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PNNL-34149

Power Supply Options for the Marpi Landfill, Saipan

Feasibility Study

May 2023

Amy E Solana
Malcolm P Moncheur de Rieudotte
Christopher R Niebylski
Lindsay M Sheridan

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Pacific Northwest National Laboratory
Richland, Washington 99354

Executive Summary

The Marpi Landfill, located on the northern end of the island of Saipan in the Commonwealth of the Northern Mariana Islands (CNMI), is powered by an on-site diesel generator that only operates when the landfill is open and staffed. The CNMI Project Team, comprised of representatives of the Department of Public Works and the Office of Planning and Development, aspires to provide the Marpi Landfill with 24-hour power availability despite its remote location and to increase the use of sustainable energy and ensure environmental compliant landfill operations. This is consistent with sustainable development goals documented in the 2021-2030 Comprehensive Sustainable Development Plan (OPD 2021), including Goal #12 which aims to ensure environmental compliant waste management facilities as well as Goal #7 as it relates to renewable energy deployment. Further, the CNMI has a 20% target for renewable energy consumption by 2030, as documented in 2021-2030 Comprehensive Sustainable Development Plan (OPD 2021) and the renewable portfolio standard (GPO 2014). To accomplish these goals, the Federal Emergency Management Agency, through its Interagency Reimbursable Work Agreement with the U.S. Department of Energy, funded this feasibility study to assess and prioritize power supply options for the landfill.

Marpi's power requirements are driven primarily by pump loads; to keep the leachate below a certain level, pumps are operated the majority of the time when the landfill is open. Due to increased pump usage to control leachate levels during the rainy season (July through November), the facility's load correspondingly increases. Based on the estimated loads for each of the site's current and future (through the end of the useful life of Cell 3) end uses, as characterized by the CNMI Department of Public Works team and the landfill operators, Marpi's expected annual consumption is estimated to be 170 MWh, with a peak load of 112 kW. Figure ES-1 shows the hourly load profile for a typical week during both the dry and rainy seasons.

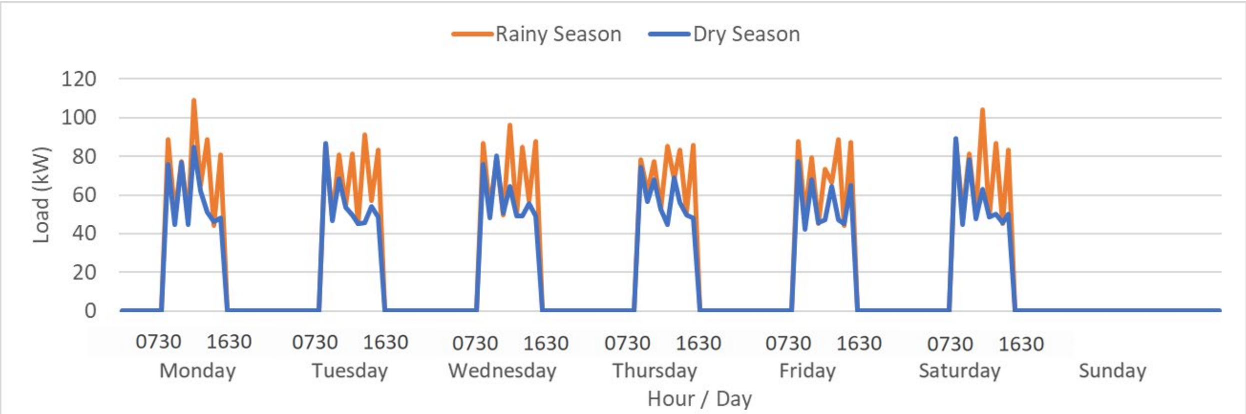

Figure ES-1. Typical Weekly Marpi Landfill Load Profile

This load profile was used as an input for the technical and economic evaluation of several power supply scenarios. The scenarios evaluated were driven by the available energy resources for Marpi, which were determined through a resource screening. The screening identified solar photovoltaics (PV), wind turbines, battery energy storage systems (BESS), and diesel generator technologies as viable options for inclusion in a microgrid located at the landfill.

The availability of solar and wind resources varies seasonally, as does the load. A BESS can help to balance mismatches between generation and load on short (hourly or daily) timescales, but not across seasons. The microgrid scenarios evaluated for Marpi consider options for technology combinations that will both meet the load and utilize available resources, despite the challenge presented by higher loads and lower solar and wind availability during the rainy season, depicted in Figure ES-2.

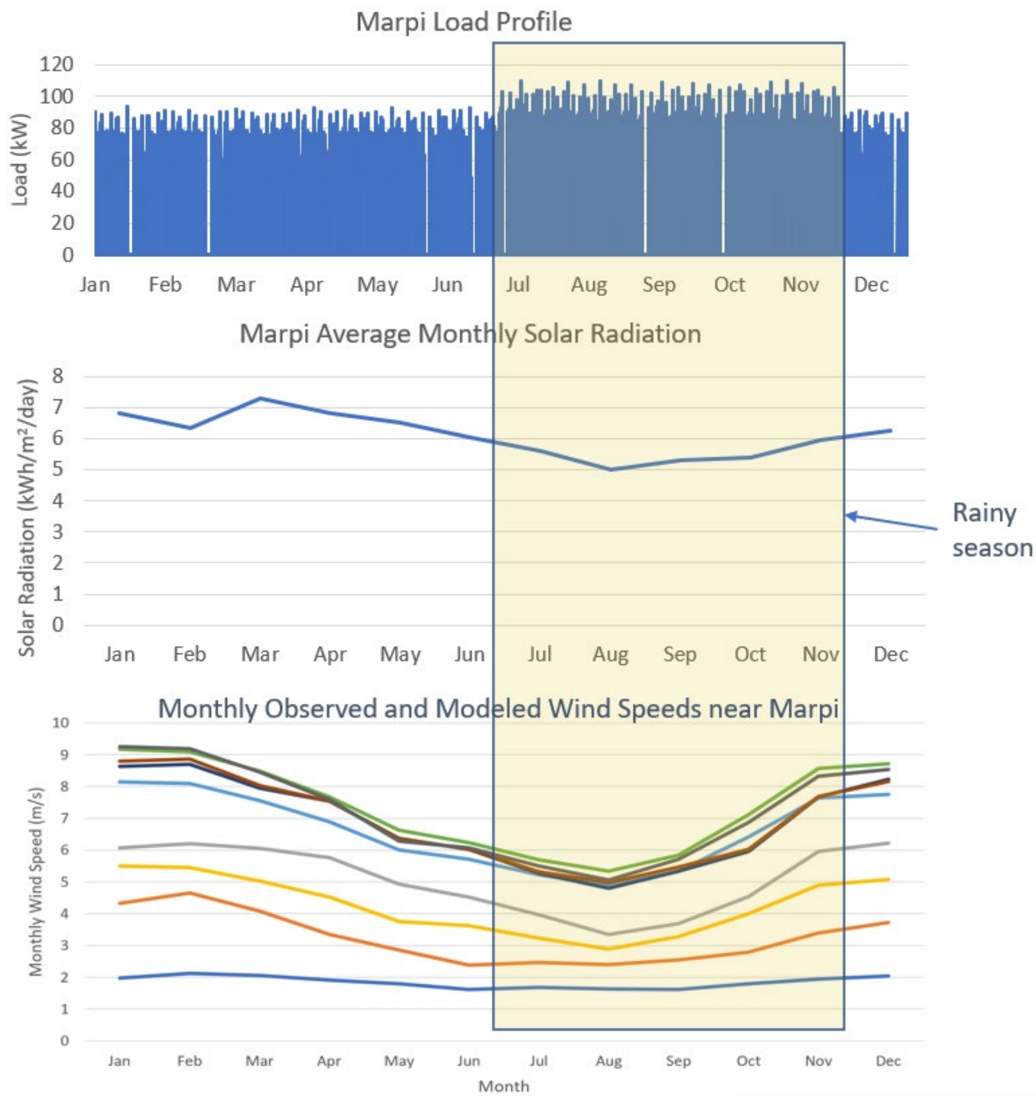

Figure ES-2. Rainy Season Impacts on Marpi Landfill Loads and Solar and Wind Resources

The seven scenarios evaluated are summarized in Table ES-1. Each scenario's configuration was optimized to include component capacities that reduce capital and operating costs, meet the load, and minimize carbon emissions, as feasible. The costs and levelized cost of energy (LCOE) shown do not assume the use of any grant funding or incentives, although these options were also evaluated.

Table ES-1. Summary of Evaluated Scenarios

Scenario*	Solar PV (kW)	Wind Turbine (kW)	Diesel Generator (kW)	Battery (kW/kWh)	Capital Cost ($M)	Annual O&M Costs ($k/yr)	25-year LCOE ($/kWh)	% Renewable Energy Curtailed Annually	% Load Not Met Annually	CO_2e Emissions Generated (tons/yr)
1	200	0	0	350/1400	4.5	8	1.93	50%	0%	0
2	0	100	0	300/1200	3.6	19	2.75	37%	34%	0
3	150	100	0	260/1040	4.3	20	1.86	61%	0%	0
4	100	0	160	75/300	2.3	18	0.96	15%	0%	22
5	0	100	160	100/400	2.7	55	1.44	46%	0%	54
6	100	100	160	60/120	2.9	25	1.17	56%	0%	12
7	0	0	160	0	0.5	90	0.75	0%	0%	122

* Scenario 1: Solar PV + BESS
Scenario 2: Wind + BESS
Scenario 3: Solar PV + Wind + BESS
Scenario 4: Solar PV + BESS + Diesel Generation
Scenario 5: Wind + BESS + Diesel Generation
Scenario 6: Solar PV + Wind + BESS + Diesel Generation
Scenario 7: Diesel Generation Only

Without grants, diesel generation alone (scenario 7) has the lowest capital cost and the lowest LCOE, but the highest annual operations and maintenance (O&M) costs. Scenario 4, with solar PV, BESS, and diesel generation, has the lowest LCOE of the scenarios that use renewable energy. The three scenarios that do not use any diesel generation (scenarios 1-3) have the highest capital costs and the highest LCOEs, but some of the lowest annual O&M costs, with solar PV and BESS (scenario 1) having the least O&M. The use of grants that may be available for purchase and installation of renewable energy technologies and energy storage results in the diesel generation-only scenario being the least economically attractive and the scenarios without diesel generators being the most attractive.

The potentially preferred location for a microgrid identified by the CNMI Project Team is in the southwest corner of the landfill property, near the location of the existing generator and electrical switchgear. A potential project layout that includes all microgrid components considered is presented in Figure ES-3, indicating potential component sizes that will fit within this space. New generators and batteries could be placed next to or at the current generator location. PV panels could be placed on a structural steel-framed roof structure shading the residential dropoff point, in addition to some ground-mounted panels. The wind turbine pictured represents a 100-kW turbine and is shown for scale relative to the other pieces of equipment.

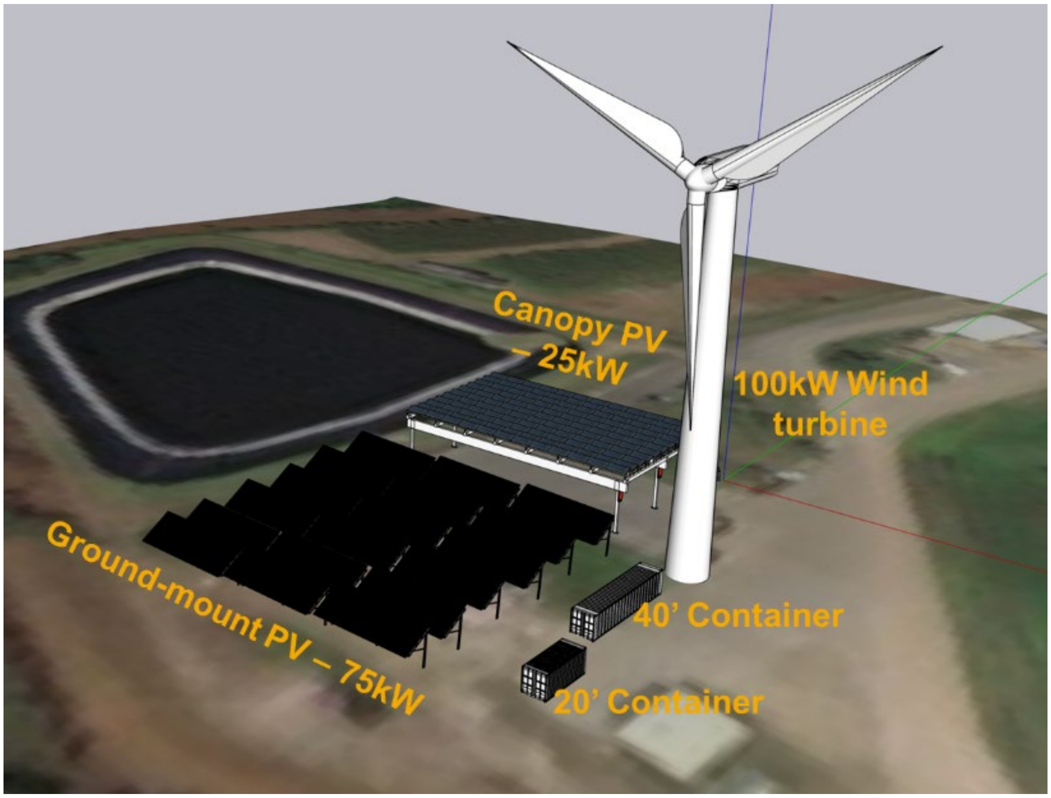

Figure ES-3. Potential Layout for Microgrid Components on Landfill Property

Several key hazards were identified for the Marpi microgrid; hardening techniques to reduce the risk of damage to the microgrid components from these hazards are summarized in Table ES-2. Existing projects on Saipan were found to follow these techniques, such as the PV system at the Commonwealth Healthcare Corporation that is designed to withstand 200 mph winds.

Table ES-2. Hardening Techniques for Microgrid Components at Marpi Landfill

Technology	Typhoons	Aerosol Salt Deposition	Earthquakes
PV panels	Wind-load rated racking to withstand ~200 mph winds and panel protection from flying debris (e.g., FEMA guidance, IEC 61730 and IEC 61215 certification)	Panels that comply with IEC 61215 standards for salt mist corrosion; UL 1703; NEMA 4X-6P rated enclosures for ancillary equipment	Rack ratings for seismically active areas (ASCE 7-10 design categories)
Wind turbines	Tilt-up technology; rotor braking; ballast foundation	Similar standards for salt mist corrosion as PV	American Clean Power Standard 61400-1 includes seismic loading recommendations
Generator, BESS	Hardened enclosure with NEMA / IP ratings; structural fencing	NEMA rated enclosure; CARC paint; MIL-STD 810G compliance IEC 61427 and 62933 and IEEE 1679 (batteries, environmental conditions)	Seismic retrofits and anchoring (e.g., for fuel tanks); adherence to Unified Facilities Criteria (UFC 3-310-04); IEEE Recommended Practices for Seismic Design of Substations (IEEE 693-2005)

To assist with decision-making, a prioritization matrix (Table ES-3) was created to compare the microgrid scenarios evaluated in this feasibility study according to various stakeholder priorities. The prioritization metrics were chosen based on discussions with OPD and will be finalized through stakeholder feedback. The scenarios were given a score between 1 and 7 for each prioritization metric (the lower the score, the higher the priority), and total scores were calculated using assigned weights based on the relative priority of each metric. The total scores were then ranked to produce a prioritized list of microgrid scenarios based on the metrics most important to the project stakeholders. As shown, scenario 4 (100 kW of solar PV, a 75 kW/300 kWh BESS, and 160 kW of diesel generation) ranks highest.

There are several aspects of implementing a microgrid that are important to consider once the equipment configuration and characteristics have been evaluated and prioritized. These include funding opportunities, procurement, ownership, operations and maintenance (O&M), and training. Evaluation of additional factors can provide further information that will allow refinement of the recommended equipment capacities. While the specific scenarios to include in the assessment were collaboratively chosen, others may warrant consideration. More refined inputs and the use of more complex optimization tools will lead to a solution that best suits the Marpi Landfill and supports sustainable and environmentally compliant operations at the site.

Table ES-3. Prioritization of Marpi Power Supply Scenarios

	Capital Cost ($M)	Annual O&M Costs ($k/yr)	25-year Levelized Cost of Energy ($kWh)	% Load Not Met Annually	Meets Permit Req. for Backup Power	CO_2e Emissions Generated (tons/yr)	Area Req. (ft^2)	Diversity of Resources (# of components)	Equipment Hardening Req.	Training Req.	Smart Safe Growth*		
Relative Metric Priority	1	5	1	3	4	1	3	3	1	2	2	**Total Weighted Score**	**Rank**
Scenario 1	7	1	6	3	7	1	4	5	2	3	2	**3.17**	**4**
Scenario 2	5	3	7	7	7	1	4	5	5	3	5	**4.17**	**7**
Scenario 3	6	4	5	3	7	1	4	2	6	5	5	**3.77**	**6**
Scenario 4	2	2	2	1	1	5	1	2	3	5	4	**1.87**	**1**
Scenario 5	3	6	4	1	1	6	4	2	4	5	7	**3.20**	**5**
Scenario 6	4	5	3	1	1	4	4	1	7	7	6	**3.03**	**3**
Scenario 7	1	7	1	1	1	7	1	7	1	2	5	**3.00**	**2**

* Please see Appendix E for Smart Safe Growth analysis of proposed options.

Acknowledgments

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This feasibility study was funded by the Federal Emergency Management Agency, through its Interagency Reimbursable Work Agreement with the U.S. Department of Energy.

Acronyms and Abbreviations

AC	alternating current
BECQ	Bureau of Environmental and Coastal Quality
BESS	battery energy storage systems
BOP	balance of plant
CHCC	Commonwealth Healthcare Corporation
CNMI	Commonwealth of the Northern Mariana Islands
CO_2e	carbon dioxide equivalent
CUC	Commonwealth Utilities Corporation
DOE	Department of Energy
DC	direct current
DPW	Department of Public Works
EPA	US Environmental Protection Agency
FEMA	Federal Emergency Management Agency
GHG	greenhouse gas
GWA3	Global Wind Atlas 3
IPP	Independent Power Producer
IRA	Inflation Reduction Act
IRWA	Interagency Reimbursable Work Agreement
ITC	investment tax credit
LCOE	levelized cost of energy
Li-ion	lithium-ion
MES	Micronesian Environment Services, LLC
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Database
O&M	operations and maintenance
OPD	Office of Planning and Development
PM	particulate matter
PV	photovoltaics
SoC	state of charge
SW	Solid Waste

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1.0 Introduction

The Marpi Landfill is located in a remote area on the northern end of the island of Saipan in the Commonwealth of the Northern Mariana Islands (CNMI). It is not served power by the local utility, but rather by an on-site diesel generator that only operates when the landfill is open and staffed. Marpi is owned by the CNMI government and operated by a contractor, Micronesian Environment Services, LLC (MES), who also operates the generator.

The CNMI's Inter-island Solid Waste Management Taskforce (SW Taskforce) is comprised of representatives from the Department of Public Works (DPW), the Office of Planning and Development (OPD), Bureau of Environmental and Coastal Quality (BECQ), representatives from offices of the Mayors, and U.S. Environmental Protection Agency. The SW Taskforce was established in 2020 to support ongoing disaster response and recovery as it relates to solid waste and develop comprehensive and sustainable integrated solid waste management systems for the CNMI. It studies, makes recommendations, builds capacity, and implements projects to improve waste management across the islands, including landfill operations, recycling programs, and reuse initiatives. Members of the SW Taskforce representing DPW Saipan, BECQ, and OPD comprise the CNMI Project Team.

The CNMI Project Team aspires to provide Marpi with 24-hour power availability despite its remote location, and to increase sustainable energy consumption within the CNMI. Accordingly, this feasibility study assesses and prioritizes power supply options to determine the optimal method for serving the landfill while meeting both reliability and sustainability goals.

1.1 Background

The need for a Backup Power Feasibility Study for the Marpi Landfill was first identified as a need to build capacity and resilience to natural disasters by the CNMI Project Team and the U.S. Environmental Protection Agency (EPA) Region 9 in early 2021. Due to its remote location on the north end of Saipan, Marpi has never been connected to the main power grid operated by the Commonwealth Utilities Corporation (CUC) and has instead been powered by diesel generators since it opened in 2003.

The CNMI Project Team solicited proposals in September 2021 for the development of a power supply feasibility assessment and cost benefit analysis for the leachate pump system and other operational loads serving the Marpi Landfill. Due to a lack of positive responses to the solicitation, the Project Team requested technical assistance from the U.S. Federal Emergency Management Agency (FEMA) and the Department of Energy (DOE) to conduct the analysis. FEMA provided funding allocated by its Interagency Reimbursable Work Agreement (IRWA) with DOE for energy recovery technical assistance in CNMI to fulfill this technical assistance request. This activity falls under deliverable 3 of the IRWA: technical and advisory assistance to the CNMI, and CNMI public entities, to support the federal investments made for the long-term resilient recovery of the CNMI's power system.

Key stakeholders who will provide feedback to support power supply improvements to Marpi include members of the CNMI Inter-island Solid Waste Management Taskforce (SW Taskforce): representatives from the DPW, OPD, Bureau of Environmental and Coastal Quality, offices of the mayors, and the EPA. The SW Taskforce was established in 2020 to support ongoing disaster response and recovery as it relates to solid waste and develop comprehensive and sustainable integrated solid waste management systems for the CNMI. The SW Taskforce studies, makes recommendations, builds capacity, and implements projects to improve waste management across the islands, including landfill operations, recycling programs, and reuse initiatives. The members of the SW Taskforce have provided local insights and perspective on current and future power needs at the landfill and considerations for various power supply options. As the lead agency in solid waste infrastructure management, the DPW is the ultimate decision maker regarding how the recommendations developed in this study will be incorporated into future Marpi Landfill operations and subsequent permit amendments and facility updates.

In response to the technical assistance request and in alignment with SW Taskforce direction, this feasibility study explores alternative energy options that support the following local goals and strategic plans:

- Expand use of residential and commercial rooftop solar PV systems to accomplish the CNMI Strategic Energy Plan's vision of creating a sustainable energy future for the CNMI (GHD 2022);
- Ensure access to affordable, reliable, sustainable and modern energy for all, which is Sustainable Development Goal #7 in the Comprehensive Sustainable Development Plan and sets a target of 20% renewable energy portfolio for power needs by 2030 (OPD 2021);
- Support sustainable and environmentally compliant waste management systems in the CNMI, which is a component of Sustainable Development Goal #12 in the Comprehensive Sustainable Development Plan (OPD 2021); and
- Achieve 20% of electricity sales from renewable resources by 2016, a target set by the CNMI renewable portfolio standard (Public Law 18-62, GPO 2014)

Ensuring Marpi can sustainably continue operations is a critical part of achieving these goals.

1.2 Scope

This report presents each step of the feasibility analysis. Inputs to the analysis include a characterization of current and future landfill electric loads (Section 2.0) and an understanding of power supply options available for Marpi (Section 3.0). Using these inputs, a technical and economic evaluation of various power supply scenarios was conducted, as presented in Section 4.0. Additional considerations for project feasibility include potential project siting options and considerations (Section 5.0) and natural hazard risks and mitigation (Section 6.0). Various stakeholders provided input on the prioritization of scenarios (Section 7.0); implementation considerations including funding, procurement, ownership, and training options are discussed in Section 8.0; and overall project recommendations and next steps are presented in Section 9.0.

2.0 Landfill Operations and Estimated Loads

The Marpi Landfill typically operates Monday through Saturday from 7:30 a.m. to 4:30 p.m. It closes during severe weather-related emergencies, and after it reopens the operational hours can change from 6 a.m. to 6 p.m. as needed. During or after high rainfall conditions, the operating hours may also change from 6 a.m. to 6 p.m., and pumps are used to control leachate and stormwater levels during these extended hours. Pumps are not used outside of these hours because the generator is turned off when the landfill is unoccupied.

The landfill consists of an office building, scale house, maintenance building, generator house, and several landfill cells (Figure 1). Cell 1 is the existing operational area, which is nearly full. Cell 2 is currently under rehabilitation, and Cell 3 is the future operational area, the design of which has been completed. This feasibility analysis included landfill operations up to the useful lives of Cell 2 and Cell 3. Cell 1 is expected to have a useful life of 2 to 3 years remaining; Cell 2 is presently under construction and is anticipated to start receiving solid waste next year. Based on current waste loads, population growth trends, and CNMI economic activity, it is estimated that Cell 2 would have a service life of about 11 years. Cell 3 has not been constructed and is designed to have a service life of about 10 years. The operations of Cell 2 and Cell 3 will involve some variability in loads but this is not expected to affect the findings of this study since only one cell is planned to be used at any one time.

Figure 1 . Marpi Landfill Cell Layout; Structures are all West of Cell 1

From 2002 to 2014, a DPW-owned 200 kW diesel generator powered Marpi. In 2014, this generator became unserviceable, and DPW rented a 175 kW diesel generator to provide power while awaiting the procurement of a 125 kW diesel backup generator. The 175 kW rental was used until DPW procured the 125 kW backup generator in 2015. DPW intended to use this backup generator to provide power to the landfill until DPW repaired the 200 kW generator.

However, the backup generator frequently broke down between 2015 and 2017 due to overuse and being operated above its rated capacity. Continuous power supply is necessary for leachate pumping operations to ensure that leachate accumulating above the HDPE liners are maintained at a level not to exceed 12 inches as required by CNMI and RCRA regulations.

Between 2017 and 2020, DPW resorted to renting a 175 kW diesel generator to meet the power requirements of the landfill. This generator was the primary source of power for Marpi until a new operator/maintenance contractor began their contract in 2021. Since 2021, a 125 kVA rental diesel generator has been the sole source of power for the landfill. This generator is not metered, and as such there is no hourly load data available.

To characterize current and future loads, an hourly load profile for the landfill was generated based on information provided by the DPW and the site operator. Marpi's power requirements are driven by pump loads; to keep the leachate below a certain level, pumps are running the majority of the time the landfill is open. Within buildings, air conditioning and lighting are the main power draws. Due to increased pump usage to control leachate levels during the rainy season, the facility's load correspondingly increases. This profile assumes that future operations remain the same as they are currently. The energy use of some equipment that is not currently functional is included in this profile, as well as that of some future loads such as the pumps for Cell 3. More information on the load descriptions, power draw, duty cycles, and assumptions used to generate the hourly load profile is detailed in Appendix B.

Based on the estimated loads for each end use characterized by the DPW team and the landfill operators (MES), the landfill's annual consumption is estimated to be 170 MWh, with a peak load of 112 kW. Figure 2 shows the hourly load profile for a typical year, and Figure 3 shows the hourly load profile for a typical week during both the dry and rainy seasons, respectively.

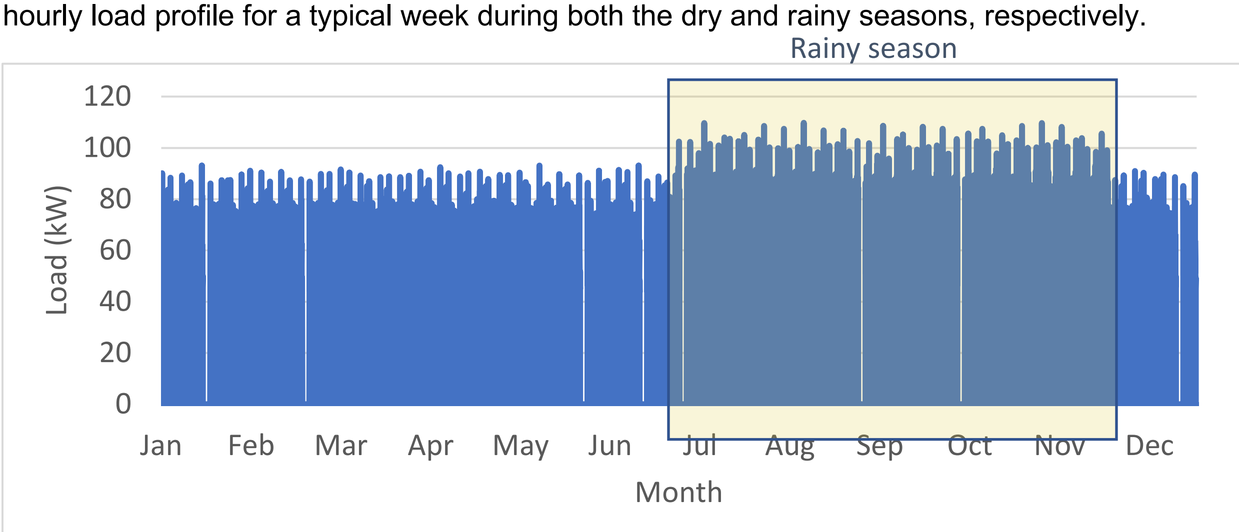

Figure 2. Hourly Marpi Landfill Load Profile

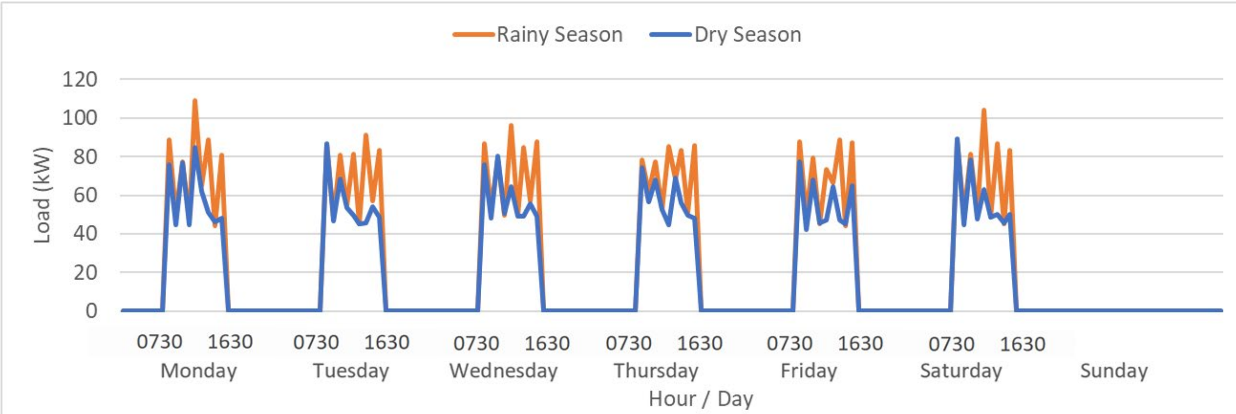

Figure 3. Typical Weekly Marpi Landfill Load Profile

This load profile was used as input for the technical and economic evaluation of various power supply scenarios described in the following section.

3.0 Power Supply Options

Power for Marpi can be supplied via renewable energy and/or fuel-based generation. A resource screening was conducted to determine the best options to evaluate in more detail, and then the most promising options were characterized in terms of resource availability and technical feasibility.

3.1 Resource Screening

Several different renewable energy and other energy resources were initially considered for providing power to the landfill. Table 1 summarizes the various options and describes why or why not they are included in this feasibility study. These determinations also align with the Draft CNMI Strategic Energy Plan (GHD 2022).

Table 1. Summary of Potential Power Supply Sources for Marpi Landfill

Potential Power Sources to Consider	Include in Feasibility Study?	Justification
Solar photovoltaics (PV)	Yes	Solar energy is abundantly available on island.
Wind turbines	Yes	Small wind turbines have been installed on the island and the wind resource appears to be strong.
Battery storage	Yes	Required with intermittent renewables to provide power when renewable resources are unavailable and for system stability.
Diesel generator	Yes	Previously used/proven.
CUC grid connection	No	Was previously investigated and determined to be cost-prohibitive and infeasible due to local opposition (see below).
Biodiesel generator	No	Would require an existing supply of biodiesel in the region. Currently unavailable.
Landfill gas	No	No existing gas collection system. Landfill is too small for required scale of production.
Waste-to-energy	No	Marpi loads are much smaller than potential output of a cost-effectively sized system, and there is insufficient waste on island for system to be cost-effectively sized and operated.
Geothermal power	No	Load is too small. Also, geothermal resources may exist on Saipan, but exploration is high risk due to limited surface or subsurface evidence (Baring-Gould, et al. 2011).
Ocean Thermal Energy Conversion	No	Technology is immature; insufficient loads at Marpi for ocean thermal energy conversion scale requirements.

Connection to the local CUC grid was previously investigated and resolved in court in 2012 (Castext 2012). The landfill is located approximately 2 miles away from the nearest grid power line. The Marpi area is only sparsely populated by subsistence farmers who do not have connections to utility supplies of power or water. Previous attempts to provide the Marpi Landfill with reliable 24-hour grid power were met with prohibitive cost estimates and opposition by public interest groups. These groups do not support large infrastructure projects in the Marpi area to preserve the natural and historical environment. For the scoping of this assessment, the

Project Team suggested that given restrictions on use of utility poles in the Marpi Conservation Area and the high cost of underground utility line deployment, the feasibility of connecting Marpi to the CUC electrical grid did not warrant any further investigation at this time, acknowledging conditions might change that would justify revisiting this option in the future.

3.2 Resource and Technology Descriptions

Based on the outcome of the screening analysis documented in Table 1, solar PV, wind turbine, battery storage, and diesel generator technologies are evaluated and discussed below. For these systems to work together to provide power to the landfill, microgrid controls are also needed in addition to other balance-of-plant (BOP) equipment as described in Section 3.2.5.

3.2.1 Solar PV

Solar PV is a renewable energy technology commonly used around the world, especially in locations with high solar availability such as the CNMI. It is low maintenance and the number of installations on Saipan continues to grow.

3.2.1.1 Technology

Solar PV arrays consist of panels installed in “strings” with inverters to convert direct current (DC) electricity to alternating current (AC). A transformer may be required to convert power to the appropriate voltage. The BOP includes the inverter, transformer, wires, mounts, racks to hold the panels, and other ancillary equipment that allows the produced power to safely and effectively integrate into an electrical distribution system.

The method by which panels are mounted onto the ground or structures is determined by several factors including availability of space, structural integrity, and cost. The mounting method influences power and energy production. Ground-mount arrays are generally the least expensive and have several options for securing the panels to the ground, including ballasts and drilled piles or piers. Roof-mounted arrays require assessments of the structure’s ability to handle both the weight of the system and the added wind loading. Penetrations may be required to secure the panels depending on the roof type and slope. Panels can also be placed on elevated structures, typically used for shading parking spaces. This is the most expensive mounting method because of the added cost of the structure but may be the most practical for many applications where available ground or roof areas are lacking.

All three mounting methods may use fixed-tilt panels; axis-tracking models are typically reserved for ground-mounting only. Fixed-tilt panels are typically installed at an angle equal to the latitude of the installation location, facing south (in the Northern Hemisphere), and do not move. Axis-tracking racks allow the panels to follow the sun’s path across the sky throughout the day. Single-axis-tracking systems tilt the panels to face the sun as it travels from east to west and the entire assembly is often tilted at an angle equal to the site latitude.

Solar PV arrays can be sized on an incremental basis to match the available area of a specific location or the load being served. Any number of PV panels can be installed to form an array. As more panels are installed together, more space is required beyond the size of the panel to allow for BOP equipment and spacing between panels. Proper spacing is required to avoid self-shading within the array and to allow access for cleaning and maintenance.

3.2.1.2 Resource Availability

Saipan has an abundant solar resource that averages 6.1 kWh/m^2/day—comparable to Los Angeles, California. Solar resource estimates for the island of Saipan come from the National Renewable Energy Laboratory's (NREL) National Solar Radiation Database (NSRDB), which contains decades of solar radiation data covering the United States and some international locations (Sengupta, et al. 2018). Figure 4 shows the solar resource for the CNMI and Guam to be at the high end of the irradiance scale, based on the available 10 years of data.

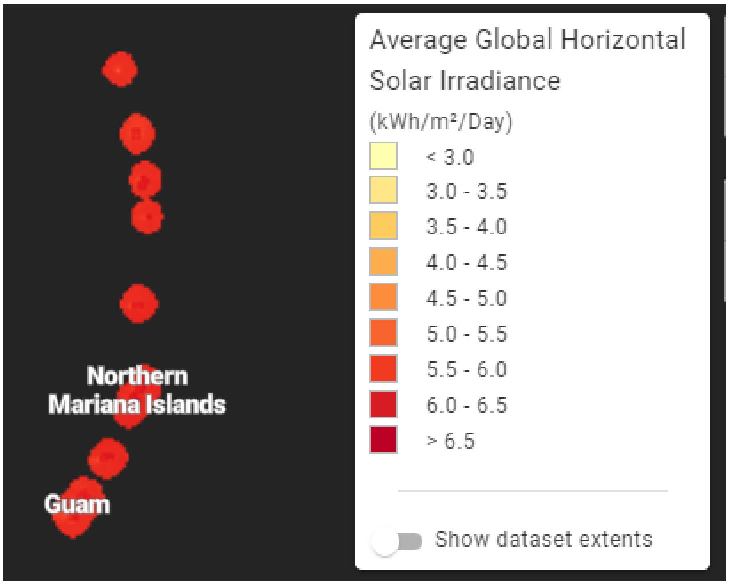

Figure 4. Solar Resource for the CNMI and Guam (NSRDB)

This resource is seasonal; there is more solar energy available during the dry season (December–June) and less during the rainy season (July–November) when cloud cover is more frequent. Figure 5 displays the average monthly solar radiation available at Marpi (lat: 15.25°N, long: 145.78°E) based on NSRDB data.

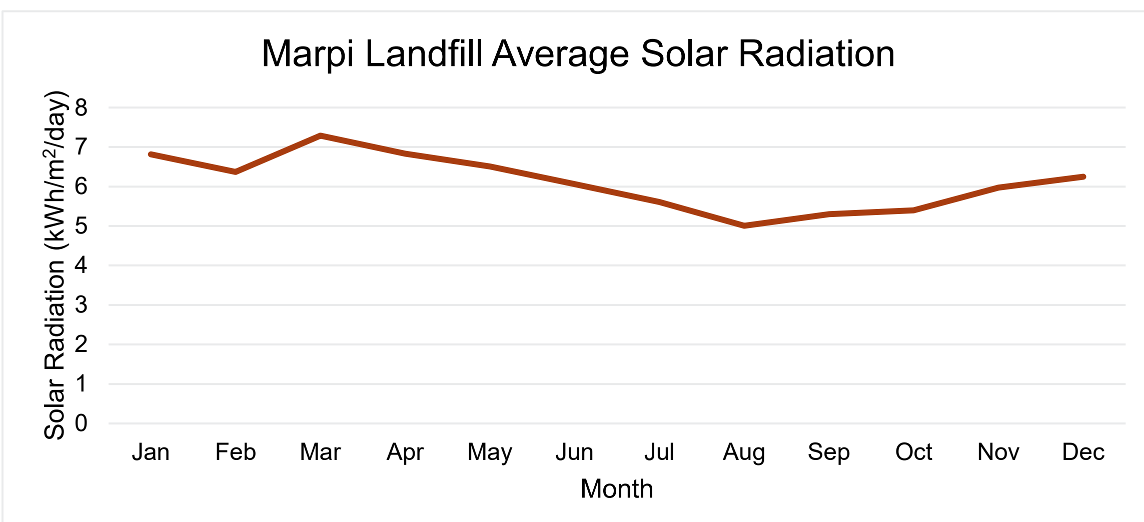

Figure 5. Monthly Variation of Solar Radiation Available at Marpi Landfill

The NSRDB distills many years of radiation data into a single typical meteorological year, which is a year of hourly data that represents median weather conditions over many years. The PVWatts® calculator[1] uses these data to estimate the energy production of user-defined solar PV systems (Dobos 2014). According to PVWatts, a 100 kW solar PV array facing due south and tilted 15°–20° will generate 170 MWh over a typical year, as shown in Figure 6. Systems tilted at an angle equal to their latitude maximize generation throughout the year, but 20° is a standard tilt angle.

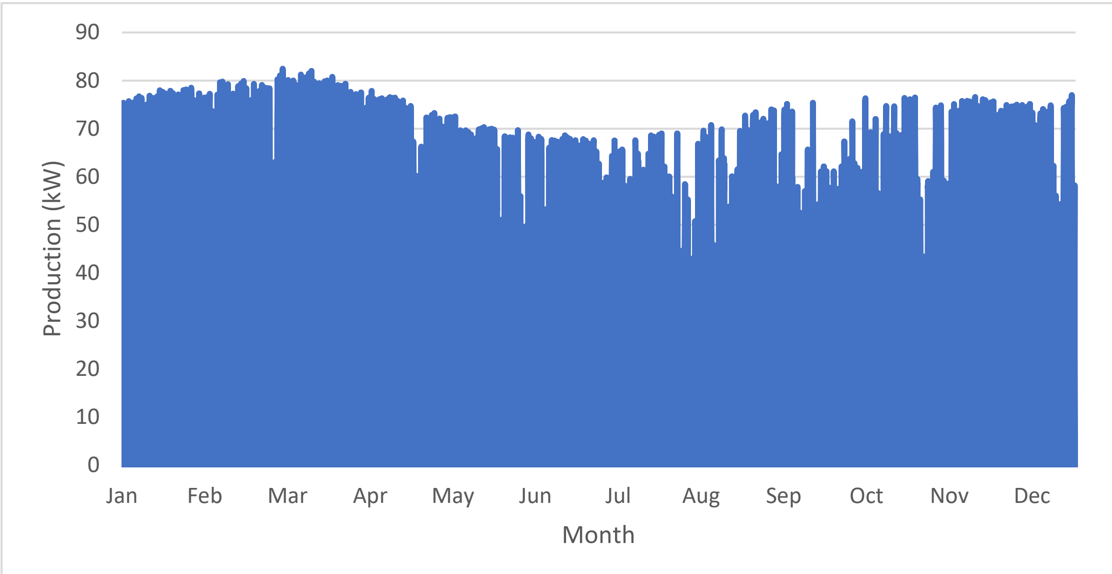

Figure 6. Hourly Output from 100 kW PV Array Facing Due South and Tilted 15°–20°

3.2.1.3 Operation and Maintenance

Operations and maintenance (O&M) for solar PV is relatively simple, especially for fixed-axis systems with no moving parts. The primary tasks that will help keep a system operational and optimize performance include module cleaning, vegetation and pest management, system inspection/monitoring, and minor component parts replacement. On Saipan, the regular rainfall may be sufficient to keep panels clean, as demonstrated by other local PV projects. However, the presence of dust at the landfill and the site's proximity to the ocean (and resulting sea spray) may result in buildup on the panels and require additional cleaning to avoid reduction in output. See Section 8.4 for a discussion of O&M responsibilities and training needs.

3.2.1.4 Example Local Projects

There are several installed solar PV arrays on Saipan, ranging in age from over a decade in service to less than a year online to not yet operational. According to the draft CNMI Strategic Energy Plan (GHD 2022), there is over 5 MW of small-scale solar PV installed on residences, public buildings, and schools across Saipan. Micronesia Renewables is the primary solar installer in the region. A few example systems are discussed below.

The largest PV system on Saipan is the 650 kW carport array at the Marianas Business Plaza (Figure 7), which was installed in 2015. It is net metered by CUC and shuts down if grid power is

[1] https://pvwatts.nrel.gov/

lost. The system is maintained by building maintenance personnel, who manually wash the panels with a mixture of rainwater and polywater approximately four times per year. The system's monitoring software was purchased with ongoing monitoring and remote diagnostic services. Aside from replacing panels lost during the typhoons, the system has required minimal parts replacement over its life. Performance has degraded approximately 15% since 2015, which is higher than expected for PV systems (approximately 2% per year instead of 0.5% per year).

Figure 7. Marianas Business Plaza Solar PV System

The roof of the DPW building supports a 2.86 kW PV system (Figure 8) that was installed in 2011. This system has sustained operations through two typhoons without degradation in performance over the years and no O&M has been performed. Frequent rain keeps the panels clean. The original installer is no longer in business, so if the system does have an issue, it will likely be decommissioned rather than repaired and the DPW building will make up for the loss of renewable energy by purchasing additional power from CUC.

Figure 8. Solar Panels on the DPW Roof

Figure 9 shows the output of the system over four years, which demonstrates a fairly consistent monthly production peak of around 460 kWh and a similar production profile each year, peaking in spring and declining in fall/winter, corresponding to the seasonal variation with the dry and rainy seasons.

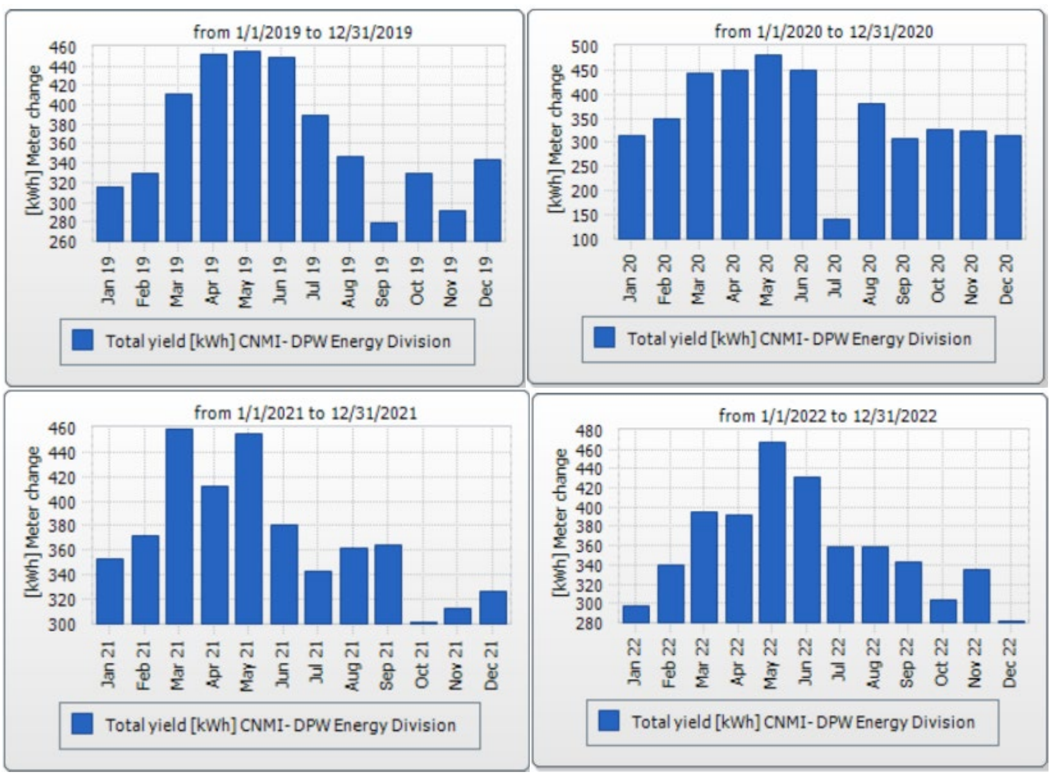

Figure 9. Electricity Production of DPW PV System for 2019–2022 (SunnyPortal 2023)

The Commonwealth Healthcare Corporation (CHCC) installed a 180 kW PV system (Figure 10) on its parking lot in 2019 and is planning to expand this by another 176 kW. The system saves CHCC money on their CUC electricity bills, but no power is sent back to the grid; it is all consumed on site. The system was built to withstand 200 mph winds by using 14 ft deep structural piers to secure the carport structures to the ground. CHCC staff reported no issues with performance or O&M to date.

Figure 10. CHCC Carport Solar PV System

The Public Schools System is installing solar PV across their facilities through a lease with Micronesia Renewables. Marianas High School has an older system that is no longer operational due to an inverter failure and another system (Figure 11) that was installed in March 2022 but has not yet been able to obtain CUC approval to begin operation.

Figure 11. Solar PV Installed at a Marianas High School Building

3.2.2 Wind Turbines

Wind turbines are used to supply renewable energy for local loads around the world. For wind energy to be economical, the available wind resource at a site of interest must exceed certain thresholds, which is explored in Section 3.2.2.2. Operations costs for distributed wind turbines tend to be low; however, maintenance costs can be substantial in remote parts of the world. Tilt-up technology, which allows wind turbines to be lowered in advance of potentially damaging weather, is explored as an option to mitigate maintenance costs.

3.2.2.1 Technology

Wind turbines are machines that convert the kinetic energy of wind into electrical energy. They are composed of a tower, rotor (which includes the blades), and nacelle (which houses a generator and other power conversion components). Like solar energy, wind turbines can be sized according to energy need. One way to align energy supply and demand is by selecting an appropriate turbine generator and hub height. The hub height is the height of the tower where the rotor is mounted. Higher hub heights correspond to greater wind energy production since wind speed tends to increase with height above ground. The turbine tip height is the hub height plus the length of the blades, i.e., the total height of the wind turbine.

While most wind turbines remain vertical for their lifetimes, tilt-up technology is available for turbines deployed in areas subject to extreme weather. Tilt-up technology allows the entire wind turbine, including the tower, to be lowered in advance of extreme weather to mitigate potential damage to the system.

A variety of wind turbine designs are available, including horizontal- and vertical-axis turbines with different numbers of blades. Three-bladed horizontal-axis turbines are the most efficient design and are therefore the most widely used in the United States.

The 100 kW Northern Power Systems 100-28 3-bladed wind turbine is selected as the optimal turbine model to supply the load at Marpi (Table 2). Two tower and hub height options are considered: a standard tower option with a higher hub height of 37 m (121 ft) to maximize wind production and a tilt-up tower at a lower hub height of 23 m (75 ft) to reduce the potential turbine damage during severe weather, such as typhoons.

Table 2. Characteristics of a Potentially Suitable Wind Turbine for Marpi Landfill

Turbine Manufacturer/Model	Northern Power Systems 100-28 (Standard)	Northern Power Systems 100-28 (Tilt-up)
Nameplate Capacity	100 kW	100 kW
Hub Height	37 m (121 ft)	23 m (75 ft)
Tip Height	51 m (167 ft)	37 m (121 ft)
Land Area Required	8,171 m^2 (87,952 ft^2)	4,301 m^2 (46,296 ft^2)

3.2.2.2 Resource Availability

Saipan has a geographically diverse wind resource that is occasionally impacted by strong storms such as typhoons. Due to its remote location, the limitations of wind models and observations on Saipan urge the gathering of on-site measurements prior to reaching a decision on wind energy deployment. The specific location evaluated for wind feasibility is shown in Figure 12.

Figure 12. Location of Potential Wind Turbine Location at Marpi Landfill

Since existing wind observations in the Northern Mariana Islands are far from the location of wind development interest at Marpi and are not close to typical small wind turbine hub heights, models are employed to estimate the on-site hub height wind resource. The wind speed for Saipan from one model, Global Wind Atlas 3, is depicted in Figure 13.

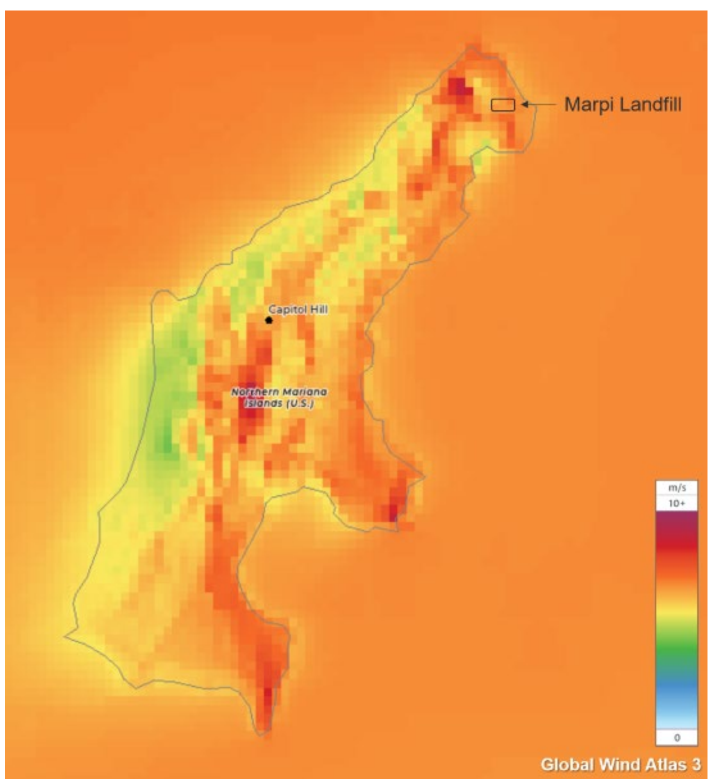

Figure 13. Wind Speed Map at 50 m from GWA3

Using the models and methods described in Appendix D, the geolocated wind speed estimates for average, high, and low wind resource years are provided in Table 3. To put these values in context, the cut-in wind speed, typically around 3 m/s, is the lowest at which a wind turbine can generate power. Considering this constraint and wind energy investment costs, project developers typically advise that annual average wind speed minima of 4 m/s (8.9 mph) at 30 m (98 ft) (DOE 2012) and 6.5 m/s (14.5 mph) at 80 m (262 ft) (DOE 2011) are required for feasible wind energy project development. Extrapolating these rules of thumb to the hub heights of interest for Marpi means that the annual average wind resource needs to be at least 3.7 m/s (8.3 mph) or 4.4 m/s (9.8 mph) for a feasible project using a wind turbine with a hub height of 23 m (75 ft) or 37 m (121 ft), respectively. As shown, even the lowest wind speed estimates meet these criteria.

Table 3. Annual Wind Speed Estimates based on Model Wind Data

Hub Height	Average Wind Resource Year	High Wind Resource Year	Low Wind Resource Year
37 m (121 ft)	5.1 m/s (11.4 mph)	6.4 m/s (14.3 mph)	4.4 m/s (9.8 mph)
23 m (75 ft)	4.3 m/s (9.6 mph)	5.5 m/s (12.3 mph)	3.7 m/s (8.3 mph)

While the annual speed estimates for an average wind resource year exceed the rule of thumb minima for both hub heights of consideration, it is important to consider that these are indeed estimates and accordingly the model wind speed error at nearby locations with observations must be examined. Figure 14 shows that the multi-annual average 10 m (33 ft) wind speed error for Global Wind Atlas 3 (GWA3) at Saipan International Airport and two locations on Guam ranges from -1.1 m/s (-2.5 mph) to +3.3 m/s (+7.4 mph). These errors are not necessarily indicative of the accuracy of wind speed estimates for Marpi, but provide a range of error possibilities to consider. As these errors are substantially greater than the difference between the Marpi estimates and the rule of thumb wind speed minima, on-site measurements are recommended to better inform decisions concerning the potential for wind energy development at Marpi.

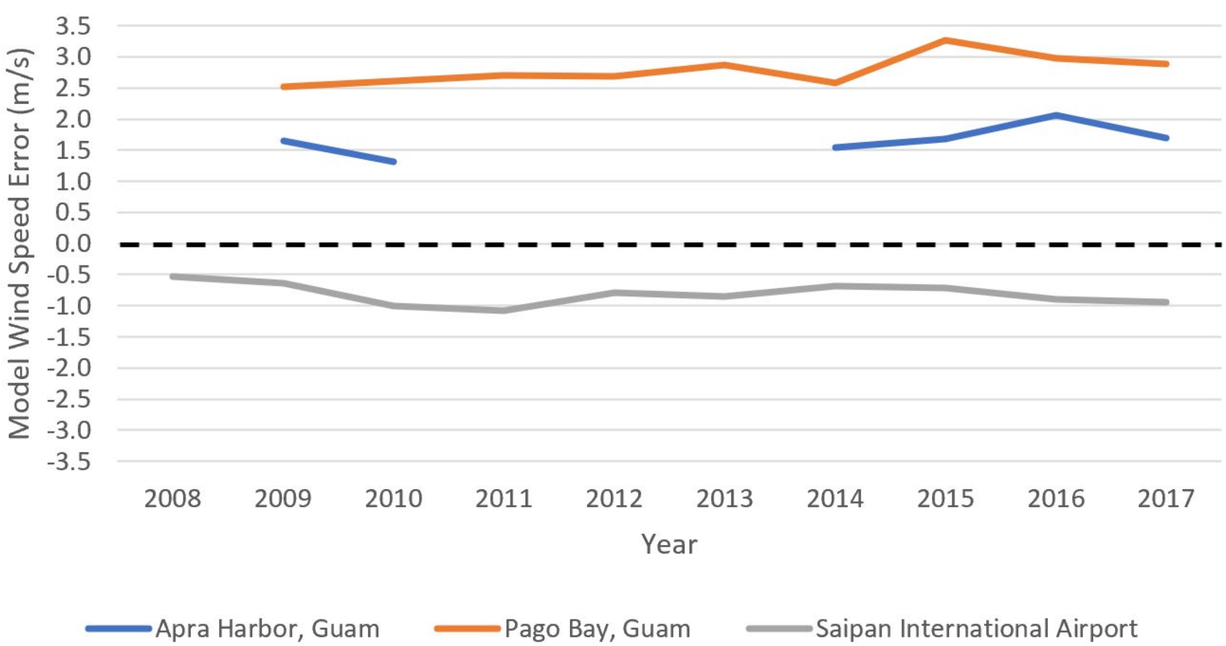

Figure 14. GWA3 Error at Locations with Wind Speed Observations on Saipan and Guam

Wind turbines exhibit generation loss for a variety of reasons. Table 4 displays the custom loss assumptions created for a potential wind project at Marpi and assumes higher loss for availability due to the length of travel likely required for personnel to perform maintenance, and environmental impacts due to the relatively frequent occurrence of severe weather. Other loss categories are assumed to be low, such as wake loss since the desired location for wind deployment at Marpi allows for a single turbine, and curtailment since the energy scenarios for Marpi feature battery energy storage systems (BESS).

Table 4. Wind Generation Loss Assumptions for Marpi Landfill

Loss Category	Typical Range	Notes	Marpi Assumption
Availability	4%-6%	Downtime for maintenance, assume higher end for lengthy travel likely required	6%
Wake (Array)	0%-15%	Not applicable for single turbine installations	0%
Turbine Performance	1%-3%	Assume high performance	1%
Electrical	2%-3%	Standard electrical losses	2%
Environmental	1%-10%	Assume weather, such as typhoons, may disrupt production	10%
Curtailment	0%-3%	All scenarios include BESS	0%
Total	12%-25%		19%

Combining the wind speed estimates presented in Table 3, the Northern Power Systems 100-28 power curve, and the loss assumptions in Table 4 yields net generation estimates ranging from 121,050 kWh to 288,300 kWh for the 37 m (121 ft) hub height and 75,850 kWh to 208,150 kWh for the 23 m (75 ft) hub height, depending on the wind resource year (Table 5).

Table 5. Annual Gross and Net Wind Generation Estimates based on Model Wind Data and the Northern Power Systems 100-28 Wind Turbine

	Gross Generation			Net Generation		
Wind resource year	Average	High	Low	Average	High	Low
37 m (121 ft) Hub Height	228,450	355,950	149,450	185,050	288,300	121,050
23 m (75 ft) Hub Height	153,450	256,950	93,600	124,300	208,150	75,850

The available wind resource varies throughout the time of day and year. At locations around Saipan and Guam, wind observations and models are in agreement that the lowest wind speeds of the year occur during the summer and early fall (Figure 15), which corresponds with the rainy season from July to November, and is the period of greatest energy need at Marpi. The monthly energy estimates for an average wind resource year are displayed in Figure 16 to assess the impact of seasonal variation in the wind resource on expected wind production.

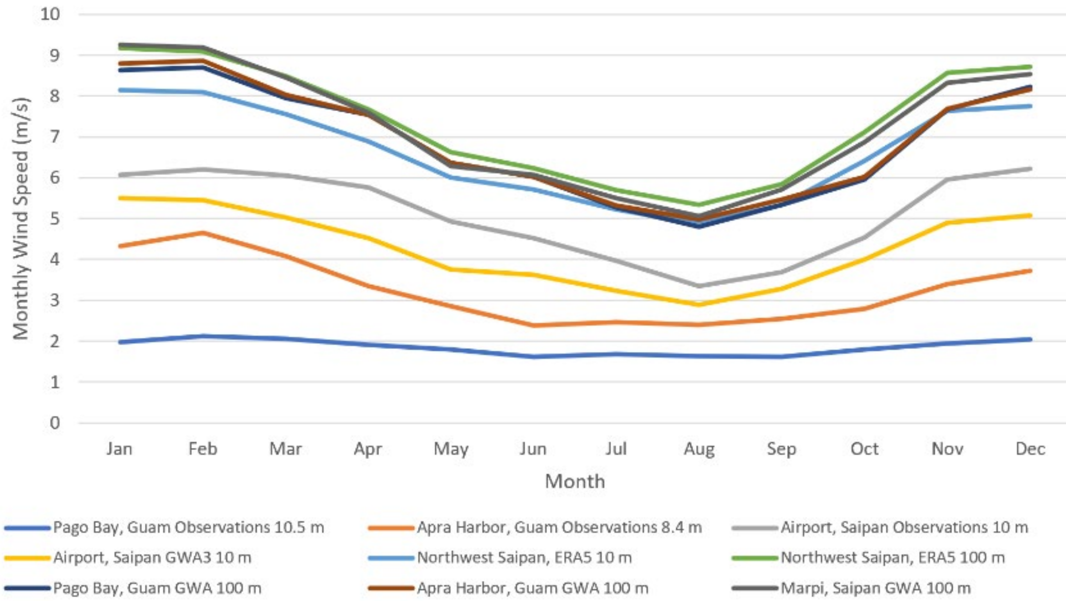

Figure 15. Monthly Observed and Modeled Wind Speeds near Marpi Landfill

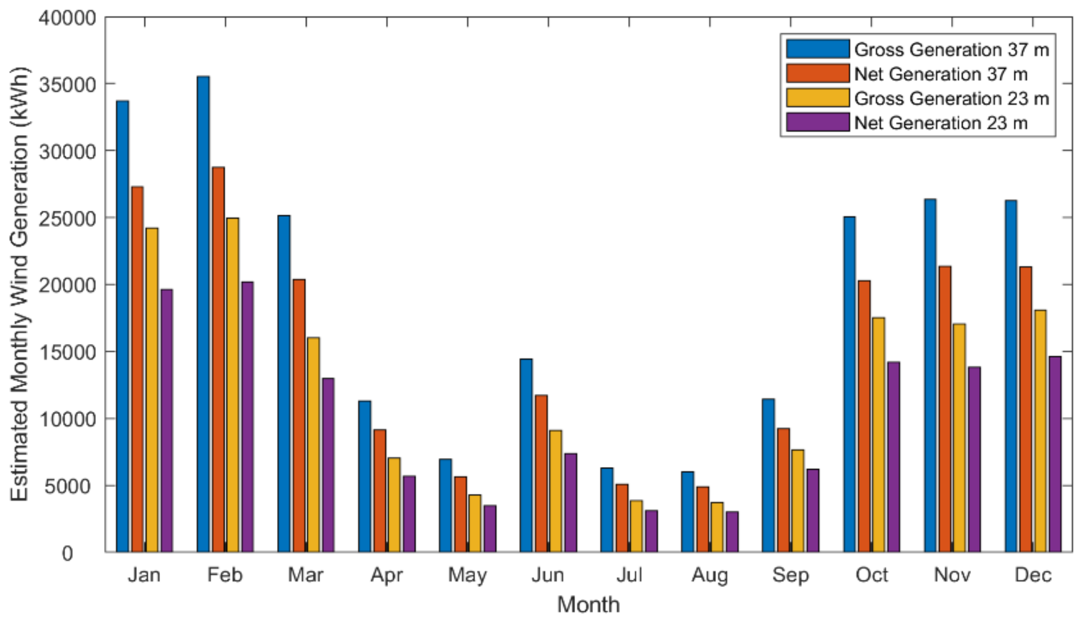

Figure 16. Estimated Monthly Gross and Net Wind Generation for an Average Wind Resource Year

The wind resource in the region of Marpi can also vary throughout the day and night. Figure 17 shows significant variation in local wind speeds throughout the day and night from observations near the surface, while the models show little to no variation with time of day. Due to the lack of observations at heights above 10 m (33 ft), it is impossible to tell whether the discrepancy in observed and simulated diurnal wind profiles is due to model performance issues or are accurate, since discrepancy in profiles with height above ground is normal and expected in many locations. On-site measurements would provide clarity on diurnal wind generation expectations in addition to annual expectations.

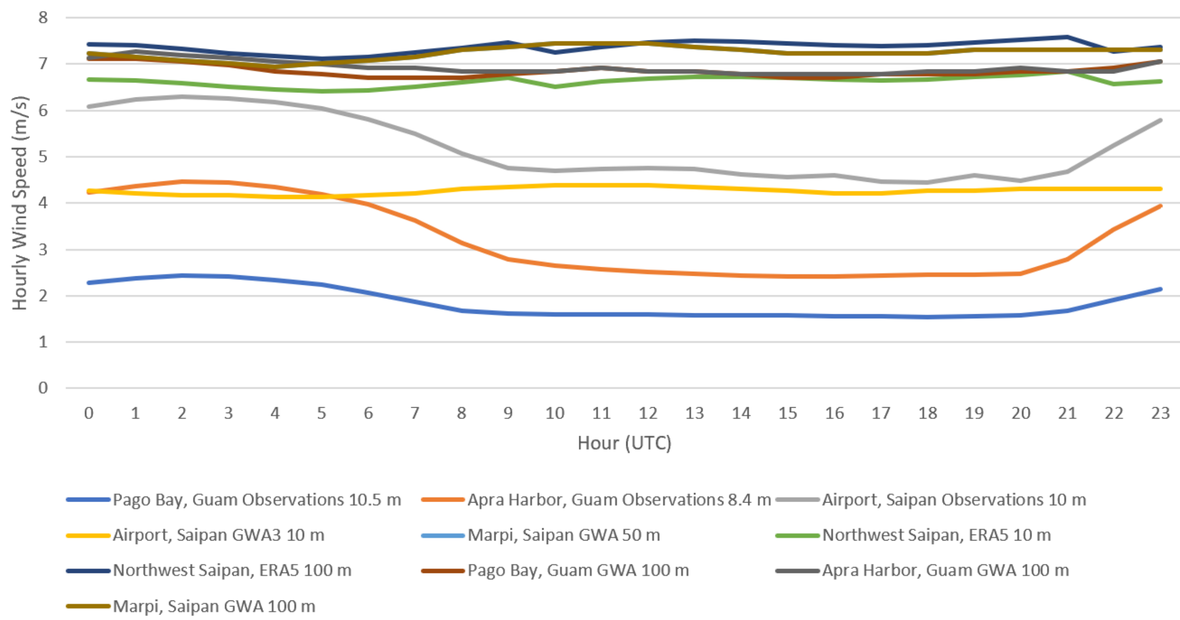

Figure 17. Hourly Observed and Modeled Wind Speeds near Marpi Landfill

In order to refine the wind energy estimates for Marpi, on-site measurements are necessary. Purchase and installation of a 60 m (197 ft) meteorological tower cost $25,000–$40,000 in the continental U.S. in 2018 (Dodd 2018). Using the area cost factor of 3.42, the cost for purchasing and installing a 60 m (197 ft) tower for Marpi is estimated to be $85,500–$136,800. The necessary meteorological tower would be shorter for Marpi (30–40 m or 98–131 ft), but the above cost estimate is anticipated to be representative due to 1) inflation since 2018 and 2) the shipment of anemometers and a monitoring system from the mainland. The cost estimate could increase depending on the availability of additional construction supplies on Saipan, along with personnel trained in installation and maintenance.

The timeline for meteorological tower purchase, transportation, installation, and at least 6 months of data gathering is estimated to be 9–12 months. The 6 months of data is recommended to refine wind speed estimates because model performance varies throughout the seasonal cycle. A full year of data observations would provide an even stronger analysis.

3.2.2.3 Operation and Maintenance

Operation costs for wind projects can include land lease payments, remote monitoring, operations contracts, insurance, and property taxes. Operations costs for a small distributed wind project are typically not substantial because the turbine owner and property owner are the same (Orrell, et al. 2022). Operations costs at Marpi are anticipated to include remote monitoring and insurance.

Maintenance costs for a small wind project vary according to the maintenance provider’s proximity to the project site (travel costs), availability of spare parts, and the complexity of maintenance and repairs (Orrell, et al. 2022). The average estimate for scheduled and unscheduled maintenance for a Northern Power Systems 100-28 turbine in the continental U.S. is $10,000 per year (Connor 2023). To minimize downtime and reduce cost, it would be critical to have some spare parts on Saipan at an estimated cost of $10,000–$20,000 and find or train local personnel to perform service activities (Connor 2023).

3.2.2.4 Example Local Projects

According to the draft CNMI Strategic Energy Plan (GHD 2022), there is only 144 kW of wind installed on Saipan. Small-scale turbines have been installed at facilities such as the Garapan Elementary School and the DPW building.

An operational 2.4 kW Skystream 3.7 wind turbine (pictured in Figure 18) is located at the DPW building. The turbine was deployed in 2011 and has survived two typhoons with no degradation in performance over the years and no O&M needed. Similar to the solar PV system at the same location, the installation company is now out of business, so if there was an issue, the system would likely be decommissioned instead of repaired. Sample output graphs for this turbine are shown in Figure 19 for an entire year (2012), in Figure 20 for a single month in the dry season (January), and in Figure 21 for the rainy season (June–July).

Figure 18. Skystream 2.4 kW Wind Turbine at DPW Building

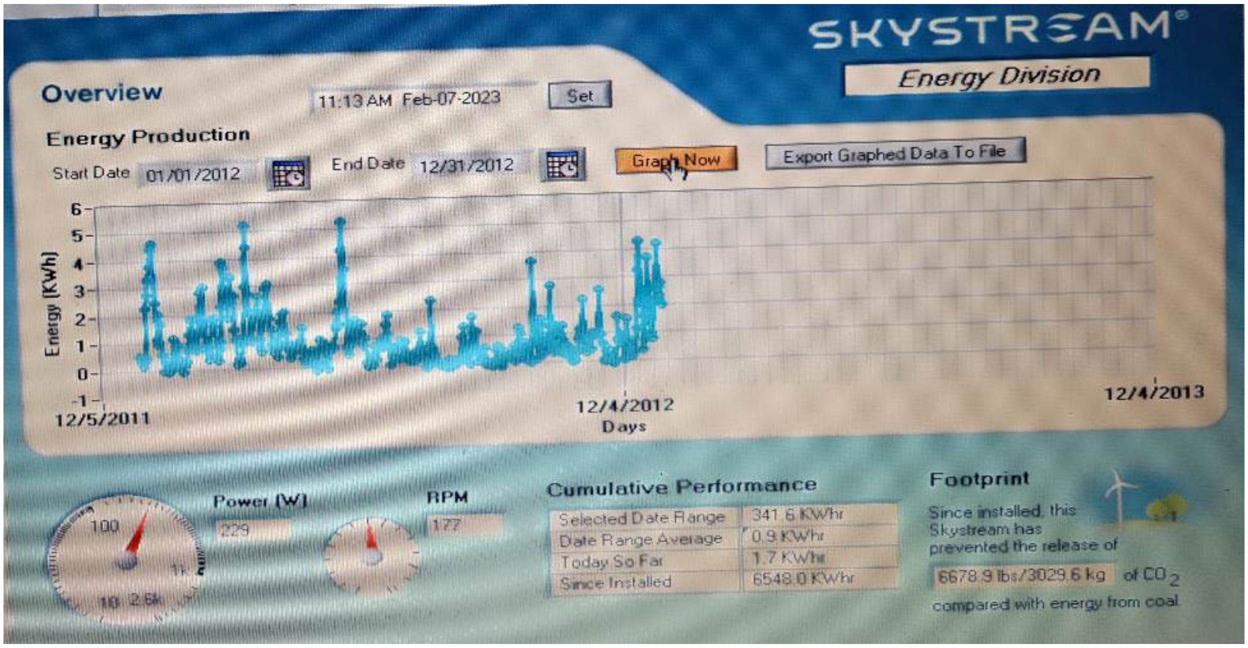

Figure 19. DPW Skystream Wind Turbine 2012 Power Production Profile

Figure 20. DPW Skystream Wind Turbine January 2023 Power Production Profile

Figure 21. DPW Skystream Wind Turbine June-July 2022 Power Production Profile

There are no turbines of the scale being considered for Marpi currently installed on Saipan. In 2016, a 275 kW Vergnet GEV MP-C wind turbine with a 55 m (180 ft) hub height was deployed on Guam. This taller turbine experienced downtime and unplanned maintenance when one of the turbine blades was damaged during Typhoon Mangkut in 2018. The turbine returned to operations in 2019 (Losinio 2019).

3.2.3 Batteries

Batteries and associated equipment for charge management, power conversion (from DC to AC), and other hardware are collectively known as BESS. They are often paired with renewable energy technologies to store generation in excess of the load and to make that power available during times when the renewable resource is not. BESS are key components in renewables-based microgrids, as has been shown in microgrid projects across the Pacific region. Various battery chemistries are available. O&M can mostly be automated through controllers.

3.2.3.1 Operation in a Microgrid

BESS serve a critical function in enabling microgrids to include increased amounts of non-dispatchable[2] renewable energy sources (solar PV, wind, etc.) while at the same time reducing reliance on dispatchable fuel-fired generators. This support takes two primary forms: 1) storage capacity associated with aligning the potentially mismatched output from renewable resources with loads that may not coincide with the availability of solar or wind power (often referred to as load shifting); and 2) grid forming and grid stability functions associated with maintaining voltage and frequency levels within prescribed limits (e.g., 60 Hz, 480 V AC power). The first of these two functions takes place on timescales of minutes or hours, while the second happens at the subsecond timescales associated with AC power cycles.

[2] Resources that can only generate power when their input is available; see Appendix A for more explanation.

Historically, grids and microgrids have relied on spinning generation (such as diesel generators) to stabilize power supply and delivery to loads, and to allow other resources such as solar and wind to contribute. Recent technology developments have enabled BESS to perform these grid-forming functions traditionally associated with spinning generation; virtual inertia, frequency and voltage reference setting (grid forming), and fast frequency response are among the capabilities that enable BESS to operate independently from a larger utility grid. This grid-forming ability is essential for microgrids that include renewable resources (such as solar PV) that use inverters dependent on a grid voltage and frequency reference to operate. There is ongoing work to further improve these capabilities, coupled with research into capability gaps; inverters lag behind spinning generators in their ability to source fault current to adequately clear faults in protective devices. Despite remarkable advances in the BESS technology space, there is still a need for standardization and long-term performance data on existing systems.

When configured with inverters capable of independently forming an AC electric grid, batteries can maintain a microgrid using renewable resources without reliance on spinning generation (from diesel generators) for stability. The ability of BESS to maintain stable grid operation is influenced in part by the battery's state of charge (SoC); when the battery SoC is very low (typically below 20%), then it may not be able to provide power to the microgrid (while it is absorbing the output of the other energy resources). In these cases, frequency may drop below acceptable thresholds. Likewise, when the battery is near full charge and unable to accept any additional input power, then system frequency can increase until other generation is curtailed.

3.2.3.2 Battery Chemistries

BESS used in microgrid applications for the power scales required for Marpi most often include lithium-ion (Li-ion) batteries. Several other battery configurations and chemistries exist, including lead-acid, sodium-metal, flow batteries (such as vanadium redox and zinc-air), and others. Of these other chemistries, lead-acid is the only one that may be suitable for a Marpi microgrid. The advantages and drawbacks to these common battery types are compared in Table 6. Other storage media used for stationary storage applications include ultra-capacitors, flywheels, pumped hydro, or pumped air storage. None of these are considered an appropriate fit because the scale required is much larger than the Marpi loads.

Table 6. Comparison of Battery Chemistries

	Advantages	Drawbacks
Li-ion	• Costs continue to fall • Multiple vendors • Fast response • Higher efficiencies	• High temperatures can result in electrolyte decomposition and flammable gas • Overcharging can lead to degradation and faults
Lead-acid	• Low cost • Ubiquitous	• Limited lifetime for older tech • Degradation from deep discharge • Low specific energy • Sulfation from prolonged storage
Sodium-metal	• Sodium is low cost • High energy density and specific power • High temp is OK	• Heaters needed when not in use • Charge/discharge limitations • Safety concerns
Redox flow	• Flexibility: separate power and energy • Multiple chemistries • Low fire hazard	• Low energy density and efficiency • Narrow temperature range • Pumped system susceptible to leaks

Li-ion batteries are the most widely deployed battery type in recent years, primarily for use in electric vehicles, which has led to decreasing costs for stationary power applications. There are numerous vendors on the market, driving performance and safety improvements. Li-ion batteries achieve a fast response necessary for grid stability and have higher efficiencies as compared to other battery chemistries.

Lead-acid batteries are another low-cost and ubiquitous offering. Older systems suffer from limited lifetimes and short cycle lives (~500-1,000 cycles), while newer lead-carbon systems can perform to ~5,000 cycles. Lead-acid batteries typically have lower specific energy than Li-ion and can suffer sulfation from prolonged storage.

3.2.3.3 Operations and Maintenance

BESS O&M consist of both ongoing operations of the battery in conjunction with the other microgrid components and periodic and long-term maintenance activities to ensure the sustained performance and safety of the equipment. Operations of the BESS require constant monitoring of the equipment's performance including power output of each of the individual battery cells, system SoC, battery temperatures, and other metrics. The data gathering and analysis for these performance metrics can be automated, with basic corrective actions being programmed into the BESS controllers. Errors or performance deviations beyond acceptable thresholds will require intervention by a trained operator.

The relatively small number and lack of long-term BESS projects in service means that reference O&M costs vary widely and are dependent on project-specific characteristics. Unlike O&M for engine generators and other types of equipment that use consumables and have a significant variable component, BESS O&M costs are often calculated as a fixed annual cost.[3] This fixed cost typically consists of a service contract that includes labor for periodic system inspections and can include payments into an escrow account designed to levelize the higher costs associated with major component overhauls or replacements (battery cells, inverters, etc.). Whether or not long-term equipment replacement (which reduces performance degradation over the entire life of the battery) is included will have a significant impact on the O&M costs.

3.2.3.4 Example Projects

BESS projects (either as grid-facing utility resources or as part of microgrids intended for resilience purposes) are increasing rapidly throughout the Pacific, as battery costs continue to fall and the deployment of renewable power generation increases to meet emissions reduction and cost savings objectives. Representative projects on Pacific islands include:

- Tafuna, American Samoa – 500 kWh battery incorporated into a site microgrid at the Te'o U.S. Army Reserve Center
- An island-wide microgrid on Ta'u (American Samoa) including 60 Tesla Power Pack Li-ion batteries with an energy rating of 6 MWh, integrated with solar PV and diesel generators
- A 185 MW / 565 MWh battery at the Port of Hawaii to provide grid services to Hawaiian Electric Company as coal generation is completely retired from service on Oahu
- Tonga Outer Islands (Asian Development Bank 2022)

[3] Where BESS projects have a high number of charge/discharge cycles (e.g., more than one per day), the variable O&M will increase, reflecting a reduced lifetime of the battery.

  - 500 kW/660 kWh BESS on Ha'apai Island
  - Multiple BESS projects ranging from 110 kW up to 295 kW on Niuafo'ou, Niuatopatapu, 'Uiha, Nomuka, Ha'ano, Ha'afeva, Kotu, Tugua, O'ua, and Mo'unga'one Islands
  - A 5 MW/2.5 MWh BESS and a separate 5 MW/17.4 MWh BESS on Tongatapu
  - Multiple 0.4–0.9 MW BESS projects on Vava'u and 'Eua
- Cook Islands
  - 0.5 MW and 1.0 MW BESS projects on Aitutaki Island
  - Multiple BESS projects from 90–216 kW on Atiu, Mauke, Mangaia, and Mitiaro Islands

The smaller systems on the Tonga outer islands and Cook Islands are all microgrids that do not have a larger utility grid as a voltage or frequency source; under most conditions, the batteries, their inverters, and their associated controls are operating in 'islanded mode', autonomously forming the microgrid. This is a similar operating profile as what would be expected for a system operating at Marpi if no CUC utility service is provisioned for the site.

The Army Reserve microgrid is also similarly sized to the potential microgrid for Marpi, and has demonstrated automated operation since March 2021, requiring minimal manpower for O&M once the system controls were optimized for cost savings and resilience. This battery allows seamless transition between the solar PV, grid, and diesel generation sources.

3.2.4 Diesel Generators

Engines used for generating electricity are often referred to as 'spinning generation' or RICE (reciprocating internal combustion engine) generators, and can be configured for standby (backup) use or prime power (constant year-round use, serving as the primary generation resource) applications. They are often configured to use liquid fuels such as diesel, gasoline, or liquid propane. Because of its relatively low cost, high power density, widespread availability, and existing infrastructure for fuel transport and distribution, diesel is the most common liquid fuel for generators.

Today, nearly all standby power systems rely on diesel generators to provide backup power because they 1) can start and accept load very quickly (within seconds), 2) occupy a small footprint relative to their output, 3) can modulate their output (follow loads) reliably while maintaining grid voltage and frequency, and 4) are relatively cheap to operate, maintain, and repair. Drawbacks associated with diesel engines include 1) ongoing operations costs for fuel and other consumables, 2) noisy operations that can require sound attenuation, and 3) significant emissions for both greenhouse gases or GHGs (CO_2, N_2O) and criteria pollutants (CO, NO_2, SO_2, particulate matter [PM]) that require expensive controls for compliance with regulations.

Whether in standby or prime power applications, diesel generators can be configured to operate in parallel with other generation resources (e.g., the utility grid or nearby solar PV) either as grid-following or grid-forming units, or they can operate entirely independently as the only source of power if no other resources are available or present.

3.2.4.1 Considerations for Marpi Application

Marpi has relied on diesel generators for power since it commenced operations; the site operators are familiar with the technology and are able to perform minor maintenance and repairs. As of February 2023, the DPW-owned generator at Marpi has been out of service for an extended period of time, requiring the use of a rental unit supplied by the site operator.

For prime power applications where there is no utility feed, or where there are additional uptime requirements, microgrids should be configured with multiple generators to optimize fuel-use efficiency, meet contingency reserve needs, and provide generation redundancy. For Marpi, a microgrid configured with two identically sized generators, each sized to meet 50–75% of the peak demand, would achieve those efficiency and redundancy objectives.

Electric loads at Marpi vary significantly throughout the day; frequently the loads are at 20 kW or less, only peaking at 100–120 kW when there are coincident pumping requirements. A single generator, sized to meet the full peak demand, would often be running at less than 20% of its rated output for most of the time. At this output, the fuel efficiency of the generator can be as little as 50% of the efficiency when the unit is operating at its rated output. If the microgrid is configured with two smaller units, then either one can operate at lower loads (but higher relative to the generator's nameplate rating), without the same fuel efficiency penalties. When loads increase beyond the capacity of a single unit, then either a battery can provide peak power or the second generator can be brought online.

In addition to the optimization of fuel efficiency, multiple units provide redundancy, to ensure some or all power needs can be met in the event of a failure of any single unit. In addition to mitigating the failure of a single generator, a second unit would also serve as contingency reserve for all generation sources in a microgrid, quickly responding to either the failure of output from the battery or a rapid decrease in output from the solar PV or wind. Diesel generators can come online from a cold start and ramp to full output very quickly (often within 10–20 seconds), minimizing the likelihood of a full system outage.

3.2.4.2 Diesel Fuel and Storage

Diesel fuel is widely available on Saipan as it is the primary source of fuel for power generation by CUC. For the existing power plants, CUC procures between 3 and 5 million gallons of diesel each month, delivered to the Port of Saipan. Diesel is also used for vehicles and other standby generators on the island; the bulk price for diesel for 2022 and early 2023 averaged approximately $6.50 per gallon.

The landfill has a bulk diesel storage tank, intended for use by both the generator and heavy equipment at the site. The tank experienced leaks from corroded sections and was emptied and removed from service. A portable trailer-mounted tank with a 10,000-gallon capacity is currently in use by the site operator and parked adjacent to the bulk tank and generator building, shown in Figure 22.

Figure 22. Portable Diesel Tank at Marpi Landfill

3.2.4.3 Operations and Maintenance (O&M)

In order to ensure reliable performance over the life of the generator, there are several maintenance activities that should be performed at vendor-specified intervals. These include:

- General inspections covering mechanical components, including the engine casing, spark plugs, exhaust, fuel, batteries (for black starting), and controls
- Lubrication system maintenance covering oil and oil filters
- Coolant system components: coolant levels, radiator inspection and cleaning, air filters, etc.
- Fuel system inspections including tank draining and dewatering, fuel filter replacement, and general tank inspection for structural integrity
- Battery testing to ensure charge to start the generator (adequate voltage and electrolyte levels)

O&M costs for diesel generators are typically expressed in variable costs, given the variability in their application (standby vs. prime power) and the impact on consumables and lifetime of the engine. Typically for prime power applications, engines can range from 1–2¢/kWh to higher amounts (5¢/kWh or more) for units that are only used for standby applications.

3.2.5 Microgrid Controls and Balance of Plant

A microgrid consists of the combination of power generation and storage resources (renewables, batteries, fuel-fired generators, etc.), distribution infrastructure (wires, switchgear, protective devices, transformers, etc.), and loads being supplied with electricity. Typically, microgrids are configured to operate either in parallel with a utility grid, or autonomously in the event that there is a grid outage, or there is no utility feed available. The microgrid controller manages all aspects of the system's operation to ensure stable, safe, and reliable delivery of power to the loads managing the system at very short (subsecond and second) and long (hourly and longer) timescales.

Other BOP pieces of equipment for the microgrid include 1) electric distribution system components to route power from generation sources to the loads, 2) heating and cooling equipment to ensure that controllers, inverters, and related components are kept within tolerable temperature ranges, 3) human interface devices, and 4) communications equipment for remote monitoring and control. Distribution system components include switchgear and protective devices (circuit breakers, relays, fuses, etc.), voltage transformers, and other related equipment.

3.2.5.1 Purpose of the Microgrid Controller

A microgrid controller performs several functions, ranging from very high-speed controls (subsecond timescales) up to mode handling and transition (seconds, minutes) to resource scheduling and dispatch (minutes, hours).

- Grid forming through voltage and frequency regulation – the controller will work in conjunction with the individual system controllers (for the generator and BESS inverters) to provide voltage and frequency reference for other resources on the microgrid.
- Real and reactive power provision to meet both real and reactive power requirements – as Marpi's electric loads are often dominated by single- and three-phase pumps with low power factors, the microgrid's ability to source adequate reactive power is important.
- System monitoring and controls for mode handling during steady-state and mode transitions (e.g., from the battery acting as the grid-forming device to the generator acting as the grid-forming unit) – this function controls how to operate the individual components (generation and storage resources, switchgear, and any load-control devices). Especially during mode changes, it is important for the controller to properly and precisely sequence commands to ensure stable and smooth transitions.
- System protection and black start functions – for the system to respond to and isolate any faults or reenergize the system after an outage.
- Dispatch functions to determine when to start and stop certain components within the microgrid – this intelligence is programmed into the controller to ensure that loads are always met and to achieve other goals such as minimized diesel consumption or adequate contingency power reserves. Dispatch algorithms can use predictive intelligence to optimize the use of renewables (by utilizing near-term weather forecasting), or control of the loads from historical usage trends or information to predict stormwater pumping needs based on recent rainfall amounts.

3.2.5.2 Operations and Maintenance

Operation of the system components can be largely automated by the microgrid controller and individual component controllers. Direct human operation of the system components and overriding automated functions or operations are possible and will require a trained operator or technician who is familiar with the controls software and power system operations. At least one operator will need to be trained in how to interact with the control software and be able to respond to faults or system alarms any time the system is operational and serving loads. During outage recovery or system black starts it may be necessary to have multiple operators available to perform activities in parallel to restore power and/or resolve faults and bring the system online. For packaged microgrid systems (e.g., systems that come integrated and preconfigured from a single vendor), operator manuals and training materials will be provided to handle normal operations and troubleshooting. For systems integrated on site, this can be requested from the installer.

For microgrids, maintenance activities include maintenance of the individual system components (solar panels, batteries, inverters, generators, distribution system, etc.) and of the control platform itself. As the microgrid controller largely consists of computer hardware, maintenance requirements will largely consist of software and/or hardware updates to resolve any issues or implement new types of functionality. The *Installation, Operation, & Maintenance of Solar PV Microgrid - Handbook for Technicians* includes a comprehensive list of basic maintenance activities for the microgrid components (GSES 2015).

4.0 Power Supply Scenarios

The resources described above can be combined in various configurations to provide power to Marpi. The seven scenarios evaluated are:

- 1: Solar PV + BESS (Section 4.1)
- 2: Wind + BESS (Section 4.2)
- 3: Solar PV + Wind + BESS (Section 4.3)
- 4: Solar PV + BESS + Diesel Generation (Section 4.4)
- 5: Wind + BESS + Diesel Generation (Section 4.5)
- 6: Solar PV + Wind + BESS + Diesel Generation (Section 4.6)
- 7: Diesel Generation Only (Section 4.7)

Each configuration provides certain benefits and challenges, as detailed in this section. For each scenario, the following are described:

- Technical configuration (equipment and sizing)
- Operating parameters (prioritization and availability of resources to meet load)
- Project economics (capital costs both with and without grant funds for renewable energy and energy storage components;[4] operations and maintenance costs; and 25-year levelized cost of energy (LCOE),[5] which can be compared to the current CUC electricity rate of $0.41/kWh; CUC 2023; see Appendix C for economic analysis details)
- Equipment siting and space requirements
- Environmental considerations, including quantification of annual air emissions

A side-by-side comparison of scenarios is provided in Section 7.0.

The operating parameters vary for each scenario depending on the resources included and the system capacities. The estimated loads described in Section 2.0 increase during the rainy season and decrease during the dry season, but the expected solar and wind generation is the opposite, as shown in Figure 23. This results in the need for renewable energy systems to be sized too large to meet needs during most of the year and potentially not large enough for the rainy season, which in turn results in a seasonally varied dispatch of resources, including BESS and generators. Specific microgrid dispatch considerations are described for each scenario.

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[4] To compare scenarios, project economics were evaluated using full capital costs as well as a likely situation where grant funds would be available to cover renewable energy and BESS technology capital costs only. Actual grant funding may cover just a portion of these capital costs, or may cover additional components such as microgrid controls. See Section 8.1 for some currently available grants.

[5] LCOE is a measure of the present cost of electricity generation over the lifetime of a generation system. LCOE is used to compare the cost of electricity generation between different generation options.

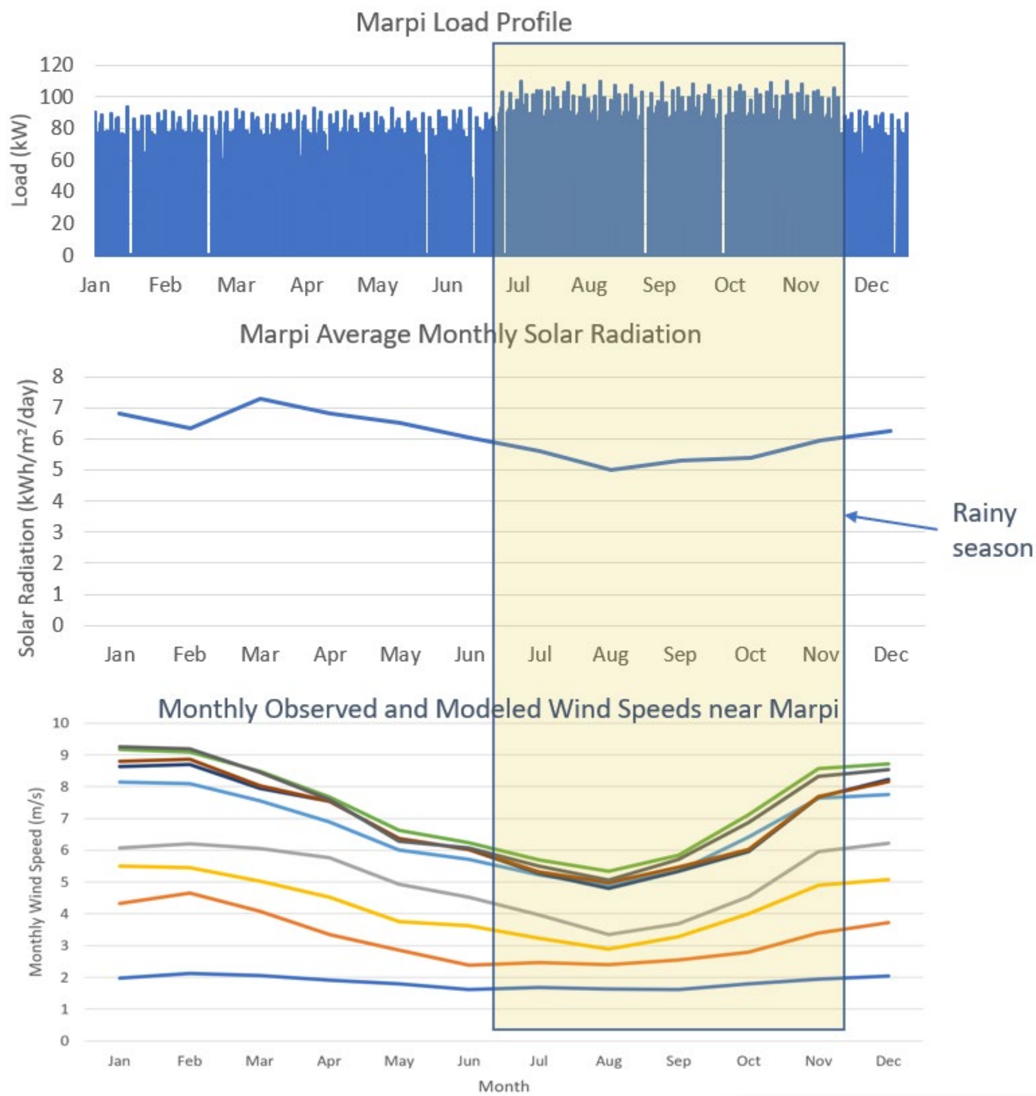


Figure 23. Rainy Season Impacts on Marpi Landfill Loads and Solar and Wind Resources

4.1 Scenario 1: Solar PV + BESS

Scenario 1 includes solar PV and BESS only. A 200 kW solar PV array would generate power for the landfill and a 350 kW/1,400 kWh BESS would store excess energy for use at a time when renewable energy is not available. Table 7 shows the nameplate capacity (size), space requirement, and expected amount of the annual load served by each component.

Table 7. Components, Space Requirements, and Load Served for Scenario 1

Component	Capacity	Space Requirement	Load Served
Solar PV	200 kW	~42,000 ft^2	100% (169 MWh)
Battery	350 kW/1,400 kWh	40-ft container	25.4 MWh charging/23.1 MWh discharging

For this scenario, 50% of the potential solar PV output (169 MWh) would need to be curtailed (not able to be used, resulting in the PV system needing to stop generating) due to generation exceeding the load when the battery is full. This would occur primarily during the dry season, when loads are lower and renewable generation is higher.

The Marpi load would be met first with any available generation from the PV array. When PV generation exceeds the load, the excess power would charge the battery. Then when the load exceeds the PV generation, the battery would discharge to supply the difference. In addition, the BESS would operate all the time to keep the grid voltage and frequency stable. Figure 24 and Figure 25 show how the generation and battery are dispatched to meet the load during a representative month in the rainy and dry seasons, respectively. A dispatch plot shows how the various energy sources and the battery are used (or dispatched) to meet the load.

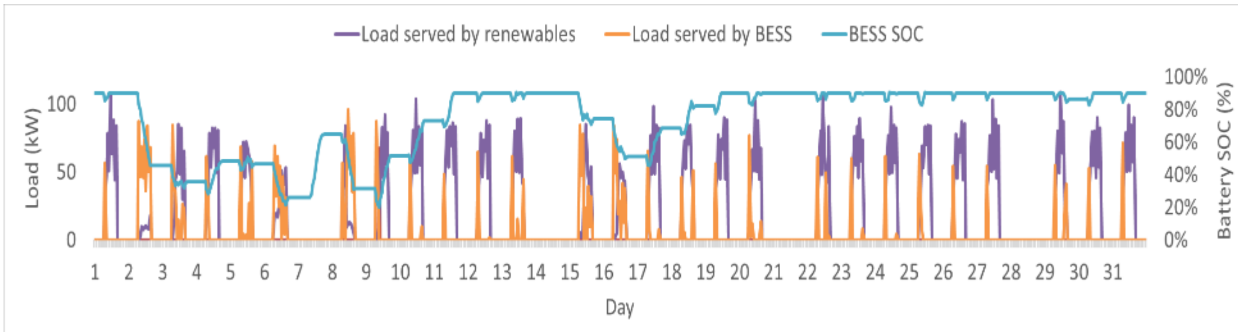


Figure 24. Scenario 1 Dispatch Plot for a Typical Month During the Rainy Season

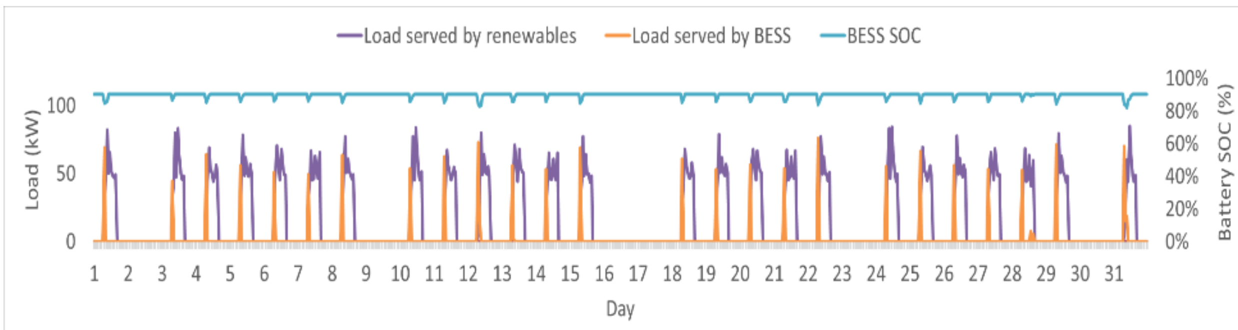


Figure 25. Scenario 1 Dispatch Plot for a Typical Month During the Dry Season

As shown in Figure 24, during the rainy season, the solar generation (purple) is not always able to meet the load, resulting in some discharging and subsequent charging of the BESS. As shown in Figure 25, during the dry season, lower loads mean that the excess solar generation can be used to keep the battery nearly fully charged.

Table 8 shows the project economics, with and without grants covering solar PV and battery costs, for Scenario 1. Some grants may pay for the entire cost of a renewable-based microgrid; that scenario would only incur O&M costs. With grants, the LCOE is below the current cost of power from CUC, but without grants, it exceeds it by nearly fivefold.

Table 8. Project Economics for Scenario 1

Economic Parameter	With Grants	Without Grants
Capital Cost	$0.4M	$4.5M
Solar PV	$0	$1.3M
BESS	$0	$2.8M
Microgrid controls	$0.4M	$0.4M
Annual O&M costs	$8k/yr	$8k/yr
25-year LCOE	$0.22/kWh	$1.93/kWh

Since this scenario uses solar PV only to power Marpi, there are no emissions associated with power generation. However, there would be environmental impacts associated with end-of-life equipment decommissioning and disposal of the retired equipment.

This scenario prioritizes climate goals by avoiding diesel generation and associated GHG emissions, but it does not have a diversity of resources to bolster resilience. It also has the second-highest LCOE of any scenario (without grants).

4.2 Scenario 2: Wind + BESS

Scenario 2 includes wind and BESS only. A 100 kW wind turbine (stationary, not tilt-up) would generate power for the landfill and a 300 kW/1,200 kWh BESS would store excess energy. Table 9 shows the nameplate capacity (size), space requirement, and expected amount of the annual load served by each component.

Table 9. Components, Space Requirements, and Load Served for Scenario 2

Component	Capacity	Space Requirement	Load Served
Wind turbine	100 kW	~88,000 ft^2	66% (112 MWh)
Battery	300 kW/1,200 kWh	40-ft container	61.0 MWh charging/56.6 MWh discharging

For this scenario, 37% of the potential wind output (69 MWh) would need to be curtailed due to generation exceeding the load when the battery is full; this would occur primarily during the dry season. In addition, 34% of the load would not be met during times that the load exceeds wind generation and the battery SoC is insufficient to meet the need; this would occur primarily during the rainy season.

The load would be met first with any available generation from the wind turbine. Then when wind generation exceeds the load, the excess power would charge the battery. When the load exceeds the wind generation, the battery would discharge to supply the difference. In addition, the BESS would operate all the time to keep the grid voltage and frequency stable. Figure 26 and Figure 27 show how the generation and battery are dispatched to meet the load during a representative month in the rainy and dry seasons, respectively.

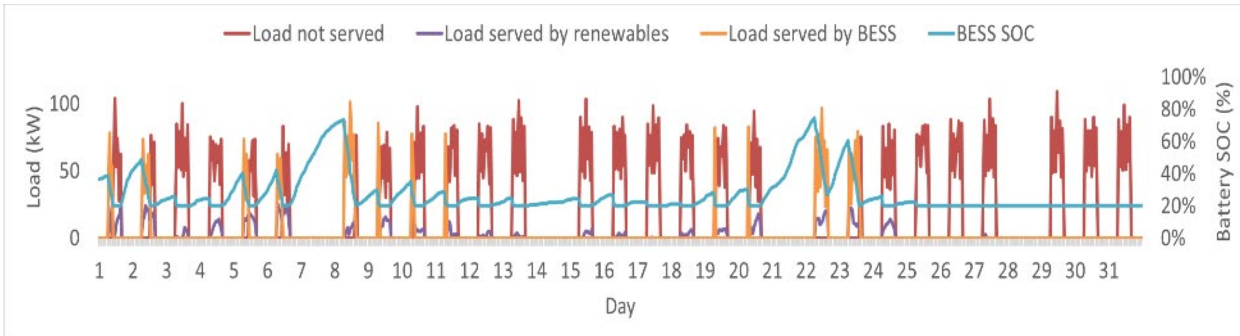


Figure 26. Scenario 2 Dispatch Plot for a Typical Month During the Rainy Season

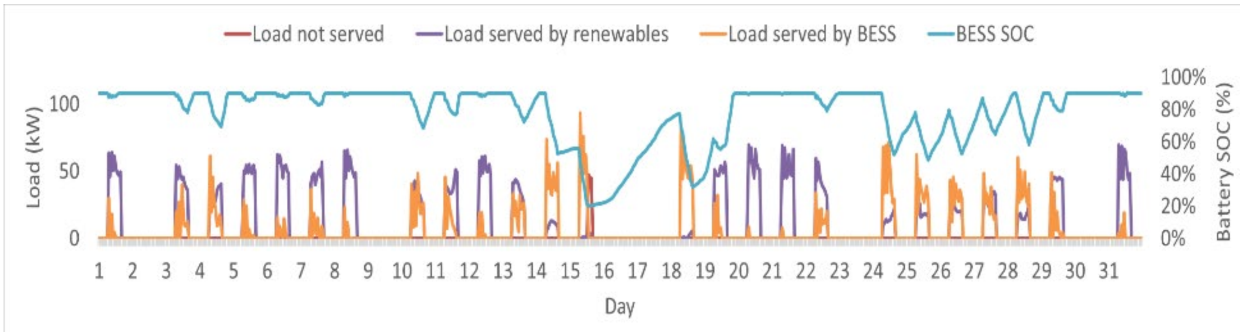


Figure 27. Scenario 2 Dispatch Plot for a Typical Month During the Dry Season

As shown in Figure 26, during the rainy season there is insufficient wind generation to meet the load (indicated by the red line showing load not being met) or keep the BESS charged (the blue line is at the minimum allowable SoC, 20%). As shown in Figure 27, however, the wind generation and BESS can meet the load, and the BESS stays close to fully charged most of the time. Over the course of the year, wind serves 66% of the load, leaving 34% of the load unmet.

Table 10 shows the project economics, with and without grants covering wind and battery costs, for Scenario 2. Some grants may pay for the entire cost of a renewable-based microgrid; that scenario would only incur O&M costs. With grants, the LCOE is similar to the current cost of power from the CUC, but without grants, it exceeds it by nearly sevenfold.

Table 10. Project Economics for Scenario 2

Economic Parameter	With Grants	Without Grants
Capital cost	$0.3M	$3.6M
Wind turbine	$0	$0.9M
BESS	$0	$2.4M
Microgrid controls	$0.3M	$0.3M
Annual O&M costs	$19k/yr	$19k/yr
25-year LCOE	$0.41/kWh	$2.75/kWh

Since this scenario uses wind only to power Marpi, there are no emissions associated with power generation. However, there are environmental impacts associated with this scenario, such as end-of-life equipment decommissioning and disposal. Wildlife impacts from the wind turbine would also need to be studied.

This scenario prioritizes climate goals by avoiding diesel generation and associated GHG emissions, but it does not meet the landfill's electricity demand a significant portion of the year. In addition, it has the highest LCOE of any scenario (without grants). Larger wind turbines could be considered to meet the load, but this would increase capital and O&M costs, increase the LCOEs, and increase the amount of wind energy needing to be curtailed.

4.3 Scenario 3: Solar PV + Wind + BESS

Scenario 3 includes solar PV, wind, and BESS. A 150 kW solar PV array and a 100 kW wind turbine (stationary, not tilt-up) would generate power for the landfill, and a 260 kW/1,040 kWh BESS would store excess energy. Table 11 shows the nameplate capacity (size), space requirement, and expected amount of the annual load served by each component. Note that the amount of load served by PV and wind can vary depending on how they are prioritized by the controller; in Table 11, PV is prioritized.

Table 11. Components, Space Requirements, and Load Served for Scenario 3

Component	Capacity	Space Requirement	Load Served
Solar PV	150 kW	~31,500 ft^2	90% (152 MWh)
Wind turbine	100 kW	~88,000 ft^2	10% (17 MWh)
Battery	260 kW, 1040 kWh	40-ft container	21.7 MWh charging / 19.7 MWh discharging

For this scenario, 61% of the potential renewable output (269 MWh) would need to be curtailed due to generation exceeding load when the battery is full. This would occur primarily during the dry season, when loads are lower and renewable generation is higher.

The load would be met first with any available generation from the PV array and wind turbine. When renewable generation exceeds the load, the excess power would charge the battery. The microgrid controller would be programmed to direct the prioritization and curtailment of generation sources during times when both solar and wind are available, generation potential exceeds the load, and the battery is full. When the load exceeds the renewable generation, the battery would discharge to supply the difference. In addition, the BESS would operate all the time to keep the grid voltage and frequency stable. Figure 28 and Figure 29 show how the solar and wind generation and BESS are dispatched to meet the load during a representative month in the rainy and dry seasons, respectively.

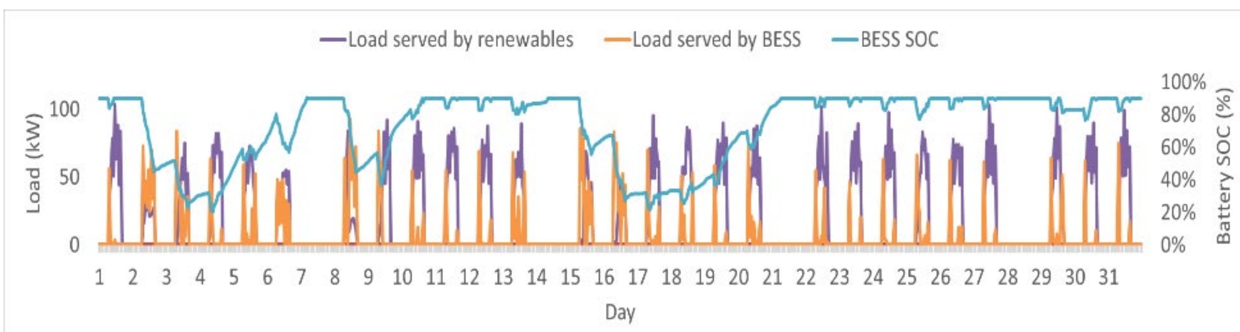


Figure 28. Scenario 3 Dispatch Plot for a Typical Month During the Rainy Season

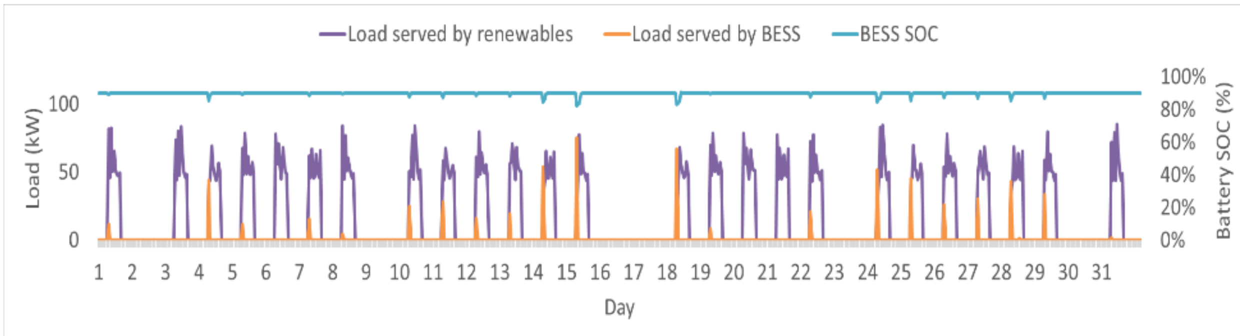


Figure 29. Scenario 3 Dispatch Plot for a Typical Month During the Dry Season

As shown in Figure 28, during the rainy season, the solar and wind generation (shown in purple) and BESS (shown in orange) work together to meet the load, resulting in a fluctuating battery SoC. As shown in Figure 29, during the dry season, lower loads mean that the excess solar and wind generation can be used to keep the battery nearly fully charged.

Table 12 shows the project economics, with and without grants covering renewables and battery costs, for Scenario 3. Some grants may pay for the entire cost of a renewables-based microgrid; that scenario would only incur O&M costs. With grants, the LCOE is below the current cost of power from CUC, but without grants, it significantly exceeds it.

Table 12. Project Economics for Scenario 3

Economic Parameter	With Grants	Without Grants
Capital cost	$0.3M	$4.3M
Solar PV	$0	$1M
Wind turbine	$0	$0.9M
BESS	$0	$2.1M
Microgrid controls	$0.3M	$0.3M
Annual O&M costs	$20k/yr	$20k/yr
25-year LCOE	$0.29/kWh	$1.86/kWh

Since this scenario uses solar PV and wind only to power Marpi, there are no emissions associated with power generation. However, there are environmental impacts associated with this scenario, including end-of-life equipment decommissioning and disposal and potentially wildlife impacts, as noted in the previous two scenarios.

This scenario prioritizes climate goals by avoiding diesel generation and associated GHG emissions, and it diversifies resources to bolster resilience, but still relies completely on intermittent resources.

4.4 Scenario 4: Solar PV + BESS + Diesel Generation

Scenario 4 includes solar PV, BESS, and diesel generation. A 100 kW solar PV array and 160 kW of diesel generation (two 80 kW units) would provide power for the landfill, and a 75 kW/300 kWh BESS would store excess energy. Table 13 shows the nameplate capacity (size), space requirement, and expected amount of the annual load served by each component.

Table 13. Components, Space Requirements, and Load Served for Scenario 4

Component	Capacity	Space Requirement	Load Served
Solar PV	100 kW	~21,000 ft^2	82% (139 MWh)
Diesel generation	160 kW	15-ft container	18% (30 MWh)
Battery	75 kW/300 kWh	20-ft container	28.6 MWh charging/23.3 MWh discharging

For this scenario, 15% of the potential solar PV output (26 MWh) would need to be curtailed due to generation exceeding load when the battery is full. This would occur primarily during the dry season, when loads are lower and renewable generation is higher.

The load would be met first with any available generation from the PV array. When solar generation exceeds the load, the excess power would charge the battery. When the load exceeds the solar generation, the battery would discharge to supply the difference, unless the battery SoC is too low, at which point the diesel generators would meet the excess load. When no generator is running, the BESS would operate to keep the grid voltage and frequency stable. Figure 30 and Figure 31 show how the generation and battery are dispatched to meet the load during a representative month in the rainy and dry seasons, respectively.

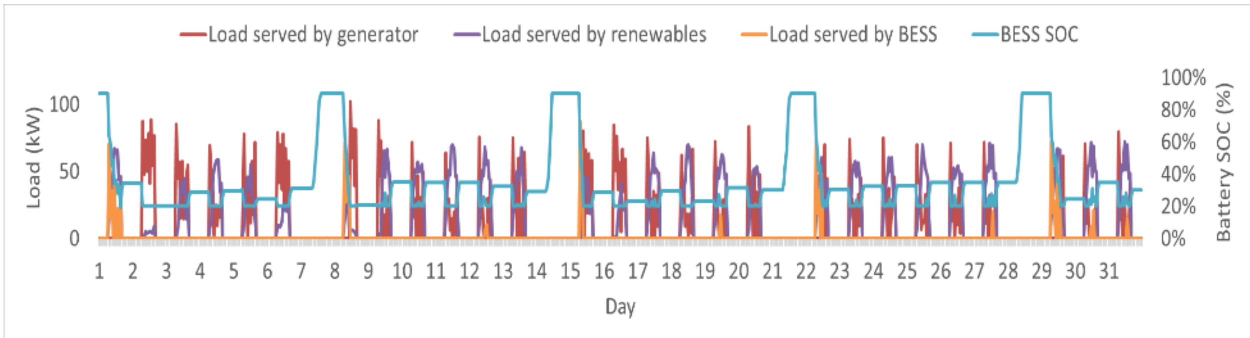


Figure 30. Scenario 4 Dispatch Plot for a Typical Month During the Rainy Season

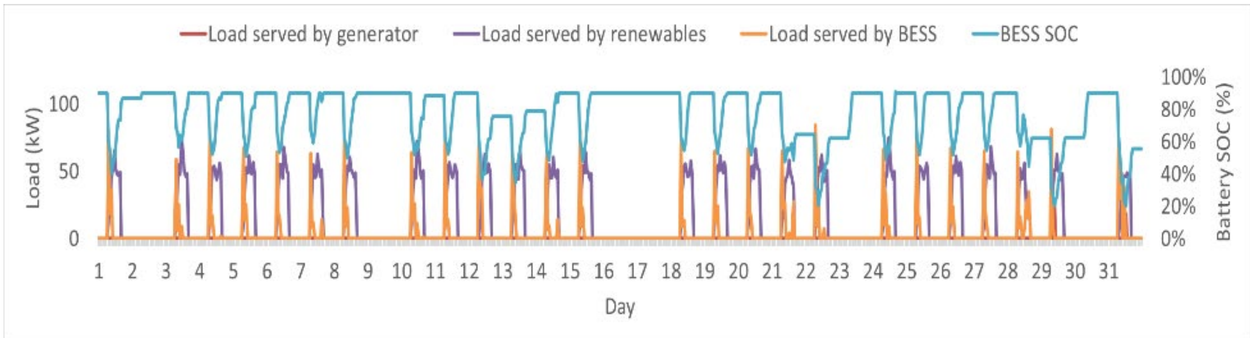


Figure 31. Scenario 4 Dispatch Plot for a Typical Month During the Dry Season

As shown in Figure 30, during the rainy season, there is insufficient solar generation (purple) to meet the load, so the diesel generators (red) are dispatched to meet the shortfall. During the dry season, as shown in Figure 31, there is sufficient solar generation to meet the load and charge the battery (orange).

Table 14 shows the project economics, with and without grants covering solar PV and battery costs, for Scenario 4. In both cases, the LCOE exceeds the current cost of power from CUC, although with grants, it is a small difference.

Table 14. Project Economics for Scenario 4

Economic Parameter	With Grants	Without Grants
Capital cost	$1.0M	$2.3M
Solar PV	$0	$0.6M
BESS	$0	$0.6M
Diesel generators	$0.8M	$0.8M
Microgrid controls	$0.2M	$0.2M
Annual O&M costs	$18k/yr	$18k/yr
25-year LCOE	$0.49/kWh	$0.96/kWh

Since this scenario uses some diesel to power Marpi, there are some emissions associated with power generation, as shown in Table 15. In additional, environmental impacts from equipment decommissioning and disposal must be considered, as well as fuel spill containment, consumable disposal, and countermeasure considerations for the diesel generation.

Table 15. Emissions Associated with Power Generation for Scenario 4

Pollutant	Emissions Generated (tons/year)
CO_2e	22
NO_X	0.01
PM	0.01

This scenario balances several goals: climate, reliability, and economics. It supports climate goals by primarily using solar energy to generate electricity, with diesel generation providing about 20% of the landfill's electricity needs. This scenario uses both intermittent and dispatchable resources for added reliability, and has the second lowest LCOE of any scenario (without grants).

4.5 Scenario 5: Wind + BESS + Diesel Generation

Scenario 5 includes wind, BESS, and diesel generation. A stationary 100 kW wind turbine and 160 kW of diesel generation (two 80 kW units) would provide power for the landfill, and a 100 kW/400 kWh BESS would store excess energy. Table 16 shows the nameplate capacity (size), space requirement, and expected amount of the annual load served by each component.

Table 16. Components, Space Requirements, and Load Served for Scenario 5

Component	Capacity	Space Requirement	Load Served
Wind turbine	100 kW	~88,000 ft^2	56% (95 MWh)
Diesel generation	160 kW	15-ft container	44% (74 MWh)
Battery	100 kW/400 kWh	20-ft container	45.6 MWh charging/39.6 MWh discharging

For this scenario, 46% of the potential wind output (84 MWh) would need to be curtailed due to generation exceeding the load when the battery is full. This would occur primarily during the dry season, when loads are lower and renewable generation is higher.

The load would be met first with any available generation from the wind turbine. When wind generation exceeds load, the excess power would charge the battery. When the load exceeds the wind generation, the battery would discharge to supply the difference, unless the battery SoC is too low, at which point the diesel generators would meet the excess load. When no generator is running, the BESS would operate to keep the grid voltage and frequency stable. Figure 32 and Figure 33 show how the generation and battery are dispatched to meet the load during a representative month in the rainy and dry seasons, respectively.

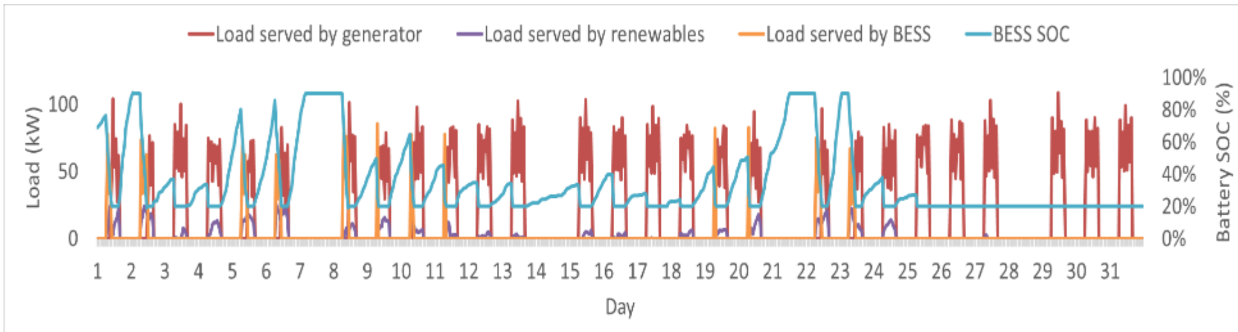


Figure 32. Scenario 5 Dispatch Plot for a Typical Month During the Rainy Season

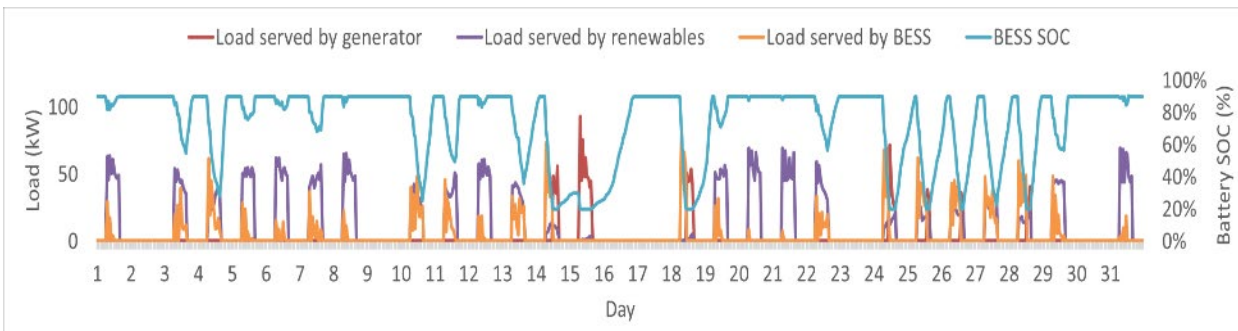


Figure 33. Scenario 5 Dispatch Plot for a Typical Month During the Dry Season

As shown in Figure 32, during the rainy season, there is insufficient wind generation (purple) to meet the load so the diesel generators (red) meets the shortfall and the BESS SoC (blue) remains at its minimum much of the time. During the dry season, as shown in Figure 33, there is sufficient wind generation to meet the load and charge the battery the majority of the time, although the diesel generators must still occasionally be dispatched to meet the generation shortfall.

Table 17 shows the project economics, with and without grants covering wind and battery costs, for Scenario 5. In both cases, the LCOE exceeds the current cost of power from CUC.

Table 17. Project Economics for Scenario 5

Economic Parameter	With Grants	Without Grants
Capital Cost	$1M	$2.8M
Wind turbine	$0	$0.9M
BESS	$0	$0.8M
Diesel generators	$0.8M	$0.8M
Microgrid controls	$0.2M	$0.2M
Annual O&M costs	$55k/yr	$55k/yr
25-year LCOE	$0.76/kWh	$1.44/kWh

Since this scenario uses some diesel to power Marpi, there are emissions associated with power generation as shown in Table 18. Additionally, there are other environmental impacts such as end-of-life equipment decommissioning and disposal; wildlife impacts; and fuel spill containment, consumable disposal, and countermeasure considerations for the diesel generation.

Table 18. Emissions Associated with Power Generation for Scenario 5

Pollutant	Emissions Generated (tons/year)
CO_2e	54
NO_X	0.03
PM	0.03

This scenario meets more than half of the landfill's load using wind energy. However, as a result of the seasonal mismatch between Saipan's wind resource and the landfill's load, diesel generation is required to meet nearly half of the load, resulting in high O&M costs and GHG emissions.

4.6 Scenario 6: Solar PV + Wind + BESS + Diesel Generation

Scenario 6 includes solar PV, wind, BESS, and diesel generation. A 100 kW solar PV array, a stationary 100 kW wind turbine, and 160 kW of diesel generation (two 80 kW units) would provide power for the landfill, and a 60 kW/120 kWh BESS would store excess energy. Table 19 shows the nameplate capacity (size), space requirement, and expected amount of the annual load served by each component. Note that the amount of load served by PV and wind can vary depending on how they are prioritized by the controller; in Table 19, PV is prioritized.

Table 19. Components, Space Requirements, and Load Served for Scenario 6

Component	Capacity	Space Requirement	Load Served
Solar PV	100 kW	~21,000 ft^2	70% (118 MWh)
Wind turbine	100 kW	~88,000 ft^2	20% (34 MWh)
Diesel generation	160 KW	15-ft container	10% (17 MWh)
Battery	60 kW/120 kWh	20-ft container	20.3 MWh charging/15.8 MWh discharging

For this scenario, 56% of the potential renewable output (198 MWh) would need to be curtailed due to generation exceeding the load when the battery is full. This would occur primarily during the dry season, when loads are lower and renewable generation is higher.

The load would be met first with any available generation from the PV array and wind turbine. When renewable generation exceeds load, the excess power would charge the battery. The microgrid controller would be programmed to direct the prioritization and curtailment of generation sources for times when both solar and wind are available, generation potential exceeds the load, and the battery is full. When the load exceeds the renewable generation, the battery would discharge to supply the difference, unless the battery SoC is too low, at which point the diesel generators would meet the excess load. When no generator is running, the BESS would operate to keep the grid voltage and frequency stable. Figure 34 and Figure 35 show how the generation and BESS are dispatched to meet the load during a representative month in the rainy and dry seasons, respectively.

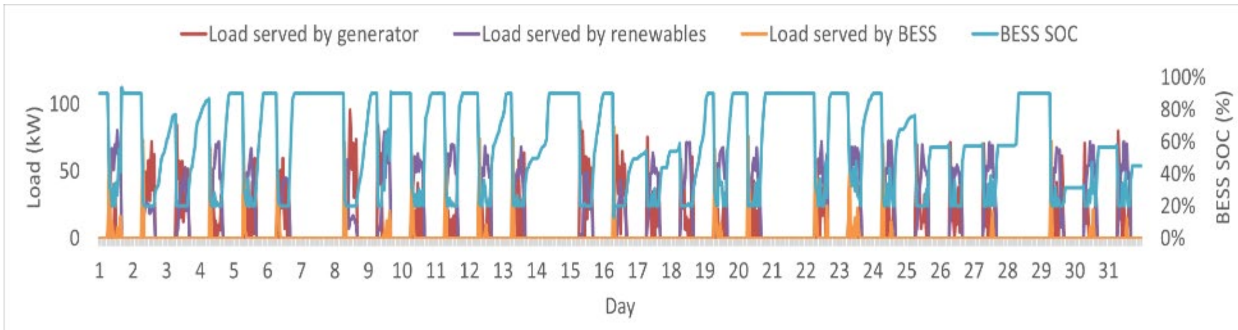


Figure 34. Scenario 6 Dispatch Plot for a Typical Month During the Rainy Season

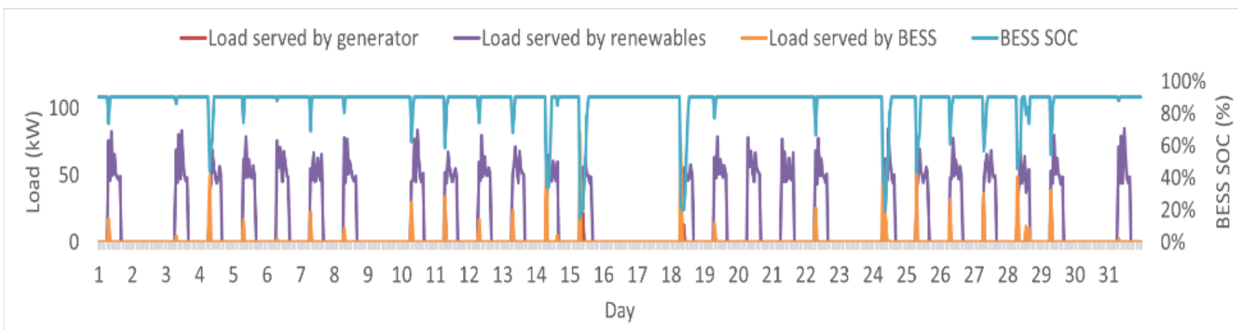


Figure 35. Scenario 6 Dispatch Plot for a Typical Month During the Dry Season

As shown in Figure 34, during the rainy season, there is insufficient solar and wind generation (purple) to meet the load, so the diesel generators (red) are dispatched to meet the shortfall and the BESS (blue) is cycled daily. During the dry season, as shown in Figure 35, there is sufficient solar and wind generation to meet the load and keep the battery nearly fully charged.

Table 20 shows the project economics, with and without grants covering renewable energy and battery costs, for Scenario 6. In both cases, the LCOE exceeds the current cost of power from CUC, although the gap is much more significant when no grants assist with defraying the cost.

Table 20. Project Economics for Scenario 6

Economic Parameter	With Grants	Without Grants
Capital cost	$1.1M	$2.9M
Solar PV	$0	$0.6M
Wind turbine	$0	$0.9M
Diesel generators	$0.8M	$0.8M
BESS	$0	$0.3M
Microgrid controls	$0.3M	$0.3M
Annual O&M costs	$25k/yr	$25k/yr
25-year LCOE	$0.56/kWh	$1.17/kWh

Since this scenario uses some diesel to power the Marpi Landfill, there are emissions associated with power generation, as shown in Table 21. Because the generator would only power 10% of the load, the amount of emissions generated is less than other scenarios that include generators. Additionally, there are other environmental impacts associated with this scenario, such as end-of-life equipment decommissioning and disposal; potential wildlife impacts; and fuel spill containment, consumable disposal, and countermeasure considerations for the diesel generation.

Table 21. Emissions Associated with Power Generation for Scenario 6

Pollutant	Emissions Generated (tons/year)
CO_2e	12
NO_X	0.006
PM	0.007

This scenario prioritizes reliability by using a variety of resources and also supports climate goals by primarily relying on wind and solar energy to generate electricity, with diesel generation providing only around 10% of the landfill's electricity needs. This scenario also has the lowest GHG emissions of any scenario that includes a diesel generator.

4.7 Scenario 7: Diesel Generation Only

This scenario uses 160 kW of diesel generation (supplied by a minimum of two 80 kW generators) to provide all the landfill's energy needs. This scenario is essentially a continuation of current practices, but is sized for future loads and is intended to be a long-term solution that can provide power 24/7 rather than a temporary fix that must be turned on daily. Table 22 shows the project economics for Scenario 7. For this scenario, the LCOE is nearly double the current cost of power from CUC. It is assumed that grants will not be available for new generators.

Table 22. Project Economics for Scenario 7

Economic Parameter	Without Grants
Capital cost	$0.5M
Diesel generators	$0.5M
Annual O&M costs	$90k/yr
25-year LCOE	$0.75/kWh

Since this scenario solely uses diesel to power Marpi, there are more emissions associated with power generation than for any other scenario, as shown in Table 23. Additionally, there are other environmental impacts associated with this scenario, such as end-of-life equipment decommissioning and disposal and fuel spill containment, consumable disposal, and countermeasure considerations for the diesel generation.

Table 23. Emissions Associated with Power Generation for Scenario 7

Pollutant	Emissions Generated (tons/year)
CO_2e	122
NO_X	0.06
PM	0.07

This scenario uses diesel as a sole generation source for the landfill. As such, it does not support climate or sustainability goals, nor does it provide a diversity of resources to bolster resilience. It does, however, have the lowest LCOE of any scenario (without grants).

5.0 Siting

The project team worked to identify a suitable location that is large enough for all system components, does not incur significant added cost, and is operationally feasible.

5.1 Space Requirements

The approximate amount of space required for each component being considered for Marpi is listed in Table 24.

Table 24. Space Requirements for Microgrid Components

Component	Footprint
Solar PV	~210 ft^2/kW_{AC} (ground-mount); ~100 ft^2/kW_{AC} (rooftop) (Gagnon, et al. 2016)
Wind turbine	No habitable structures within radius equal to tip height (51 meters for a 100 kW turbine with a 37 m tower height)
Batteries	Standard ISO 20–40-foot container (approximately 8' x 8' x 20' or 40'), depending on battery size and vendor specifications
Generators	15-foot ISO-style enclosure for 160 kW generator or an equivalent space requirement for smaller units totaling 160 kW
Microgrid controls and BOP	10-foot ISO enclosure; can be collocated with generator or BESS

5.2 Potential System Locations

The primary location for a microgrid identified by the CNMI Project Team is in the southwest corner of the landfill property (Figure 36). The existing generator is located here (yellow rectangle) and power distribution lines already serve this site.

Figure 36. Satellite Image of Potential Location Identified for Microgrid

This area has several terrain changes, an elevated residential dropoff point, temporary piles of waste, and some landscaping (see Figure 37) that would need to be removed or accommodated in some way if this site were to be used for solar PV and/or a wind turbine. New generators and batteries could be placed next to or at the current generator location. PV panels could be placed on a carport structure shading the residential dropoff point, in addition to some ground-mounted panels. A potential project layout that includes all microgrid components considered is presented in Figure 38, indicating potential component sizes that will fit within this space.

Figure 37. Overhead View of Potential Location Identified for Microgrid

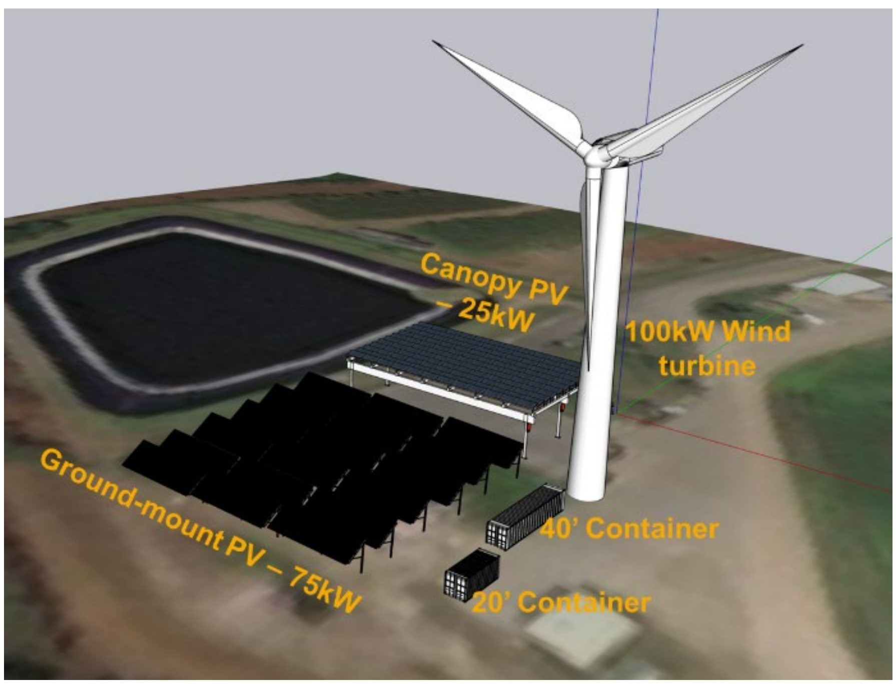


Figure 38. Potential Layout for Microgrid Components on Landfill Property

The footprint of the new generator recommended for Marpi in several scenarios would be approximately the same as the current generator house (200–300 ft^2). The existing structure could be used, potentially keeping the existing electric switchgear in its current location, and removing the existing generator to make room for two new units, each housed in dedicated enclosures. While the existing structure does provide some protection from rain and blown dust and other airborne debris, it provides minimal protection against corrosion from the marine environment. Further, the sheet-metal construction does not appear to be hardened to withstand any significant wind events or major storms.

New generators could also be delivered in a containerized format with enclosures rated to withstand adverse weather and corrosion. If this option were pursued, then additional consideration for replacement of the existing panelboard and switchgear into dedicated metal-clad enclosures is warranted. For the new generator(s), an integrated day tank (configured as a belly tank underneath the generator enclosure) would minimize the footprint and reduce fuel pumping requirements. Installing the generator(s), either for this scenario or any of the others, in either a new building or new vendor-supplied enclosure also enables the DPW to relocate the generators to be more optimally located within the available footprint relative to any other system components that are installed (solar PV, BESS, controls, etc.).

Other locations were discussed for solar PV, as this is the component requiring the most land area.

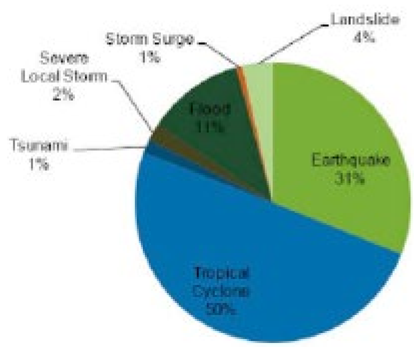
- Installing the panels on capped Cell 1 is an option, but would be challenging given the expected timeline for capping (possibly a decade or more down the road). In addition, mounting the panels to withstand typhoon winds requires structural piers buried approximately 14 feet deep, which is much deeper than the liner at just a few feet deep.
- Using other areas of the landfill property or surrounding public lands[6] would provide additional space, but would require long electrical runs that would add cost and potential loss of voltage.

[6] Public land parcels surrounding the Marpi Landfill can be explored using the BECQ Public Permitting App (https://becq-dcrm.opendata.arcgis.com/apps/becq-public-permitting-app/explore)

6.0 Natural Hazard Risk and Mitigation

The risk of natural hazards must be considered for projects intended to provide a resilient source of power. Equipment can be hardened to reduce the risk of failure, but this adds cost to the project and so it is important to understand which hazards hardening efforts should target.

Figure 39 shows the most prevalent natural hazards in the South Pacific and the estimated annual damage for each hazard. This figure shows that tropical cyclones are the hazard of greatest concern, both in terms of frequency and damage, and earthquakes, floods, and drought are all significant hazards as well in the region. Note that drought was not included in the prevalence analysis shown on the left.



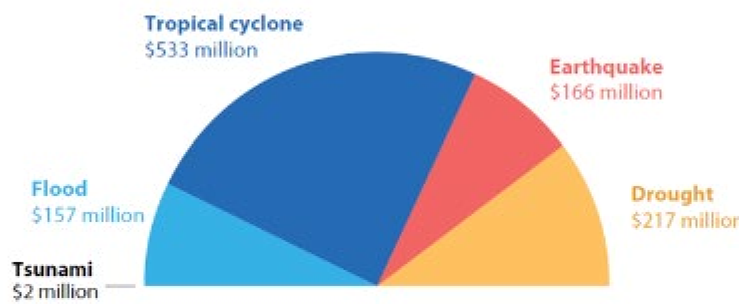


Figure 39. (Left) Natural Hazard Prevalence (World Bank 2023) and (Right) Annual Financial Impact of Natural Hazards in South Pacific Island Nations (United Nations 2020)

Table 25 summarizes the most prevalent hazards affecting Saipan and the CNMI. The table indicates the most common time of year when the hazard occurs, how susceptible electrical infrastructure is to the hazard, and whether the hazard has been demonstrated to be increasing over time. The infrastructure susceptibility is for general purposes and is not location specific. The risk level is assigned based on the information presented below.

Table 25. Summary of Prevalent Regional Hazard Risks and Infrastructure Susceptibility

Hazard	Season	Risk	Electric Infrastructure Susceptibility to Damage	Increase in Future
Typhoon	Aug-Dec	High	High	Yes
Aerosol salt deposition	Year-round	High	High	No
Earthquake	Year-round	High	High	No
Flooding	Year-round	Low (landfill at 40 m elevation)	High	Yes
Drought	Dec-Apr	Mod	Low (does not impact electrical equipment)	Yes

6.1 Typhoons

Typhoons are storm systems that originate over tropical or subtropical water and are equivalent in the Pacific to a hurricane in the Caribbean or Atlantic. The intensity and frequency is expected to increase in the future due to climate change (World Bank 2013; United Nations 2020; Grecni, et al. 2021).

Typhoons pose a significant threat to infrastructure through direct damage from wind and from flying debris. Wind speeds and pressure differentials in air commonly destroy telephone poles, roof tiling, vehicles, antennae, and other smaller objects and structures, but the wind can also turn these objects into projectiles that can cause significant damage to larger, sturdy structures. Typhoons are often accompanied by torrential rainfall and sea water surges, which can cause coastal and inland flooding. Category 5 Super Typhoon Yutu hit the Northern Mariana Islands in 2018, leaving the region without electricity, and is the second strongest storm system to ever hit U.S.-owned land and the fifth strongest worldwide that has hit land, with sustained winds of 180 mpg (Chiu, et al. 2018). Widespread damage also delayed restoration of utility services, but many solar PV systems were left intact and were fully operational once CUC service was restored (all are grid-connected and cannot operate without grid service), such as at the DPW building and at the U.S. Army Reserve facility. Others were only partially damaged, such as at the Business Plaza (Figure 40). Another event occurred in 2015, when Typhoon Souldelor struck, leaving the area without electric, water, or wastewater services for several months.

Figure 40. Damage from Typhoon Yutu to the Solar PV System at the Marianas Business Plaza

Figure 41 shows historical paths of tropical cyclones in the Pacific. The Northern Mariana Islands are in an area with a heavy concentration of typhoons.

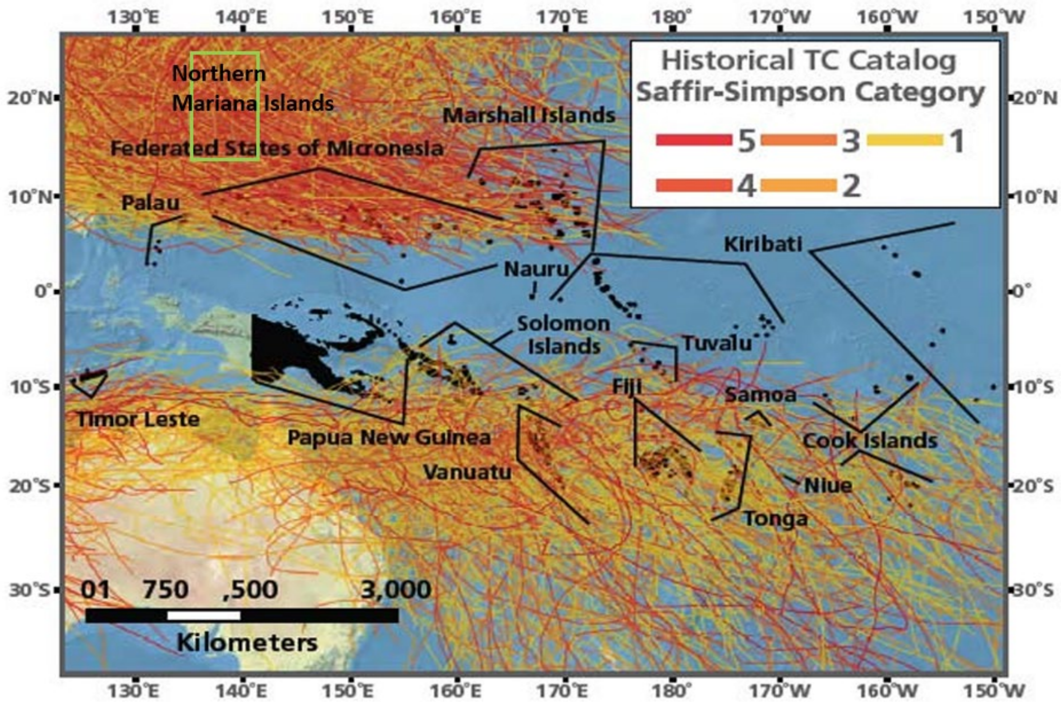


Figure 41. Map of Tropical Cyclone Paths Through the South Pacific (World Bank 2013)

6.2 Aerosol Sea Salt Deposition and Corrosion

Salt acts as a corrosion agent, deteriorating metal, paint, and finishes, and causes metals to oxidize. Several factors influence the corrosion rate of aerosolized salt air on metal, including wind speed and direction, coastal topography, humidity, and wave height. Each of these factors plays a role on determining the distance salty air travels. The impact of the salty air on metal material is so extensive that it can affect structures up to 50 miles inland (Poma 2022). Sea salt deposition can significantly impact the longevity of exposed electrical infrastructure, accounting for as much as 40% of an asset’s lifecycle cost (DoD n.d.), and cause utility disruptions if preventive maintenance is not taken.

Marpi is located within a mile of the Saipan coast, on the windward side of the island. Figure 42 shows corrosion of a metal pipe around a groundwater monitoring well. The rental generator is located in a shelter but is not fully enclosed; corrosion can be seen in Figure 43.

Figure 42. Corroded Pipes Surrounding Water Monitoring Wells

Figure 43. Rental Generator in Enclosure with Some Corrosion

6.3 Earthquakes

The earthquake zone that lines the perimeter of the Pacific Ocean is called the Ring of Fire or the Circum-Pacific Belt, and about 90% of the world's earthquakes occur in this area (National Geographic Society 2022). As a result, earthquakes are a significant risk across the Pacific. The Northern Mariana Islands are on the edge of the Philippine Sea Plate, where many strong earthquakes occur. There have been 11 earthquakes of magnitude 7.0 or greater (defined as major earthquake with serious damage) in the last century that have been in range of Saipan

(Earthquake Track n.d.). Figure 44 shows the prevalence of earthquakes in the Pacific. Saipan is in a high hazard area.

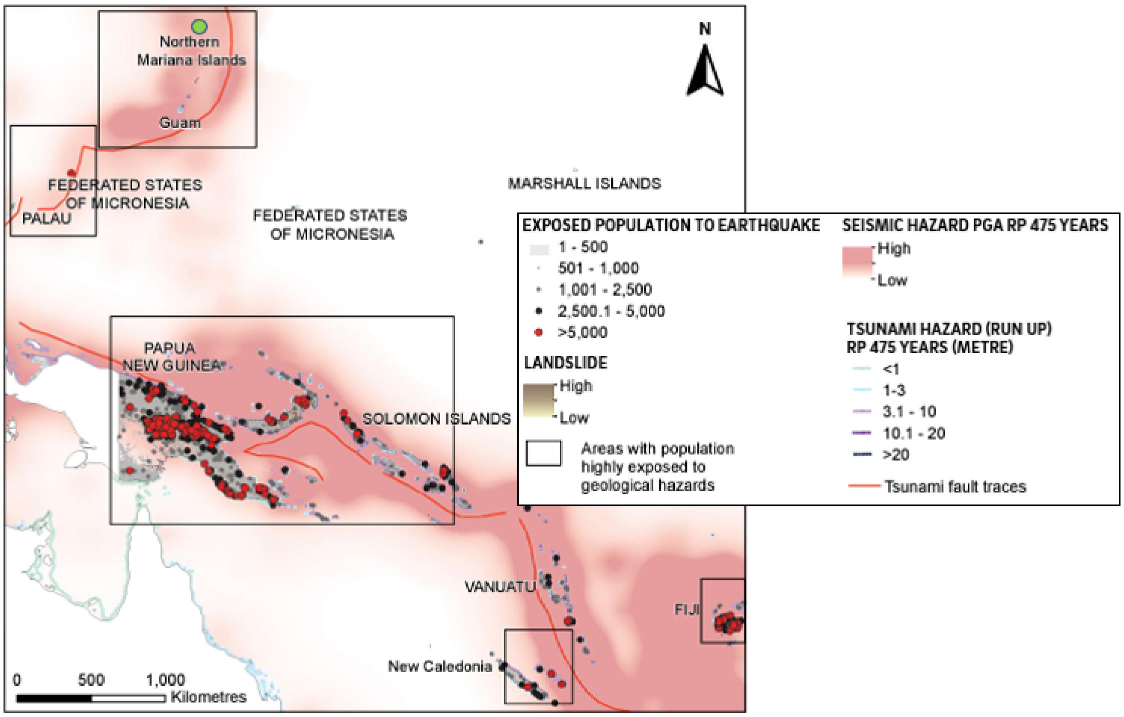


Figure 44. Earthquake Hazard Zones in the South Pacific (United Nations 2020)

6.4 Other Hazards

There are additional hazards that are not high risk for power supply systems at Marpi and/or do not have distinct mitigation measures for power supply equipment. These are discussed below and outlined in the CNMI's 2014 Standard State Mitigation Plan (CNMI 2014). Climate change has also been identified as a threat that can interact with or exacerbate some of these hazards.

6.4.1 Flooding

Hydrologic hazards in the CNMI include coastal and inland floods, storm surge, coastal erosion, and droughts. Six areas on Saipan are prone to flooding and include Kanat Tabla, the San Roque village, the road at Tanapag, the lower base industrial area, Garapan/Putan Muchot, and the Chalan Kanoa-Lake Susupe area. However, Marpi is not located near any of those areas and is at 40 m of elevation, so risk of flooding and associated impacts to landfill power generation is low.

6.4.2 Drought

During the past 15 years, the driest years in the Mariana Islands have been associated with the El Niño phenomenon, which can change weather patterns within the Pacific. During the 1997–1998 El Niño, drought was so extensive as to cause widespread water rationing. However, drought does not impact electrical equipment, and as such risk to Marpi's power generation infrastructure is low.

6.4.3 Wildfire

There are hundreds of wildfires on the CNMI every year, especially during severe drought conditions. An uncontrolled wildfire near the landfill could damage power generation infrastructure.

6.4.4 Volcanic Activity

There are several active volcanic areas within the Mariana Islands, including Anatahan, Pagan, Alamagan, and Agrigan. While all areas exist on remote islands to the north, wind could cause ashfall on the southern islands. This ash could cause corrosion to metallic surfaces or lower PV array efficiency if allowed to settle.

6.4.5 Tsunami

There is no historical record of tsunamis in the CNMI; however, it is possible that an underwater volcanic eruption could cause one. Given the landfill's elevation, the hazard intensity rating is low.

6.5 Hardening Techniques

Hardening techniques to reduce the risk of damage from the key hazards identified for microgrid components at Marpi are summarized in Table 26 and additional details are provided below. Costs for hardening these technologies are included in project costs throughout the report, with the exception of tilt-up wind turbines.

Table 26. Sample Hardening Techniques for Microgrid Components at Marpi Landfill

Technology	Typhoons	Aerosol Salt Deposition	Earthquakes
PV panels	Wind-load rated racking to withstand ~200 mph winds and panel protection from flying debris (e.g., FEMA guidance, IEC 61730 and IEC 61215 certification)	Panels that comply with IEC 61215 standards for salt mist corrosion; UL 1703; NEMA 4X-6P rated enclosures for ancillary equipment	Rack ratings for seismically active areas (ASCE 7-10 design categories)
Wind turbine	Tilt-up technology; rotor braking; ballast foundation	Similar standards for salt mist corrosion as PV	American Clean Power Standard 61400-1 includes seismic loading recommendations
Generator, BESS	Hardened enclosure with NEMA/IP ratings; structural fencing	NEMA rated enclosure; CARC paint; MIL-STD 810G compliance IEC 61427 and 62933 and IEEE 1679 (batteries, environmental conditions)	Seismic retrofits and anchoring (e.g., for fuel tanks); adherence to UFC 3-310-04; IEEE 693-2005

Some measures can be implemented to reduce the risk of typhoon wind damage to power systems. PV panels should be designed and anchored sufficiently through the mounting systems to withstand 179-215 mph[7] wind speeds at Marpi, depending on the risk category chosen for solar PV (which is not specifically identified in the structure types listed by FEMA) (FEMA 2020). The carport PV system at CHCC was engineered to withstand 200+ mph winds using structural piers buried 14 ft deep and encased in concrete and rebar. The carport PV system at the Marianas Business Plaza is rated for 180 mph winds, and has 3 rails and 6 clamps per panel, more than the recommended amount. Even so, more than a quarter of the system's panels were blown away by Typhoon Yutu. Several specific design and construction recommendations for PV survival in a typhoon are documented in the Rocky Mountain Institute's "Solar Under Storm" best practices report, which is based on lessons learned in the Caribbean from Hurricanes Irma and Maria. Recommendations include not only design for high wind loads but also methods such as through-bolting and QA/QC of bolt torquing (Burgess and Goodman 2018). Cost premiums for several recommendations applicable to Marpi are summarized in Table 27. Solar PV System Hardening Cost Premiums (Elsworth and Van Geet 2020). These costs are included in the overall project costs presented for solar PV options throughout this report.

Table A-27. Solar PV System Hardening Cost Premiums

Measure	Base Case	Hardened Case	Ground Mount Premium	Roof/Carport Premium
Module Selection	Standard modules (2400 Pa uplift)	Highest rated modules (≥ 3600 Pa uplift)	$100/kW	$100/kW
Three-Framed Rail System	Two-rail racking	Three-rail racking	$52/kW	$57/kW
Two-Pier Mounting	One driven steel pier	Dual post piers	$59/kW	N/A
Through Bolting	Top-down clamps	Through bolts	$6/kW	$7/kW
System Audit	No system audit	Torque-check fasteners (2% / 100% of fasteners)	$0.50/kW / $25/kW	$0.50/kW / $27/kW

Wind turbines should use tilt-up technology (including the hydraulic system to operate it) so that they can be lowered when a storm is coming to reduce damage to the system. A ballast foundation further improves resilience in high winds. Together these cost approximately $50k more than a turbine with a stationary tower and concrete foundation (Connor 2023).

Additional general construction and maintenance mitigation measures based on lessons learned from Super Typhoon Yutu are documented by FEMA (2021).

Measures to reduce the impact of salt air on electrical infrastructure include burying, enclosing, or otherwise protecting generators, batteries, and inverters, and using galvanized steel fasteners and frames/structures that do not corrode for PV panels and wind turbines. Although stainless steel, aluminum, copper, and galvanized steel have corrosion-resistant properties, they still react to salty air and oxygen unless a specialized metal finish that is designed for coastal areas with high levels of salty air is used (McCutcheon 2019). The Marianas Business Plaza uses synthetic rubber strips to separate PV panels from the aluminum rails to mitigate the effect of salty air and reduce rust. Equipment should be rated to NEMA 4X and IP65 ratings for

[7] According to FEMA's Special Wind Region Maps for CNMI, https://hazards.atcouncil.org/#/wind?lat=15.271285794690895&lng=145.8158297274414&address=

resistance to corrosion and water ingress. Use of marine-grade steel is common in island environments. As an example of how this impacts project costs on Saipan, fasteners for PV using marine-grade steel have a premium of approximately $11/kW over standard grade steel fasteners (Elsworth and Van Geet 2020).

Earthquake resistant (seismic) design and construction of buildings and nonstructural systems and components of the microgrid should be implemented to minimize the risks associated with the earthquake seismic loading data for Saipan. This includes anchoring of components, seismic restraints for floor-mounted or suspended equipment, and bracing for rigid and flexible pipes (including exhaust stacks) and electric conduit. Certification of components to meet earthquake hazard standards should strive to achieve the standards in the Unified Facilities Criteria 3-310-01, Table C-2 (DoD 2005).

7.0 Prioritization of Scenarios

To assist with decision-making, a prioritization matrix was created to compare the microgrid scenarios evaluated in this feasibility study according to various SW Taskforce priorities. The prioritization metrics (described below) were chosen based on discussions with OPD and will be finalized through stakeholder feedback. The scenarios were given a score between 1 and 7 for each prioritization metric (the lower the score, the higher the priority) and total scores were calculated using assigned weights based on the relative priority of each metric. The total scores were then ranked to produce a prioritized list of microgrid scenarios based on the metrics most important to the project stakeholders. This matrix (provided in a separate file) can be used to reprioritize if needs or scenarios change.

The prioritization metrics include elements listed in the scenario descriptions as well as factors described in other sections of this report. Scores were determined both quantitatively and qualitatively, and relative weights for each metric were assigned. The metrics are:

- Capital cost – Costs without grants were scored. Scores were assigned by ranking each scenario: the lower the capital cost, the better the score. A low priority was assigned to this metric because of the potential for grants to reduce the cost in most scenarios.
- Annual O&M costs – Scores were assigned by ranking each scenario: the lower the O&M costs, the better the score. The highest priority was assigned to this metric because it impacts ongoing landfill responsibilities and is a concern for stakeholders.
- 25-year LCOE – Scores were assigned by ranking each scenario: the lower the LCOE, the better the score. Similar to capital cost, this metric was assigned a lower priority.
- Percent of load not met annually – Any scenario that could meet 100% of the load and includes diesel generation to cover unexpected renewable energy shortfalls was assigned a score of 1, any scenario that could meet 100% of the load and does not include diesel generation was assigned a score of 3, and any scenario that is not sized to meet 100% of the load was assigned a score of 7. This is a high priority metric because reliable, 24/7 power availability is a key goal for the landfill.
- Meets permit requirements for backup power – Any scenario with diesel generation was assumed to meet backup requirements and was assigned a score of 1; any scenario without diesel generation was assigned a score of 7. This was given a high priority because permit requirements must be met.
- Carbon dioxide equivalent (CO_2e) emissions generated per year – Scores were assigned by ranking each scenario: the lower the CO_2e emissions, the better the score. This was given a low priority but may be weighted more if certain grants requiring carbon reduction are pursued.
- Area requirement – If the scenario components are expected to fit within the identified location at the landfill, that scenario was assigned a score of 1. If it is unclear whether the components for a scenario will fit within the identified location, that scenario was assigned a score of 4. Scenarios with configurations that will not fit were assigned a score of 7. This metric was assigned a medium priority because other locations may be able to be used.
- Diversity of resources – Scores were assigned by ranking each scenario based on the number of microgrid components included: the higher the number of components, the lower the score. This metric was assigned a medium priority because it helps to determine the reliability of the system but is not the sole determinant.

- Equipment hardening requirements – More equipment and larger capacities require more hardening. In general, wind turbines are the most difficult and expensive to harden, then PV, and then BESS and generators, which are housed in enclosures and therefore have some protection from certain hazards. Scores were assigned by ranking each scenario based on the types of equipment included and the hardening requirements for each equipment type. This metric was assigned a low priority because it does not significantly impact the feasibility of any scenario.
- Training requirements – All components (including diesel generators if O&M will not be contracted out) and microgrid equipment will require training of dedicated operators. Scores were assigned by ranking each scenario based on the equipment and training requirements for each equipment type. This metric was assigned a lower priority because training is not expected to be a hindrance to project development.
- Smart, Safe Growth – Smart, safe growth (SSG) is a set of complementary development strategies and practices focused on improving the resiliency and recoverability of the built environment. This guidance and evaluation tool (available at opd.gov.mp) supports multiple sustainable growth objectives and is a foundational policy document incorporated into the CNMI's Comprehensive Sustainable Development Plan. SSG scores indicate consistency with SSG guiding principles. This metric was given a lower priority based on its less direct impact on the project. The SSG principles include:
  - Climate change
  - Retreat
  - Retrofit
  - Critical facilities location
  - Development incentives
  - Sustainable development best management practices
  - Ecosystem services
  - Green infrastructure
  - Development decision process
  - Early collaboration
  - Knowledgeable Smart, Safe Growth communities
  - Adaptive management

Summaries of the scenarios' quantitative metric results are shown in Table 28 (metrics scored using qualitative results are not included in this table). The scores for each metric and scenario and the overall scenario ranking scores are shown in Table 29.

This ranking shows that a microgrid that includes solar PV, BESS, and a diesel generator is the favored option. Diesel generators alone rank second. Scenarios without diesel generation are ranked lowest, and scenarios using wind without solar PV are also less favored.

Table 28. Summary of Marpi Power Supply Scenario Prioritization Metric Details

	Capital Cost, no grants ($M)	Capital Cost, with grants ($M)	Annual O&M Costs ($k/yr)	25-year LCOE, no grants ($/kWh)	25-year LCOE, with grants ($/kWh)	% Load Not Met Annually	Meets Permit Requirements for Backup Power	CO_2e Emissions Generated (tons/yr)	Area Required for PV and Wind (ft^2)	Diversity of Resources (# of components)
Scenario 1	4.5	0.4	8	1.93	0.22	0%	no	0	42,000	2
Scenario 2	3.6	0.3	19	2.75	0.41	34%	no	0	88,000	2
Scenario 3	4.3	0.3	20	1.86	0.29	0%	no	0	119,500	3
Scenario 4	2.3	1.0	18	0.96	0.49	0%	yes	22	21,000	3
Scenario 5	2.7	1.0	55	1.44	0.76	0%	yes	54	88,000	3
Scenario 6	2.9	1.1	25	1.17	0.56	0%	yes	12	109,000	4
Scenario 7	0.5	0.5	90	0.75	0.75	0%	yes	122	0	1

Table 29. Prioritization of Marpi Power Supply Scenarios (no grants)

	Capital Cost ($M)	Annual O&M Costs ($k/yr)	25-year LCOE ($kWh)	% Load Not Met Annually	Meets Permit Req. for Backup Power	CO_2e Emissions Generated (tons/yr)	Area Req. (ft^2)	Diversity of Resources (# of components)	Equipment Hardening Req.	Training Req.	Smart Safe Growth		
Relative Metric Priority	1	5	1	3	4	1	3	3	1	2	2	**Total Weighted Score**	**Rank**
Scenario 1	7	1	6	3	7	1	4	5	2	3	2	**3.17**	**4**
Scenario 2	5	3	7	7	7	1	4	5	5	3	5	**4.17**	**7**
Scenario 3	6	4	5	3	7	1	4	2	6	5	5	**3.77**	**6**
Scenario 4	2	2	2	1	1	5	1	2	3	5	4	**1.87**	**1**
Scenario 5	3	6	4	1	1	6	4	2	4	5	7	**3.20**	**5**
Scenario 6	4	5	3	1	1	4	4	1	7	7	6	**3.03**	**3**
Scenario 7	1	7	1	1	1	7	1	7	1	2	5	**3.00**	**2**

8.0 Implementation Considerations

There are several aspects of implementing a microgrid that are important to consider once the equipment configuration and characteristics have been evaluated and prioritized. These include funding opportunities, procurement, ownership, and O&M training, among others.

8.1 Funding/Grant Opportunities

Depending on the technology configuration, system ownership, and implementation timing of the microgrid for Marpi, there may be opportunities to defray some or all of the capital costs associated with purchasing and installing the equipment and infrastructure. These funding opportunities can take the form of federal agency grants that directly offset (pay for) capital expenses (either directly or via a cost-share requirement), or tax benefits that can improve project financing terms.

The availability of federal grants is largely contingent on agency and administration priorities, which are currently focused on decarbonization and energy security/resilience. Some grant programs are available on a yearly basis (e.g., from the Office of Insular Affairs) while others may only occur as a single instance, driven by agency priorities or a precipitating event (e.g., American Recovery and Reinvestment Act or typhoon recovery funds). Tax credits, such as those associated with the Inflation Reduction Act (IRA), have a predetermined window of availability for projects to qualify.

CNMI and other U.S. territories and freely associated states are eligible for grants from the Office of Insular Affairs, which are announced annually, typically in the fall (https://www.doi.gov/oia/financial-assistance). These fall under several categories, two of which are relevant to a Marpi microgrid.

- The Energizing Insular Communities program provides grant funding for energy strategies that reduce the cost of electricity and reduce dependence on foreign fuels. The proposed strategies should support documented Strategic Energy Plans, as the Marpi microgrid supports the CNMI Strategic Energy Plan (see Section 1.1). This program has previously funded microgrids, solar PV, wind, and battery projects and studies.
- The Maintenance Assistance Program develops insular institutions and capabilities that improve the operation and maintenance of infrastructure in the island areas. This grant could be used for staff and contractor microgrid O&M training, as it has been used for power plant operator training in the past.

As of Spring 2023, several federal grants are available or announced that may be options for the Marpi microgrid project:

- FEMA has funding options available to territories to mitigate risks associated with natural hazards
  - The Hazard Mitigation Grants Program (https://www.fema.gov/grants/mitigation/hazard-mitigation), which includes the Building Resilient Infrastructure Communities (BRIC) grants (FEMA 2022), funds communities pursuing hazard mitigation activities (in the form of capital projects or capabilities development), with a focus on innovative partnerships and project approaches. Areas of focus include infrastructure projects benefiting disadvantaged communities, climate resilience and adaptation and projects that adopt

hazard resistant building codes: https://www.fema.gov/grants/mitigation/building-resilient-infrastructure-communities

- DOE anticipates making grant money available to fund microgrids for underserved communities. The notice of intent to issue that funding opportunity announcement is available: https://www.energy.gov/oe/articles/notice-intent-issue-funding-opportunity-announcement-underserved-and-indigenous
- EPA Greenhouse Gas Reduction Fund provides competitive grants that are designed to mobilize private capital in support of projects that include clean energy and climate resilience measures: https://www.epa.gov/greenhouse-gas-reduction-fund

In addition to federal agency grant funds, the IRA (GPO 2022) extends existing tax benefits and authorizes new tax benefits that can reduce the capital (and ongoing) costs for numerous types of clean energy projects. The following stipulations are potentially applicable to the Marpi microgrid project:

- Section 13102 of the IRA amends the tax code (26 U.S. Code § 48) to provide Investment Tax Credits (ITC) for Energy Property extended through 2023/2024 (construction before 1/1/2025).
  - Solar PV, small wind, batteries (>5 kW), microgrid controllers (<20 MW)
  - Base credit amount is 6% of qualified investment (basis of the energy property)
  - Bonus credits (up to 30%) for prevailing wage, domestic content, and energy communities
- For the ITC, tax-exempt organizations (states and political subdivisions, tribal governments, and Alaska Native corporations) are eligible for direct pay of the benefit. Depending on the project ownership for the Marpi microgrid, the ITC benefit may go to a private (tax-paying) company or may be available as a direct payment to the CNMI government as the owner of the system, pending additional clarification by the IRS.
  - Eligibility of Territories is not explicitly stated in the IRS Sec 6417 language that defines ITC eligibility
  - Precedence set for ITC eligibility in Puerto Rico for U.S. corporation, citizen, or partnership owning the project (IRS private ruling)[8, 9]
  - Solar production tax credit eligibility for territories (especially mirror-code jurisdictions) in Internal Revenue Code Section 45[10]
- ITC eligibility for DPW/OPD (CNMI public entities) to take direct payment is unclear but may be possible; may require an IRS Private Letter Ruling.

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[8] Additional information on ITC eligibility for projects executed in Puerto Rico: http://dpny8pxabs9qx8.devcloud.acquia-sites.com/sites/default/files/2022-10/Reimagining%20Grid%20Solutions_Final%20SIPA%20REPORT_0.pdf

[9] The IRS Private Letter Ruling establishing eligibility for a US corporation to receive the ITC for a project built in Puerto Rico: https://www.irs.gov/pub/irs-wd/1324006.pdf

[10] Clean Energy Production Tax Credit in Puerto Rico and U.S. territories: https://crsreports.congress.gov/product/pdf/R/R44651

- Beginning in 2025, the existing ITC will be replaced by the Clean Electricity Investment Tax Credit, which will provide similar incentives and have similar requirements; the phase-out will begin in 2032.[11]
- The IRA did not modify existing accelerated bonus depreciation provisions in the tax code. Accelerated bonus depreciation (MACRS) allows private businesses to write off a portion of an asset's cost in its first year of use; qualifying clean energy technologies have historically been eligible for accelerated schedules. The current bonus provisions will be phased out beginning in 2023 and ending in 2027. This tax benefit is only available to private tax-paying businesses (incorporated in the U.S.) and would not be available if the CNMI government procured the system directly.

8.2 System Procurement

The procurement of microgrid systems at the scale suitable for Marpi can largely fall into two approaches: 1) integrated solutions that specify the design, procurement, and construction of the distinct microgrid components into a customized solution, or 2) single-vendor packaged systems that consist of components that have been designed and fabricated by the vendor to operate as a preconfigured system. The pros and cons of these options are summarized in Table 29 and detailed below.

Table 30. Considerations for Single Vendors versus Integrated Microgrid Systems

	Pros	Cons
Single Vendor	• Minimizes site work for equipment integration • Should have single O&M offering	• Equipment sizing will be limited to vendor offerings and may not be optimal for site • Inherently design-build style contracts that can have higher costs and fewer vendor options
Integrator	• Allows for customization and selection of best-in-breed technologies optimal for Marpi project • Design-bid-build procurement can align with external requirements for competitive source selection by public agencies	• Longer installation and commissioning timelines • Multiple warranties and need for interoperability guarantees • May require multiple maintenance contracts

For integrated solutions, procurement may be design-build, where design and construction are bundled under the same contract, or design-bid-build, where elements are contracted separately. Each procurement approach has tradeoffs that impact the execution of the project.

Design-build projects may have accelerated timelines, better management of project risks, consistent and predictable budgets, and easier communication and project management. However, design-build projects are likely more expensive as there are fewer opportunities to solicit competitive bids and therefore lock in with a single vendor.

Design-bid-build projects can offer more competitive bidding and pricing, more control over the design and construction elements of the project, and often align with procurement requirements for public agencies (like DPW or OPD). Adverse impacts of pursuing design-bid-build include longer execution timelines, a lack of product and logistics insight early in the process (design

[11] Details on the various elements of the Inflation Reduction Act can be found in the accompanying Guidebook: https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf

firms will not have the same knowledge about equipment options and availability as construction firms), increased conflicts and potential change-orders, and late-stage definition of cost budgets. These factors should be considered when contemplating solutions that require significant system design and integration.

Integrated solutions will enable system designers and builders to identify a mix of technologies that are optimized for Marpi's energy needs and designed to meet specifications set by OPD and DPW. While this approach can result in a right-sized mix of generation and storage components, it will require a design and construction firm that is experienced in microgrid integration and operation.

The alternative approach to design-built integrated systems is to procure packaged microgrids from single vendors that deliver a microgrid solution where the components are preconfigured to operate together, eliminating many of the integration elements associated with design-built options. These systems reduce risks and timelines associated with project execution, but offer far less customization or opportunities for optimizing equipment sizing. Because the solution is provided by a single vendor, ongoing maintenance support and warranties can be simplified under a single contract.

8.3 System Ownership

As with procurement, there are multiple options for ownership and operation of a Marpi microgrid. These broadly fall into two categories: 1) a government-owned system where ownership of the equipment resides with DPW and responsibility for O&M can fall on the government and/or support contractors, or 2) third-party ownership of the system by a separate entity that retains any and all tax benefits and O&M responsibilities to provide power to the landfill. These options are summarized in Table 30 and detailed below.

Table 31. Comparison of Ownership Models

	Pros	Cons
DPW-owned	• Less expensive capital • Better funding eligibility for certain programs • Operations and maintenance can be performed in-house (DPW personnel) or included as part of Marpi site operations contract	• Requires operator know-how for complex technology • Ability for CNMI government to qualify for the ITC is unclear
Third-party owned	• O&M responsibility with an entity that knows power generation • Tax credits (ITC, MACRS, etc.) are available for U.S.-based companies	• DPW is a customer for power output, may not have to cover the upfront capital costs of the system if a long-term power purchase agreement can be executed • Potential limitations on funding eligibility

Under a government-owned option, DPW would acquire and own the system and then either assign DPW personnel to operate and maintain the equipment (for O&M activities not within the scope of a vendor service contract), or contract the operation of the microgrid to the site operator or another entity. Operation of a government-owned system by a third party may reduce labor and other related costs, but performance risk may still reside with the government-owned equipment. Training of DPW and contractor staff would be the responsibility of the government, and contract/staff turnover would complicate training efforts.

For third-party owned and operated systems, DPW would pay for energy services (electricity sales) from the third party. Risks and responsibility for system performance would reside with the system owner and would be managed via the contractual obligations. System ownership would reside with an entity that knows power systems and how to optimize their operation and minimize risks. Typically, a utility company (such as CUC) or an energy services company has the expertise and is well-suited to fill this role.[12] In some ways, this could be a similar configuration to how the DPW pays for and receives CUC electricity at other locations; in this case, CUC (or another third-party entity) would calculate a cost of power and associated rate ($/kWh) to sell power to DPW, accounting for their requirements for recouping capital expenditures and returns on investment, as well as ongoing operating costs for the microgrid.

The ability of DPW to pursue and secure grant funding for the capital expenses for the project may be determined by (or may determine) the ownership model chosen; certain grants may only be available for projects where ownership is retained by the public entity, while tax credits, accelerated tax depreciation, and other grants may only be available to private entities. Considerations for funding opportunities are discussed in Section 8.1.

8.4 Operations and Maintenance Training

O&M requirements specific to individual technologies are discussed in the respective subsections of Section 3.2, with overall microgrid system O&M included in Section 3.2.5.2. As described in that section, trained operators will be required. Trained system operators help to avoid and quickly resolve system issues by monitoring the system and calling appropriate professional assistance as needed. Quick resolution and prevention of outages is important for Marpi because there is no grid power to rely on in case of equipment failure. DPW may use a maintenance contract to manage the system, but with or without a maintenance contract, DPW staff will need training for system familiarity at a minimum and ideally to troubleshoot and fix issues as well.

The microgrid equipment vendors (whether for individual components or for a single-vendor system, but usually the microgrid controls company) will provide manuals to guide operators on specific O&M tasks, including when to call vendors or other trained maintenance personnel. The project statement of work should include training for basic O&M as part of system commissioning, and some vendors also offer more detailed online or in-person training on their equipment. In addition, educational institutions (community colleges, universities, trade schools, etc.) offer a variety of in-person and online courses covering microgrids and renewable energy systems in varying amounts of detail. The following example training resources are available for microgrids and components being considered for Marpi.

- Microgrid: Online courses are available through organizations such as
  - Arizona State University (Microgrid Master Classes, https://leaps.asu.edu/trainings/)
  - IEEE (https://www.ieee.org/education/academy-index/smartgrid.html)
  - Tonex (https://www.tonex.com/training-courses/microgrid-certification-training/)
- Wind turbines:

[12] For larger power plants in deregulated electricity markets, an Independent Power Producer (IPP) can own and operate large-scale microgrids or power plants; the size of the Marpi project is well below the threshold of a typical IPP. As part of their large-scale solar PV and energy storage project for Saipan, CUC is evaluating options to have an IPP own and operate systems and sell power to CUC.

- https://windexchange.energy.gov/training-programs provides a list of training courses based on U.S. location and institution type (community college, university, or other education)
- ENSA, a provider of “work at height” safety trainings for wind, telecom, and other industries provides both basic and advanced tower climbing and safety trainings in person (https://www.ensa-northamerica.com/).

8.5 Additional Considerations

The CNMI DPW Solid Waste Management Facility’s Bureau of Environmental and Coastal Quality (BECQ) permit requires, within two years of the effective date of the permit (June 24, 2021), the installation of an electrical source (either CUC grid interconnection or alternative energy such as solar or storage with a BESS) that can provide continuous power to perform 24-hour monitoring and automatic leachate pumping. While this permit is likely to be amended, and this feasibility study evaluates the alternative energy options, connection to CUC could also be considered. As described in Section 3.1, it has been considered in the past and was determined to be infeasible due to environmental concerns and cost. Conversations with Dr. Dallas Peavey at CUC in February 2023 indicated that the utility is building a solar PV and BESS project at the Marianas Country Club, which is closer to the Marpi Landfill and may provide an alternative route that is less expensive. A new route will require new archaeological and environmental studies, which can add significant cost to a project, along with Historic Preservation Office requirements. On the other hand, a CUC connection may impact the desired configuration for on-site power supply options, potentially resulting in smaller system requirements and the offset of those project costs. Even with a CUC connection, on-site generation is still important for the prevention of extended loss of power; any disruptions on the CUC grid that require repairs may take some time to fix, especially to serve the landfill’s far northern location.

Another consideration is the need to plan for future growth or changes to power needs. The systems evaluated in this feasibility study are sized to power loads based on estimates of current and future operations. While limited data were available for current power requirements, the recommended microgrid sizing is expected to cover all loads considered. However, in the case that future loads (beyond the 5–10-year projections included here) exceed estimates and output of the selected microgrid systems, expansion of the power generation technologies is possible. For instance, additional PV could be considered for other locations in the future, or space could be reserved in the project footprint for additional PV, batteries, wind turbines, or generators. Reservation of space would need to be included in the project statement of work and design.

9.0 Recommendations and Next Steps

The details and results of this feasibility study are presented in this report for consideration by the SW Taskforce. Of the power supply options presented here, a microgrid that includes solar PV, BESS, and diesel generation was shown to best meet Marpi, OPD, DPW, and SW Taskforce requirements and goals. Based on landfill operator and DPW inputs, the evaluation found that approximately 100 kW of solar PV, a 75 kW/300 kWh BESS, and 160 kW of diesel generation will provide the necessary power requirements for continuous landfill operations. This option is estimated to cost approximately $2.3M in total, including hardening, with annual O&M costing approximately $18,000 per year. This is the lowest cost microgrid[13] option, both in terms of capital cost and life cycle cost, and it meets the annual load using a diversity of resources, providing added resilience.

One potential path forward is for OPD to move forward with a request for information or request for proposals and consider the options presented by potential vendors. Suitable solutions may result from such a process, especially if a single-vendor microgrid is desired. Evaluation of responses will need to be done carefully in cases where proposed solutions do not closely align with the scenarios presented here, because there are still many undefined factors and other options may also be viable.

Alternatively, evaluation of various factors can provide additional information that will allow refinement of the recommended equipment capacities. While the specific scenarios to include in the assessment were collaboratively chosen, others may warrant consideration. More refined inputs and use of more complex optimization tools will lead to a solution that best suits Marpi. Factors that may impact the system configuration recommended here include:

- CUC interconnection, as described in Section 8.5.
- Addition of electric vehicles or other loads that may use excess power generated during the dry season. If the shape of the load profile changes, required component capacities may change, especially that of the BESS. The LCOE may also improve, depending on the strategy to serve the added load during the rainy season.
- A change in operation patterns once 24/7 power is available. Some loads may shift from times when the landfill is open and the generator is currently on to times when the landfill is closed, including nights and Sundays.
- Evaluation of output from different capacity wind turbines, different turbine technologies such as tilt-up turbines, and/or different numbers of wind turbines.
- Collection of meter data for loads, to confirm or revise current load assumptions.
- Collection of wind data, which will allow better estimates of output from a turbine(s) sited at the landfill.
- Evaluation of non-diesel fuels for generators such as propane.

Factors that may impact the prioritization of scenarios include:

- The cost of carbon
- Grant or financial incentive availability
- Inclusion of new distribution lines at the landfill

[13] The generator-only option is less expensive but is not considered a microgrid.

- Inclusion of a new fuel tank
- Availability of packaged systems that are sized appropriately to meet Marpi needs.

After assessing this report and considering alternatives, the SW Taskforce will be able to decide which energy supply scenario(s) and/or additional factors should be further pursued.

10.0 References

Asian Development Bank. 2022. “Hybrid and Battery Energy Storage Systems – Review and Recommendations for Pacific Island Projects.” 10.22617/TCS220320-2

Baring-Gould, I, R Hunsberger, C Visser, and P Voss. 2011. "Commonwealth of Northern Mariana Islands Initial Technical Assessment". United States. https://www.osti.gov/servlets/purl/1018874

Burgess, C and J Goodman. 2018. Solar Under Storm: Select Best Practices for Resilient Ground-Mount PV Systems with Hurricane Exposure. Rocky Mountain Institute, Colorado. https://rmi.org/wp-content/uploads/2018/06/Islands_SolarUnderStorm_Report_digitalJune122018.pdf.

Casetext. 2012. Friends of Marpi v. Commonwealth Supreme Court Decision. https://casetext.com/case/friends-of-marpi-v-commonwealth

Chiu, A, C Mooney, and J Eilperin. 2018. “Extreme Category 5 Typhoon, the Worst U.S. Storm Since 1935, Leaves Northern Mariana Islands Devasted.” Washington Post. Accessed June 23, 2022 at https://www.washingtonpost.com/energy-environment/2018/10/24/extreme-category-typhoon-yutu-makes-devastating-landfall-northern-mariana-islands-us-commonwealth/

CNMI. 2014. *Standard State Mitigation Plan*. Commonwealth of the Northern Mariana Islands. https://opd.gov.mp/library/reports/2014-cnmi-ssmp-11.5.2014.pdf

Cole, W and AW Frazier. 2020. Cost Projections for Utility-Scale Battery Storage: 2020 Update. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy20osti/75385.pdf

Connor, C. 2023. Email conversation. 18 January 2023.

CUC. 2023. Schedule of Electric Charges and Rates. Commonwealth Utilities Corporation https://www.cucgov.org/cuc_content/uploads/2023/03/Electric-Charges-Rates-2023-03-01-rv.pdf

Dobos, AP. 2014. "PVWatts Version 5 Manual." United States. https://doi.org/10.2172/1158421. https://www.osti.gov/servlets/purl/1158421

DoD. n.d. “Facility and Infrastructure Corrosion Prevention and Control: Sustainment (Maintenance and Repair).” Internal Training Document. U.S. Department of Defense.

DoD. 2005. Unified Facilities Criteria (UFC): Structural Load Data. UFC 3-310-01. https://www.wbdg.org/FFC/DOD/UFC/ARCHIVES/ufc_3_310_01_2005_c2.pdf

Dodd, J. 2018. “Do we still need met masts?” Wind Power Monthly. Accessed 1 March 2018 at https://www.windpowermonthly.com/article/1458018/need-met-masts

DOE. 2011. U.S. Annual Average Wind Speed at 80 Meters. https://windexchange.energy.gov/maps-data/319

DOE. 2012. U.S. Annual Average Wind Speed at 30 Meters. https://windexchange.energy.gov/maps-data/325

DTU. 2023. Global Wind Atlas. Technical University of Denmark. Accessed 1 March 2023 at https://globalwindatlas.info/

Earthquake Track. n.d. “Biggest Earthquakes Near Saipan, Northern Mariana Islands.“ Accessed 06/10/2022 at https://earthquaketrack.com/p/northern-mariana-islands/saipan/biggest

ECMWF. 2023. ERA5. European Centre for Medium-Range Weather Forecasts. Accessed 1 February 2023 at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5

Elsworth, J and O Van Geet. 2020. Solar Photovoltaics in Severe Weather: Cost Considerations for Storm Hardening PV Systems for Resilience. Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-75804. https://www.nrel.gov/docs/fy20osti/75804.pdf.

FEMA. 2018. Guidance Manual for Smart, Safe Growth Commonwealth of the Northern Mariana Islands. https://opd.gov.mp/assets/cnmi-ssg-guidance-manual-final-2018-11-14.pdf

FEMA. 2020. Special Wind Region (SWR) Maps for the Commonwealth of the Northern Mariana Islands (CNMI). https://opd.gov.mp/library/reports/special-wind-region-swr-maps-for-the-commonwealth-of-the-northern-mariana-islands-cnmi/special-wind-region-swr-maps-for-the-commonwealth-of-the-northern-mariana-islands-cnmi.pdf.

FEMA. 2021. Performance of Public Buildings and Critical Facilities: Mitigation Assessment Team Summary Report and Recommendations, Commonwealth of the Northern Mariana Islands, Super Typhoon Yutu. P-2179. https://opd.gov.mp/assets/cnmi-mat_p2179_final_508.pdf.

FEMA. 2022. Hazard Mitigation Assistance: Mitigation Action Portfolio. Federal Emergency Management Agency. https://www.fema.gov/sites/default/files/documents/fema_fy-22-mitigation-action-portfolio.pdf

Gagnon, P, R Margolis, J Melius, C Phillips, and R Elmore. 2016. *Rooftop solar photovoltaic technical potential in the United States. A detailed assessment.* NREL/TP-6A20-65298. National Renewable Energy Laboratory.

GHD. 2022. *DRAFT CNMI Strategic Energy Plan*. Prepared for the CNMI Office of The Governor, Energy Task Force by GHD, Saipan MP, Northern Mariana Islands.

GPO. Public Law 117-169. 2022. U.S. Government Publishing Office. https://www.congress.gov/117/plaws/publ169/PLAW-117publ169.pdf

GPO. Public Law 18-62. 2014. U.S. Government Publishing Office. https://www.cnmilaw.org/pdf/public_laws/18/pl18-62.pdf

Grecni, Z, EM Derrington, R Greene, W Miles, and V Keener. 2021. *Climate Change in the Commonwealth of the Northern Mariana Islands: Indicators and Considerations for Key Sectors*. Pacific Islands Regional Climate Assessment. Honolulu, HI: East-West Center. https://www.eastwestcenter.org/PIRCA-CNMI

GSES. 2015. *Installation, Operation & Maintenance of Solar PV Microgrid Systems: A Handbook for Technicians.* GSES India Sustainable Energy Pvt. Ltd. for Clean Energy Access Network (CLEAN). www.thecleannetwork.org/pdf/Installation-Operation-and-Maintenance-of-Solar-PV-Microgrid-Systems-A-Handbook-for-Technicians.pdf

Losinio, L. 2019. "Cotal wind turbine back in operation." The Guam Daily Post. https://www.postguam.com/news/local/cotal-wind-turbine-back-in-operation/article_38924fa0-1e19-11e9-b496-27f7672afed1.html. 28 January 2019

McCutcheon, B. 2019. "Impacts of Salty Air on Metal Building Systems and How to Reduce Them." Beck. Accessed March 8, 2022 at https://info.fascoamerica.com/blog/salty-air-and-metal-buildings.

National Geographic Society. 2022. "Ring of Fire." Accessed March 10, 2022 at https://www.nationalgeographic.org/encyclopedia/ring-fire/.

Olauson, J. and M. Bergkvist. 2015. “Modelling the Swedish wind power production using MERRA reanalysis data.” Renewable Energy, 76717-725, https://doi.org/10.1016/j.renene.2014.11.085

OPD. 2021. *Comprehensive Sustainable Development Plan 2021-2030*. Prepared for the Commonwealth of the Northern Mariana Islands by the Office of Planning and Development under the Office of the Governor with support from the Planning and Development Advisory Committee.

Orrell, A and E Poehlman. 2017. Benchmarking U.S. Small Wind Costs With the Distributed Wind Taxonomy. PNNL-26900. Pacific Northwest National Laboratory. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-26900.pdf

Orrell, A, K Kazimierczuk, and L Sheridan. 2022. *Distributed Wind Market Report: 2022 Edition*. DOE/GO-102022-5764. Pacific Northwest National Laboratory. https://doi.org/10.2172/1893256

Poma, J. 2022. “Studies show salt air affects metals more than 50 miles inland.” Poma Metals. Accessed March 8, 2022 at https://pomametals.com/salt-air-inland-distance-for-metal/

Sengupta MY, A Xie, A Lopez, G Habte, G Maclaurin, and J Shelby. 2018. The National Solar Radiation Data Base (NSRDB). Renewable and Sustainable Energy Reviews 89 (June): 51-60. https://doi.org/10.1016/j.rser.2018.03.003

SunnyPortal. 2023. CNMI – DPW Energy Division Plant. www.sunnyportal.com.

United Nations. 2020. Economic and Social Commission for Asia and the Pacific (ESCAP). *The Disaster Riskscape across the Pacific Small Island Developing States: Key Takeaways for Stakeholders*. ST/ESCAP/2880.

World Bank. 2013. *Acting On Climate Change & Disaster Risk for the Pacific*. https://www.worldbank.org/content/dam/Worldbank/document/EAP/Pacific%20Islands/climate-change-pacific.pdf

Appendix A – Terms and Definitions

Battery SoC – The amount of energy stored in the battery. A minimum SoC is typically around 20% and a maximum is typically around 90% for Li-ion batteries.

Curtailment – Shutting down the generation of a system during times when the potential output cannot be used, resulting in a reduction of the output and therefore capacity factor and financial gains for the project

Dispatchable/non-dispatchable – Energy resources are often characterized by whether they can be turned on and off and produce power whenever the operator or system requires it or whether they depend on a natural resource that may be available intermittently. Dispatchable generation includes resources like engines, turbines, fuel cells, and batteries, which can supply power on command. Non-dispatchable resources include solar PV, wind, and some hydropower resources that can only generate power when their input (sunlight, wind, flowing water) is available.

LCOE – A measure of the present cost of electricity generation over the lifetime of a generation system. This LCOE calculation accounted for capital, fixed O&M, variable O&M, fuel, major maintenance, and insurance costs. LCOE is used to compare the cost of electricity generation between different generation options.

$$LCOE = \frac{Net\ Present\ Value\ of\ Costs}{Net\ Present\ Value\ of\ Output} \tag{1}$$

Appendix B – Marpi Landfill Load Assumptions

Operations at the landfill were characterized based on the following assumptions, with information provided by OPD and MES staff.

Equipment	Load (VA)	Dry Season Duty Cycle (h/day)	Dry Season Wh/day	Rainy Season Duty Cycle (h/day)	Rainy Season Wh/day	Load %	Assumptions / Notes
Existing Office Building							
General illumination @ 3.5 VA/SF	3,885	9	34965	9	34965	100%	Assumed used at full capacity.
General use receptacles @ 1 VA/SF	1,110	9	2497.5	9	9990	50%	Assumed only used at partial capacity.
Miscellaneous outlets @ 1 VA/SF	1,110	9	2497.5	9	9990	50%	Assumed only used at partial capacity.
Air conditioning	4,050	9	36450	9	36450	75%	Assumed to turn on above 62°F. Assumed 75% of load to account for building area that is not cooled.
Supply pump	2,400	9	21600	9	21600	100%	Assumed 9h/day when facility is open.
Dryer	5,000	1	5000	2	10000	100%	Per DPW, should be provided as regulators require it.
Washer	1,100	1	1100	2	2200	100%	Per DPW, should be provided as regulators require it.
Electric Water Heater	4,500	3	13500	5	22500	100%	Per DPW, should be provided as regulators require it.
Scale House							
General illumination @ 3.5 VA/SF	875	9	7875	9	7875	100%	Assumed used at full capacity.
General use receptacles @ 1 VA/SF	250	9	1125	9	1125	50%	Assumed only used at partial capacity.
Miscellaneous outlets @ 1 VA/SF	250	9	1125	9	1125	50%	Assumed only used at partial capacity.
Air conditioning	1,958	9	17622	9	17622	100%	Per MES operator has cooling on for 9 hours during both dry and rainy season instead of 4 hours only for dry season.
Maintenance Building							
General illumination @ 2.5 VA/SF	3,620	9	16290	9	16290	50%	Assumed only half the lights are in use.
General use receptacles @ 1 VA/SF	1,810	9	8145	9	8145	50%	Assumed used at partial capacity.
Miscellaneous outlets @ 1 VA/SF	1,810	9	8145	9	8145	50%	Assumed only used at partial capacity.
Ventilation	3,620	0	0	0	0		Per MES not currently in use.

Equipment	Load (VA)	Dry Season Duty Cycle (h/day)	Dry Season Wh/day	Rainy Season Duty Cycle (h/day)	Rainy Season Wh/day	Load %	Assumptions / Notes
Air compressor	16,800	1	16800	1	16800	100%	Assumed 1 h/day, 3 days/week
Welding machine	18,013	1	18013	1	18013	100%	Assumed 1 h/day, 2 days/week
Pump, 1/2 HP	2,400	9	21600	9	21600	100%	A 1/2 HP water pump is presently used for Maintenance bldg. No other pumps are being used.
Roll-up doors, 3 each 1 HP	4,500	2	9,000	2	9,000	100%	DPW suggests to provide for this item to power up when funds are available. Assumed 1h of use in morning and evening.
Generator Building							
General illumination @ 3.5 VA/SF	1,575	9	14175	9	14175	100%	DPW suggests including these loads for future rehabilitation plans.
General use receptacles @ 1 VA/SF	450	9	2025	9	2025	50%	DPW suggests including these loads for future rehabilitation plans.
Miscellaneous outlets @ 1 VA/SF	450	9	2025	9	2025	50%	DPW suggests including these loads for future rehabilitation plans.
Fuel pump	1,100	4	4400	4	4400	100%	DPW suggests including these loads for future rehabilitation plans.
Cell 1							
Storm pump*	11,190	0	0	0	0	100%	Per MES Cell 1 stormwater pump is no longer used.
Standard pump**	3,730	4	14920	4	14920	100%	Per MES operator runs pump 4 h/day.
Leak detection pump	1,120	1	1120	1	1120	100%	Assumed 1 h/day when facility is open.
Cell 2							
Storm pump*	11,190	2	22380	5	55950	100%	Per MES operator runs this pump approximately 2 hrs/day during dry season and 5 hrs/day during rainy season.
Standard pump**	1,490	5	7450	5	7450	100%	Assumed operates every other hour when facility is open.
Leak detection pump	1,120	1	1120	1	1120	100%	Assumed 1 h/day when facility is open.

Equipment	Load (VA)	Dry Season Duty Cycle (h/day)	Dry Season Wh/day	Rainy Season Duty Cycle (h/day)	Rainy Season Wh/day	Load %	Assumptions / Notes
Leachate pond	1,490	9	13410	9	13410	100%	Per MES operator runs 2 HP pump 9 hrs/day all year
Blower/aeration pump	14,920	9	134280	9	134280	100%	Per MES blowers run alternately. Operator is supposed to run blowers 9 hours per day all year as part of treatment cycle under normal conditions.
Vegetative submerged beds effluent sump force main pump	2,240	9	20160	9	20160	100%	
Cell 3							
Storm pump*	22,380	2	44760	5	111900	100%	Per MES operator runs this pump approximately 2 hrs/day during dry season and 5 hrs/day during rainy season.
Standard pump**	2,240	5	11200	5	11200	100%	Assumed operates every other hour when facility is open.
Leak detection pump	400	1	400	1	400	100%	Assumed 1 h/day when facility is open.

Appendix C – Economic Assumptions and References

The financial analysis calculated the levelized cost of electricity (LCOE) as net present value of costs divided by net present value of output. This approach was used to account for generation output degradation, BESS efficiency losses, and major maintenance at different intervals for each component. The costs and production for each asset were discounted back to the present using the real discount rate of 0.45%. The rate was based on interpolation of 20-year and 30-year real interest rates as specified in Appendix C of OMB Circular No. A-94.

Capital costs occurred in Year 0. Major maintenance occurred in years 8 and 16 for solar, 10 and 20 for wind, 8 and 24 for BESS, and 15 for microgrids, which was a major asset replacement. The remaining value of assets at the end of the 25-year project was added back in year 25, using straight-line depreciation. These costs as well as annual O&M and fuel costs were discounted to present. The total present value of costs for all assets were summed and divided by the total present value of production in kWh, resulting in the LCOE of each scenario.

Table C-1 lists the parameters used in the economic analysis, along with references for each. Lists of example projects and other reference costs used to determine cost assumptions for each technology are included in the subsections below.

Table C-1. Economic Parameters and Assumptions

Parameter	Value	Source
PV capital cost	$4,250/kW	Research on equivalent local projects
PV O&M cost	$12/kW-year	Various
Wind capital cost	$6,000/kW	Manufacturer
Wind O&M cost	$140/kW	Manufacturer
Battery capital cost	$490/kW of power capacity plus $1,226/kWh of energy capacity (~$1,347/kWh total)	Viswanathan, et al. “2022 Grid Energy Storage Technology Cost and Performance Assessment” + ACF
Battery O&M cost	$15.5/kW-year	Viswanathan, et al. “2022 Grid Energy Storage Technology Cost and Performance Assessment” + ACF
Generator capital cost	$3,424/kW	GSA costs for marine-rated generators, estimated costs for installation and NEMA enclosures, + ACF
Generator O&M cost	Variable: $0.0333/kWh	Lazard’s Levelized Cost of Energy Analysis, v11.0, + ACF
Microgrid capital cost	$450/kW	
Diesel fuel cost	$6/gallon	Current local price
Economic life	25 years; BESS and microgrids are reinvested in during this time	Per scope of work
Real discount rate	0.45%	OMB (https://www.wbdg.org/FFC/FED/OMB/OMB-Circular-A94.pdf)
Insurance rate	0.5%	Speer, et al. “Insuring Solar Photovoltaics: Challenges and Possible Solutions”
Area cost factor (ACF)	3.42 (capital), 3.33 (O&M); included in above costs	USACE (https://www.usace.army.mil/Cost-Engineering/Area-Cost-Factors/)
Battery round-trip efficiency	85%	Viswanathan, et al. “2022 Grid Energy Storage Technology Cost and Performance Assessment”

C.1 Solar PV

Table C-2 lists several relevant capital cost references for solar PV.

Table C-2. Solar PV Capital Cost References

Source	Mounting Type	System Size	Year of Cost	PV Cost ($/kW)
Installed Systems				
Rota Aquaponics (https://www.saipantribune.com/index.php/solar-power-system-for-rota-aquaponics-underway/)	Rooftop	36 kW_{DC}	2022	4250
US Army Reserve in American Samoa; costs incl. microgrid design	Rooftop	325 kW	2017	5880
USDA grant for 82 homes, 3kW each (https://sablan.house.gov/press-release/17-million-awarded-solar-energy-efficiency)	Rooftop	246 kW	2015	5526
Marianas Business Plaza (https://www.mbjguam.com/2015/01/26/saipan-center-completes-solar-project/)	Carport	650 kW	2015	3538
Commonwealth Healthcare Corporation (per conversation with Warren Villagomez on 7 Feb 2023)	Carport	178 kW	Planned: ~2024	7955
Estimated Costs				
CNMI Strategic Energy Plan	Rooftop Ground	>10 kW >10 kW	2022 2022	2664 3056
Bloomberg New Energy Finance (BNEF) cost for system in Hawaii	Ground	Commercial (~1 MW)	2023	1150
BNEF cost above, with area cost factor	Ground	Commercial (~1 MW)	2023	3933
"U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks, With Minimum Sustainable Price Analysis: Q1 2022" (NREL report) - modeled market price, (https://www.nrel.gov/docs/fy22osti/83586.pdf)	Ground	Commercial (200-500 kW)	2022	2139
NREL report cost above, with area cost factor	Ground	Commercial (200-500 kW)	2022	7315

O&M costs for solar PV systems were estimated from BNEF and NREL, and include module cleaning, vegetation/pest management, system inspection/monitoring, and minor component parts replacement. The CNMI Strategic Energy Plan quotes $11.70/kW for PV O&M.

C.2 Wind

Capital and O&M costs for a wind turbine were based on conversations with the vendor of a suitable 100 kW wind turbine, Northern Power Systems (Connor 2023). The capital cost includes a 50% markup for shipping and construction in Saipan over U.S. mainland costs. O&M costs include the cost for skilled laborers to travel to Saipan from the U.S. mainland once per year for annual inspections. These costs are in line with the cost of the 275 kW wind turbine installed in 2016 in Guam ($2.1M, a 40% premium over U.S. mainland prices at the time).

C.3 BESS

Table C-3 lists several relevant capital cost references for BESS.

Table C-3. BESS Capital Cost References

Source	Year of Cost	Cost per kWh
Installed Systems		
Ta'u added battery capacity (1.5 MWh)	2016	$618
American Samoa added battery capacity (345 kWh)	2021	$966
Estimated Costs		
CNMI Strategic Energy Plan	2022	$1000
2022 Grid Energy Storage Technology Cost and Performance Assessment	2021	$448
Cost above, with area cost factor	2021	$1532
2022 Grid Energy Storage Technology Cost and Performance Assessment	2030	$340
Cost above, with area cost factor	2030	$1162
U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks, With Minimum Sustainable Price Analysis: Q1 2022	2022	$672
Cost above, with area cost factor	2022	$2298

In surveys of system performance and O&M costs by NREL, DNV GL, PNNL, and others, a representative annual cost of about 2.5% of the installed capital cost of the battery; this produces a range of $8/kW to $25/kW for the surveyed systems (Cole & Frazier 2020). Several factors will influence the O&M costs: size and type (chemistry) of the batteries used, location and climate of the system (and associated cooling requirements); system utilization and dispatch (frequency of cycling the battery), and others.

Appendix D – Wind Assessment Details

The wind models that provide coverage in the CNMI region fall into two categories: (1) high spatial resolution but low temporal resolution or (2) high temporal resolution but low spatial resolution. High spatial resolution is needed to represent the wind resource as it follows the local terrain, which is especially important for islands. High temporal resolution is needed to understand the wind resource as it changes seasonal, diurnally, and on other timescales to facilitate the assessment of wind resource relative to load. The wind resource assessment for Marpi employed the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) (ECMWF 2023) to provide the long-term hourly trends in wind speed and direction and the GWA3 (DTU 2023) to provide more localized wind information for the site of interest (Table D-1).

Table D-1: Characteristics of the Models that Provided Wind Resource Data for this Study

Model	ERA5	GWA3
Developer	ECMWF	DTU Wind Energy, World Bank Group
Temporal Coverage (years)	1950 – present	2008 – 2017
Temporal Output Frequency	1-hr	Annual
Horizontal Spatial Coverage	Global	Global
Horizontal Grid Spacing	0.25° (~25 km)	0.25 km
Wind Speed Output Heights	10 m, 100 m	10 m, 50 m, 100 m, 150 m, 200 m

Wind speed data at 10 m and 100 m above ground level at the nearest neighbor ERA5 grid point (15.25°N, 145.75°E) were extracted from 2008–2017 (the overlapping temporal period with GWA3). In order to produce wind speed timeseries at hub heights of interest z_{HH}, the power law shown in Eq. (1), in conjunction with a dynamic shear exponent (α), as shown in Eq. (2), was used to calculate the simulated wind speeds v_{10} and v_{100} from the two surrounding model heights 10 m and 100 m. This vertical interpolation scheme for simulation of the wind speed at the measurement height was selected because it considers multiple levels in the wind speed profile and does not rely on static stability assumptions (Olauson and Bergkvist 2015).

$$v_{ERA5,HH} = v_{10}\left(\frac{z_{HH}}{10}\right)^{\alpha} \quad (1)$$

$$\alpha = \ln\left(\frac{v_{100}}{v_{10}}\right)/\ln\left(\frac{100}{10}\right) \quad (2)$$

Using the overlapping grid cell to the site from the high-resolution GWA3 (Figure 13) (DTU 2023), the ERA5 wind speed timeseries $v_{ERA5,HH}$ was geolocated to the potential turbine location in Figure 12 for two hub heights available for a Northern Power Systems 100-28 wind turbine (37 m for a standard tower and 23 m for a tilt-up tower) via Eq. (3):

$$v_{Site,HH} = v_{ERA5,HH} \cdot \frac{\overline{v_{GWA3,50}} \cdot \overline{v_{GWA3,50,norm}}}{\overline{v_{ERA5,50}}} \quad (3)$$

where $\overline{v_{GWA3,50}}$ is the mean GWA3 50-m wind speed for a year of interest, $\overline{v_{ERA5,50}}$ is the mean ERA5 50-m wind speed for a year of interest, and $\overline{v_{GWA3,50,norm}}$ is the mean GWA3 50-m wind speed for a year of interest normalized by the mean GWA3 50-m wind speed for all years.

Because power curves are typically developed at an air density of 1.225 kg/m^3 before converting wind speeds to power, the hub height wind speed estimates were adjusted for the local and temporally varying density using the following calculation:

$$v_{Adjusted} = v_{Site,HH} \cdot \left(\frac{density}{1.225\ kg/m^3}\right)^{1/3} \quad (4)$$

Appendix E – Smart Safe Growth Analysis

Smart, safe growth (SSG) is a set of complementary development strategies and practices focused on improving the resiliency and recoverability of the built environment. As reflected in the CNMI's SSG Guidance Manual and Assessment Tool (FEMA 2018), and as incorporated into the 2021-2030 Comprehensive Sustainable Development Plan (OPD 2021), SSG principles (listed in Figure E-1) support project scoping and alternatives analysis. The SSG Guidance Manual and evaluation tool supports multiple sustainable growth objectives and is a foundational policy document incorporated into the CNMI's Comprehensive Sustainable Development Plan.

	Principle	Definition
1	Climate Change	Consider long-term climate change impacts of sea level rise, coastal inundation, increased storm intensity, variabilities in precipitation, and drought in planning, design, and cost determination for infrastructure and development projects as well as natural area preservation and enhancement planning.
2	Retreat	Plan to retreat from the areas of highest risk by discouraging or regulating development in these areas and promoting alternative uses of high-risk land, such as walkable public waterfront parks and recreation areas.
3	Retrofit	Retrofit existing structures and infrastructure located in hazard-prone areas to reduce vulnerabilities.
4	Critical Facilities Location	Locate new critical facilities (e.g., water and sewer systems, roads, hospitals, power plants, transmission and communication lines, and public safety facilities) outside of high-risk zones.
5	Development Incentives	Utilize regulatory and financial incentives to locate new development away from high risk areas into lower risk areas or to areas where risk can be reduced through management measures.
6	Sustainable Development BMPs	Establish regulatory policies that recommend/require the use of "*CNMI Sustainable Development Manual: Best Management Practices*" for commercial/public/multifamily developments.
7	Ecosystem Services	Maintain sufficient key natural resource areas (e.g., coral reefs, wetlands, mangroves, riparian zones, and vegetated slopes) that support and enhance ecosystem services, to protect infrastructure investments and developed areas.
8	Green Infrastructure	Encourage green infrastructure, soft stabilization measures and living shoreline alternatives at development sites, island open spaces and infrastructure deployment.
9	Development Decision Process	Ensure that development decision processes are predictable, fair, and transparent.
10	Early Collaboration	Encourage early-stage government agency collaboration and stakeholder engagement in development planning and decision making.
11	Knowledgeable SSG Communities	Promote a community of leaders and networks knowledgeable in the principles of smart, safe growth.
12	Adaptive Management	Integrate adaptive management approaches to smart, safe growth development and incorporate lessons learned into future planning and development efforts. Periodic assessments and updates to be scheduled and funded.

Figure E-1. Smart, Safe Growth Principles

The CNMI Project Team scored each power supply scenario according to each of eight principles that would be impacted by a power supply project at Marpi and then averaged the scores over the eight principles assuming they all have the same relative weight. Scores ranged from 1 to 9 with 1 indicating a beneficial impact on the SSG principle and 9 indicating a detrimental impact. (The climate change principle was scored based on additional factors, as shown in Figure E-2.) The result was a total score for each scenario, representing a high-level analysis of its consistency with SSG guiding principles. The results of this analysis are shown in Figure E-3 and used in the prioritization of scenarios. The full SSG analysis tool is available at https://opd.gov.mp/assets/SSG%20Project%20Evaluation%20Tool_Blank.xlsx.

		1	2	3	4	5	6	7	8	9	10	
Scenario	Climate Change factors - considered for energy mix below:	Impacts sea level rise (causes global warming i.e. emissions)*	Impacts coastal inundation (indirectly from sea level rise)	Increased storm intensity (indirectly from dispersed , warming climate that changes weather patterns)	Affects variabilities in precipitation	Drought	Planning	Design	Cost	Natural area preservation	Enhancement planning (towards conservation)	**Score**
1	PV, BESS	1	CF	CF	CF	CF	CF	CF	CF	CF	1	**1**
2	Wind Turbine, BESS	1									5	**1**
3	PV, Wind Turbine, BESS	1									5	**1**
4	PV, BESS, Generator	7									1	**6**
5	Wind Turbine, BESS, Generator	7									5	**7**
6	PV, Wind Turbine, BESS, Generator	5									5	**5**
7	Generator	9									1	**8**

Notes:

1. * assumes that diesel generators have CO2 emissions known to cause global warming
2. The choice of energy mix scenarios assumes that the contribution of the Climate Change factors 1 (Impacts sea level rise) and 10 (Enhancement planning) are 90% and 10%, respectively
3. CF - confounding variable. As such, the choice of energy mix is only one confounding variable of the many that has impacts on Climate Change

Figure E-2. Climate Change Scores

Smart, Safe Growth Principles

Scenario	Infrastructure Mix	Climate Change	Retreat	Retrofit (discourages or regulates high risk development)	Facilities Location (at high risk zones, rank 1-9)	Incentives (risk can be reduced through management	Sustainable Development BMPs	Ecosystem Services	Green Infrastructure	Development Decision Processes	Early Collaboration	SSG Knowledgeable Communities	Adaptive Management	Score*
	SSG Principles	1	2	3	4	5	6	7	8	9	10	11	12	
1	PV, BESS	1	1	1	6	1	1	1	1	No Effect	No Effect	No Effect	No Effect	2
2	Wind Turbine, BESS	1	9	9	6	5	1	7	5	""	""	""	""	5
3	PV, Wind Turbine, BESS	1	9	9	6	5	1	5	6	""	""	""	""	5
4	PV, BESS, Generator	6	1	5	6	1	1	9	3	""	""	""	""	4
5	Wind Turbine, BESS, Generator	7	9	9	6	5	1	9	8	""	""	""	""	7
6	PV, Wind Turbine, BESS, Generator	5	9	9	6	5	1	9	7	""	""	""	""	6
7	Generator	8	1	5	6	1	1	9	9	""	""	""	""	5

* averaged over the 8 SSG principles assuming they have equal relative weights

Figure E-3. Smart, Safe Growth Analysis

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