An Assessment of Wind-Hybrid Microgrids in Puerto Rico Using Microgrid Design Toolkit

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***Abstract*—In recent years, Puerto Rico has struggled with unreliable power supply and frequent blackouts. The island's vulnerability to natural disasters, due to its isolation from any mainland grid, highlights the need for resilient and reliable energy solutions. Microgrids have emerged as a promising solution for rural communities in Puerto Rico, helping to enhance grid resilience and reliability. Wind energy generation can be a suitable resource for microgrids, as it diversifies sources of electricity generation and decentralizes power production. Moreover, wind energy adoption has become a growing focus in Puerto Rico, with the goal of achieving 100% renewable energy generation by 2050. This paper examines the feasibility of fully renewable microgrids in Puerto Rico, integrating wind energy alongside solar energy and energy storage. Candidate locations within Puerto Rico are selected, and a high-level overview of microgrids in these locations is analyzed using the Microgrid Design Toolkit (MDT). The results provide a preliminary understanding of the potential for applying wind power generation in microgrids across different regions of Puerto Rico.**

***Index Terms*—Microgrids, energy diversification, microgrid design toolkit, photovoltaic, wind turbine generator, resilience**

I. Introduction

Puerto Rico is an island with an isolated electric grid that does not have any interconnection with a mainland grid. This isolation results in an unreliable power supply and frequent blackouts, making the island particularly vulnerable to natural disasters. When Hurricane Maria struck in September 2017, Puerto Rico experienced a complete blackout, affecting approximately 3.4 million people. It took nearly 11 months to fully restore power to all customers, marking the longest blackout in United States (U.S.) history [1]. Incidents like this underscore the urgent need for more resilient and reliable energy solutions in Puerto Rico.

Microgrids have been gaining attention as an energy solution to enhance grid resiliency and reliability [2], [3]. Microgrids can operate independently from the larger bulk grid, supplying electricity from local energy resources [4]. This means that when a centralized generation unit is down, electricity can still be supplied to the local area. While distributed energy resources incorporated into microgrids range from conventional diesel generators to renewable energy generation units, significant efforts are being made to include more renewable energies, with the goal of achieving 100% renewable energy in Puerto Rico by 2050 [5].

As of 2020, Puerto Rico has 400 MW of solar capacity, driven by high solar irradiance and the ease of installation [6]. In contrast, wind energy adoption has been more limited, with the installation of wind turbines amounting to only 101 MW [7], [8]. Challenges such as land availability, permitting processes, grid integration issues, and costs have hindered the widespread adoption of wind power on the island [6]–[9]. However, there is growing interest and investment in wind energy projects in Puerto Rico, driven by the need to diversify the island's energy mix, reduce dependence on fossil fuels, enhancing energy resilience and sustainability [5], [7]–[10].

This work focuses on the integration of wind turbine generators (WTGs) into a microgrid consisting of photovoltaic systems (PVs) and an energy storage system (ESS). For this microgrid analysis, the Microgrid Design Toolkit (MDT) is utilized. The MDT is a decision support software tool aimed to assist microgrid designers in the initial stages of the design process. It helps users find the optimal settings for a microgrid based on the desired optimization objectives. Several MDT analyses have been conducted for various communities in Puerto Rico, as documented in the literature [11], [12]. However, these studies primarily considered diesel generators, solar energy, and energy storage, without evaluating the potential of distributed wind energy. The contributions of this work are as follows: 1) assessing the renewable resources, specifically wind and solar, in Puerto Rico; 2) conducting MDT analysis for microgrids based on wind, solar, and energy storage at selected candidate locations; and 3) providing a preliminary understanding of integrating wind energy into microgrids across various locations.

II. Description of Puerto Rico

Puerto Rico is a territory of the U.S. located in the northeastern Caribbean. With a population of approximately 3.3 million people as of 2021, it is the most populous territory of the U.S. Geographically, Puerto Rico consists of the main island of Puerto Rico and several smaller islands, including Vieques, Culebra, and Mona. The main island has a total land area of 9,104 km^2. The terrain of Puerto Rico is diverse, ranging from lush tropical rainforests to sandy beaches and rugged mountains. The renewable resources for the locations marked in Fig. 1 are investigated. Among the locations examined, the eight locations marked with an orange diamond, which exhibited the highest wind resource, will be analyzed for the MDT analysis.

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Fig. 1. Candidate microgrid sites in Puerto Rico.

III. Wind Energy Resource Assessment

Puerto Rico has significant wind energy potential, particularly along the northern and eastern coastal areas, which experience relatively higher wind speeds due to the unobstructed flow of trade winds. These consistent winds provide a favorable environment for the deployment of wind turbines for energy generation. The wind energy potential of an area can be evaluated from wind speed measurements at that location. For this study, hourly wind speed data obtained from the Caribbean Coastal Ocean Observation System (CariCOOS), the National Oceanic and Atmospheric Administration (NOAA), and the National Data Buoy Center (NDBC) are utilized [13], [14]. The coordinates of the meteorological stations and the heights of the anemometers at which the wind speed was measured are tabulated in Table I for the locations of interest.

TABLE I
Summary of Meteorological Stations of Interest

Location	Station	Latitude	Longitude	Height (m)
Las Mareas	XMRS	17.9286	-66.1597	8.8
San Juan	SJNP4	18.4589	-66.1164	15
Fajardo	XREY	18.2894	-65.6320	13.4
Vieques	ESPP4	18.0939	-65.4714	8.5
Arecibo	AROP4	18.4806	-66.7022	6.4
Aguadilla	XAGU	18.4330	-67.1566	4.3
Yabucoa	YABP4	18.0550	-65.8331	6.4
Mayaguez	MGZP4	18.2175	-67.158889	8.4

A. Wind Speed Distribution

Due to aerodynamic drag, a gradient exists in the wind flow, causing wind speed to increase with height above the ground. Since wind speeds are measured at different heights at each location, they need to be adjusted to a unified height. The relationship between wind speed and height is defined by the wind profile power law equation [15] formulated as

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

In this equation, v_2 is the wind speed at the desired height h_2, v_1 is the wind speed measured at a known height h_1, and α is the wind shear coefficient. The wind shear exponent varies with pressure, temperature and time of day. A commonly used value is one-seventh (1/7). The distributions of the wind speed, adjusted to a height of 18 m over the course of one year, are illustrated in Fig. 2 for the locations of Las Mareas, San Juan and Fajardo.

B. Wind Power Estimation

In order to estimate wind power production, the power curve of a commercially available wind turbine is used to convert wind speed data into energy. The power curve is a characteristic graph that represents the output power of a wind turbine at different wind speeds and is typically provided by the wind turbine's manufacturer. The residential WTG model NPS 60C-24 rated at 60 kW at 11 m/s, a cut-in wind speed of 3 m/s and a cut-out wind speed of 25 m/s, is selected for this analysis. The power curve of NPS 60C-24 is provided in Fig. 3. Using the wind speed data and the power curve, the annual wind energy that can be generated from a single selected WTG is estimated. The annual wind energy generation estimation and capacity factor at each location are given in Fig. 4. The capacity factor is a metric that quantifies the actual electricity generation of a power plant or a group of generators over a specific period. It is calculated by dividing the annual generation by the product of the capacity and the number of hours in that period. Essentially, the capacity factor assesses how much electricity a power plant produces compared to its maximum potential output without any interruptions. Las Mareas, San Juan, and Fajardo turn out to be the top three locations yielding rich wind resources, with capacity factors of approximately 45%, 38%, and 34%, respectively.

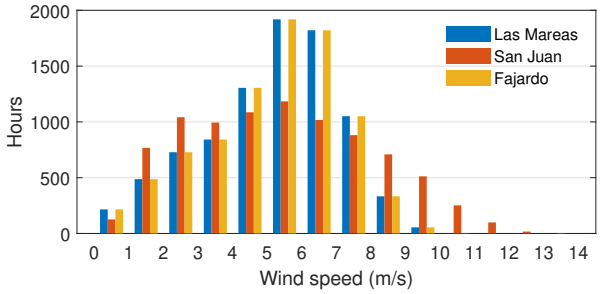

Fig. 2. Wind speed distribution at selected sites.

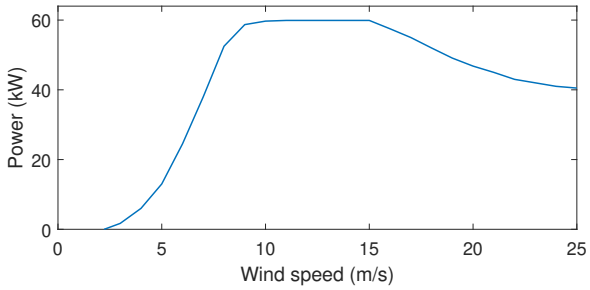

Fig. 3. Power curve of the wind turbine generator NPS 60C-24.

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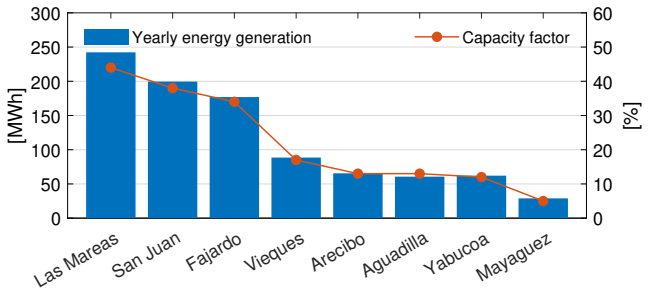

Fig. 4. Estimated annual wind power generation at weather stations and their capacity factors.

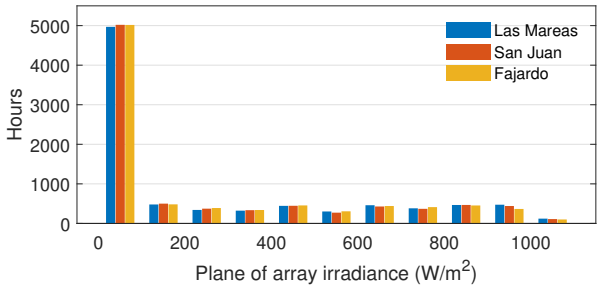

Fig. 5. Solar irradiance distribution at selected sites.

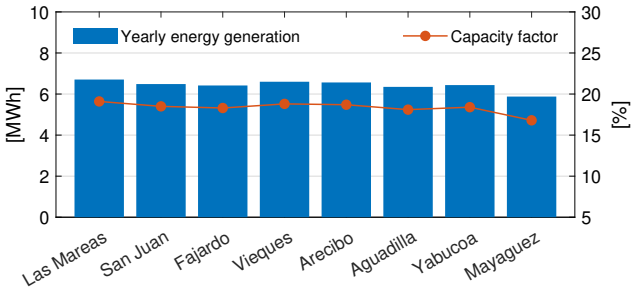

Fig. 6. Estimated annual solar power generation at weather stations and their capacity factors.

IV. Solar Energy Resource Assessment

Puerto Rico has abundant solar energy resources, advantaged by its geographical location at a low latitude. The island receives intense sunlight for extended periods, especially during the summer months, making it a favorable location for solar power generation. The solar energy potential can be evaluated from solar irradiance data. In this study, PVWatts is utilized for solar energy assessment. PVWatts is a tool developed by the National Renewable Energy Laboratory (NREL) that estimates the energy production of a grid-connected PV system based on the location and the system parameters. PVWatts uses the solar resource data of the system's location prepared from the NREL National Solar Radiation Database (NSRDB) where it is available, and from other sources for the rest of the world.

A. Solar Irradiance Distribution

The NSRDB provides a high temporal and spatial resolution solar radiation and meteorological data over the U.S. and the regions of the surrounding countries. The satellited-derived atmospheric and land surface properties are used in the radiative transfer model and the solar radiation through the Earth's atmosphere is numerically solved [16]. PVWatts uses hourly typical meteorological year (TMY) data. These tools are used to generate a solar irradiance distribution of the selected sites. The distributions of TMY solar irradiance at the selected sites are shown in Fig. 5 for Las Mareas, San Juan and Fajardo. Notice from this analysis that solar irradiance is fairly uniform across different regions in Puerto Rico.

B. Solar Power Estimation

In order to estimate solar power production, a PV system is assumed as the solar power generation unit. Solar PV technology is the primary means of harnessing solar energy in Puerto Rico. PV systems are deployed across the island in various applications, including residential, commercial, and utility-scale projects. Given the parameters of the PV system, PVWatts returns hourly power production (W) for an entire year based on the meterological data and solar irradiance profile discussed in the previous subsection. For this study, the default PV system parameters provided by PVWatts are utilized. These parameters include a DC system size of 4 kW, a standard module type, an open-rack fixed array type, system losses assumed at 14.08%, a tilt angle of 20°, and an Azimuth angle of 180°. Fig. 6 summarizes the annual energy production of the PV system at selected locations, as well as their corresponding capacity factors. Note that the solar energy resource is relatively consistent across the entire area of Puerto Rico, with capacity factor around 20% in any location.

V. Microgrid Design

The MDT employs search algorithms to identify and characterize the trade space of alternative microgrid design decisions based on the user defined objectives such as cost, performance, and reliability. In the MDT, a detailed configuration for the microgrid is available from the equipment and site, and microgrid specification, and based on the information provided, and decision variables of interest, it proposes the optimal solutions based on the desired optimization objective. The following subsections discuss the parameters selected for this study.

A. Electrical Load Profiles

At each site location, the geographical boundary of a potential microgrid is identified. Initially, the boundary is established to include critical loads such as hospitals and public services. Starting from a boundary that encompasses one or more critical loads, it is then extended to incorporate some residential blocks that are supplied by the same feeder as the selected critical loads. Additionally, loads connected to the same feeder may be included if they are not significantly distant from the pre-selected loads, the microgrid is not

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excessively large, and there is ample capacity remaining on the feeder. In certain cases, where feasible, the entire feeder may be included within the boundary if it is confined to a relatively small area. An example of boundary selection for Las Mareas is shown in Fig. 7.

After establishing the boundary of each microgrid, the roof areas of the buildings within these boundaries were measured using publicly available Geographic Information System (GIS) layers of buildings in Puerto Rico [17]. For commercial buildings, the measured areas are multiplied by an electricity consumption factor, expressed in kWh/ft^2, based on the building's usage type, such as education or healthcare [17]. This calculation yields each building's annual energy consumption, which is then further scaled to account for multiple-story buildings. Given the annual energy consumption amount and a building type, an hourly load demand profile for a building over the course of a year can be obtained from the REopt web tool [18]. For residential buildings, the selection of factors depends on the type of residence. If the building is a single-story up to a three-story multifamily residential dwelling, factors from [19] are used. Conversely, if it is an apartment building or public housing, the factor for a midrise level apartment from the REopt web tool [18] is applied. The residential load profiles introduced in [20] are employed: a load profile representing a typical residential load demand in Puerto Rico, two load profiles generated from energy consumption surveys conducted by the University of Puerto Rico among community residents, and the average of these three profiles. These load profiles are applied to each residential load in a random manner. The load profiles have a 1-year interval with 1-hour periods, resulting in 8,760 data points for each building. Finally, these load profiles will be aggregated per location and will serve as load inputs to the MDT models. The commercial and residential loads generated for Las Mareas, San Juan, and Fajardo are shown in Fig. 8 through Fig. 10, respectively.

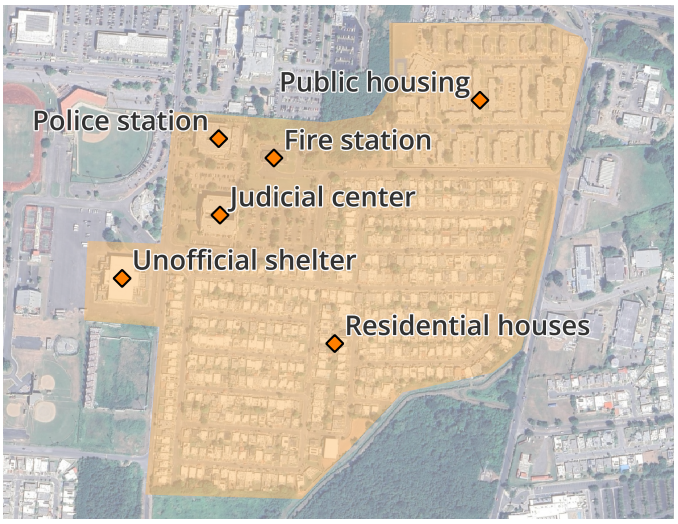

Fig. 7. Boundary defined for a potential microgrid in Las Mareas.

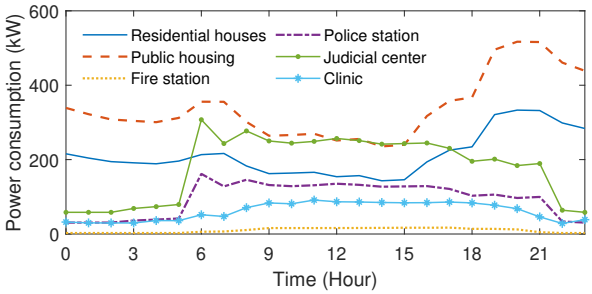

Fig. 8. Estimated average daily power consumption in Las Mareas.

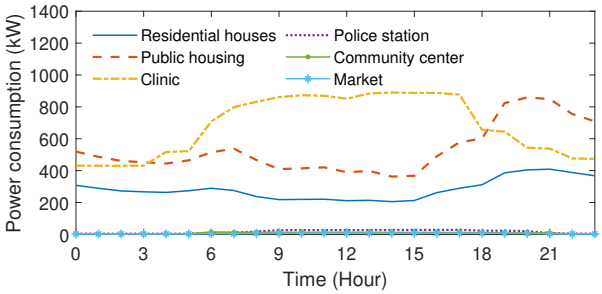

Fig. 9. Estimated average daily power consumption in San Juan.

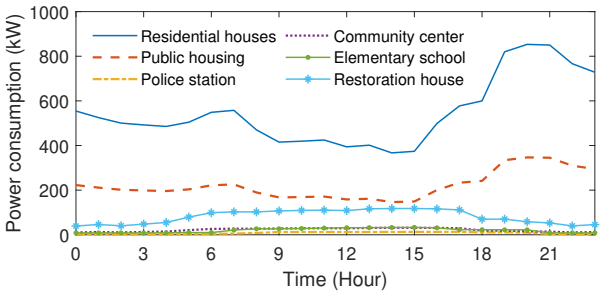

Fig. 10. Estimated average daily power consumption in Fajardo.

B. Optimization Setup

The islanded portion of MDT requires the definition of design-basis threats (DBT). DBTs are a means of defining the primary grid outages to which the microgrid will need to be designed to withstand. DBTs consist of a "time between outages" and "duration", where each can be given a probability distribution to vary the frequency and duration of outages, if desired. For this study, one DBT occurring approximately once a year lasting exactly 30 days was implemented. Coupled with the length of simulation set to 130 years, this resulted in approximately 120 simulated outages per run, or approximately 10 outages per month. It can be theorized that this DBT setting covers the entire year of load data and renewable resource coincidences, making for a robust design target. Minimizing cost is usually a default desire in most optimizations, but the other most used performance metric for optimization in MDT is energy availability. Energy availability is defined as the percentage of load energy delivered in proportion to full load service. This is an energy-based metric rather than temporal-based, as loads vary throughout time. For this study, the energy

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availability objective was set to 100%, with the limit for being considered a successful design set at 99.9999%. This essentially translates to a design that can support all 30-day coincidences between the load demand and renewable resource assumptions, further adding to a robust design. The increment sizes of assets used for iteration are tabulated in Tabel II.

TABLE II
ASSET SIZE AND COST INCREMENT FOR OPTIMIZATION

Asset	Increment	Cost/Increment
PV	500 kW	$666 k (1,331.39/kW)
Wind	600 kW	-$3.17 M ($5,289.98/kW)
Battery	489.5 kW/ 1,958 kWh	$13.4 k/unit

VI. CASE STUDIES

For this study, six cases were simulated for each location. Firstly, two bookend cases were established: one with no wind resource, where only PV and batteries are considered (Case 1), and the other with no PV, where only wind and batteries are considered (Case 6). The remaining four cases, Cases 2 through 5, involve wind turbine capacities of 20%, 40%, 60%, and 80% of the wind only bookend case, respectively.

Each case simulation in MDT results in multiple design options, allowing for the observation of trade-offs in the designs for different levels of the performance metrics entered. For this study, especially considering the very high energy availability targets, most cases yielded only one design that met the energy availability target, as it would be unreasonable to provide numerous designs with surplus energy availability when minimizing cost. For cases with multiple solutions, the least-cost solution is reported for each case.

Graphical summaries of the MDT analysis for Las Mareas, San Juan, and Fajardo are provided in Fig. 11 through Fig. 13, respectively. For Las Mareas, compared to the solar-only scenario, the integration of wind resources results in a reduction in the required energy storage size to some extent, with Case 5 yielding the smallest battery size. For San Juan, Case 2 demonstrates the most significant reduction in battery size. For Fajardo, Case 3 provides the smallest battery size, although it is not meaningfully distinct from the solar-only scenario. Unlike the two preceding locations, the integration of wind resources does not significantly reduce the size of the battery compared to the solar-only case. Additionally, in Case 6, where no solar resource is integrated, the battery size is more than double that of Case 1, despite its generation capacity also being more than double that of Case 1, indicating that the wind resource is not abundant in this location.

The case with the smallest storage size is selected and summarized in Table III for each location. If multiple cases tie, the case with the lower cost is selected. From Vieques to Mayaguez, the results are similar to those shown in Fig. 13 for Fajardo. Specifically, wind energy has a minimal effect on storage size for Cases 1 through 5, but requires substantial generation capacity and storage for Case 6. In Vieques, there was even a case where the solar-only scenario required the least storage. Fig. 4 supports this observation: locations with the highest wind generation capacity factors show a greater impact of wind energy in reducing energy storage requirements and improving generation efficiency, while wind has a minimal influence in locations with lower capacity factors.

Findings suggest that wind energy can help reduce storage size in areas with abundant wind resources. This impact appears to be more dramatic in wind-abundant areas, whereas it is minimal or even negligible in areas with insufficient wind resources. Notably, in locations where wind energy has a meaningful impact, storage size tends to be minimal in wind-solar energy mix cases rather than in bookend cases. The nature of wind energy, which is not limited by the time of day, enhances the consistency of power supply by synergizing with solar energy, which is only available during daylight hours.

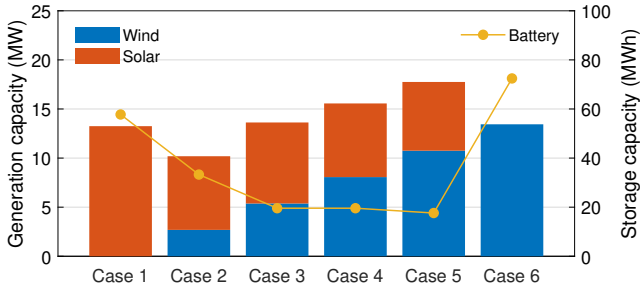

Fig. 11. The microgrid solutions for Las Mareas at various wind integration levels, optimized targeting 100% energy availability.

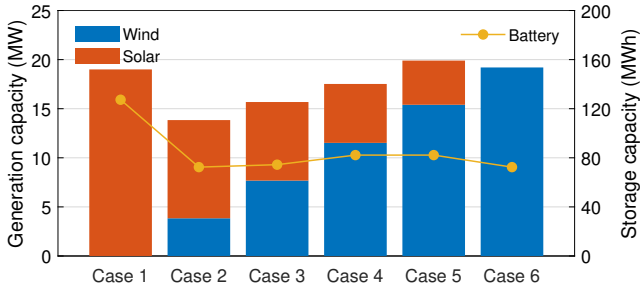

Fig. 12. The microgrid solutions for San Juan at various wind integration levels, optimized targeting 100% energy availability.

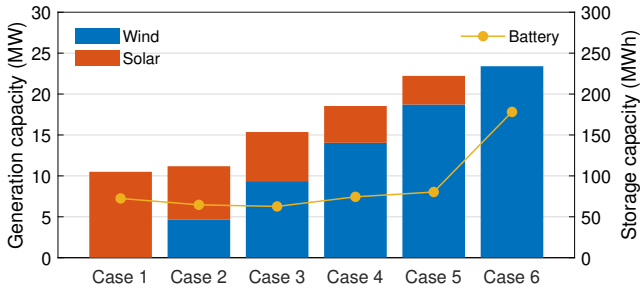

Fig. 13. The microgrid solutions for Fajardo at various wind integration levels, optimized targeting 100% energy availability.

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TABLE III
MICROGRID DESIGN OPTION FOR MINIMUM STORAGE SIZE

Location	Case	Wind (MW)	Solar (MW)	Storage (MWh)
Las Mareas	5	10.8	7.0	17.6
San Juan	2	3.8	10.0	72.4
Fajardo	3	9.4	6.0	62.7
Vieques	1	0.0	2.0	13.7
Arecibo	2	7.2	5.5	23.5
Aguadilla	3	5.3	3.0	25.5
Yabucoa	3	2.4	2.5	17.6
Mayaguez	4	6.0	31.0	37.2

VII. CONCLUSION

This work proposes a high-level analysis of 100% renewable wind-hybrid microgrids in Puerto Rico. Wind and solar energy resources in Puerto Rico are assessed and used for the microgrid analysis. A microgrid at different locations is designed to support critical, residential, and commercial loads in those regions. The design option of a microgrid consisting of wind, solar, and energy storage is analyzed using the MDT, with solutions optimized for a 100% energy availability metric. Six case studies for 0%, 20%, 40%, 60%, 80%, and 100% wind energy scenarios are investigated. The findings show that wind energy integration has the effect of reducing the required energy storage size in wind-abundant areas. The findings also indicate that mixed wind and solar cases effectively reduce required storage size compared to extreme cases relying on a single energy resource.

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