Rulemaking No.: **20-08-020**
Exhibit No.: **PAO-08**
Witness: **Brad Heavner and Joshua Plaisted**
Commissioner: **Martha Guzman Aceves**
ALJ: **Kelly A. Hymes**
Dated: **July 30, 2021**

Excerpt from Rooftop Solar Photovaltaic Technical Potential in the United States: A Detailed Assessment by NREL

Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment

Pieter Gagnon, Robert Margolis, Jennifer Melius, Caleb Phillips, and Ryan Elmore

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Technical Report
NREL/TP-6A20-65298
January 2016

Contract No. DE-AC36-08GO28308

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment

Pieter Gagnon, Robert Margolis, Jennifer Melius, Caleb Phillips, and Ryan Elmore
National Renewable Energy Laboratory

Prepared under Task No. SS13.1040

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

Technical Report
NREL/TP-6A20-65298
January 2016

Contract No. DE-AC36-08GO28308

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Available electronically at SciTech Connect http:/www.osti.gov/scitech

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
OSTI http://www.osti.gov
Phone: 865.576.8401
Fax: 865.576.5728
Email: reports@osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312
NTIS http://www.ntis.gov
Phone: 800.553.6847 or 703.605.6000
Fax: 703.605.6900
Email: orders@ntis.gov

Cover Photos by Dennis Schroeder: (left to right) NREL 26173, NREL 18302, NREL 19758, NREL 29642, NREL 19795.

NREL prints on paper that contains recycled content.

Acknowledgements

This work was funded by the Solar Energy Technologies Office of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy under contract number DE-AC36-08GO28308. The authors would like to thank Mike Gleason, Carolyn Davidson, Sean Ong, Rebecca Hott, Steve Wade, Eric Boedecker, Paul Denholm, Donna Heimiller, Michael Bolen, Laura Vimmerstedt, and Paul Donohoo-Vallett for their reviews and input. We would like to thank Adnan Zahoor, Britney Sutcliffe, and Julian Abbott-Whitley for their assistance in processing data. Lastly, we would like to thank Jarett Zuboy for his diligence and attention to detail while editing this report.

List of Acronyms

AC	alternating current
ACS	American Community Survey
ANOVA	analysis of variance
CBECS	Commercial Building Energy Consumption Survey
DC	direct current
DHS	U.S. Department of Homeland Security
EIA	U.S. Energy Information Administration
GIS	geographic information system(s)
GW	gigawatt
GWh	gigawatt-hour
kW	kilowatt
kWh	kilowatt-hour
Lidar	light detection and ranging
NCES	National Center for Education Statistics
NLCD	National Land Cover Database
NREL	National Renewable Energy Laboratory
PV	photovoltaic
RMSE	root-mean-square error
SAM	System Advisor Model
TMY3	Typical Meteorological Year 3
TWh	terawatt-hour
W	watt
ZIP code	Zoning Improvement Plan code

Executive Summary

This report quantifies the technical potential of photovoltaic (PV) systems deployed on rooftops in the continental United States, estimating how much energy could be generated by installing PV on all suitable roof area. The 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.

Although methods have been developed to estimate rooftop PV technical potential at the individual building level, previous estimates at the regional and national levels have lacked a rigorous foundation in geospatial data and statistical analysis. This report helps fill this gap by providing a detailed data-driven analysis of U.S. (national, state, and ZIP-code level) rooftop PV availability and technical electricity-generation potential. First, we use light detection and ranging (lidar) data, geographic information system (GIS) methods, and PV-generation modeling to calculate the suitability of rooftops for hosting PV in 128 cities nationwide—representing approximately 23% of U.S. buildings—and we provide PV-generation results for a subset of these cities. Second, we extend the insights from this analysis of areas covered by lidar data to the entire continental United States. We develop two statistical models—one for small buildings and one for medium and large buildings—that estimate the total amount of roof area suitable for hosting PV systems, and we simulate the productivity of PV modules on the roof area to arrive at the nationwide technical potential for PV.

Our analysis of the trends in the suitability of rooftops for hosting PV systems reveals important variations in this key driver of rooftop PV technical potential that have not been captured by previous approaches. Figure ES-1 shows the results—from our statistical modeling grounded in lidar data—for the percentage of small buildings that are suitable for PV in each ZIP code in the continental United States. In the figure we can identify regional trends in the suitability of small building rooftops, with high densities of suitable small buildings in California, Florida, and the West South Central census division. Such trends are also critical to estimating PV technical potential at finer resolution, and our report illustrates this with a high-resolution analysis of 11 representative cities.

Figure ES-2 shows the annual energy generation potential from rooftop PV as a percentage of each state's electricity sales in 2013. The estimates of energy generation are based on the rooftop suitability of small, medium, and large buildings as well as specific roof orientations, local solar resources, PV system performance assumptions, and building footprints.[1]

[1] Because the medium and large building estimates are available only at the state level, the combined results are presented at that level.

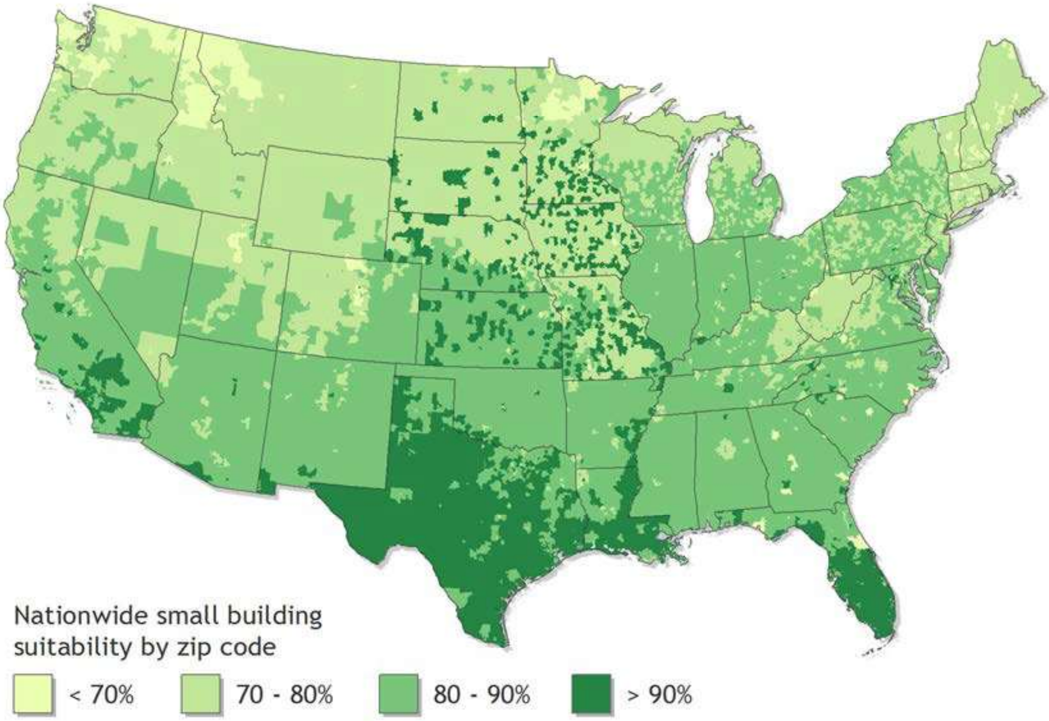

Figure ES-1. Percentage of small buildings suitable for PV in each ZIP code

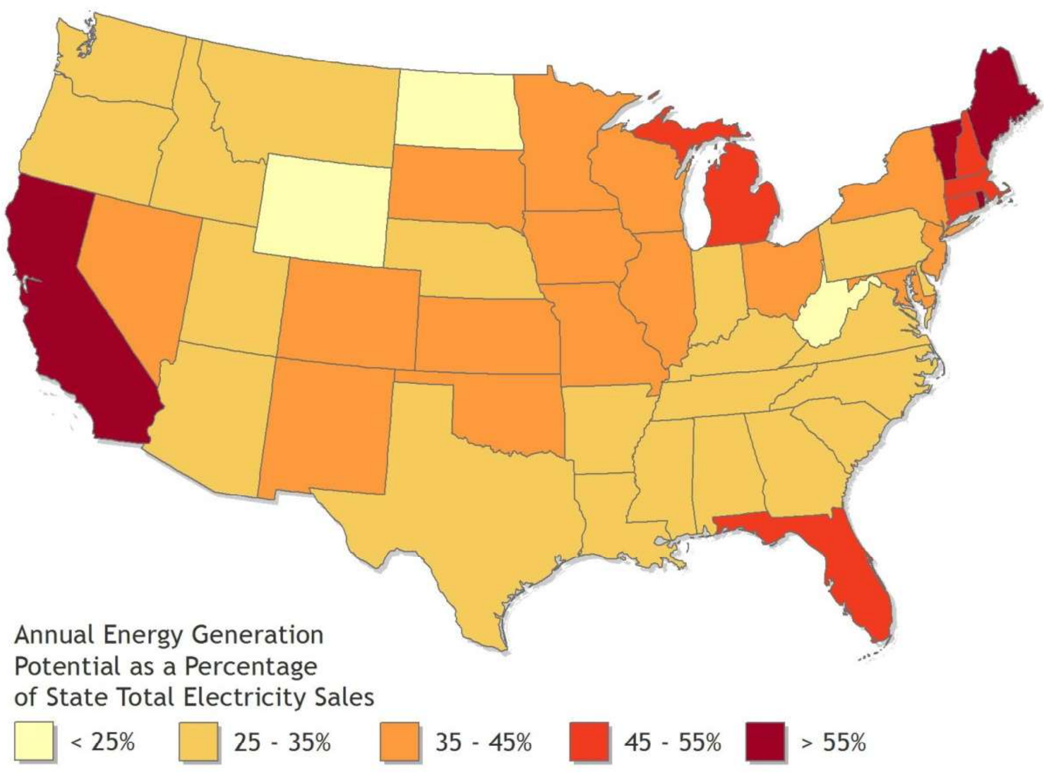

Figure ES-2. Potential rooftop PV annual generation from all buildings as a percentage of each state's total electricity sales in 2013

Figure ES-2 shows that California has the greatest potential to offset electricity use—its rooftop PV could generate 74% of the electricity sold by its utilities in 2013. A cluster of New England states could generate more than 45% because these states' low per-capita electricity consumption offsets their below-average solar resource. Washington, with the lowest population-weighted solar resource in the continental United States, could still generate 27%. Some states with below-average solar resource (such as Minnesota, Maine, New York, and South Dakota) have similar or even greater potential to offset total sales compared to states with higher-quality resource (such as Arizona and Texas).

The difference between Florida and other South Atlantic states illustrates the interplay between variables that affect technical potential. Florida can offset 47% of its total consumption despite having an average household consumption of 130% of the national average. This is largely explained by significantly below-average electricity consumption outside of the residential sector, which makes the state's total per-capita electricity sales slightly lower than the national average. In contrast, the other South Atlantic states range from a potential 23% to 35% of electricity offset owing to lower average rooftop suitability (see Figure ES-1[2]), slightly lower quality solar resource, and higher per-capita total electricity sales.

Table ES-1 shows our aggregate results.[3] The total national technical potential of rooftop PV is 1,118 gigawatts (GW) of installed capacity and 1,432 terawatt-hours (TWh) of annual energy generation. This equates to 39% of total national electric-sector sales, and it is significantly greater than a previous National Renewable Energy Laboratory estimate of 664 GW of installed capacity and 800 TWh of annual energy generation (Denholm and Margolis 2008). The difference can be attributed to increases in module power density, improved estimation of building suitability, higher estimates of the total number of buildings, and improvements in PV performance simulation tools that previously tended to underestimated production.

Although only 26% of the total rooftop area on small buildings (those with a footprint smaller than 5,000 ft^2) is suitable for PV deployment, the sheer number of buildings in this class gives small buildings the greatest technical potential. Small building rooftops could accommodate 731 GW of PV capacity and generate 926 TWh/year of PV energy, which represents approximately 65% of rooftop PV's total technical potential. Medium and large buildings have a total installed capacity potential of 386 GW and energy generation potential of 506 TWh/year, which represents approximately 35% of the total technical potential of rooftop PV.

These results are sensitive to assumptions about module performance, which is expected to continue improving over time. For example, this analysis assumed a module efficiency of 16% to represent a mixture of various technology types. If a module efficiency of 20% were assumed instead, which corresponds to current premium systems, each of the technical potential estimates would increase by about 25% above the values stated in this report. Furthermore, our results are only estimates of the potential from existing suitable roof planes, and they do not consider the immense potential of ground-mounted PV. Actual generation from PV in urban areas could exceed these estimates by

[2] Figure ES-1 shows suitability results for only small buildings because more than 99% of medium and large buildings have at least one roof plane suitable for a PV system.
[3] Because the relative magnitudes of the results are a strong function of the square footage used as a cutoff between building classes, these results should not be presented without that information.

Table 3. Estimated Rooftop PV Technical Potential for Small 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 m^2)
California	43.6%	76.8	114.0	525.5
Vermont	40.3%	2.0	2.3	13.6
Maine	40.0%	4.2	4.7	28.0
New Mexico	32.8%	4.6	7.6	32.6
New Hampshire	32.4%	3.2	3.6	21.5
Arizona	31.6%	15.0	23.9	103.1
Rhode Island	31.2%	2.1	2.4	14.0
Michigan	30.6%	28.3	31.5	189.2
Florida	30.3%	50.3	67.3	343.4
South Dakota	29.5%	2.9	3.6	19.2
Missouri	28.1%	18.8	23.5	126.3
Connecticut	27.6%	7.2	8.2	48.2
Wisconsin	27.6%	16.3	19.0	109.0
Oklahoma	27.4%	12.2	16.4	80.9
Kansas	27.3%	8.2	10.9	55.3
Colorado	27.1%	10.0	14.5	67.4
Montana	26.7%	3.0	3.7	20.1
Massachusetts	25.5%	12.3	14.1	82.8
Utah	25.1%	5.4	7.7	36.2
New Jersey	24.9%	15.6	18.6	104.6
Iowa	24.9%	9.8	11.6	65.8
New York	24.8%	31.3	36.7	210.0
Illinois	23.6%	28.4	33.5	192.4
North Carolina	23.5%	23.9	30.6	160.1
Oregon	23.4%	9.7	11.2	65.3
Pennsylvania	23.2%	29.6	33.9	198.8
Ohio	23.1%	31.0	34.7	206.5
Minnesota	23.0%	13.9	15.8	92.7
Arkansas	22.5%	8.3	10.5	55.7
Idaho	22.2%	4.0	5.4	26.7
Delaware	22.1%	2.0	2.5	13.7
Texas	22.0%	62.7	83.2	424.6
Tennessee	22.0%	17.0	21.3	114.6