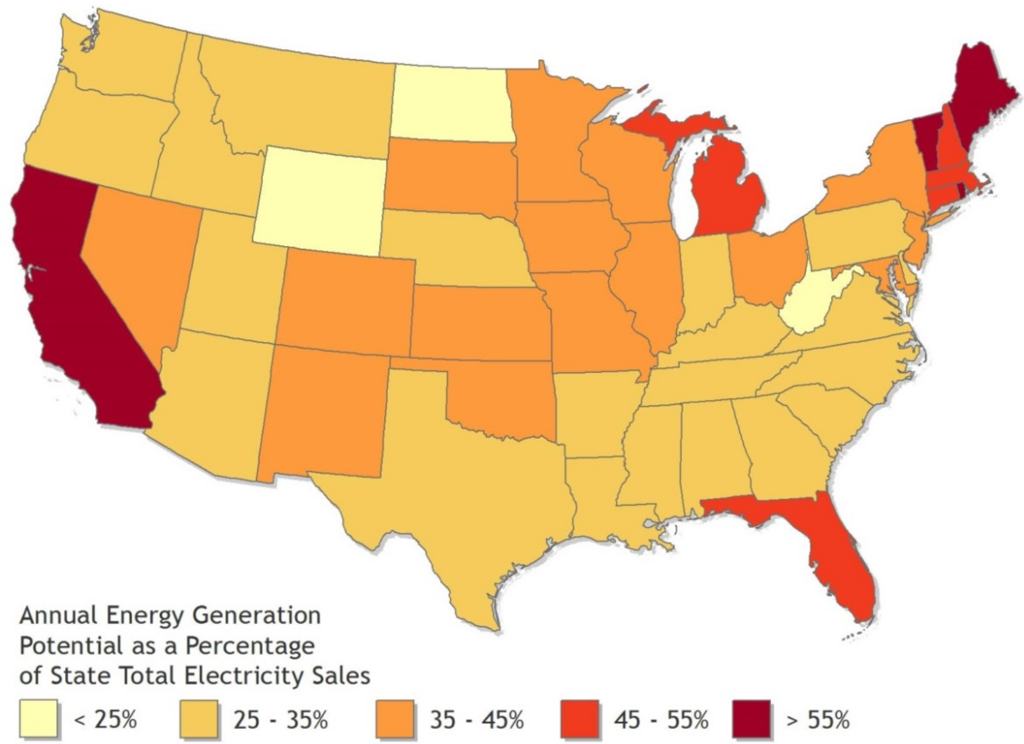
Introduction

- **Research question:**
  - How much energy could be generated if we installed PV on all existing, suitable roof area in the United States?
- We answered this question through lidar-based GIS analysis, statistical modeling, and PV-generation simulations.
- Our results do not exclude systems based on their economic performance, and thus they provide an upper bound on potential deployment rather than a prediction of actual deployment.
- The results are sensitive to assumptions about module performance, which is expected to continue improving over time. Furthermore, these estimates do not consider the immense potential of ground-mounted PV.



Estimated Suitable Area and Rooftop PV Technical Potential by Building Class

Building Class (building footprint)	Total Suitable Area (billions of m²)	Installed Capacity Potential (GW)	Annual Generation Potential (TWh/year)	Annual Generation Potential (% of national sales)
Small (< 5,000 ft²)	4.92	731	926	25.0%
Medium (5,000–25,000 ft²)	1.22	154	201	5.4%
Large (> 25,000 ft²)	1.99	232	305	8.2%
All Buildings	8.13	1,118	1,432	38.6%

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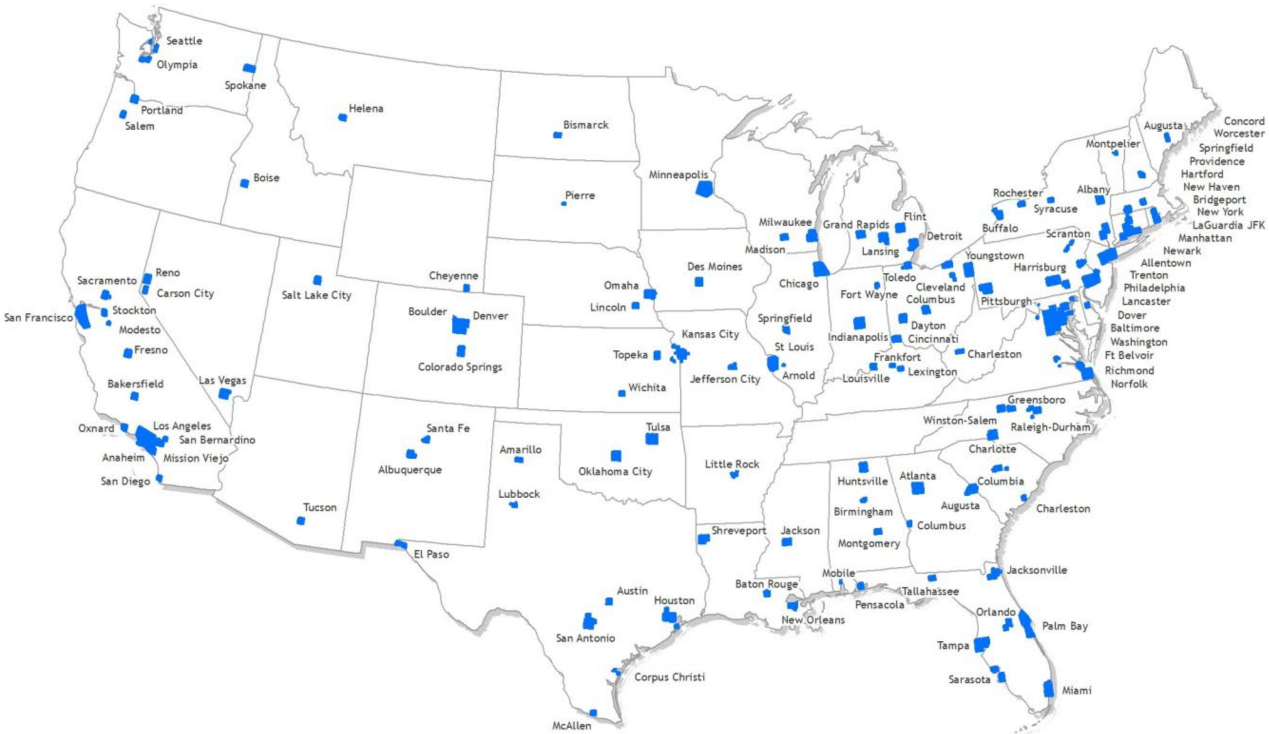
Input Lidar Data

- The lidar data used in our analysis were obtained from the U.S. Department of Homeland Security (DHS) Homeland Security Infrastructure Program for the years 2006–2014.
- For each of the 128 cities in the data set, DHS provided lidar data in raster format at 1-m by 1-m resolution and a corresponding polygon shapefile of building footprints.
- The data set includes 26.9 million buildings and 7.7 billion m^2 of rooftop area, or about 23% of U.S. buildings.
- The area covered represents about 122 million people or 40% of the U.S. population.



Area Covered by Lidar Data

Excluding Unsuitable Roof Area

- We used the lidar data to determine how much roof area was available for PV deployment.
- Roof Area was considered unsuitable for PV if:
    - The solar energy loss from shading was >20% of energy that would be received if unshaded.
    - The roof tilt was greater than 60 degrees.
    - The roof azimuth faced northeast through northwest.
    - The contiguous area of the roof plane was less than 10m2.

Example of Suitable Roof Planes in a Neighborhood within our Lidar Dataset

Observed Roof Plane Characteristics

- We subdivided all 26.9 million buildings into three classes according to the planar area of their footprints:

Building Class	Building Footprint (ft^2)	Percentage of Building Stock	Percentage of Total Roof Area	Percentage of Buildings with at Least One Suitable Roof Plane	Percentage of Roof Area Suitable for PV within each Size Class
Small	< 5,000	94%	58%	83%	26%
Medium	5,000–25,000	5%	18%	99%	49%
Large	> 25,000	1%	24%	99%	66%
All Buildings	-	100%	100%	84%	32%

- Small buildings show substantially more variability in rooftop PV suitability than do medium and large buildings, because they have more diverse architectures (e.g., roof tilt) and more shadowing from trees and neighboring buildings.
- Flat planes are very common on large buildings (93% of planes on large building are flat) and medium buildings (74%) but less common on small buildings (26%).

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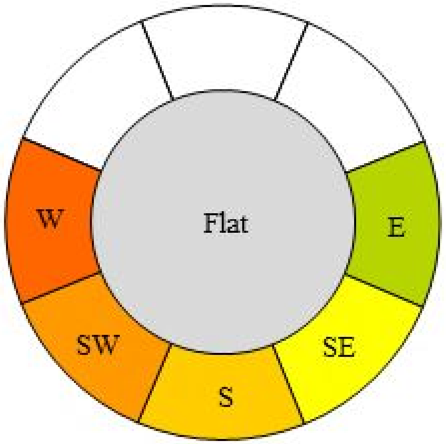
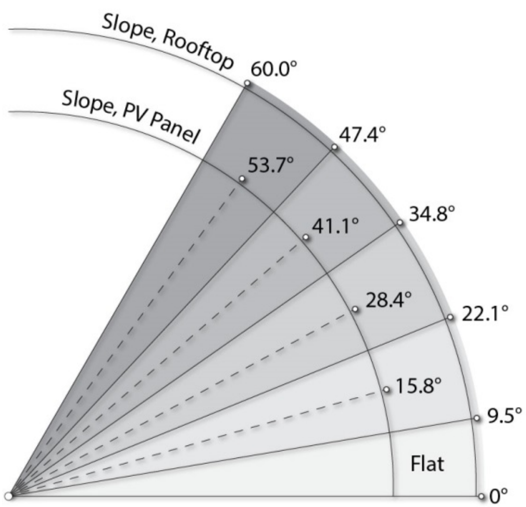
Simulating PV Productivity on Suitable Rooftop Area

- Energy generation of PV modules covering suitable roof area was simulated using NREL's System Advisor Model (SAM).
- Technical assumptions reflect average performance of PV systems as they were installed in 2014, representing a mixture of monocrystalline-silicon, multicrystalline-silicon, and thin film modules, as opposed to universal installation of premium systems.



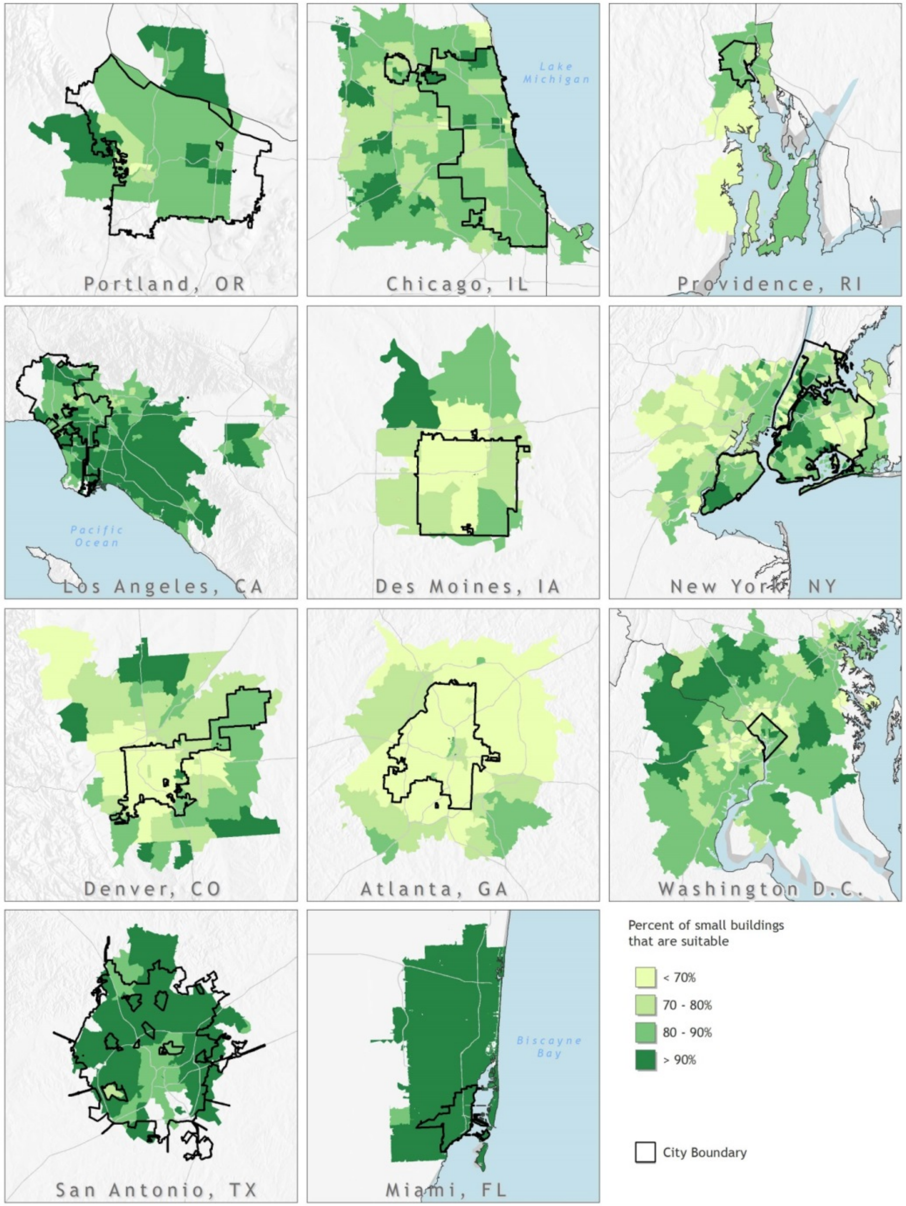
Assumptions for PV Performance Simulations

PV System Characteristics	Value for Flat Roofs	Value for Tilted Roofs
Tilt	15 degrees	Midpoint of tilt class
Ratio of module area to roof area	0.70	0.98
Azimuth	South facing	Midpoint of azimuth class
Module power density	160 W/m^2	
Total system losses	14.08%	
Inverter efficiency	96%	
DC-to-AC ratio	1.2	



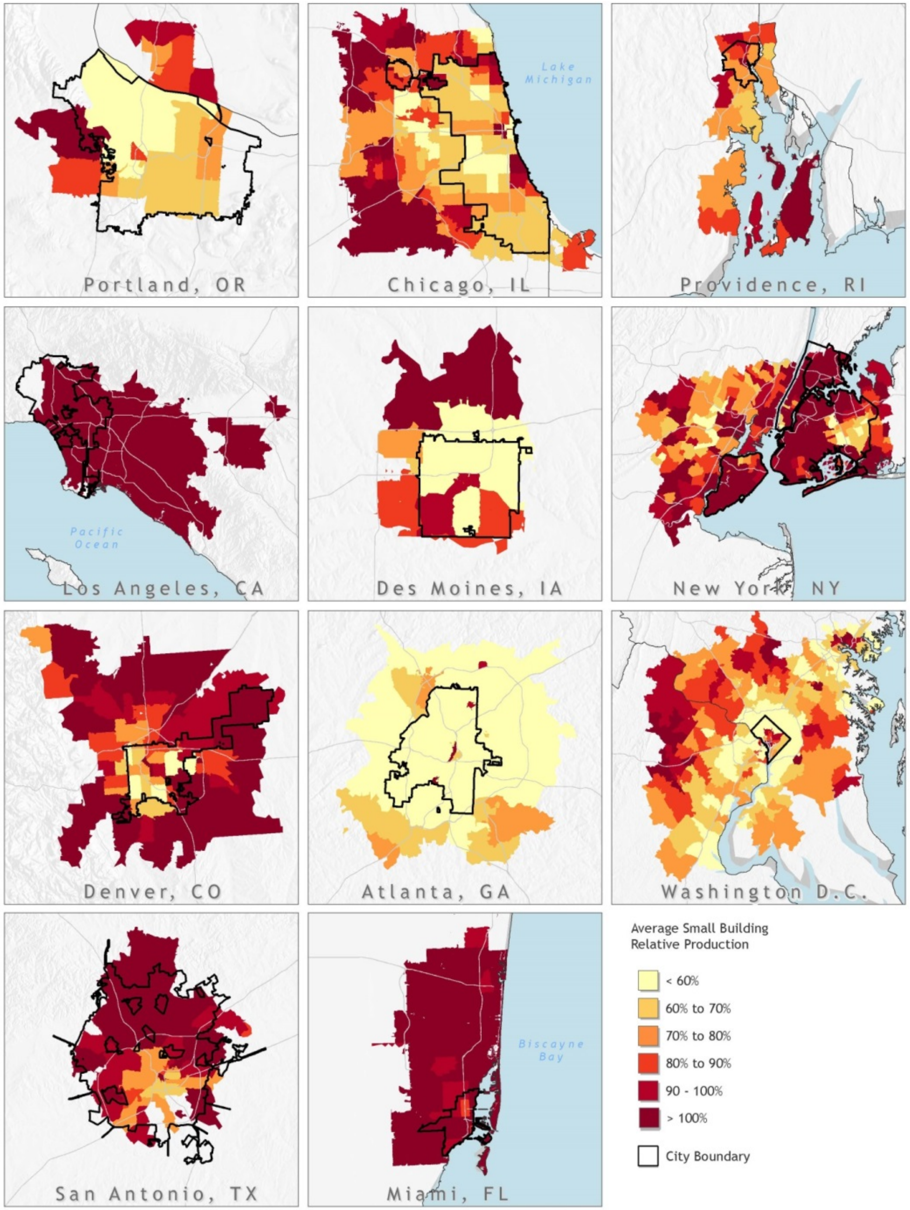
Small Building Suitability

- This figure shows the percentage of small buildings that have a suitable roof plane at the ZIP code level.
  - Only small building suitability is mapped, because over 99% of medium and large buildings have at least one roof plane suitable for PV deployment.
- There is only a weak trend of high building density driving down the suitability of small buildings.
  - Most of the highly developed downtown ZIP codes in these cities have suitability similar to the suitability in other ZIP codes within the city boundaries.
  - However, some suburban ZIP codes outside city boundaries do show higher levels of suitability.



Small Building Average Relative Production

- *Average relative production* of small buildings is defined here as the annual electricity generation potential for an average small building as a percentage of the average household annual electricity consumption in that city's state (EIA 2009).
- In many parts of the United States, ZIP-code-sized aggregations of households can collectively generate enough electricity to offset their expected annual consumption.



Note: Because the consumption value is a state average, it is constant across all ZIP codes for a given city and therefore does not capture household-level variation in consumption that would be driven by socioeconomic status, building size, and other household-specific factors. Therefore, the average relative production values shown should only be interpreted as a simple estimation of the potential ability for a group of households in a given ZIP code to offset its consumption.

Technical Potential of All Buildings in 47 Cities Covered by Lidar

City	Installed Capacity Potential (GW)	Annual Energy Generation Potential (GWh/year)	Ability of PV to meet Estimated Consumption
Mission Viejo, CA	0.4	587	88%
Concord, NH	0.2	194	72%
Sacramento, CA	1.5	2,293	71%
Buffalo, NY	1.2	1,399	68%
Columbus, GA	1.1	1,465	62%
Los Angeles, CA	9.0	13,782	60%
Tulsa, OK	2.6	3,590	59%
Tampa, FL	1.4	1,952	59%
Syracuse, NY	0.6	657	57%
Amarillo, TX	0.7	1,084	54%
Charlotte, NC	2.6	3,466	54%
Colorado Springs, CO	1.2	1,862	53%
Denver, CO	2.3	3,271	52%
Carson City, NV	0.2	386	51%
San Antonio, TX	6.2	8,665	51%
San Francisco, CA	1.8	2,684	50%
Little Rock, AR	0.8	1,099	47%
Miami, FL	1.4	1,959	46%
Birmingham, AL	0.9	1,187	46%
St. Louis, MO	1.5	1,922	45%
Cleveland, OH	1.7	1,881	44%
Toledo, OH	1.4	1,666	43%
Providence, RI	0.5	604	42%

City	Installed Capacity Potential (GW)	Annual Energy Generation Potential (GWh/year)	Ability of PV to meet Estimated Consumption
Worcester, MA	0.5	643	42%
Atlanta, GA	1.7	2,129	41%
New Orleans, LA	2.1	2,425	39%
Hartford, CT	0.4	404	38%
Baltimore, MD	2.0	2,549	38%
Bridgeport, CT	0.4	435	38%
Detroit, MI	2.6	2,910	38%
Portland, OR	2.6	2,811	38%
Milwaukee, WI	2.1	2,597	38%
Boise, ID	0.5	760	38%
Des Moines, IA	0.8	1,026	36%
Cincinnati, OH	1.0	1,176	35%
Norfolk, VA	0.8	1,047	35%
Wichita, KS	1.1	1,537	35%
Newark, NJ	0.6	764	33%
Philadelphia, PA	4.3	5,289	30%
Springfield, MA	0.3	370	29%
Chicago, IL	6.9	8,297	29%
St. Paul, MN	0.8	903	27%
Pittsburgh, PA	0.9	907	27%
Minneapolis, MN	1.0	1,246	26%
Charleston, SC	0.3	407	25%
New York, NY	8.6	10,742	18%
Washington, DC	1.3	1,660	16%

- The cities with the largest potential installed capacity are Los Angeles (9.0 GW) and New York (8.6 GW).

Note: City boundaries defined by U.S. Census Bureau 2013 TIGER/Line Shapefiles. Roof area outside the city boundaries were not included in calculating the total capacity and energy estimates.

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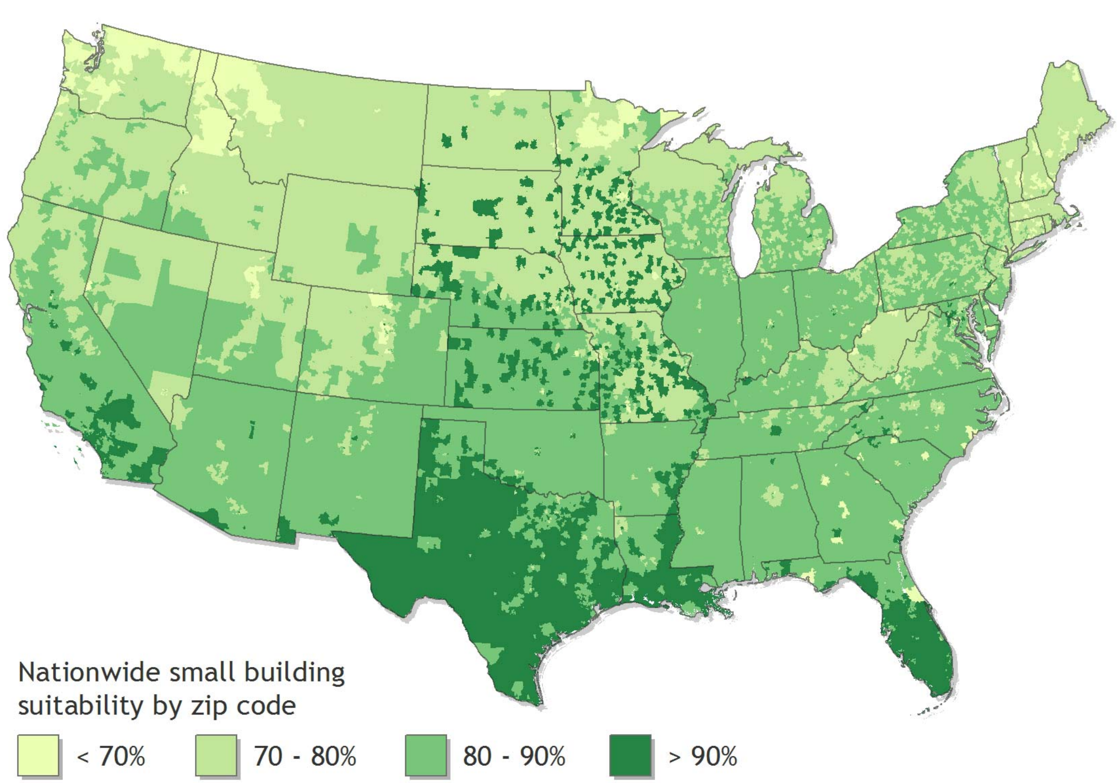
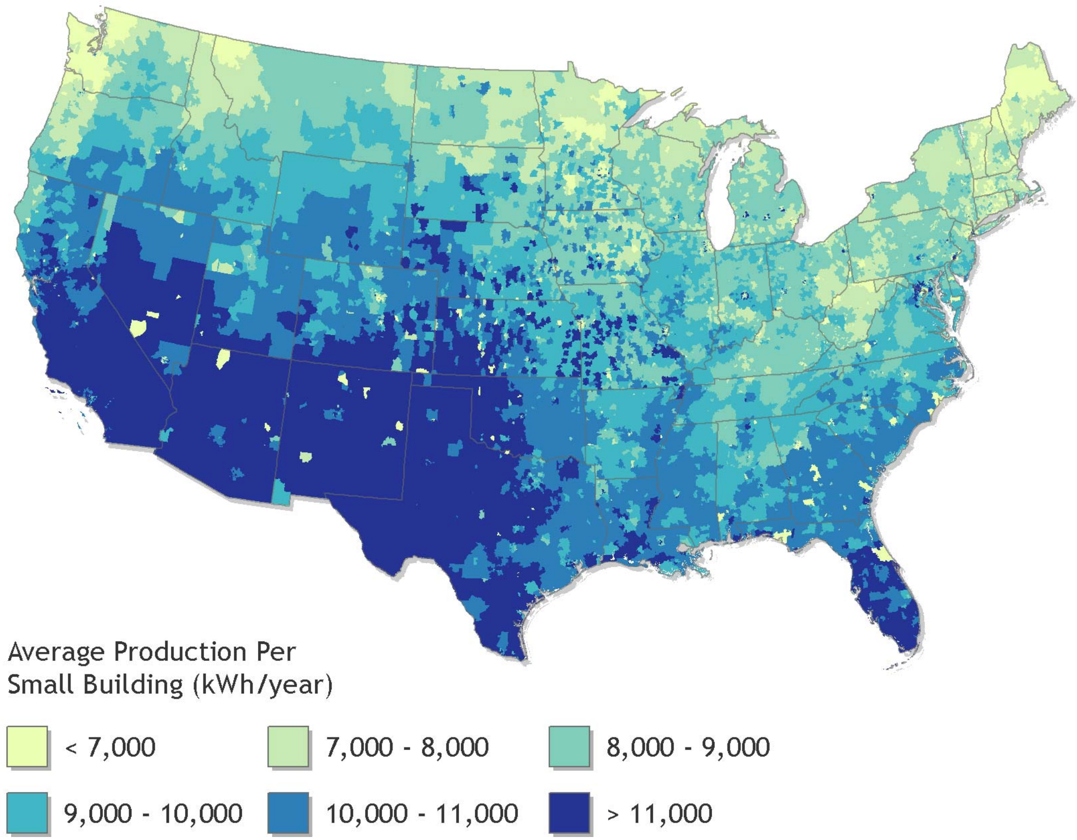
Estimate of Small Building Suitability

- Previously we presented results for regions where we have lidar coverage. The remainder of this presentation shows estimates for larger regions where there is incomplete or no lidar coverage.



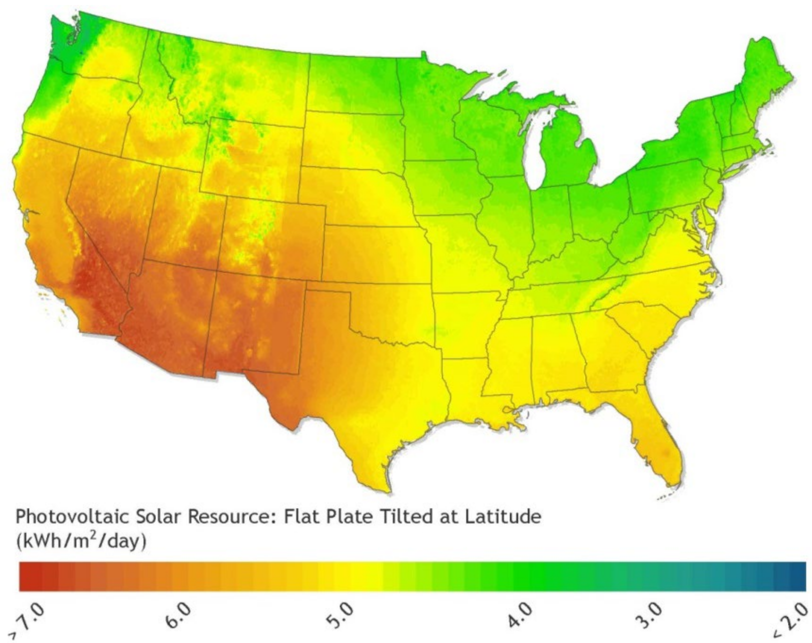
- There are regional trends in small building suitability.
- The percentage of small buildings that are suitable tends to be higher in regions without significant tree canopy coverage.
  - For example, the relatively unforested southeast portion of Washington has a higher percentage of suitability than the northeastern region of the state.

Estimate of Small Building Productivity



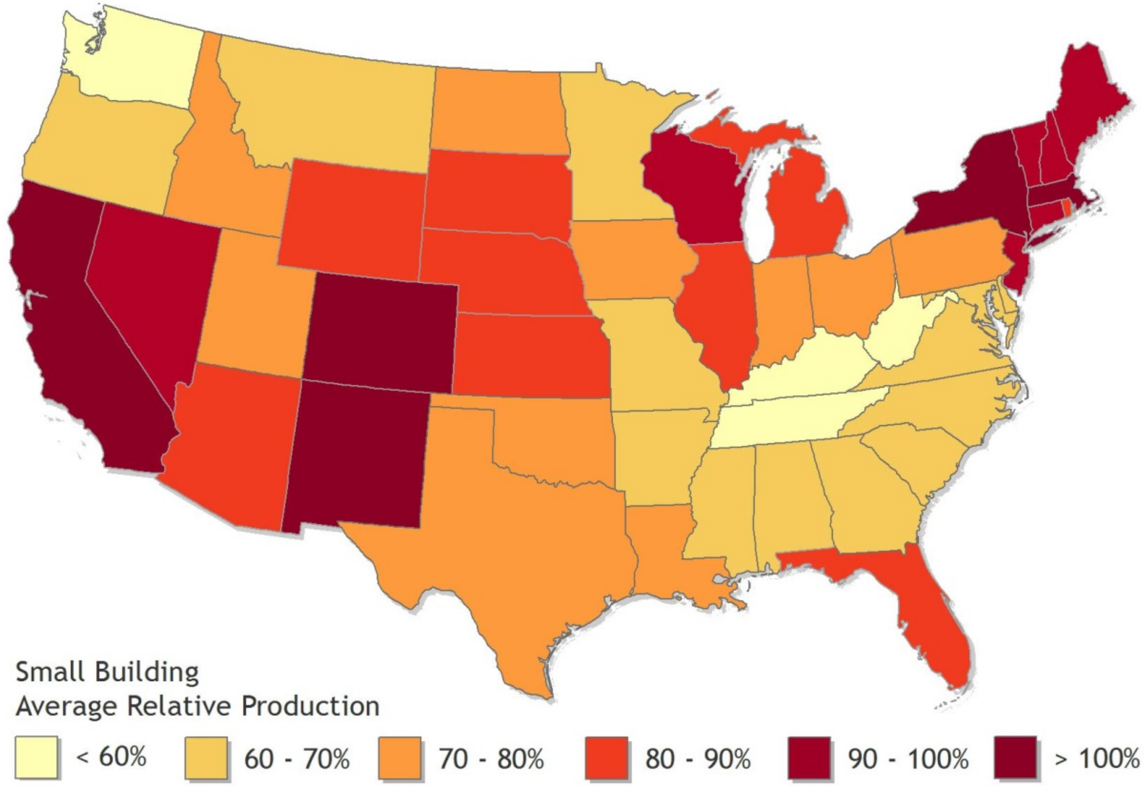
- Broadly speaking, average small building production strongly correlates with the solar resource; however, there exists significant local variation driven by average household footprint and suitability.
  - For example, the simulated average production in Florida is 12,100 kWh/year per small building (130% of the national average) owing to an above-average solar resource, but it ranges from 5,300 kWh/year to 30,100 kWh/year on a ZIP code level because of variation in suitability and building footprint.

- Differences in suitability can drive differences in total productivity between regions with similar solar resource.
  - For example, lower suitability in the south Atlantic states leads to lower average small building productivity compared to the Florida peninsula, despite a solar resource of similar quality.



Estimate of Small Building Average Relative Production

- **Average relative production of small buildings at the state level:** Defined as the annual rooftop PV generation of an average small building as a percentage of each state's average annual household consumption.
    - For example, the average generation potential of small buildings in Colorado is 8,760 kWh/year, and the average annual household consumption is 7,370 kWh/year. Therefore the average relative production of Colorado's small buildings is 118%.



- These results show that a relatively poor solar resource does not preclude a state's residential sector from offsetting a significant percentage of its consumption.
    - An average small building across all of New England's states, except Rhode Island, could generate greater than 90% of the electricity consumed by an average household in the region. This is driven by the low average household consumption of 8,011 kWh/year in the region (70% of the national average), which is due in part to high use of natural gas and oil for heating as well as relatively low summer cooling requirements.

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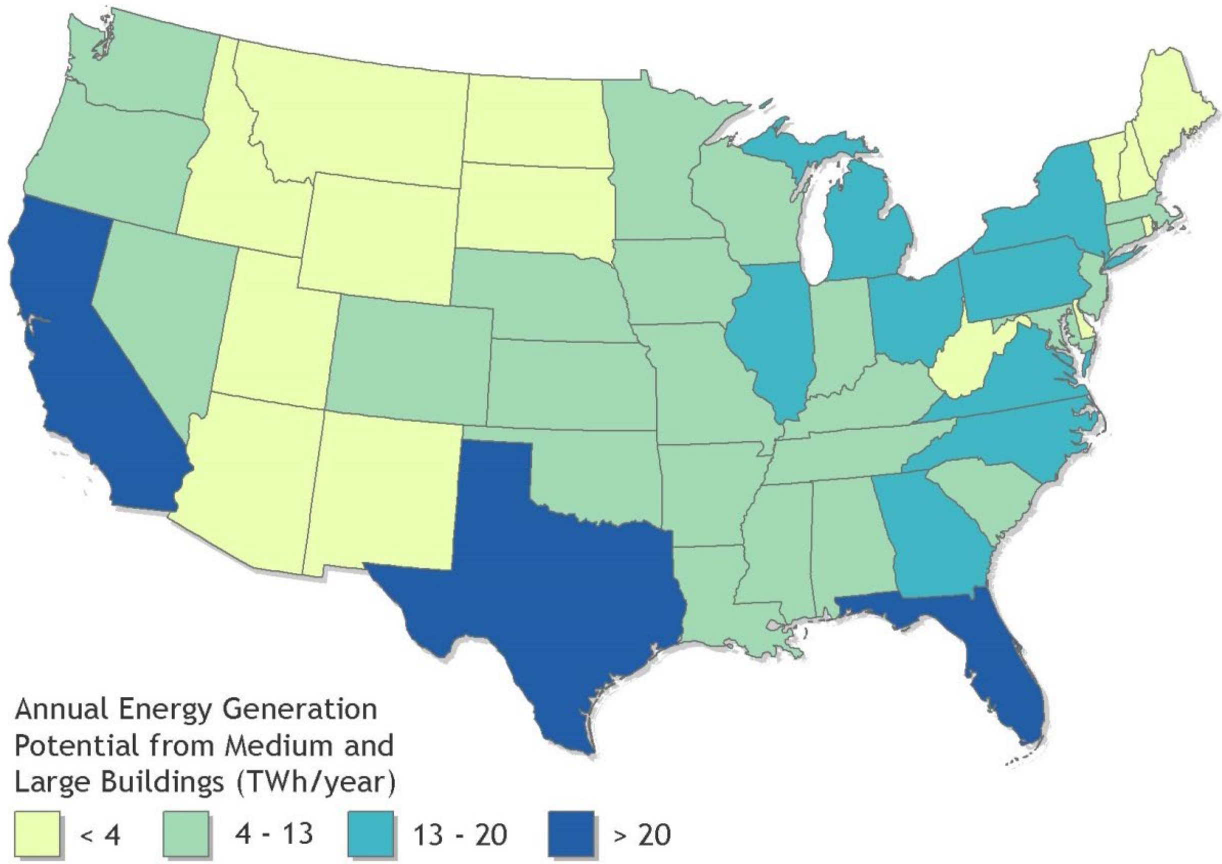
Estimated Energy Production for Medium and Large Buildings

- Across all states, small buildings have greater potential (926 TWh/year, or 25% of total national electricity sales) than the combined potential of medium and large buildings (506 TWh/year, or 14% of total national sales).



- The differences in potential between building size classes can largely be explained by the total suitable roof area and the utilization of the available space.
  - Despite the higher percentage of medium and large building roof area suitable for PV deployment, the far smaller numbers of these buildings resulted in a lower total developable area (3.2 billion m^2) compared to small buildings (4.9 billion m^2).
  - The generally tilted roof area on small buildings can be used more efficiently than the predominantly flat roofs of large buildings, because flat roofs require greater spacing between modules to prevent excessive losses from shading.

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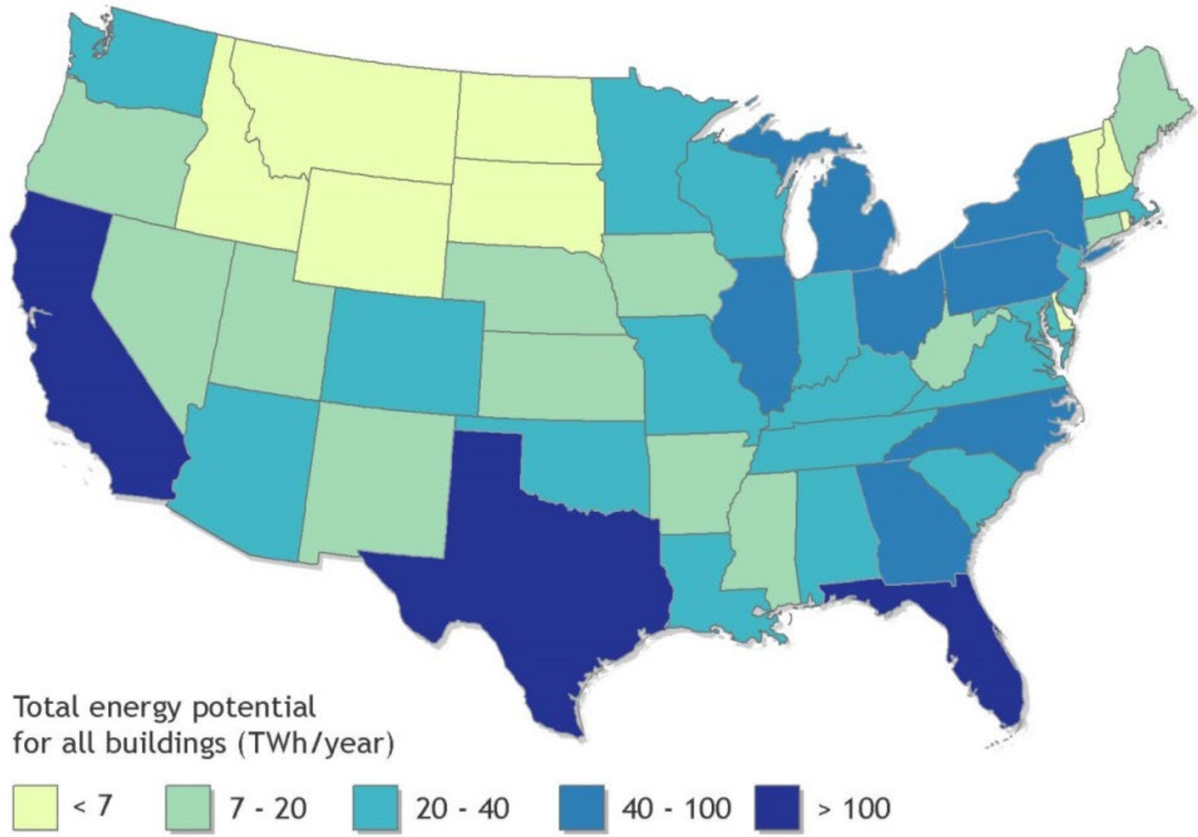
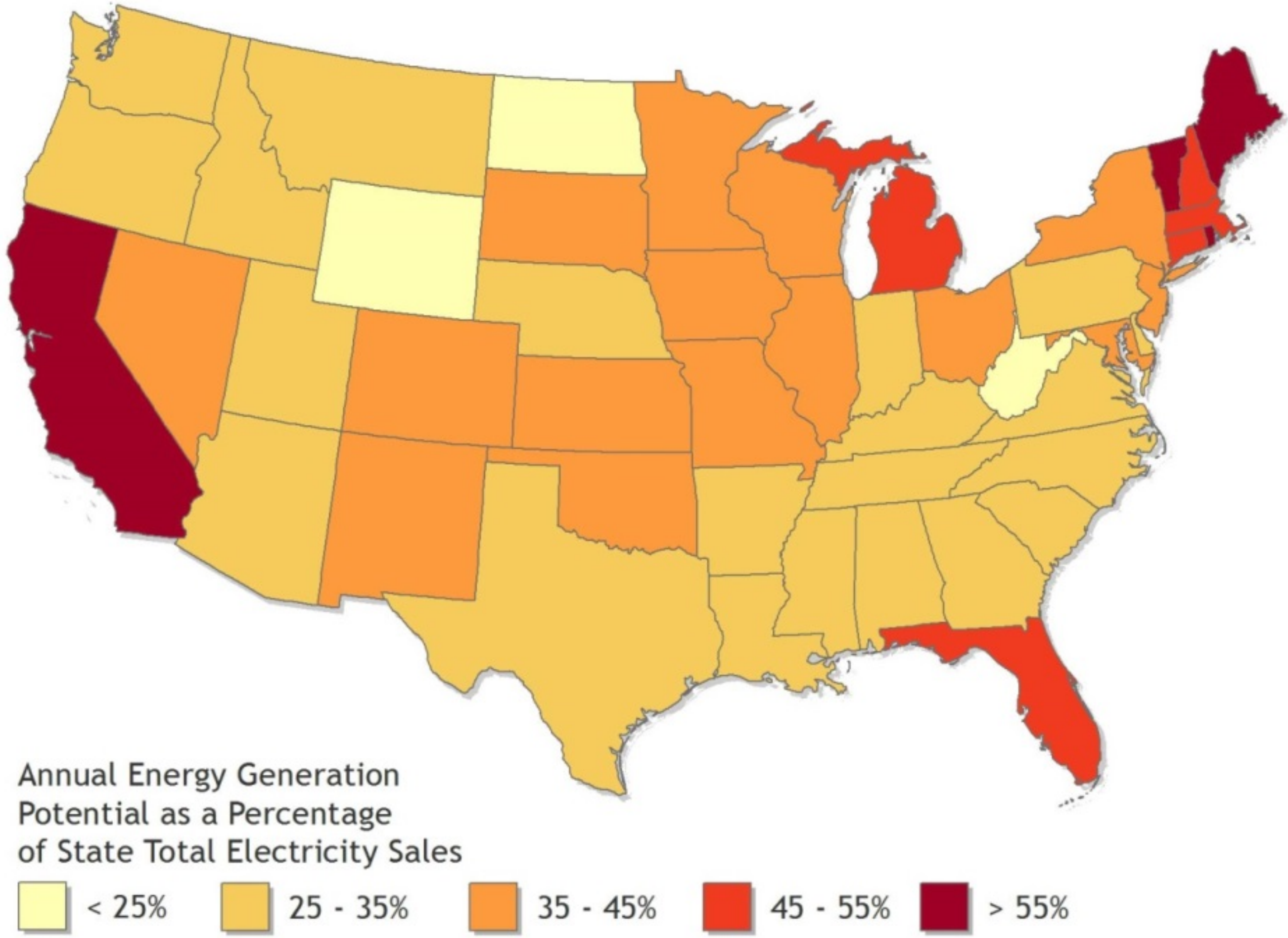
Estimated Energy Production for All Buildings



The total nationwide technical potential of PV from buildings of all sizes 1,118 GW of installed capacity and 1,432 TWh of annual energy generation, which equates to 39% of total national electric sales.

Technical Potential of All Buildings

- California has the greatest potential to offset use—PV on its rooftops could generate 74% of the electricity sold by its utilities in 2013.
- A cluster of New England states could generate more than 45%, despite these states' below-average solar resource.



- Washington, with the lowest population-weighted solar resource in the continental United States, could still generate 27%.

Total Estimated Rooftop PV Technical Potential of All Buildings by State

State	Annual Generation Potential (% of sales)	Installed Capacity Potential (GW)	Annual Generation Potential (TWh/year)	Total Roof Area Suitable for PV Deployment (millions of m²)
California	74.2%	128.9	194.0	961
Maine	60.0%	6.3	7.1	45
Vermont	60.0%	3.0	3.4	21
Rhode Island	56.6%	3.8	4.4	28
New Hampshire	53.4%	5.3	5.9	38
Connecticut	49.8%	12.8	14.8	95
Massachusetts	47.0%	22.5	26.0	165
Florida	46.5%	76.2	103.2	557
Michigan	45.9%	42.1	47.3	303
Colorado	44.0%	16.2	23.5	119
Oklahoma	44.1%	19.3	26.4	140
New Mexico	43.4%	6.1	10.0	45
Missouri	42.7%	28.3	35.6	204
Kansas	41.7%	12.5	16.6	90
Nevada	39.6%	8.7	13.9	67
New Jersey	40.4%	24.9	30.1	184
Wisconsin	40.1%	23.6	27.7	169
Maryland	38.7%	19.3	23.9	142
Minnesota	38.5%	23.1	26.4	168
South Dakota	38.7%	3.8	4.7	26
New York	37.4%	46.6	55.3	340
Illinois	37.0%	44.1	52.5	324
Ohio	35.3%	46.8	53.0	338
Iowa	35.5%	14.0	16.6	99
Texas	34.6%	97.8	131.2	715

State	Annual Generation Potential (% of sales)	Installed Capacity Potential (GW)	Annual Generation Potential (TWh/year)	Total Roof Area Suitable for PV Deployment (millions of m²)
North Carolina	34.9%	35.0	45.3	252
Pennsylvania	34.5%	43.6	50.4	316
Nebraska	34.1%	8.2	10.5	60
Utah	34.3%	7.2	10.4	52
Oregon	34.2%	14.1	16.3	101
Georgia	33.8%	34.6	44.1	251
Arizona	34.4%	16.3	26.1	114
Arkansas	33.3%	12.2	15.5	88
Virginia	32.4%	28.5	35.8	205
Tennessee	31.9%	24.4	30.9	175
Mississippi	31.2%	11.7	15.2	84
Delaware	31.0%	2.9	3.5	20
Louisiana	29.8%	20.1	25.6	146
Alabama	29.8%	20.4	26.2	147
Indiana	29.5%	26.3	31.1	188
Montana	28.0%	3.2	3.9	21
Washington	26.6%	22.8	24.7	164
Idaho	26.4%	4.7	6.4	33
Kentucky	25.2%	18.0	21.4	131
South Carolina	25.5%	15.2	20.0	108
North Dakota	24.6%	3.3	3.9	23
West Virginia	22.9%	6.3	7.2	45
Washington DC	15.1%	1.3	1.7	11
Wyoming	14.2%	1.7	2.4	12
Contiguous U.S. Total	38.6%	1,118	1,432	8,130

- The six states with the highest potential PV generation as a percent of total state sales all have significantly below-average household consumption, suggesting the role an energy-efficient residential sector could play in achieving a high penetration of energy from rooftop PV.

Data for Public Use

- We have posted the supporting data on maps.nrel.gov/pv-rooftop-lidar.
    - Data layers include a regional summary and ZIP-code-level summary for all areas where lidar data are available as well as national coverage of ZIP code estimates as predicted by the methods described in this report.
    - Detailed documentation of each step in our analysis, including scripts for running the GIS tools, are linked to in the metadata section of each layer. This information can be accessed by clicking the question mark icon next to each layer in the table of contents.
- **This slide deck is a summary. For full report, see Gagnon, P., R. Margolis, J. Melius, C. Phillips, and R. Elmore. 2015. "Rooftop Solar Photovoltaic Technical Potential in the United States." Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-65298.**