RESILIENT ENERGY

COMMUNITY-SCALE SOLAR MICROGRID SITING ON THE ISLAND OF PUERTO RICO

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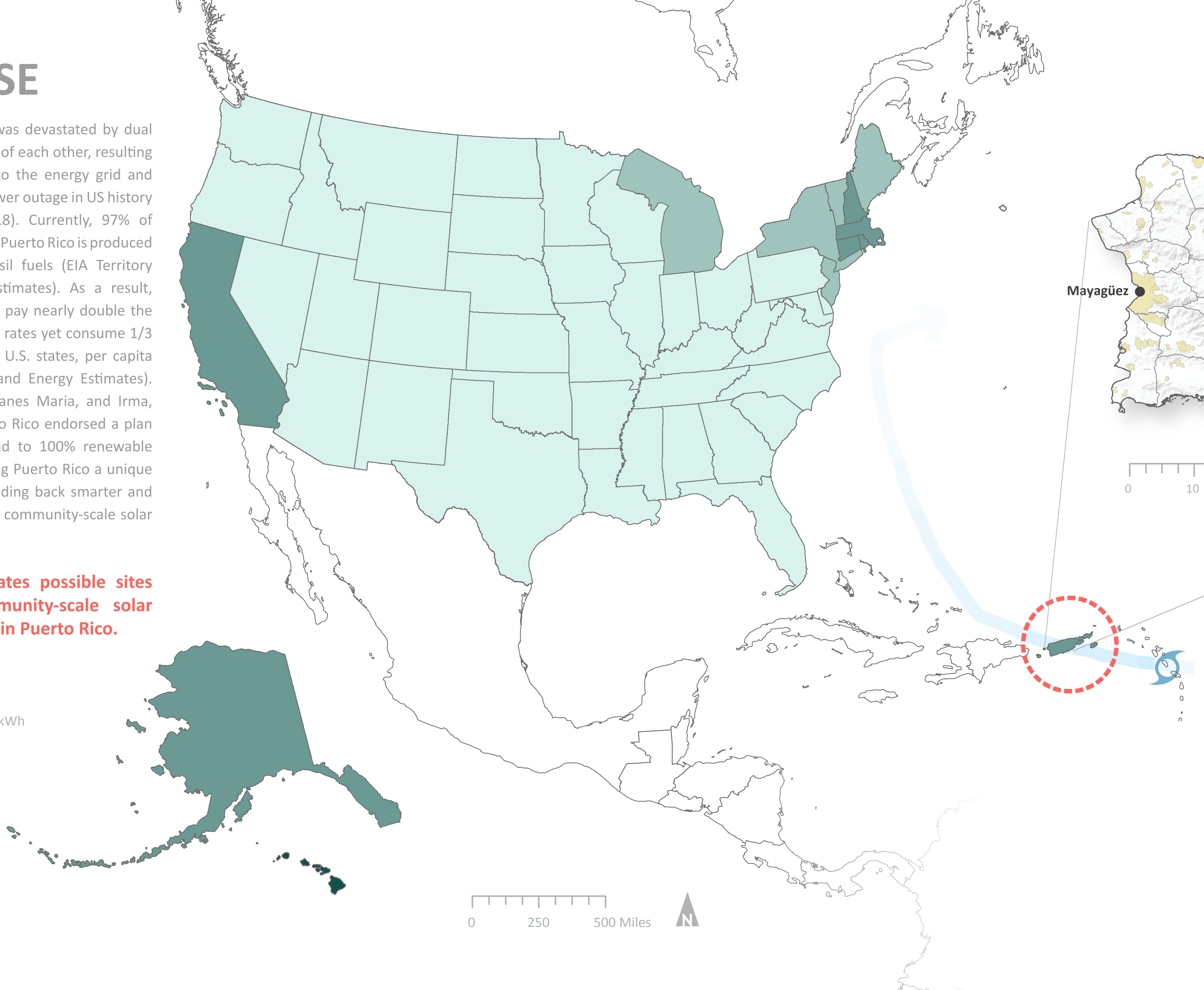
PURPOSE

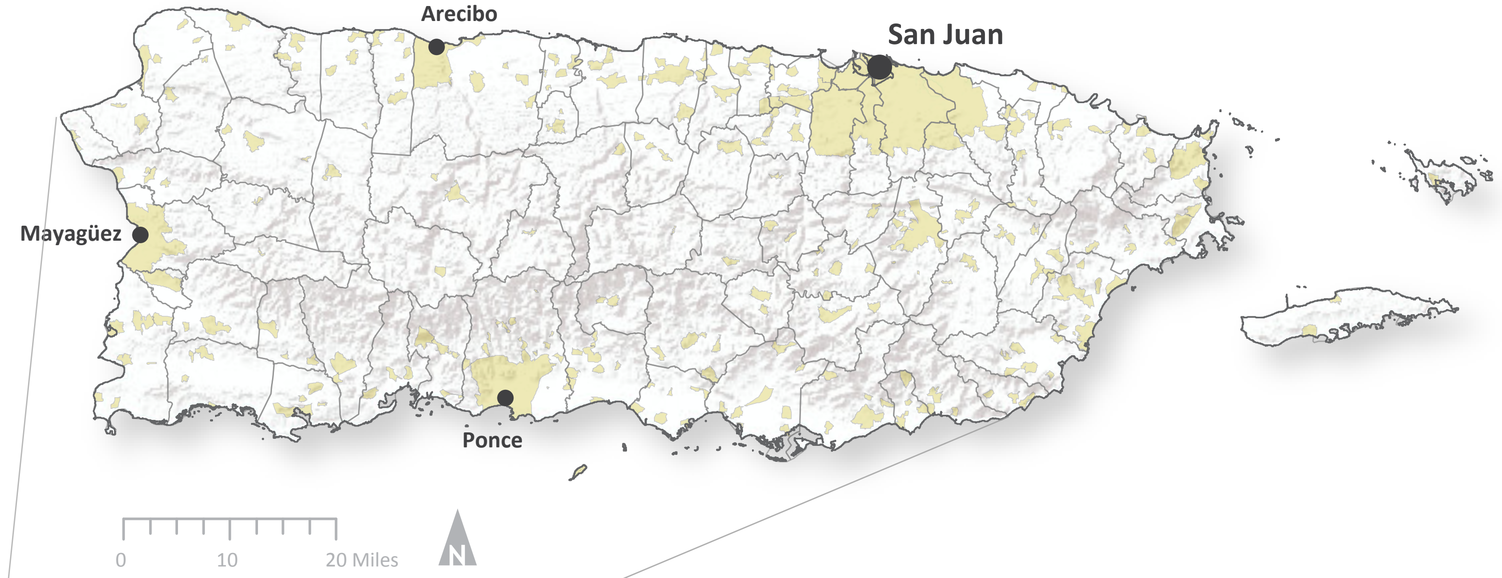
In 2017, Puerto Rico was devastated by dual hurricanes within days of each other, resulting in extensive damage to the energy grid and causing the longest power outage in US history (Rhodium Group, 2018). Currently, 97% of electricity generated in Puerto Rico is produced through imported fossil fuels (EIA Territory Profile and Energy Estimates). As a result, Puerto Rican residents pay nearly double the U.S. average electricity rates yet consume 1/3 the average energy of U.S. states, per capita (EIA Territory Profile and Energy Estimates). In the wake of hurricanes Maria, and Irma, the Governor of Puerto Rico endorsed a plan to transition the island to 100% renewable energy by 2050, making Puerto Rico a unique testing ground for building back smarter and more resilient through community-scale solar microgrids (EIA,2019).

This report evaluates possible sites for piloting community-scale solar microgrid projects in Puerto Rico.

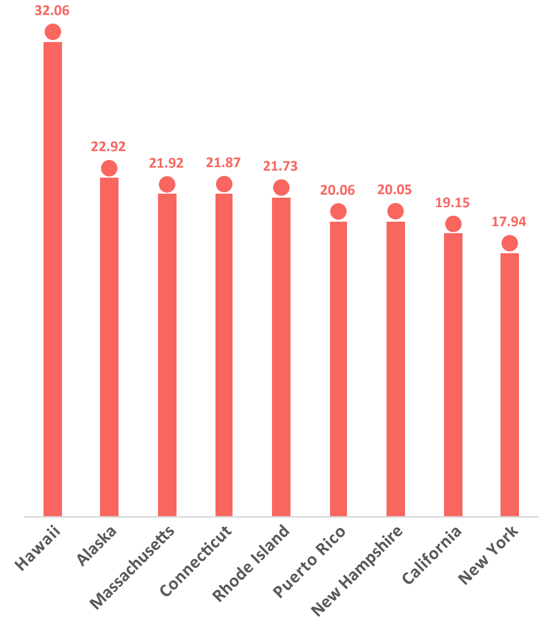


2019 Electricity Cost per kWh
- 27.59 - 32.06
- 23.13 - 27.58
- 18.65 - 23.12
- 14.19 - 18.65
- 9.71 - 14.18

2019 Residential Retail Price of Electricity by State in cents per kilowatt hour. data source: US Energy nformation Administration.

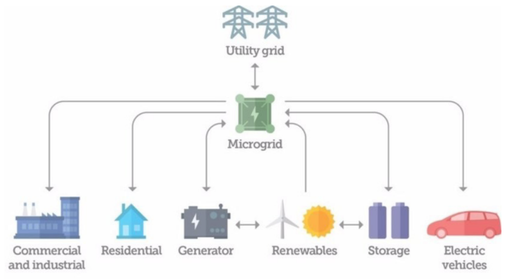


If Puerto Rico were a U.S. State it would have the **sixth most expensive** electricity rate



BACKGROUND

Solar microgrid technology enables communities to generate power in isolation from the broader energy grid during power outages (Center for Climate and Energy Solutions, 2017). In times of extreme weather and natural disaster, this technology can provide a critical resilience opportunity, particularly for rural and vulnerable communities with limited access to disaster response resources.

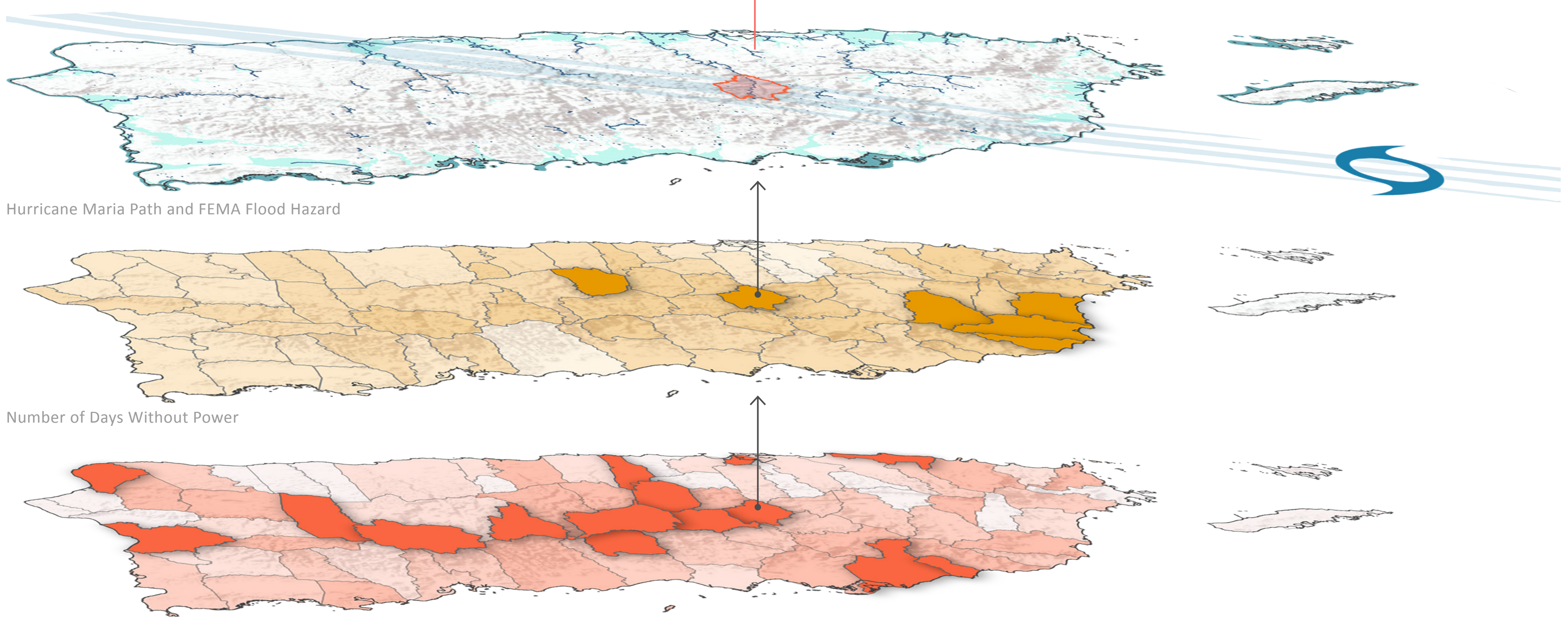


microgrid conceptual diagram. source: PEW

Microgrids may be owned and managed by a small group, a local government, or through public-private cooperative agreements. Replacing conventional energy generation with renewable energy sources represents an opportunity to lower per unit energy cost, decrease reliance on non-renewable energy resources, and reduce climate change inducing carbon dioxide (CO2) emissions. In other words, community-scale solar microgrid technology presents a cost-effective multi-benefit solution to mitigate climate change while building resiliency for the most vulnerable.

What sites would be optimal for piloting community-scale solar microgrids in Puerto Rico?

STUDY AREA SELECTION



Hurricane Maria Path and FEMA Flood Hazard

Number of Days Without Power

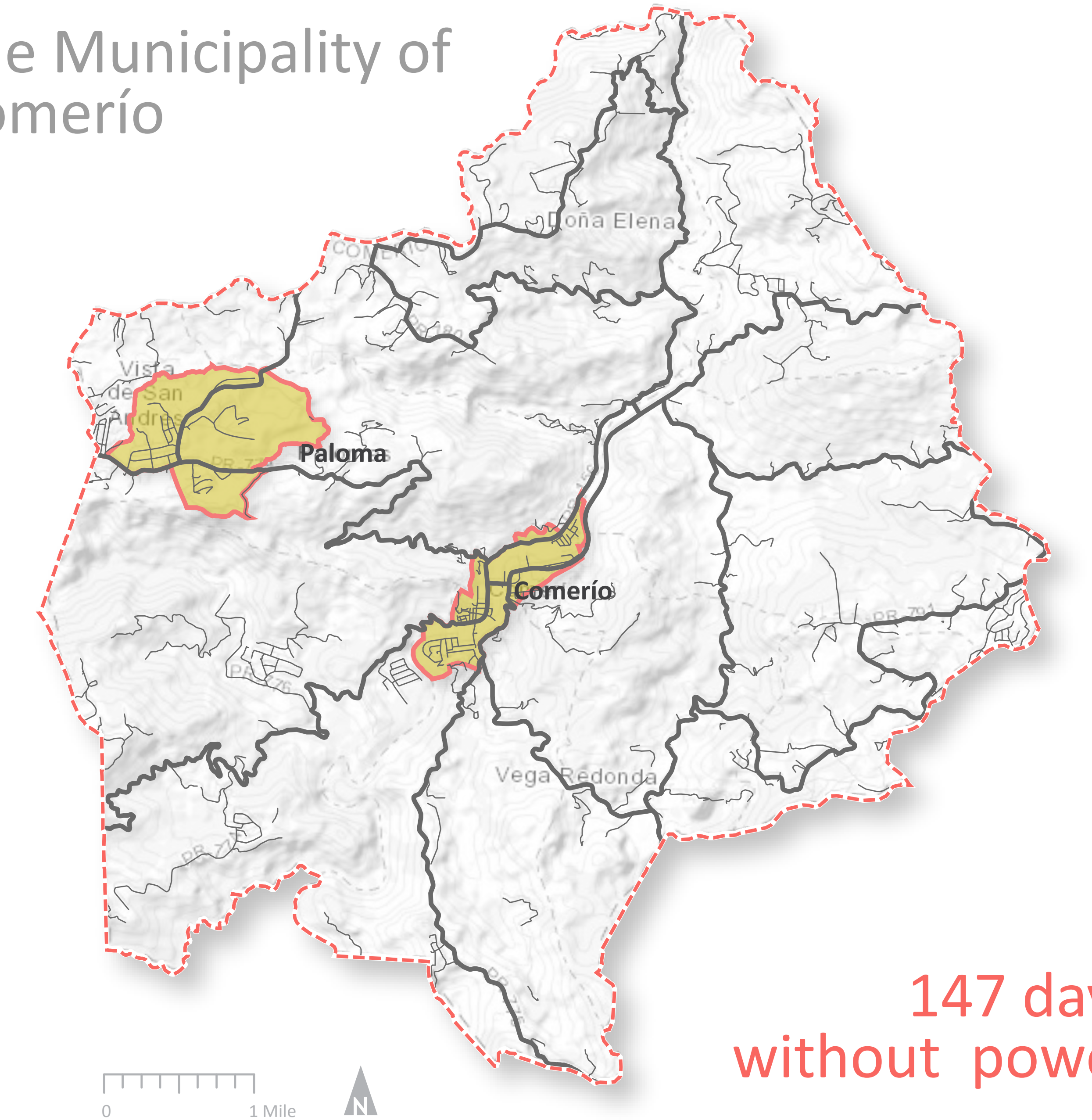
Social Vulnerability Index

Social and Environmental Vulnerability Analysis:

Social and environmental vulnerability across Puerto Rico are analyzed to determine a priority study area. The Center for Disease Control Social Vulnerability Index composit is mapped using Geographic Infomation Systems (GIS), depicting the municipalities with the highest vulnerability based on socioeconomic status, household composition, housing and transportation access, and race and ethnicity. NASA satellite imagery showing the number of days without power after Hurricane Maria is assigned to each municipality based on an average of the total number of days without power using "zonal statistics." The selected study area can be seen directly in María's path; a category 5 hurricane which stuck the municipality of Comerío on September 20th, 2017 at wind speeds of 115 miles per hour.

STUDY AREA

The Municipality of Comerío



147 days without power

Comerío is a municipality in central Puerto Rico with a high social vulnerability, as designated by the Center for Disease Control, and a community particularly impacted by Hurricane Maria, enduring approximately 147 days without power following the storm event. While a river does flow through the area, most buildings are not subject to major FEMA 100 year flood hazard or susceptible to coastal sea level rise.

Within the municipality of Comerío lie the towns of Comerío and Paloma, designated as "places" by the U.S. Census Bureau. Buildings within these census place boundaries are evaluated to identify four possible facilities to locate a pilot project. The following three criterion are assessed: 1) facility size, 2) facility ownership, and 3) the number of buildings within a 1.5 mile service area of the facility.

The four facilities are further analyzed for their maximum potential electricity generation, how many customers each might serve, and how many pounds of CO_2 emissions might be offset as a result of substituting fossil-fuel-generated electricity with a renewable energy source. Final recommendations indicate which facility meets the greatest number of selection criteria.

CRITERIA 1: ROOF AREA

Reclassification Method

The amount of potential energy generated is limited by the rooftop area available for housing a solar system. Theoretically, larger rooftops are capable of housing larger systems which will generate more electricity and be able to supply energy to more customers. Building polygons within the study are "reclassified" to "0," "1," "2," or "3" based on square footage.

Results: (25) building over 5,000sf exist within Comerío and Paloma. (22) of those are less than 10,000sf, (2) are between 10,000sf and 20,000sf, and (1) is over 20,000sf.

- 20,001sf + = 3
- 10,001 – 20,000sf = 2
- 5,001sf – 10,000sf = 1
- below 5,000 sf = 0

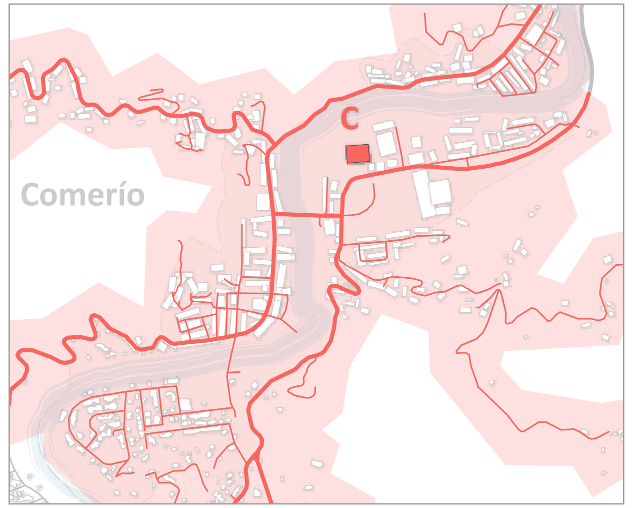
CRITERIA 2: OWNERSHIP

Reclassification Method

While a public facility may aquire grants, enter into cooperative agreements, or provide public utilities more easily, large private facilities may be incentivized to provide electricity to a larger customer service area. Public facilities "point data" is "spatially joined" to the (25) building polygons of at least 5,000sf and "reclassified" as "1" for public facilities and "0" for private.

Results: (9) public buildings are identified. The two largest buildings within the study area are privately owned (Facility "A" and "D"). Only one of the five largest buildings is a public facility (Facility "C"). In order to offer a balance of public and private facilities, a grouping of centrally located public facilities in the urbanized area of Comerío with a combined roof area of 21,669sf is carried forward in the analysis (Facilities "B1, B2 and B3").

CRITERIA 3: SERVICE NETWORK



Reclassification Method

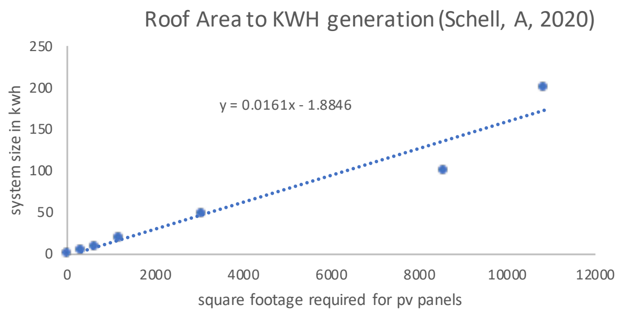
While a solar microgrids' isolation mode offers resiliency against power outages, an optimal system is tied to a grid to distribute power to local consumers or to sell surplus power. Not only should a microgrid be tied to distribution infrastructure for practical purposes, balancing the panels' spatial requirements with the maximum potential customers in the service area should yield optimal cost-benefit ratios.

A "network analysis" quantifies the number of buildings within a 1.5 mile service zone of each of the four facilities. Transportation infrastructure is used as a proxy for the energy distribution grid. A count of building polygons within an offset of roads is assigned to each zone through a "spatial join," yielding an "actual number of buildings" within the grid service zone.

FACILITY ID	ROOF AREA	MAXIMUM POTENTIAL ENERGY (KWH)	MAXIMUM POTENTIAL CUSTOMERS	MAXIMUM POTENTIAL # OF BUILDINGS	ACTUAL # BUILDINGS IN FACILITY SERVICE ZONE	CO2 EMISSION OFFSET POTENTIAL (LBS/Yr)	ROOF AREA RECLASSIFICATION	OWNERSHIP RECLASSIFICATION	SYSTEM OPTIMIZATION RECLASSIFICATION	CO2 OFFSET POTENTIAL RECLASSIFICATION	TOTAL
A	10,171	809	162	59	299	292,427	2	0	0	0	2
B1, B2, B3	21,669	1,735	347	126	604	626,914	1	1	0	2	4
C	14,727	1,176	235	86	526	424,955	2	1	0	1	4
D	43,222	3,470	694	252	503	1,253,866	3	0	0	3	6

Maximum Potential Energy

A solar microgrid's maximum electricity generation potential is limited by the physical space available for mounting photovoltaic (pv) panels. Data for sizing solar pv systems is plotted in Excel to reveal a relationship between the square footage requirement and system output in kilowatt-hours (kwh) (Schell, 2020). Each facility's "maximum potential energy" is calculated by multiplying the facility roof area by this ratio (see figure below and appendix).



Maximum Customer Potential

The potential number of customers a facility could service is a function of the daily per capita energy consumption rate, the building occupancy rate, and the facility's "maximum energy potential" based on roof area. According to the U.S. Energy Information Administration, Puerto Ricans consume on average 4.9 kwh per person per day (2019) and according to the U.S. Census Bureau the average household size of occupied housing units is 2.75 (2019). The "maximum potential energy" divided by 4.9 kwh, divided 2.75 people results in the "maximum potential number of buildings" (see appendix).

Optimization is calculated by subtracting the actual number of buildings in the 1.5 mile service zone from the "maximum potential number of buildings" to verify if the system is adequately sized to cover the demand of the entire service area or if there is a shortage or surplus.

Results: No single facility could fully meet community demand. A combination of multiple facilities would be required to meet the entire 1.5 mile service area demand. Alternatively, the service area could be reduced to optimize the system.

CO2 Emissions Offset Potential

According to the U.S. Energy Information Administration, 1 kilowatt-hour of fossil-fuel generated electricity produces 0.99 pounds of carbon dioxide (CO_2) emissions (2018). Facility "CO2 offset potential" is calculated by multiplying the "maximum potential energy" generation by 0.99, then by 365 days to reveal pounds per year (see appendix). Facilities are ranked by the quantity of carbon dioxide they could potentially displace.

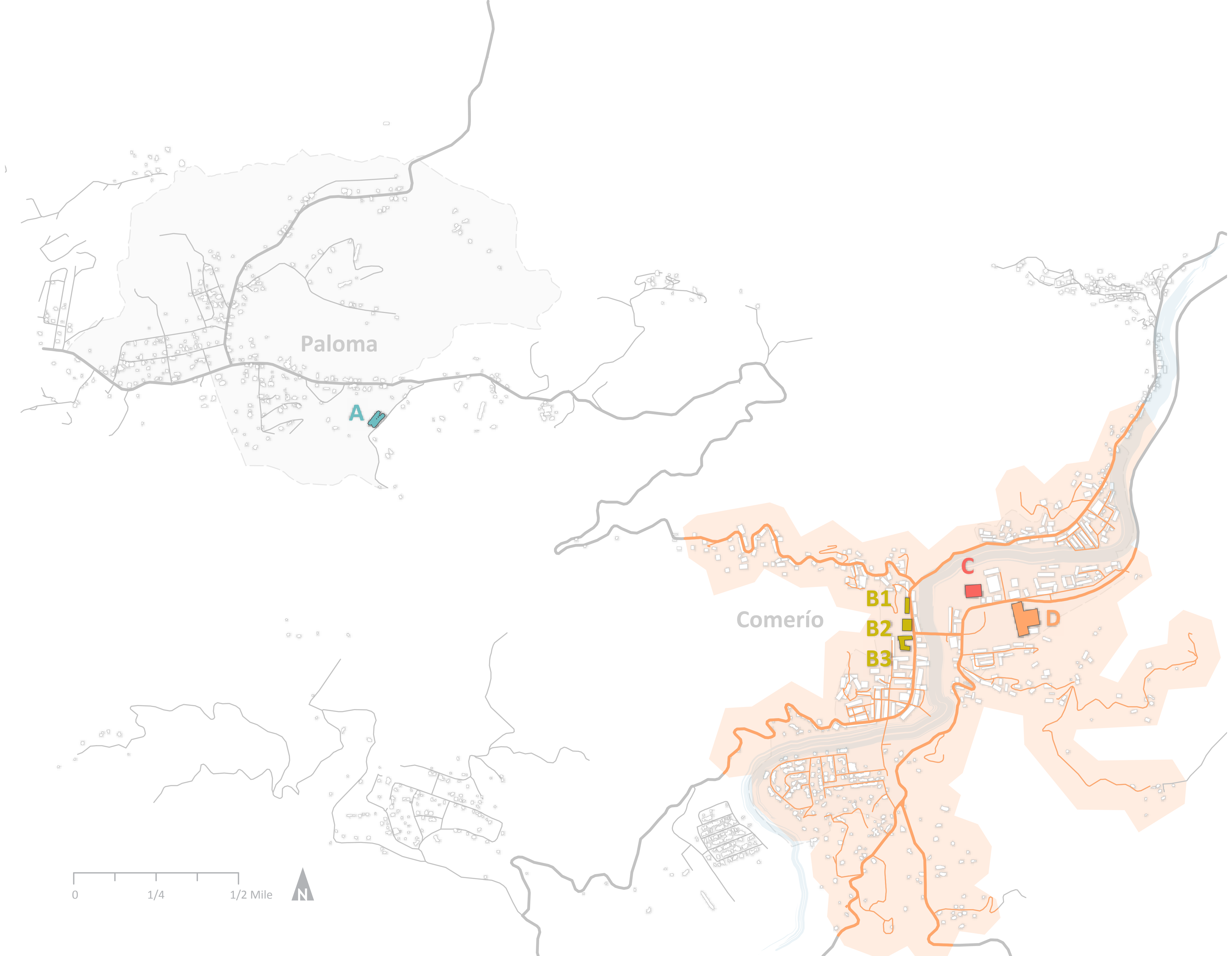
RECOMMENDATIONS

For final recommendation, a weight is assigned to facilities based on potential carbon emissions diplaced. Facilities "A," "B1, B2, and B3," "C," and "D" are ranked based on their potential carbon offset from "0" to "3." A final recommendation is generated from a sum of Criteria 1, 2, 3, and this final weighting.

Facility "D" meets the greatest number of criteria.

Larger facilities will have more roof surface area to house solar microgrid systems. Larger systems have the potential to generate more electricity, reach more customers, and offset more carbon. **In order to meet the demand for the entire 1.5 mile service area, a combination of Facilities "B" and "C" and "D" would be necessary.** Though public-private ownership models may be complex, the barriers are worth overcoming for improved community resilience.

Facility A (private)
809 potential kwh/day
162 potential customers
292,427 lbs CO_2/year



Facility B1, B2, B3 (public)
1,735 potential kwh/day
347 potential customers
626,914 lbs CO_2/year

Facility C (public)
1,176 potential kwh/day
235 potential customers
424,955 lbs CO_2/year

Facility D (private)
3,470 potential kwh/day
694 potential customers
1.25 million lbs CO_2/year

APPENDIX/METADATA

Additional Methods and Meta Data - Social and Environmental Vulnerability Analysis:

Meta Data: US Center for Disease Control Social Vulnerability Index obtained from https://www.atsdr.cdc.gov/placeandhealth/svi/data_documentation_download.htm, US FEMA flood hazard map, USGS rivers, transportation, state and municipal boundaries, US Census Bureau Census Place, population by census place, Puerto Rico Selected Housing Characteristic Table DP04 from 2018 ACS 5-year Estimates, NHC Best Track Hurricane Maria path and points, an approach developed by Roman, M, Stokes, E, Shrestha R, Wang Z, Schultz, L, Carlo EAS, et al. utilizes NASA captured "daily satellite nighttime lights data" to spatially analyze power outages after Hurricane Maria over time. The raster dataset Number of Days Without Electricity (NDWE) was obtained from https://disasters.nasa.gov/hurricane-maria-2017/suomi-npp-sees-power-outages-puerto-rico-hurricane-maria. Zonal statistics assigned an average of the number of days without power raster to the USGS municipality boundary.

Assumptions and limitations: Additional studies by Roman, M, Stokes, E, Shrestha R, Wang Z, Schultz, L, Carlo EAS, et al. maps "Remoteness Vulnerability" that could be a stronger determinant of vulnerability than number of days without power alone.

Additional Methods and Meta Data - Site Evaluation Criteria:

A building polygon shapefile was obtained from ArcGIS.com. Building polygons within the study are were converted from square meters to square feet.

Assumptions and limitations: The building polygon shapefile had no metadata explaining its creation and after the study was being conducted it was found to be relatively inaccurate compared to ArcGIS base map aerial imagery. The size and shape of building polygons were mostly accurate but there were many buildings visible on aerial imagery that did not have a corresponding building polygon in the shapefile. This skews the study and data because more buildings exist in the study area than are accounted for. Multispectral imagery could not be located for the site so remote sensing reclassification could not be applied. Due to constraints of time and more accurate data, the study was completed with the inaccurate polygons.

Additional Methods and Meta Data - Maximum Customer Potential Calculations:

- The spatial requirements of a photovoltaic (PV) systems according to Andy Schell, 2020 set a baseline correlation between system size in kilowatt-hours and area needed in square feet based on the number of 330 watt panels.
- According to Abhishek Jain, 2016, "a photovoltaic system should be estimated by dividing the maximum daily usage by 5" because a 1 peak kilowatt-hour (kWp) system generates 5 to 7 units per day.
- According to the U.S. Energy Information Administration, "Electric Power Monthly Table 8.1. Puerto Rico - Sales of Electricity to Ultimate Consumers," 2019 residential sales equaled 6,205 thousand megawatt hours.
- According to the U.S. Census Bureau 2019 ACS 1-year estimation, the 2019 population of Puerto Rico was 3,193,694.
- 6,205 thousand megawatt hours divided by 3,193,694 people equals 1.94 megawatt hours per person per year, or 4.9 kilowatt-hours per person per day.
- Using an average "per capita daily electricity demand" of 5 as a proxy for peak load, the estimated number of Puerto Rican customers served by a 1 kWp system is 5 people.
- Thus a 5 kw system would requiring approximately 320 square feet could support 25 customers in Puerto Rico.
- The relationship between system size, estimated space needed, and number of Puerto Rican customers served was plotted, revealing an power trend line with strong positive correlation (R = 0.9883).
- A trend extrapolation method was used to estimate how many square feet would be required to service the entire population of each census place, according to Puerto Rico Selected Housing Characteristics 2018 ACS 5-year Estimate Table DP04.
- This resulted in a target square foot area required to optimize the system/ provide electricity to exactly the number of residents within the census place.
- Comerío population: 4,661, area required to optimize system: 57,965 sf.
- Paloma population: 1,462, area required to optimize system: 18,182 sf.
- The "maximum number of potential customers" served was calculated by reverse engineering this trend extrapolation using the roof area of Facilities "A," "B1, B2, and B3," "C," and "D." The resulting maximum number of customers was divided by the average household size of 2.75, according to census Table DP04 above. The result was the "maximum number of buildings" each facility could serve, regardless of distance.
- GIS was utilized to quantify the actual number of buildings within a 1.5 mile service network or "grid service zone." This number was subtracted from the "maximum number of buildings" to reveal optimization. The number "2" was assigned to facilities with excess capacity, "1" was assigned for facilities that closely met capacity, and a "0" was assigned for undersized facilities.

calculated in excel

generated in GIS

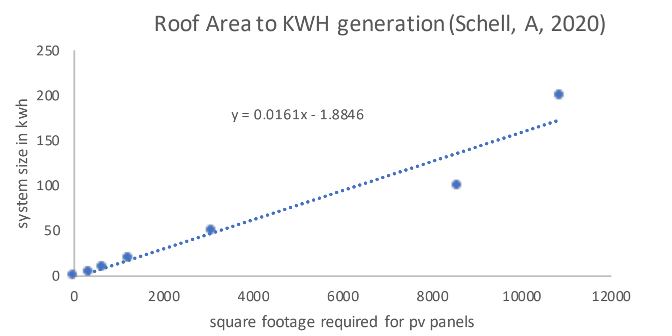
research from (Jain, sizing batteries and inverters for solar PV system)

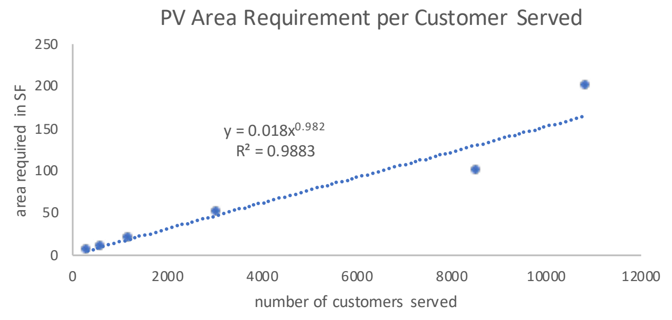
research from (Schell, how many solar panels)

data from Energy Information Agency

Puerto Rico Selected Housing Characteristics 2018 ACS 5-year Estimate Table DP04

system size (peak kilo watt)	amount of panels (based on 330w panels)	estimated space needed	(actual kwh generated) * based on 1kWp (peak kilo watt) system generates 5-7 units per day by Jain	projected area needed per customer in PR based on daily consumption rate of 4.9 kwh	* based on PR average consumption rate of 4.9 kwh per person per day
5	16	321	25	64.20	
10	32	624	50	62.40	
20	61	1189	100	59.45	
50	157	3061	250	61.22	
100	438	8541	500	85.41	
200	556	10842	1000	54.21	
				64.48	





BUILDING	ROOF AREA FROM GIS	MAX POT ENERGY per day (total kwh units)	MAX_CAPACITY People Served	MAX BLDGS Served	BLDG_GRID_ZN (actual #bldgs in 1.5 mile service network)	MAX BLDGS Served minus BLDGS 1.5 mile service network	CO2 potential	LBS/year
BLDG A	10,170	809	162	59	299	-240	801	292,427
BLDG B1,B2,B3	21,669	1,735	347	126	604	-478	1,718	626,914
BLDG C	14,726	1,176	235	86	526	-440	1,164	424,955
BLDG D	43,222	3,470	694	252	503	-251	3,435	1,253,866
		*based on roof area to kwh generation Schell, 2020)	* based on PR average consumption rate of 4.9 kwh per person per day	* based on occupied household size (owner and renter average) of 2.75. This does not account for vacant			1kwh = 0.99 LBS CO2	
		*multiplied by 5 units generated per 1kWp (peak) as per Jain						

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Data download: https://www.atsdr.cdc.gov/placeandhealth/svi/data_documentation_download.html

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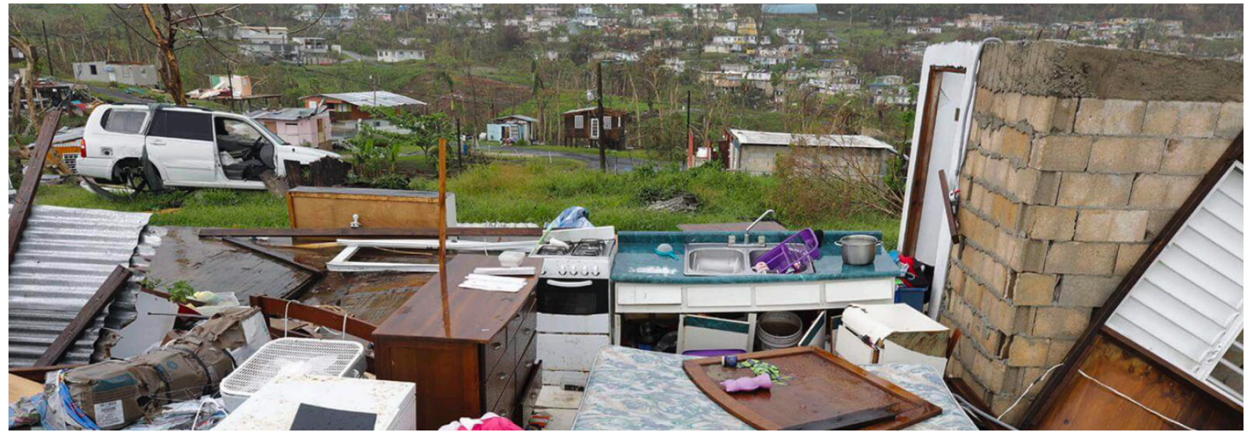
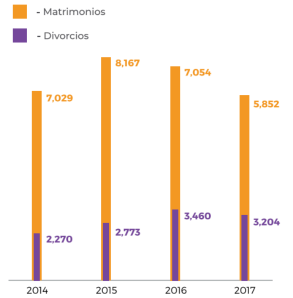


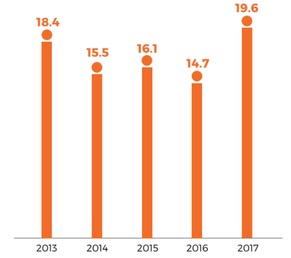
MATRIMONIOS Y DIVORCIOS



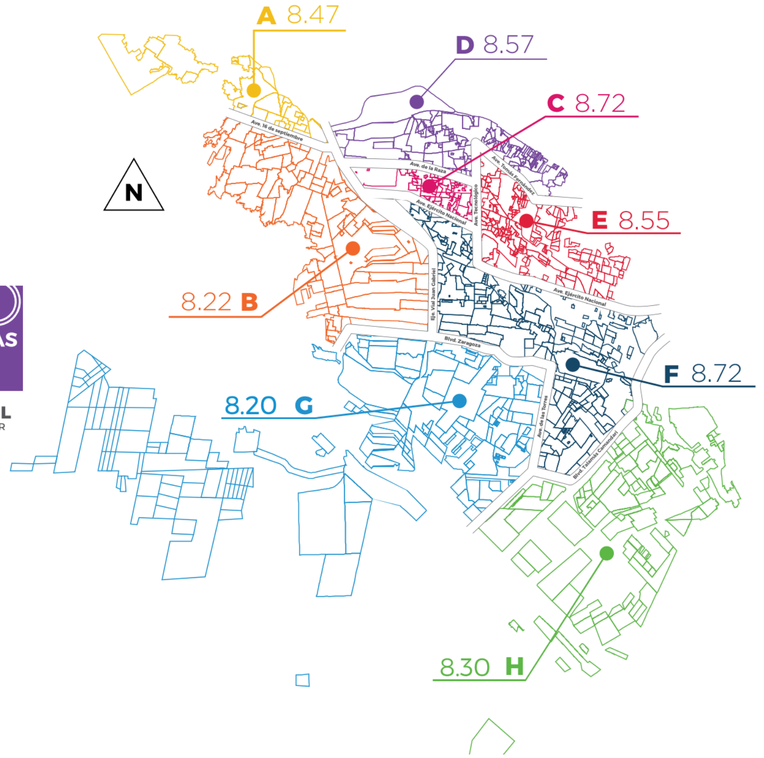
Fuente: INEGI.

EN 2017 POR CADA 100 MATRIMONIOS **54.8 PAREJAS SE DIVORCIARON**

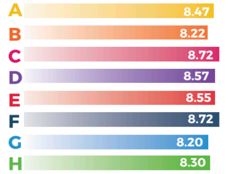
TASA DE MORTALIDAD INFANTIL
(DEFUNCIONES DE MENORES DE UN AÑO DE EDAD POR CADA MIL NACIDOS VIVOS)



Fuente: Elaboración propia con datos de Natalidad y Defunciones Generales del INEGI.



EN GENERAL ¿QUÉ TAN FELIZ ES USTED?



CALIFICACIÓN PROMEDIO **8.47**

CALIFICACIÓN **MÁS ALTA** **8.72**

CALIFICACIÓN **MÁS BAJA** **8.20**

La felicidad se enmarca en el bienestar subjetivo (un enfoque que coadyuva en el entendimiento y medición de aquello relevante para las personas, según Mariano Rojas). Su medición sistemática es necesaria para conocer el progreso de las sociedades, así como para diseñar programas sociales y tomar decisiones de política pública que impacten de manera positiva el bienestar experimentado por la ciudadanía (Rojas).

El indicador de felicidad, junto con el referente al orgullo que siente la ciudadanía de ser o vivir en Juárez y a si ha pensado irse de la ciudad representan de manera directa lo que la población juarense siente de manera general. Posteriormente se tratan otros datos de percepción que, en contraste con información oficial, resultan necesarios para medir los efectos de las políticas y reajustar para el bienestar social.

En 2018, la percepción de felicidad descendió de 8.62 del año anterior a 8.47.