Microgrid Design Toolkit Optimization of Wind-PV Hybrid Microgrids for Energy Resilience in Puerto Rico

Rolando J. Tremont-Brito[1], Jeewon Choi[2], Jimmy E. Quiroz[2],
Rachid Darbali-Zamora[2], Erick E. Aponte-Bezares[1], and Matthew S. Lave[2]

[1]University of Puerto Rico-Mayagüez, Mayagüez, Puerto Rico 00681, USA
[2]Sandia National Laboratories, Albuquerque, New Mexico, 87185, USA

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***Abstract* – Puerto Rico's aging power infrastructure has been struggling for decades. However, in recent years it has seen its worst due to the impact of extreme weather events such as Hurricanes Irma, Maria, and Fiona. Puerto Rico has ambitious goals of becoming 100% supplied by renewable energy resources by 2050. Microgrids are becoming attractive alternatives to renewable energy integration and for energy resilience by bringing distributed energy resources (DERs) close to the loads. This work explores the viability of hybrid microgrid design alternatives for 8 candidate locations throughout Puerto Rico. Wind turbine generators and solar photovoltaic panels (PV) are considered the main sources of energy. However, lithium-ion batteries are included in the analysis for better utilization of the renewable energy generated and diesel generators (DGs) for backup power. The Microgrid Design Toolkit (MDT) is used to perform multi-objective and event-based optimization. Results highlight the potential cost benefits of hybrid wind-PV microgrids for various regions throughout Puerto Rico.**

Keywords – hybrid microgrid, optimization, wind turbine generators, solar photovoltaics, energy resilience.

I. Introduction

Puerto Rico is an archipelago located in the Caribbean with a land area of 3,423.3mi^2. 16% of its terrain is urbanized [1], where 71% of its 3.285 million population lives. In 2017, Puerto Rico was partially impacted by Hurricane Irma on the 6th of September as a category 5 hurricane. Two weeks later, on the 20th of September, the main island was directly impacted by Hurricane Maria, a category 4 hurricane at the time with sustained winds of 155mph. The archipelago's power grid infrastructure was completely devastated by the impact. Although 90% of the population got power back within 150 days, it took another 150 days to bring power back the last 10% [2]. That last 10% is mostly composed of remote rural communities deep in the central mountain range of Puerto Rico's main island. This outage resulted in the longest blackout in U.S. history.

Due to events like Hurricanes Irma, Maria and Fiona, and seismic events such as the event of January 7, 2020, when Puerto Rico was struck by an earthquake with a 6.5 magnitude, the strongest of a sequence of earthquakes that started on December 28, 2019, communities in Puerto Rico are finding themselves in a situation where they must look for alternatives to fulfill their energy needs other than relying on the aging and affected power infrastructure they currently have. On April 11, 2019, Puerto Rico committed to meeting its energy needs with 100% renewable energy by 2050 via the Act. No. 17 "Puerto Rico Energy Public Policy Act", also known as PR100. Microgrids have emerged as an attractive solution to both PR100's renewable energy integration goals, communities' goals of locally sourcing their energy needs, and to enhance overall grid resilience and reliability.

This work expands on [3] by adding a backup diesel generator (DG) to the microgrid design alternatives. Hybrid wind and solar photovoltaic (PV) with backup DG and energy storage in the form of commercially available lithium-ion battery packs (Tesla Megapack 4hrs: 979kW/3,916kWh) are evaluated for eight potential microgrid locations throughout Puerto Rico. The optimization for the microgrid design alternatives is performed using the Microgrid Design Toolkit (MDT). MDT is a sophisticated microgrid design optimization tool developed by the Sandia National Laboratory (SNL) [4] and has previously been used to evaluate renewable microgrids in Puerto Rico [5], [6], [7]. MDT leverages multi-objective and event-based optimization to evaluate a trade space of optimal microgrid design configuration for a given system. This work also follows Sandia's Microgrid Conceptual Design Methodology (MCDM) [8] guidelines.

II. Locations Description

A. Microgrid Locations

This study evaluates hybrid and other microgrid design alternatives for eight locations throughout Puerto Rico. The potential microgrid boundaries evaluated in this work are in the municipalities of Aguadilla, Arecibo, Fajardo, Las Mareas (Guayama), Mayagüez, San Juan, Yabucoa and Vieques, illustrated in Fig. 1.

Fig. 1: Eight potential microgrid locations throughout Puerto Rico.

B. Natural Energy Resources

Puerto Rico, located in the Caribbean Sea at 18° north latitude, benefits from abundant sunlight, with global horizontal irradiance ranging between 4.45 and 6.02 kWh/m^2/day across the island, based on studies by the National Renewable Energy

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Laboratory (NREL) [9]. The island also has significant wind energy potential, particularly along the eastern and northern coastal regions. These areas, known for their consistently high wind speeds, are well-suited for the deployment of wind turbines (WTGs).

i. Wind Speed

Wind speed data for the potential microgrid locations is obtained from the National Oceanic and Atmospheric Administration (NOAA), the Caribbean Coastal Ocean Observation System (CariCOOS), and the National Data Bouy Center (NDBC) [10], [11]. Table I summarizes the meteorological stations of interest, with coordinates and the measurement height.

TABLE I:
LOCATION OF METEOROLOGICAL STATIONS OF INTEREST

Location	Station	Height (m)	Longitude	Latitude
Aguadilla	XAGU	4.3	18.4330	-67.1566
Arecibo	AROP4	6.4	18.4806	-66.7022
Fajardo	XREY	13.4	18.2894	-65.6320
Las Mareas	XMRS	8.8	17.9286	-66.1597
Mayagüez	MGZP4	8.4	18.2175	-67.15889
San Juan	SJNP4	15	18.4589	-66.1164
Vieques	ESPP4	8.5	18.0939	-65.4714
Yabucoa	YABP4	6.4	18.0550	-65.8331

As noted in Table I, wind speeds are recorded at varying heights across stations. To standardize these measurements to a consistent height of 18m, the wind profile law equation is used [12]. This equation adjusts the recorded wind speed (v1) at the original height (h1) to the targeted height (h2) of 18m, resulting in a new speed (v2) that is generally higher due to aerodynamic drag. The shear wind coefficient, α, typically assumed as one-seventh (1/7), varies with local wind conditions.

$$\frac{v_1}{v_2} = \left(\frac{h_1}{h_2}\right)^{\alpha} \quad (1)$$

Using the standardized 18m wind speeds, the energy production for a 60kW residential wind turbine (WTG) can then be calculated. This process involves feeding the adjusted wind data into a WTG model, using its power curve to determine hourly energy output. The output is then normalized to per-unit or percentage of turbine's nameplate capacity, aligning with the MDT's method of representing energy resources for wind, solar, and hydro as a percentage of nameplate capacity during each period. MDT then multiplies these percentages by the WTG capacity to compute period-specific energy production.

ii. Solar Irradiance

The solar energy data for this study was sourced from PVWatts, an online tool developed by NREL, used to estimate the hourly energy production of a 1 kW PV system over a year for different microgrid locations. This output, expressed as kW in AC, is normalized by the system's capacity to create a dataset for MDT analysis, shown as a percentage of nameplate capacity. Table II presents the average daily renewable energy production across all potential microgrid sites, using the units kWh-kWp/day, which factors in system losses, resulting in slightly lower values than the common kWh/m2/day. The energy generation from these locations typically ranges between 4 – 4.55 effective sun hours. For wind energy, the new unit of measurement allows direct comparison to solar, quantified in effective wind hours, with Fajardo, Las Mareas, San Juan, and Vieques showing high wind potential, while Aguadilla, Arecibo, and Mayagüez record the lowest.

TABLE II:
SUMMARY OF ESTIMATED AVERAGE DAILY RENEWABLE ENERGY PRODUCTION ON SITES

Location	Solar Resource (kWh-kWp/day)	Wind Resource (kWh-kWp/day)
Aguadilla	4.3471	2.7689
Arecibo	4.4958	3.0299
Fajardo	4.3955	**8.0785**
Las Mareas	4.5399	**11.0961**
Mayagüez	4.0252	1.1377
San Juan	4.4422	**9.1672**
Vieques	4.5197	4.0245
Yabucoa	4.4083	**9.3646**

C. Loads Estimation

For each potential microgrid site, a geographical boundary is established by initially identifying critical loads within a targeted power distribution feeder. This study focuses on feeders that experienced extended outages during Hurricane Maria, identifying critical loads based on the Cybersecurity and Infrastructure Security Agency (CISA) essential critical infrastructure sectors [13]. Once the initial critical boundary is set, it can be extended to encompass additional facilities like commercial buildings or residential areas, depending on their proximity to the original boundary, boundary size constraints, or other technical considerations. Where feasible, a microgrid might cover an entire power distribution feeder. In some cases, it may be necessary to merge feeders or design new ones. An example of a potential microgrid boundary for San Juan is depicted in Fig. 2.

Fig. 2: Boundary for potential microgrid in San Juan.

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Once the potential boundary for each location is established, open-source Geographical Information System (GIS) tools along with publicly available data layers [14] are employed to map out the roofs of buildings within the microgrid boundary. A dataset is then created where the roof area of each building is multiplied by the number of floors to estimate the total building area. For non-residential buildings, this area is further multiplied by a specific factor to derive annual energy consumption estimates based on the U.S Energy Information Administration's commercial building energy consumption survey (CBECS) [15].

For residential structures such as apartment buildings or public housing developments, energy consumption is estimated using the factor for midrise apartments provided by NREL's REopt [16]. Finally, the annual energy consumption data for each building type is broken down into a detailed profile spanning one year with hourly intervals, utilizing load profiles from NREL's REopt tool, applied according to the .

Fig. 3 illustrates the yearly power consumption profiles for the potential microgrids in (a) Las Mareas, (b) San Juan, and (c) Vieques. Additionally, Table III summarizes the estimated hourly load averages, maximum power consumption, and average daily energy usage across all potential microgrid locations evaluated in this study. Notice San Juan with the highest estimated daily energy consumption of 45.552 MWh and estimated power consumption peak of 2.595 MW while Vieques is the lowest at 6.384 MWh of energy consumed daily and a peak power consumption of 333 kW.

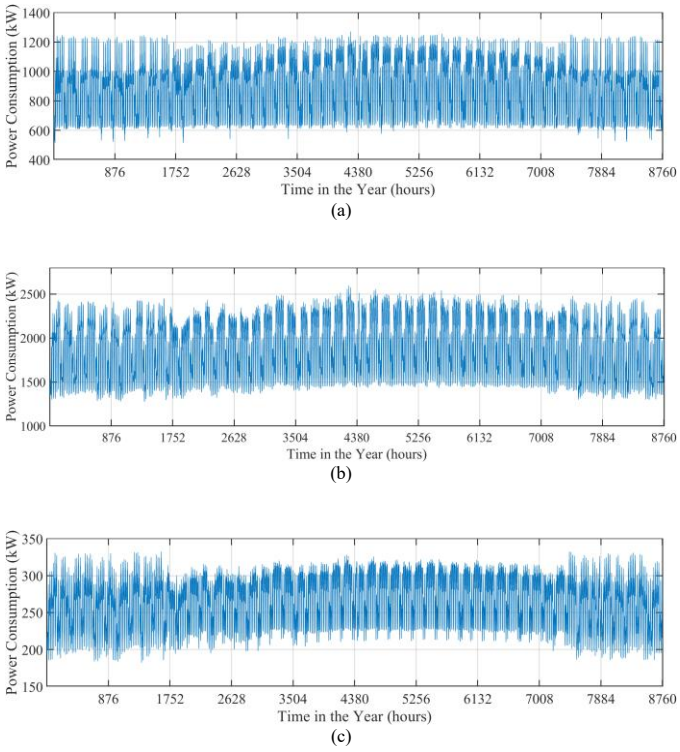

Fig. 3: Estimated yearly power consumption profile for (a) Las Mareas, (b) San Juan, and (c) Vieques potential microgrid boundaries.

TABLE III:
SUMMARY OF ESTIMATED AVERAGE, PEAK AND DAILY ENERGY CONSUMPTION ON SITES

Location	Estimated Average Load (MW)	Estimated Peak Load (MW)	Average Daily Energy Consumption (MWh)
Aguadilla	0.659	0.956	15.816
Arecibo	0.956	1.502	22.944
Fajardo	1.222	1.891	29.328
Las Mareas	0.881	1.273	21.14
Mayagüez	1.110	1.688	26.640
San Juan	1.898	2.595	45.552
Vieques	0.266	0.333	6.384
Yabucoa	0.464	0.714	11.136

III. MDT PARAMETERS

A. Design Basis Threats

MDT uses design basis threats (DBTs) to simulate events that cause grid outages that in turn requires the microgrid to operate in island mode. DBTs can be defined from natural occurring events, such as extreme weather events, to man-made or intentional, such as a cyber-attack. In MDT, DBTs are defined with a time between event occurrence and grid outage duration time. The microgrid operates during the outage time and that's when MDT optimizes the generation and energy storage technologies. The DBTs are defined following methods presented in [17] [18].

i. *Extreme Weather Events*

Due to its location in the Caribbean, Puerto Rico is highly susceptible to tropical cyclones, whether tropical storms or hurricanes. For this study, two events are modeled. A minor hurricane event that occurs every two years around the 5,300th hour of the calendar year, around mid-August. This is possible using MDT's *Time of Year Biased* distribution definition, which allows an event to occur in a specific time of the year. A major hurricane event is also modeled to occur every five years early in September. The grid outage durations for the minor and mayor hurricane events are set to 720 and 1,440 hours respectively.

ii. *Regular Outages*

Due to the aging and fragile power infrastructure, residents of Puerto Rico suffer constant outages. Whether it is due to heavy rains, load shedding due to low generation, faults caused by heavy vegetation, or any other potential risks, residents may experience power loss independently of where they live. To account for this, a *Regular Outages* event is modeled to occur once a month with a grid outage duration of 8 hours per event.

iii. *1-Year Fixed Grid Fault*

Minor hurricanes, major hurricanes and regular outages events are modeled together for case scenarios 1 – 5, further discussed in subsection D. However, this optimization only focuses on certain periods of time in the year, disregarding the rest of the time and not fully utilizing the wind and solar resources during the optimization. To account for this, a 1-year fixed grid fault is included and used alone with no other DBT

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in a 6th case scenario. This provides a unique perspective to the optimization by including the whole year in the optimization period and hence optimizing the generation and energy storage technologies with the full wind and solar resources in each location. Table IV describes the DBTs used in this work.

TABLE IV:
DESIGN BASIS THREATS SUMMARY

Event	Time Between Occurrence (hours)	Duration (hours)
Minor Hurricanes	TOYB(#Years: F[2]; ToY: F[5,300])	720
Major Hurricane	TOYB(#Years: F[5]; ToY: F[5,800])	1,440
Regular Outages	720	8
1-Year Fixed Grid Fault	0.001	8760

B. Optimization Metrics

An important aspect of the MDT analysis is the optimization metrics definition which guides the optimization of the potential microgrid solutions for the locations and defines the feasibility region of the solutions. The feasibility of a microgrid configuration is based on a cost versus performance analysis. For cost, the metric *Purchase Cost* is used. This metric tallies the costs of the technologies selected on a given solution configuration. This metric is set to minimize. Four metrics are used to evaluate the performance of the microgrid configurations: *Energy Availability*, *Average Energy Supplied by Renewables*, *Diesel Fuel Cost*, and *Diesel Fuel Used*. Table V summarizes the optimization metrics used for all microgrid locations in this study, along with the action performed for each.

TABLE V:
OPTIMIZATION METRICS SUMMARY

#	Name	Action
1	*Purchase Cost ($ in Millions)*	*Minimize*
2	*Energy Availability(%)*	*Maximize*
3	*Average Energy Supplied by Renewables (%)*	*Maximize*
4	*Diesel Fuel Cost ($/hr. of outage)*	*Maximize*
5	*Diesel Fuel Used (gal/hr. of outage)*	*Minimize*

C. DER Technologies

Depending on the microgrid design alternative, different combinations of energy generation and storage technologies are used. This study considers WTGs, PV, DG and BESS. The WTGs are modeled as 600kW turbines with a cost that follows NREL's 2023 Annual Technology Baseline for the CAPEX in 2024 of a midsize, distributed WTG using the conservative scenario [19]. The cost for PV follows the same scenario characteristics, however it is modeled as 500kW farms.

The DG capacity is fixed to at least two times the peak load, depending on the location. This is done since the load profiles are defined in 1-hour periods which lacks the true representation of instant load peaks and therefore although the optimization for the DG may be right in terms of energy, the power capacity required would not be representative of a real scenario. For energy storage, 4hr Tesla Megapacks are used for the simulations. Table VI summarizes the generation and energy storage technologies considered for this study.

TABLE VI:
TECHNOLOGIES SUMMARY

Asset Type	Range (MW)	increments (MW)	Capital Cost ($/kW)
WTG	0 – 36	0.60	3,300.81
PV	0 – 50	0.50	1,331.39
DG	0 - 10	0.25	450.00
BESS	0 – 98MWh	3.92MWh	1074.87

D. Case Scenarios

This work evaluates six case scenarios, each a different microgrid design alternative or set of conditions, for each potential microgrid location. The first case scenario considers a diesel and energy storage microgrid. For the second case scenario, WTGs are added and the third considers PV instead of WTGs. The fourth case scenario considers all four technologies for a hybrid wind and PV microgrid design alternative. For comparison, the fifth case scenario removes the DG from the design. As mentioned in the DBTs section, case scenarios 1 – 5 are simulated as event-based optimizations with minor hurricanes, major hurricanes and regular outages events as the DBTs in MDT. These simulations are run for 130 years each to increase the events occurrence sample. Case scenario 6 is the same hybrid microgrid design alternative as case scenario 4 but changing the DBTs with the 1-year grid outage fault DBT. Table VII provides a summary of the case scenario evaluated for each of the locations.

TABLE VII:
STUDY CASES SUMMARY

Case	Description
1	*Fixed: DG; Optimized: BESS*
2	*Fixed: DG; Optimized: WTG, BESS*
3	*Fixed: DG; Optimized: PV, BESS*
4	*Fixed: DG; Optimized: WTG, PV, BESS*
5	*Optimized: WTG, PV, BESS*
6	*Fixed: DG; Optimized: WTG, PV, BESS* *1-year fixed grid fault.*

E. Microgrid Cost Estimation

Initially, MDT will be used to estimate equipment cost for the microgrid configurations for each case scenario for each potential microgrid site. Then, a final cost estimate is developed following MCDM's cost estimation method. This includes adding 20% and 12.5% of the equipment cost for construction management, and design and engineering respectively. Additionally, 25% of each of the adders is considered due to incomplete information at this design level, which is conceptual. The equipment cost for a particular configuration is taken from the result of the *Purchase Cost* metric.

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IV. Results and Discussion

A. Potential Microgrid 1 – Las Mareas

6 case scenarios were simulated for each of the locations in this study. Las Mareas is the location with the highest wind resource available. Results of the MDT simulations are presented in the form of a pareto frontier with cost and performance axes. When viewing a pareto plot, the solutions at the top left corner are the high-cost-high-performance solutions, while the low-cost-low-performance solutions are located on the lower right corner. The optimal region can then be observed on the top right quadrant of the pareto frontier. The optimal region is also referred to as the "knee", as its shape resembles that of a bent human knee. The pareto frontier for case scenario 2 for Las Mareas is shown in Fig. 4.

Further analysis of the solutions is presented in the form of stacked bar charts. This is achieved by using MDT's data extraction feature and by processing the data via a MATLAB script. Fig. 5 illustrates the low, high and knee solutions for Las Mareas' case scenario 2. Case scenario 2 represents a microgrid design that considers wind, diesel, and energy storage. According to the optimal region of microgrid configurations, a range of WTGs capacity from 2.4 MW to 3.0 MW (4 to 5 WTGs) combined with two to four batteries provides the best cost to performance trade-off. A 3.0 MW WTG in Las Mareas would generate approximately 33 MWh of energy per day on average. Backup diesel generation ranges from 2.5 – 4.25 MW. Equipment cost in the optimal region is between $13M - $14M.

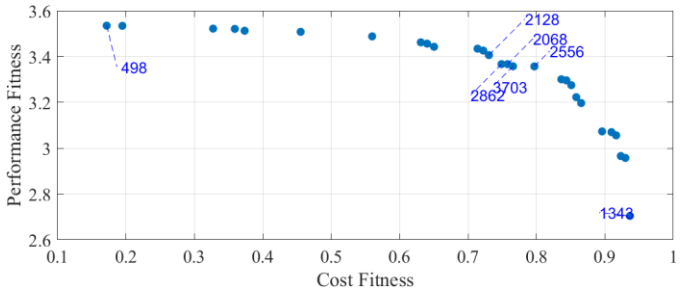

Fig. 4: Pareto frontier of feasible solutions for Las Mareas – Case 2.

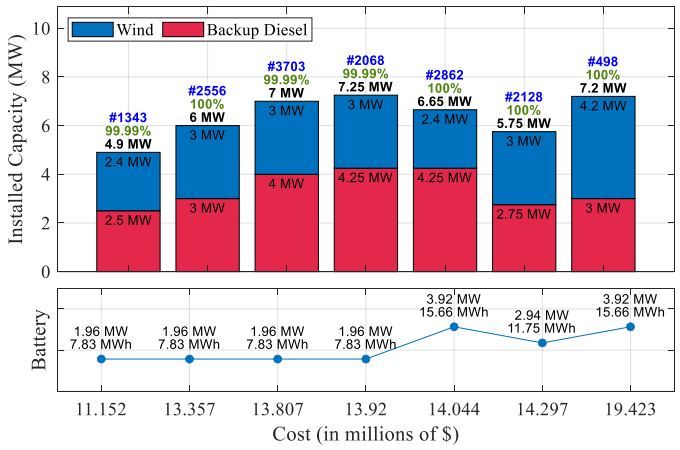

Fig. 5: Low, high, and knee solutions for Las Mareas – Case 2.

Pareto frontier and bar chart summary for Las Mareas case scenario 4 are presented in Fig. 6 and Fig. 7. Case scenario 4 considers a wind and PV hybrid microgrid with backup DG and BESS. Results for this microgrid configuration show a healthy combination of PV and wind capacity. Compared to case scenario 2, the selected wind capacities are reduced and compensated for by the addition of the PV asset, which comes at a much lower cost per kW. Although the energy storage remains similar, the cost is reduced approximately $10M across the optimal region in order to achieve the same performance as solution on the knee region for case scenario 2. These results highlight the potential cost benefits of a hybrid wind and PV microgrid design versus a wind or PV microgrid design alternative on their own.

Table VIII summarizes the case scenarios simulated for Las Mareas, highlighting the cost-effective but non-renewable diesel and energy storage microgrid. Case scenarios 2 and 3, for a wind microgrid and PV microgrid respectively, are more expensive than the hybrid wind and PV microgrid design alternative of scenario 4, demonstrating the benefits of the hybrid approach. The PV microgrid shows a significant increase in the required energy storage. In scenario 5, removing the diesel generator increases PV and storage capacity. For a year-long grid outage, this scenario shows a reduction in wind and an increase in PV and storage compared to scenario 4. Scenario 6 examines an optimal hybrid design that fully utilizes renewable resources throughout the year, resulting in a decrease in energy storage required for feasible configurations.

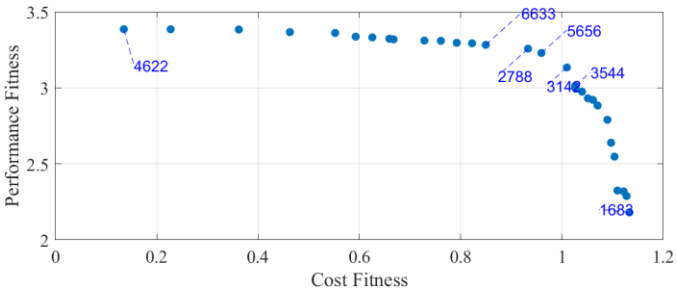

Fig. 6: Pareto frontier of feasible solutions for Las Mareas – Case 4.

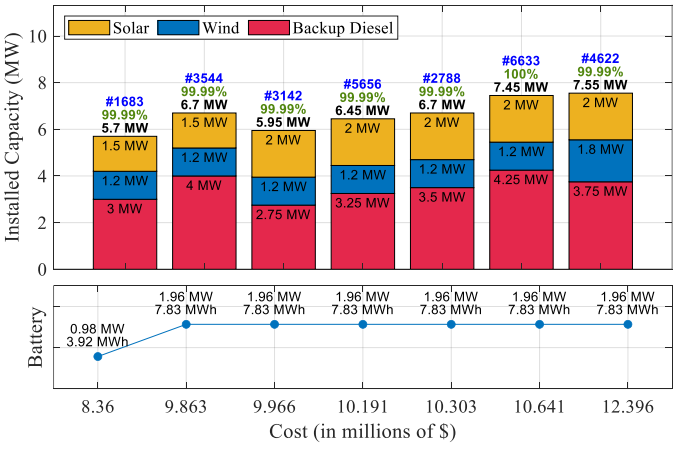

Fig. 7: Low, high, and knee solutions for Las Mareas– Case 4

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TABLE VIII:
LAS MAREAS CASE SCENARIO RESULTS SUMMARY

Case	Diesel (MW)	Wind (MW)	Solar (MW)	Battery (MW/MWh)	Availability (%)	Estimated Equipment Cost ($ in Millions)	Estimated Total Cost ($ in Millions)	ID
1	*3.50*	*-*	*-*	*1.96/7.83*	*100*	*3.68*	*5.18*	*89*
2	*4.00*	*3.00*	*-*	*1.96/7.83*	*99.99*	*13.81*	*19.42*	*3703*
3	*3.00*	*-*	*6.50*	*7.83/31.33*	*100*	*18.42*	*25.90*	*2315*
4	*3.25*	*1.20*	*2.00*	*1.96/7.83*	*99.99*	*10.19*	*14.33*	*5656*
5	*-*	*1.20*	*5.00*	*5.87/23.50*	*99.96*	*16.93*	*23.81*	*1235*
6	*4.00*	*1.20*	*2.00*	*0.98/3.92*	*99.98*	*9.48*	*13.33*	*1234*

B. Potential Microgrid 2 – San Juan

The boundary for the potential microgrid in San Juan has the highest estimated daily energy consumption at 45.55 MWh. The peak hourly power consumption for the potential San Juan microgrid reaches 2.6 MW (yearly 1-hour periods profile) with an average of 1.9 MW. The wind energy production potential in San Juan is estimated at 9.1672 kWh-kWp/day, one of the highest for the locations in this study.

The 130-year simulation of case scenario 2 for the wind microgrid in San Juan produces feasible solutions starting at around $30M. The pareto frontier for this set of solutions is shown in Fig. 8. The bar chart summary for case scenario 2 is presented in Fig. 9. For a wind microgrid, the optimal region for San Juan shows WTG capacities of 6.0 MW and 6.6 MW (10 to 11 WTGs) with combinations of six to seven batteries, depending on the configuration. Configurations with as low as five batteries can be seen in the low-cost-low-performance region of the pareto frontier.

Wind microgrid configurations for San Juan come at a higher cost, compared to configurations for the system in Las Mareas. This is to be expected since San Juan has over twice the estimated energy consumption. This increase in energy consumption results in higher wind capacity required to serve the load and in turn a higher implementation cost due to the high cost of WTGs. An increase in energy storage is noticed as well. The combination of wind generation, diesel generation and energy storage provide a stable supply of energy to the loads. Solutions on the optimal region produce configurations with over twice the equipment purchase cost.

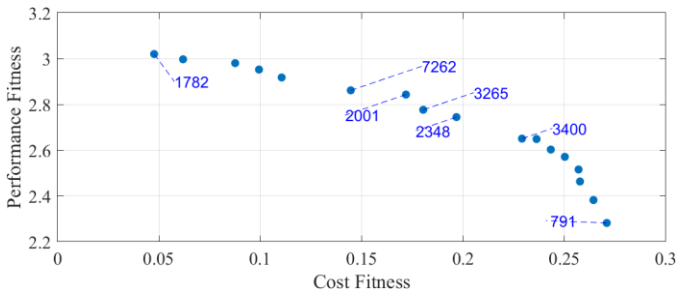

Fig. 8: Pareto frontier of feasible solutions for San Juan – Case 2.

Results for case scenario 4 for the potential microgrid in San Juan are presented in Fig. 10 and Fig. 11. Similar to Las Mareas' results, microgrid configuration for the hybrid PV and wind approach results in lower cost. The addition of the PV asset significantly reduces the required WTG capacity. The cost benefits of the hybrid microgrid approach are more noticeable in the system in San Juan due its higher estimated load compared to the system in Las Mareas. While the wind resource is higher in Las Mareas, its lower estimated load results in lower cost differences when comparing the wind versus hybrid microgrid design alternatives. This suggests that the cost benefits of a hybrid microgrid are more pronounced on systems with higher energy consumption. However, such system would require adequate wind resource. The lower cost of implementation of PV allows the MDT to reduce wind capacity up to 70% and take advantage of the solar resource available.

When compared to case scenario 2 for the potential microgrid of San Juan, it is noticeable the reduction in the energy storage capacity selected in the hybrid microgrid design alternative. There is a reduction in WTGs of approximately 50% across the optimal region of feasible microgrid configurations for the hybrid microgrid design alternative. The hybrid approach produces feasible microgrid configurations starting around $10M lower in equipment cost.

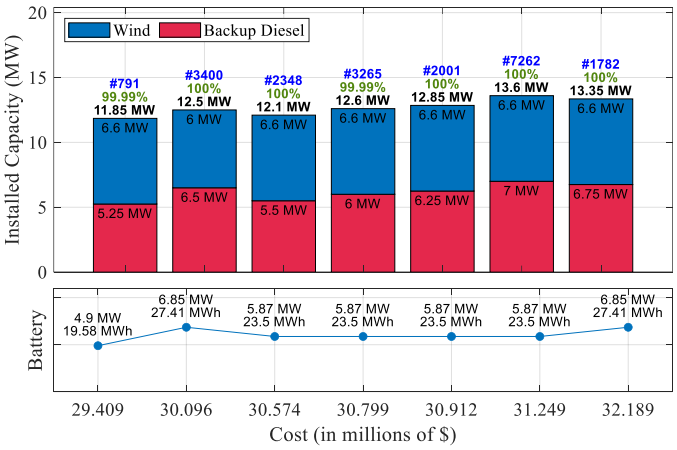

Fig. 9: Low, high, and knee solutions for San Juan – Case 2.

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TABLE IX:
SAN JUAN CASE STUDY RESULTS SUMMARY

Case	Diesel (MW)	Wind (MW)	Solar (MW)	Battery (MW/MWh)	Availability (%)	Estimated Equipment Cost ($ in Millions)	Estimated Total Cost ($ in Millions)	ID
1	*6.50*	*-*	*-*	*1.96/7.83*	*99.99*	*5.03*	*7.07*	*265*
2	*6.00*	*6.60*	*-*	*5.87/23.50*	*99.99*	*30.80*	*43.31*	*3265*
3	*5.50*	*-*	*13.50*	*9.79/39.16*	*100*	*30.97*	*43.55*	*894*
4	*5.50*	*3.00*	*4.50*	*3.92/15.66*	*99.99*	*22.58*	*31.75*	*6625*
5	*-*	*6.60*	*9.00*	*16.64/66.57*	*99.98*	*51.66*	*72.65*	*2054*
6	*5.50*	*1.80*	*5.50*	*2.94/11.75*	*99.98*	*18.79*	*26.42*	*8521*

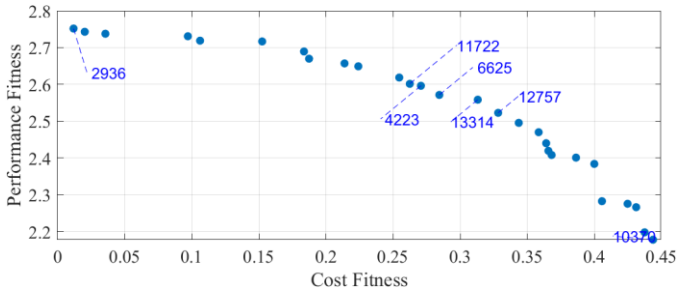

Fig. 10: Pareto frontier of feasible solutions for San Juan – Case 4.

Results from all case scenarios for the potential microgrid in San Juan are presented in Table IX. The hybrid microgrid with no diesel generator is the costlier one, followed by the wind and PV microgrids of scenarios 2 and 3 respectively. The hybrid microgrid with backup diesel generator produces optimal solutions in the range of $30M (total cost estimate). Case scenario 6, the 1-year fixed grid outage, results in a different balance of wind, PV and energy storage that comes at a slightly lower average cost compared to the event-based optimization performed in case scenario 4. This results in a reduction in wind capacity and an increase in PV and energy storage capacity with similar or slightly reduced cost across the optimal region of configurations.

A comprehensive summary of optimal microgrid configurations derived from case scenario 4 simulations for all potential locations evaluated in this study is presented in Table X. A solution from the optimal region is selected and detailed for each location. For locations with low wind resources such as Aguadilla, Arecibo, and Mayagüez, the optimal configurations do not include any WTG and rely solely on the PV asset as the primary renewable energy resource, complemented by diesel generators and batteries for backup. On the other hand, areas with high wind resources like Fajardo and Yabucoa benefit from optimal hybrid microgrid configurations that effectively combine both wind and PV technologies. In Vieques, the similar availability of wind and solar resources leads to configurations with minimal wind capacity, which, combined with the lowest estimated energy consumption among the locations, results in the lowest estimated cost for its microgrid configurations.

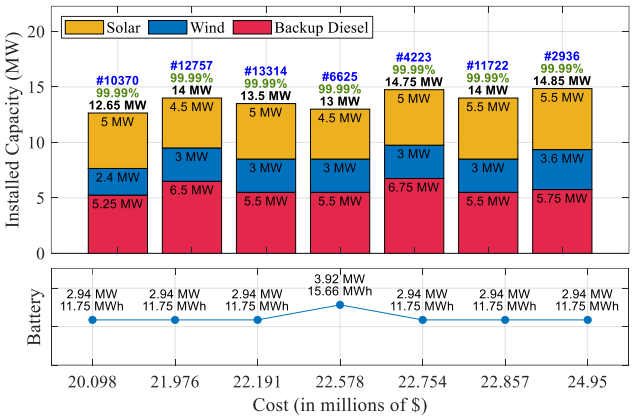

Fig. 11: Low, high, and knee solutions for San Juan – Case 4.

Although not shown due to space constraints, results from locations with strong wind resources like Fajardo and Yabucoa mirror those from Las Mareas and San Juan, showing that hybrid microgrid designs are more cost-effective than standalone wind or PV alternatives. However, in areas with poor wind resources, such as Aguadilla, Arecibo, and Mayagüez, both the PV-only and hybrid microgrid designs from scenarios 3 and 4 yield similar configurations without WTGs being selected. In these low-wind areas, including WTGs is cost-prohibitive, with the expenses for scenario 2 reaching over $160M in Mayaguez and over $50M in Aguadilla and Arecibo, rendering wind energy impractical.

TABLE X:
CASE SCENARIO 4 OPTIMAL SOLUTION FOR ALL LOCATIONS

Location	DG (MW)	WTG (MW)	PV (MW)	BESS (MWh)	$\text{Cost}_{\text{TOTAL}}$ (M of $)
Aguadilla	3.00	0.00	4.00	15.66	15.31
Arecibo	4.50	0.00	5.50	15.66	19.07
Fajardo	4.25	2.40	4.00	7.83	24.29
Las Mareas	3.25	1.20	2.00	7.83	14.33
Mayagüez	4.00	0.00	8.00	23.50	26.40
San Juan	5.50	3.00	4.50	15.66	31.75
Vieques	1.25	0.60	1.50	7.83	9.35
Yabucoa	1.75	0.60	3.00	7.83	12.47

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V. Conclusion

This paper presents a comprehensive analysis of various microgrid design alternatives, including hybrid wind and PV, for eight potential microgrid locations in Puerto Rico. Event-based optimization was performed in five scenarios while a sixth scenario evaluates a microgrid design optimized for a full year fixed grid fault, optimizing with the full renewable energy resources. Results from the location with the highest wind energy resource and the location with higher estimated energy consumption are discussed. General results from all locations are also presented and discussed in this paper. This work highlights the cost benefits of hybrid wind and PV microgrids when compared to wind or PV microgrid design alternatives. Results suggest that the cost benefits provided by a hybrid microgrid design are more significant the higher the system's energy needs are. This is attributed to the high cost of wind technology in wind microgrids, and high storage needed for PV microgrids when compared to the balance provided by the hybrid microgrid approach that results in a cost-effective balance of technologies.

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References

[1] Martinuzzi, S., Gould, W.A., Ramos González, O.M., Quiñones, M., Jiménez, M.E. 2008. Urban and rural land use in Puerto Rico. Scale 1:260 000. IITF-RMAP-01. Río Piedras, PR: US Department of Agriculture Forest Service, International Institute of Tropical Forestry.

[2] Marcel Castro-Sitiriche, "Boricua Energy Equity", Panel on Data-enriched Grid Modeling of End-user Profiles, Energy Equity, and Situational Preparedness, IEEE-ISGT, San Juan Puerto Rico, November 7, 2023. Available: https://www.pnnl.gov/sites/default/files/media/file/PNNL_panel-Nov07_Fan_4Slides.pdf.

[3] J. Choi, J. E. Quiroz, R. T. Brito, R. Darbali-Zamora, E. E. Aponte-Bezares and M. S. Lave, "An Assessment of Wind-Hybrid Microgrids in Puerto Rico Using Microgrid Design Toolkit," 2024 56th North American Power Symposium (NAPS), El Paso, TX, USA, 2024, pp. 1-6, doi: 10.1109/NAPS61145.2024.10741697.

[4] Gilletly, Samuel Drew, Jones, Katherine A., Bandlow, Alisa, Arguello, Bryan, Gearhart, Jared Lee, Quiroz, Jimmy Edward, & Eddy, John P. (2024). Microgrid Design Toolkit (MDT) User Guide: Software v1.4. https://doi.org/10.2172/2480225.

[5] R. J. Tremont-Brito, R. Calloquispa-Huallpa, G. Irrizary-Martínez, R. Darbali-Zamora, G. L. López-Ramos and E. E. Aponte-Bezares, "Comprehensive Microgrid Design Toolkit Analysis for a Remote Rural Community in Puerto Rico," *2024 IEEE 52nd Photovoltaic Specialist Conference (PVSC)*, Seattle, WA, USA, 2024, pp. 0935-0942, doi: 10.1109/PVSC57443.2024.10749146.

[6] R. J. Tremont-Brito, R. Darbali-Zamora, R. Broderick, E. E. Aponte-Bezares, E. O'Neill-Carrillo and M. S. Lave, "Microgrid Design Toolkit Cost Optimization for a Rural Community in Puerto Rico," *2023 IEEE 50th Photovoltaic Specialists Conference (PVSC)*, San Juan, PR, USA, 2023, pp. 1-7, doi: 10.1109/PVSC48320.2023.10359772.

[7] R. J. Tremont-Brito, E. Aponte-Bezares, L. R. Orama-Exclusa, R. Darbali-Zamora and A. J. Malave-Sanabria, "Microgrid Design Toolkit Evaluation and Trade-offs Analysis for Rural Community in Cayey Puerto Rico," *2023 IEEE PES Innovative Smart Grid Technologies Latin America (ISGT-LA)*, San Juan, PR, USA, 2023, pp. 220-224, doi: 10.1109/ISGT-LA56058.2023.10328296.

[8] Broderick, Robert, Garcia, Brooke Marshall, Horn, Samantha E., & Lave, Matthew S. (2022). Microgrid Conceptual Design Guidebook | 2022. https://doi.org/10.2172/1863659

[9] Grue, Nick, Grant Buster, Andrew Kumler, Yu Xie, Manajit Sengupta, and Murali Baggu. 2021. Quantifying the Solar Energy Resource for Puerto Rico. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-75524.

[10] R. Darbali-Zamora and A. Díaz-Castillo, "Feasibility of residential wind energy generation in Puerto Rico," in International Conference on Renewable Energies and Power Quality (ICREPQ), 2013, pp. 20–22.

[11] R. Darbali-Zamora, C. J. Gómez-Méndez, and A. J. Díaz-Castillo, "Comparison of residential wind and solar energy generation in the island of Puerto Rico," terrain, vol. 7, p. 4, 2015.

[12] T. Burton, N. Jenkins, D. Sharpe, and E. Bossanyi, Wind energy handbook. John Wiley & Sons, 2011.

[13] Cybersecurity and critical infrastructure: Homeland security. U.S. Department of Homeland Security. (n.d.). Available: https://www.dhs.gov/archive/coronavirus/cybersecurity-and-critical-infrastructure.

[14] Humanitarian OpenStreetMap Team. (n.d.). *Puerto Rico Buildings (OpenStreetMap Export)*. Humanitarian Data Exchange. Available: https://data.humdata.org/dataset/hotosm_pri_buildings.

[15] U.S. Energy Information Administration - EIA - independent statistics and analysis. Energy Information Administration (EIA)- About the Commercial Buildings Energy Consumption Survey (CBECS). (n.d.). Available: https://www.eia.gov/consumption/commercial/data/2012/c&e/cfm/pba4.php.

[16] REopt web tool: REOPT Energy Integration & Optimization. REopt Web Tool. (n.d.). Available: https://reopt.nrel.gov/tool.

[17] R. J. Tremont-Brito, R. Darbali-Zamora and E. E. Aponte-Bezares, "Microgrid Design Toolkit Methodology for Incorporating Extreme Events, Hazards and Fragility Data, and Mitigation Trade-off Analysis for Rural Communities in Puerto Rico," *2024 IEEE 52nd Photovoltaic Specialist Conference (PVSC)*, Seattle, WA, USA, 2024, pp. 0915-0921, doi: 10.1109/PVSC57443.2024.10749516.

[18] R. J. Tremont-Brito, R. Darbali-Zamora and E. E. Aponte-Bezares, "Implementing Extreme Events, Hazards and Fragility Data, and Mitigation Trade-Off Analysis Using the Microgrid Design Toolkit for a Rural Community in Puerto Rico," 2024 IEEE 52nd Photovoltaic Specialist Conference (PVSC), Seattle, WA, USA, 2024, pp. 0926-0932, doi: 10.1109/PVSC57443.2024.10748754.

[19] National Renewable Energy Laboratory. (n.d.). 2023 electricity ATB Technologies and Data Overview. National Renewable Energy Laboratory ATB. Available: https://atb.nrel.gov/electricity/2023/index.

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