Puerto Rico Low-to-Moderate Income Rooftop PV and Solar Savings Potential

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December 17, 2020

Why Does Rooftop Solar Potential for LMI Matter?

LMI households represent 50% of PR population and spend disproportionately more of their income on energy

=> Dollar savings from solar likely more impactful

Solar has been disproportionately adopted by higher-income households

=> Growing backlash against rooftop solar policies that appear to favor the more affluent

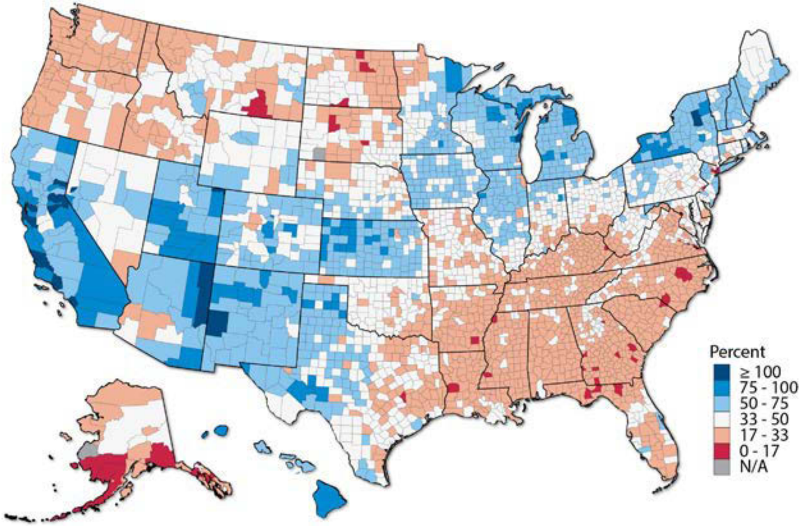
Increasing interest in policy interventions to include LMI households and create more equitable rooftop solar access

=> However, poor understanding of how much rooftop solar LMI communities can accommodate may lead to ineffective policies

Household Classification	% of Area Median Income
Very Low Income	0-30%
Low Income	30-50%
Moderate Income	50-80%
Middle Income	80-120%
High Income	>120%

Building off previous research

- Estimates for LMI PV Rooftop technical potential and solar savings potential exist for the U.S.
- Sigrin and Mooney (2018) found:
  - 43% of U.S. is LMI
  - Nearly 1000 TWh of residential potential, with 42% belonging to LMI buildings
  - 60% of LMI potential belonging to non-traditional buildings (i.e., renter and multi-family)
- This study extends this work for Puerto Rico



Percent of LMI electrical consumption offsettable by rooftop solar generation in the U.S. (Sigrin and Mooney, 2018)

Sigrin, Ben, and Mooney, Meghan. 2018. Rooftop Solar Technical Potential for Low-to-Moderate Income Households in the United States. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20- 70901. https://www.nrel.gov/docs/fy18osti/70901.pdf.

Key Questions for Technical Potential Analysis

1. How is rooftop solar potential distributed geographically, by income group, building type, and tenure of the building occupants?

2. How much electrical consumption can be offset by rooftop solar?

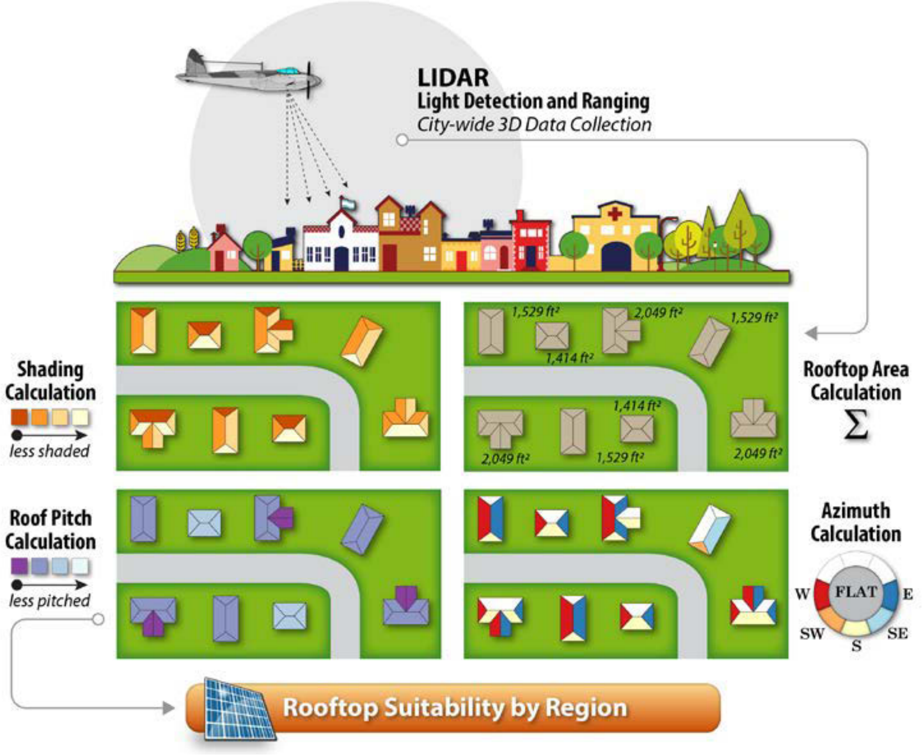
Summary of methodology

- This study processes 2015-2017 LiDAR scans (<0.35 nominal resolution) of Puerto Rico's building stock (96% of Puerto Rico building stock).

- LiDAR data intersected with Census demographics tables of household counts by income, tenure, and building type. LiDAR data does not allow direct observation of the tenant's attributes, thus a bootstrapping method is used.

- A statistical model, trained on LiDAR tracts, is used to impute building stock characteristics (area, orientation, shading, etc.) for 4% of building stock without sufficient LiDAR data.

- Finally, simulate solar generation for each roof plane using NREL PVWATTS and aggregate at the tract and county level



Assumptions for Building Suitability

Rooftop Suitability Assumptions

Roof Physical Characteristics	Description
Shading	Measured shading for four seasons and required an average of 80% unshaded surface
Azimuth	All possible azimuths
Tilt	Average surface tilt <= 60 degrees
Minimum Area	>= 1.62 m^2 (area required for a single solar panel)

PV Performance Assumptions

PV System Characteristics	Value for Flat Roofs	Value for Tilted Roofs
Tilt	15 degrees	Tilt of plane
Ratio of module area to suitable roof area	0.70	0.98
Azimuth	180 degrees (south facing)	Midpoint of azimuth class
Module Power Density	183 W/m^2	
Total system losses	Varies (SAM defaults + individual surface % shading)	
Inverter efficiency	96%	
DC-to-AC ratio	1.2	

Puerto Rico Residential PV Solar Rooftop Potential

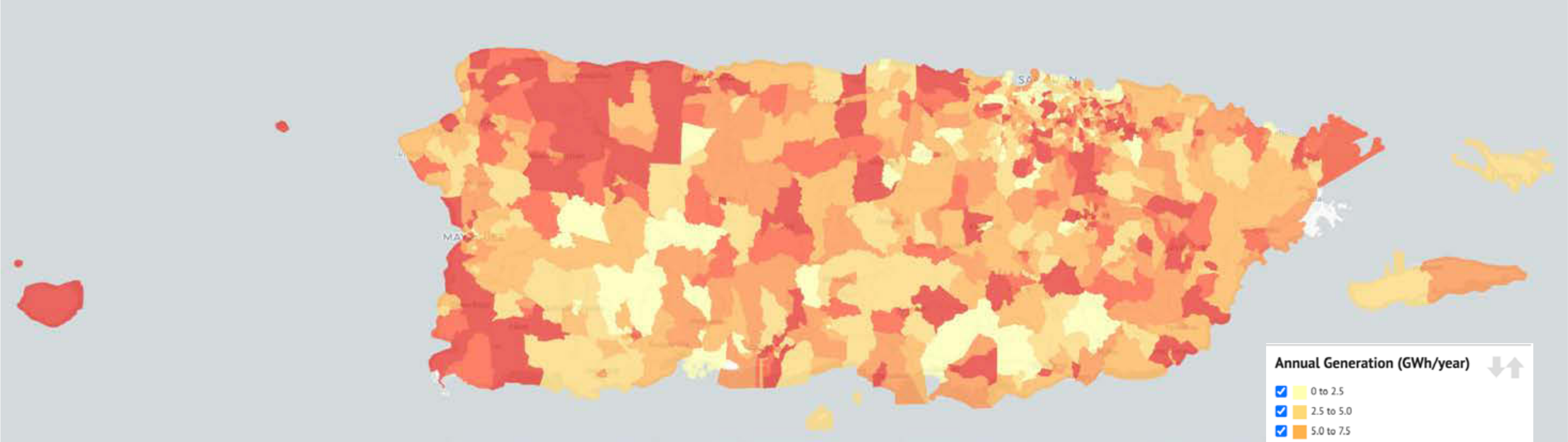
- Annual residential solar potential is 24.6 TWh
  - Roughly 4x of residential electricity consumption
- LMI opportunity is 11.87 TWh, nearly half (48%) of total annual residential solar potential
- Average household potential is 19,883 kWh
  – Potential is slightly greater for higher incomes but still considerable for even very low income group (17,924 kWh/household)

Residential PV rooftop technical potential by income group

Income Group	Households (thousands)	Suitable Buildings (thousands)	Suitable Module Area (millions of m2)	Capacity Potential (GW_{DC})	Annual Generation Potential (TWh/year)
Very Low (0-30% AMI)	267.8	203.6	21.9	4.0	4.8
Low (30-50% AMI)	151.2	129.1	13.5	2.5	3.0
Moderate (50-80% AMI)	203.3	177.4	18.6	3.4	4.1
Middle (80-120% AMI)	297.8	267.7	28.2	5.1	6.2
High (>120% AMI)	317.1	279.5	29.6	5.4	6.5
All LMI Buildings	622.3	510.1	54.0	9.8	11.9
All Residential Buildings	1,237.2	1,057.3	111.8	20.4	24.6

Total LMI Solar Potential By Tract

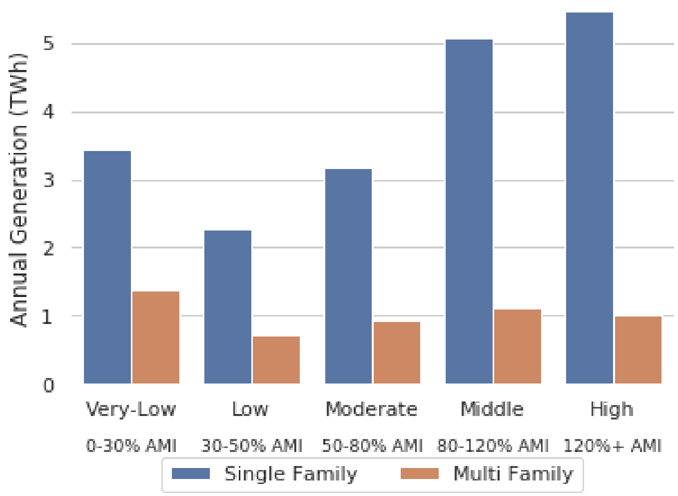
- Highest potential of LMI in densely populated areas with more building stock, though lots of potential throughout the territory in more rural communities.



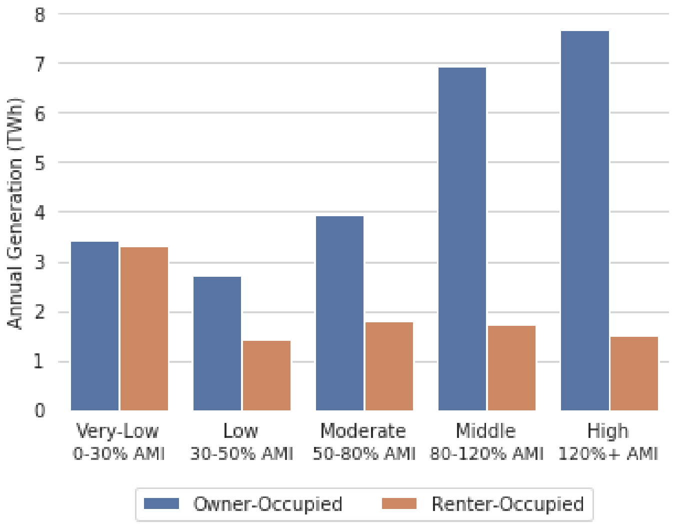
Census tract LMI technical potential (GWh)

Solar Potential By Income, Building Type and Tenure

Generation potential by income group & building type



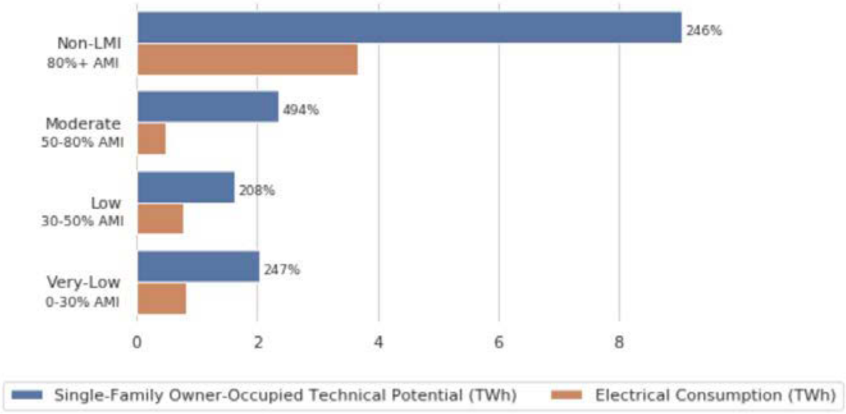
Generation potential by income group & building tenure



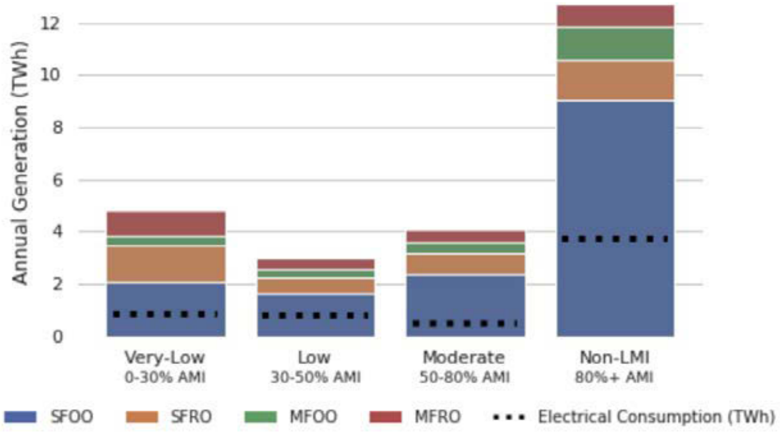
- In Puerto Rico, 50% of the LMI potential is on on renter-occupied and multi-family buildings, with the highest percentages among the lowest income group (58%).
- Though less than in the U.S. (60%), non-traditional types of buildings (i.e. multi-family and renter), are an important factor. Puerto Rico has 50% of potential in non-traditional types. Improving LMI solar access in Puerto Rico will likely require novel deployment models (e.g. shared solar).

We Can Offset All Residential Electricity Consumption With Residential Rooftop Solar in PR

Solar generation can technically meet *all* Puerto Rico electrical consumption for all income groups



Comparison of fraction of consumption met by generation potential for single-family owner-occupied buildings alone, by income group



Technical feasibility of matching residential electric consumption with rooftop solar, by income group

NOTE: The residential electric consumption reported here are from PREPA in 2018. Due to Hurricane Maria, it is estimated that 5% of PREPA residential customers were still without power in April, 2018.

Offsetable Consumption is High No Matter How You Slice It

Percent of LMI electrical consumption offsettable by rooftop solar generation

% of Offsetable Electric Consumption Offsetable by Rooftop PV – All LMI Buildings

% of Offsetable Electric Consumption Offsetable by Rooftop PV – LMI Single-Family Owner-Occupied Buildings

High Solar/ Low Load: The Case of Puerto Rico Rooftop Solar Potential

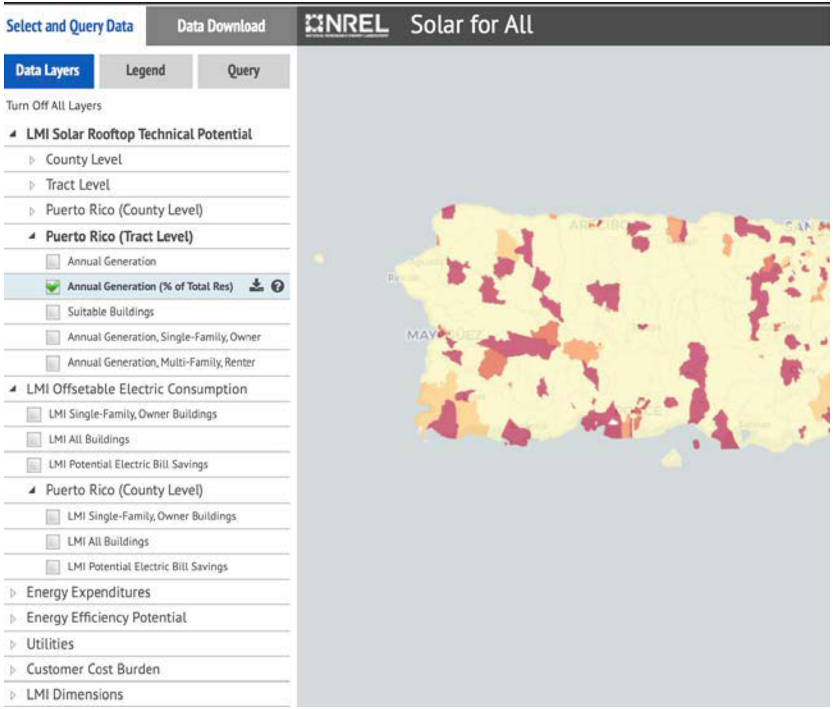
- **High Solar:**
  - The average annual GHI (5.89 kWh/m^2/day) in Puerto Rico is 22% greater than the average US GHI
  - In total, PR has more residential buildings to households. This contributes to higher technical potentials per household electric consumptions.
- **Low Load:**
  - PR has a significantly lower per capita electric consumption compared to U.S. (4,665 kWh vs 12,900 kWh per household annually)
  - Even if PR consumed electricity at the rate of the U.S., there would still be nearly 150% the amount of rooftop potential than electric consumption for the entire residential electric sector.
- **The Result:**
  - On an aggregate, for all residential buildings, Puerto Rico has 425% more rooftop generation potential than electric consumption. For LMI buildings only, Puerto Rico has 570% more rooftop generation potential than electric consumption.
  - Even if we assume that 50% of the LMI buildings in Puerto are structurally unsuitable for rooftop PV, there would still be >2.5x the amount of rooftop potential than current consumption.

All data used in the study is publicly available

Puerto Rico LMI PV Rooftop Technical Potential and Solar Savings Potential Dataset – Access tract and county level data on residential rooftop potential and solar savings potential, by income, building type, and tenure. https://data.nrel.gov/submissions/144

SolarForAll web application - Explore, download, and intersect data in interactive web application; Updated with PR data layers.

https://maps.nrel.gov/solar-for-all/



Screenshot of SolarForAll app

All data used in the study is publicly available

PV Rooftop Database – Puerto Rico (PVRDB-PR) – Access the raw GIS data of roof planes for all buildings in Puerto Rico. Available through the DOE Open Energy Data Initiative (OEDI) and hosted on Amazon Web Services

- **OEDI:** https://data.openei.org/submissions/2862
- **S3 Path:** s3://oedi-data-lake/pv-rooftop-pr/developable-planes/
- **Bucket Viewer:** https://data.openei.org/s3_viewer?bucket=oedi-data-lake&prefix=pv-rooftop-pr%2F
- **Documentation:** https://github.com/openEDI/documentation/blob/master/PVROOFTOPS_PR.md

Screenshot of the PVRDB-PR GIS data

Use the AWS CLI command to list the data:

```
aws s3 ls s3://oedi-data-lake/pv-rooftop-pr/developable-planes/ --no-sign-request
```

Use the AWS CLI to download the data:

```
aws s3 sync s3://oedi-data-lake/pv-rooftop-pr/developable-planes/ pv-rooftop-pr --no-sign-request
```

Contact: Meghan.Mooney@nrel.gov | Katy.Waechter@nrel.gov

Puerto Rico PV Rooftop LMI Technical Potential and Solar Savings Potential Data Set: https://data.nrel.gov/submissions/81

PVRDB-PR (GIS): **s3://oedi-data-lake/pv-rooftop-pr/developable-planes/**

Web App: https://maps.nrel.gov/solar-for-all

Thank you

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NREL/PR-6A20-78756

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. 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 U.S. Government purposes.

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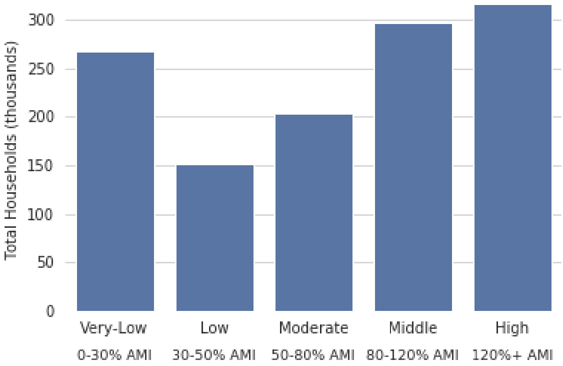
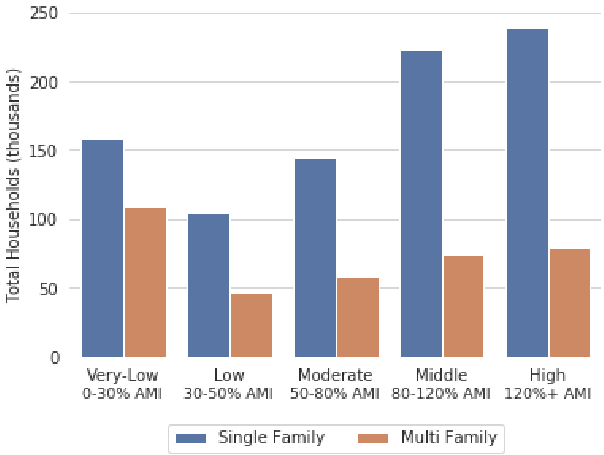
Supplemental Material

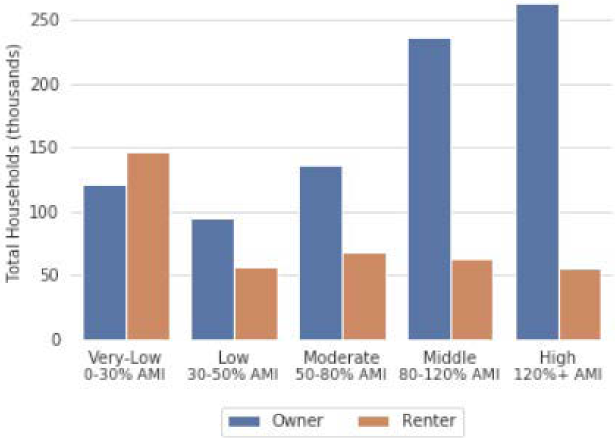
PR LMI Household Statistics



HH by Income

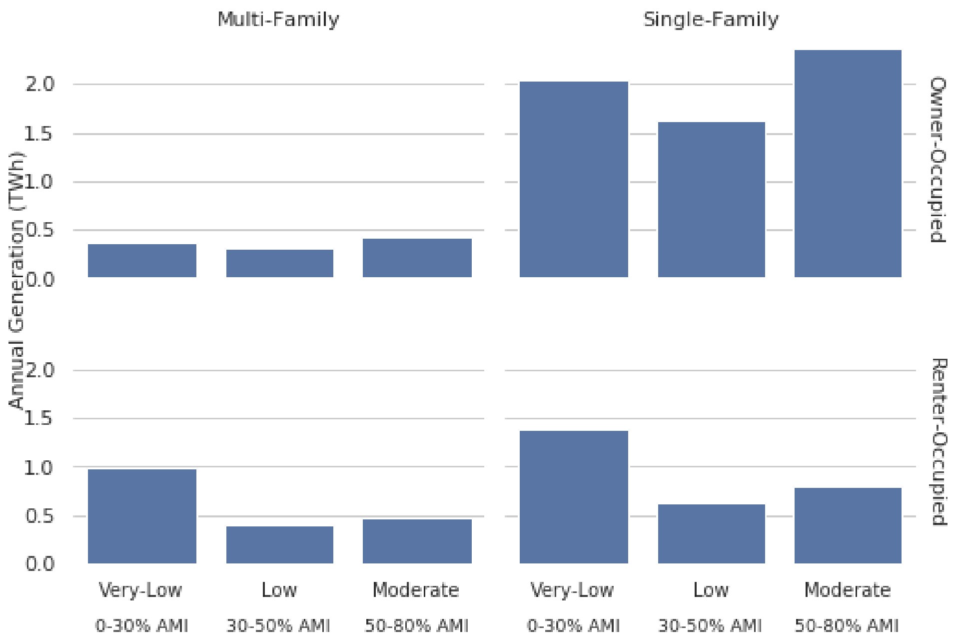


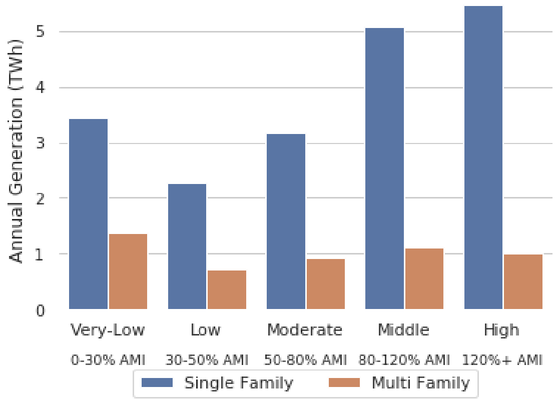
HH by Income
by **Building Type**

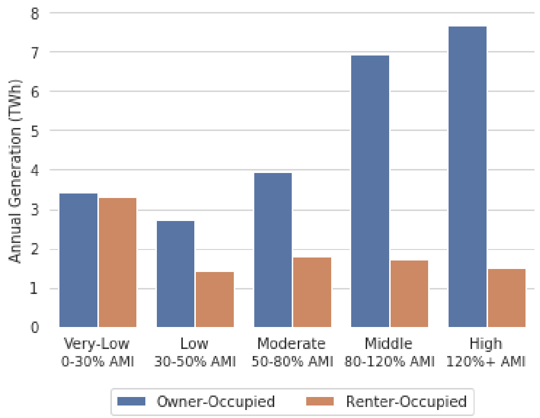


HH by Income
by Tenure

PR Residential Rooftop Technical Potential by Building Type and Tenure







PR PV Rooftop Technical Potential Results Compared to U.S.

	Puerto Rico					Mainland U.S.				
	All	Residential		LMI		All *	Residential **		LMI Buildings**	
Suitable Buildings (millions)	1.34	1.06	78.68% of all suitable buildings	0.51	48.25% of all residential	N/A	67	-	25.50	37.95% of all residential
Households (millions)	-	1.24		0.62	50.30% of all residential	-	117	-	49.80	42.60% of all residential
GW	27.5	20.35	73.97% of all suitable buildings	9.84	48.32% of all residential	1,118.00	794	71.02% of all buildings	329.40	41.49% of all residential
TWh	33.18	24.55	74.00%of all suitable buildings	11.87	48.36% of all residential	1,432.00	999.80	69.82% of all buildings	415.90	41.60% of all residential

* = Gagnon et al. 2016
** = Sigrin and Mooney, 2018

There are *1,343,874* suitable buildings in Puerto Rico of *1,500,106* total buildings in Puerto Rico.

Compared to the U.S. technical potential numbers, Puerto Rico is based off on higher precision LiDAR data (3-30cm) and updated solar technology assumptions of solar technologies, such as solar panel power densities, more accurate (and stricter) percent shading assumptions when estimating generation at the developable plane level, different assumptions related to minimum area requirements, different assumptions related to panel orientation as candidates for rooftop PV suitability.

Notes on PR Technical Potential Compared to the U.S. Estimates

- Puerto is lower in latitude than the rest of the US; therefore, shading from adjacent trees is less impactful on the suitability of a rooftop.
  - We assume an 80% of illumination criteria for the PR study, meaning that a plane must be illuminated for at least 80% of the year's daylight hours to be considered suitable for rooftop PV. In the Northern Hemisphere, there is a 2% increase in the solar elevation angle for every 1-degree decrease in latitude. In PR's lower latitude, its higher solar elevation angles creates shorter shadows and, therefore, less shading, especially during the winter seasons, relative to its higher elevation states.
- Puerto Rico technical potential estimates are based on *NREL'S PV ROOFTOP Model v2.0* updated assumptions, such as:
  - Power Density is assumed to be 182 W/m^2 (compared to the 160 W/m^2 assumption in the 2016 U.S. study).
  - North facing planes are not excluded for PR, however, they were excluded from the 2016 U.S. study. In PR, 13% of the technical potential is a N, NE, NW facing plane.
  - Minimum size requirement for a developable plane is set to 1.62 m^2, which is the average size required for 1 250-Watt solar panel. A building is considered suitable if it meets the other criteria and it has at least one plane large enough for a solar panel. In the 2016 U.S. Study, a suitable building needed a minimum 10m^2. If we applied the same >= 10m^2 assumption to Puerto Rico, generation would be reduced by ~4 TWh for the total building potential (all residential buildings).
  - The shading assumption in this PR assessment was updated to apply percent shading directly at the developable plane level into the System Advisor Model (SAM) when calculating generation potential. For the U.S. assessment, % shading was used to screen potential planes, but it was not used directly at the plane level when processed in SAM to get the generation; instead, the SAM default of 3% was applied. This new approach is more accurate than previous estimates, but it results in a lower kWh/kW estimate for Puerto Rico compared to the U.S..

Taken together, the PR and the Gagnon et al. (2016) and Sigrin and Mooney (2018) U.S. estimates are not an apples-to-apples comparison.

Puerto Rico Residential PV rooftop technical potential by Income Group, Building Type, and Tenure

Income Group	Tenure	Building Type	Buildings (millions)	Suitable Area (millions of m2)	Capacity (GW)	Annual Generation (TWh)
Very Low 0-30% AMI	Owner-Occupied	Single-Family	0.102	13.245	1.694	2.050
	Owner-Occupied	Multi-Family	0.009	2.338	0.316	0.380
	Renter-Occupied	Single-Family	0.070	8.987	1.154	1.396
	Renter-Occupied	Multi-Family	0.022	6.105	0.831	0.998
Low 30-50% AMI	Owner-Occupied	Multi-Family	0.007	1.876	0.254	0.304
	Owner-Occupied	Single-Family	0.080	10.516	1.349	1.631
	Renter-Occupied	Multi-Family	0.010	2.463	0.335	0.402
	Renter-Occupied	Single-Family	0.032	4.099	0.525	0.634
Moderate 50-80% AMI	Owner-Occupied	Multi-Family	0.010	2.661	0.360	0.432
	Owner-Occupied	Single-Family	0.116	15.195	1.953	2.363
	Renter-Occupied	Multi-Family	0.012	2.970	0.403	0.484
	Renter-Occupied	Single-Family	0.040	5.166	0.662	0.800
Middle 80-120% AMI	Owner-Occupied	Multi-Family	0.016	4.044	0.549	0.658
	Owner-Occupied	Single-Family	0.203	27.364	3.538	4.280
	Renter-Occupied	Multi-Family	0.011	2.743	0.375	0.448
	Renter-Occupied	Single-Family	0.038	5.116	0.664	0.804
High >120% AMI	Owner-Occupied	Single-Family	0.223	30.786	3.962	4.775
	Owner-Occupied	Multi-Family	0.014	4.062	0.546	0.652
	Renter-Occupied	Single-Family	0.034	4.509	0.579	0.698
	Renter-Occupied	Multi-Family	0.008	2.254	0.306	0.365

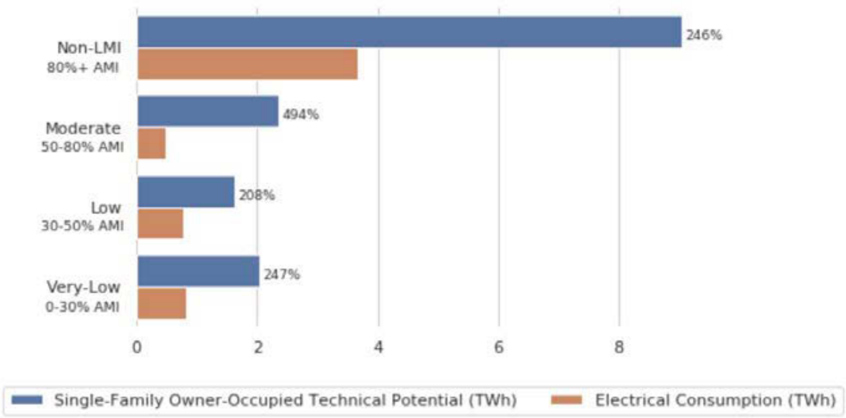
Validation of PV Rooftop Modeling

- Without ground truth data on existing rooftop systems in Puerto Rico, most of the model validation had to be centered around assumptions and modeling standards, comparing results to previous study's estimates.
  - Results on a per building basis for a random set of buildings were evaluated along side Google Sunshot's rooftop potential estimates. Though variations exist between our set of underlying assumptions, our results were consistently within a 5% of Google's estimates.
  - Potential estimates for PR were compared, to the degree possible, to previous U.S. estimates of potential (see slide 9).
  - LMI estimates were compared to previous studies (e.g., LEAD).
- Azimuth and Slope Validation:
  - A sample of developable planes stratified by azimuth and slope was randomly selected to validate roof plane classification. Each plane was compared to raw aspect and slope models as well as manual verification of roof orientation. Roof planes have an overall agreement of 92.06% with reference data. Among unique orientation classes, omissions of east-oriented planes are correlated with commissions of south-oriented planes while there is additional confusion between north-oriented planes and northwest-oriented planes, which may be the result of signal scattering.

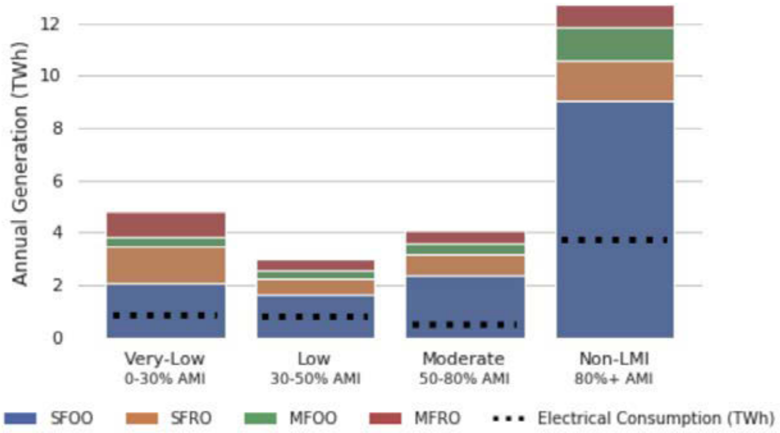
PR Electric Consumption

- 5.77 TWh of annual residential electricity consumption in PR (PREPA, 2018 consumption)
  - This estimate may not be complete of all consumption in PR. As of April 2018, it is estimated that as much as 5% of the PREPA customers still did not have electricity from blackout caused by Hurricane Maria (https://www.eia.gov/todayinenergy/detail.php?id=36832).

Solar Savings Results



Comparison of fraction of consumption met by generation potential for single-family owner-occupied buildings alone, by income group



Technical feasibility of matching residential electric consumption with rooftop solar, by income group

Electric Consumption by Income, Building Type, Tenure

Income Group	Building Type	Tenure	Annual Electric Consumption (TWh)
Very Low 0-30% AMI	multi family	own	0.073
		rent	0.282
	single family	own	0.363
		rent	0.113
Low 30-50% AMI	multi family	own	0.098
		rent	0.134
	single family	own	0.467
		rent	0.084
Moderate 50-80% AMI	multi family	own	0.064
		rent	0.056
	single family	own	0.313
		rent	0.045
Middle 80-120% AMI	multi family	own	0.064
		rent	0.041
	single family	own	0.295
		rent	0.035
High >120% AMI	multi family	own	0.626
		rent	0.173
	single family	own	2.307
		rent	0.138

Underlying Datasets

- **NASA G-LiHT:** 3cm LiDAR data collected in spring of 2017 (pre-hurricane)
- **USGS 3DEP: <**0.35 m nominal resolution LiDAR data collected in 2015 – used to fill in coverage where G-LiHT is incomplete.
- **HOTOSM** building footprints – used to identify building footprints across island and overlaid with LiDAR data.
- **PREPA** 2018 residential monthly electric consumption and billing, by municipality
- **Low-income Energy Affordability Database (LEAD):** Electric consumption by tenure, income, and building class by municipality, used to disaggregate PREPA by income, building type and tenure.
- **2011-2015 American Community Survey (ACS)** – Various ACS tables used to identify cross tabs of number of households by income group, building type, and tenure at the Census Tract level
  - B19001: Household Income in the Past 12 Months
  - B25118: Tenure by Household Income in the Past 12 Months
  - B25032: Tenure by Units in Structure
  - B25124: Tenure by Household Size by Units in Structure
- **2013 RECS:** Used for distributions of building size by type and income; used to generate probabilities of residential buildings from building footprint information.