SANDIA REPORT
SAND2020-12720
Printed December 2020

Sandia National Laboratories

Regional Resource Planning for Puerto Rico Mountain Consortium

Cody J. Newlun
Daniel R. Borneo
Susan Schoenung
Tu Nguyen

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

Issued by Sandia National Laboratories, operated for the United States Department of Energy by National Technology & Engineering Solutions of Sandia, LLC.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone:	(865) 576-8401
Facsimile:	(865) 576-5728
E-Mail:	reports@osti.gov
Online ordering:	http://www.osti.gov/scitech

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandria, VA 22312

Telephone:	(800) 553-6847
Facsimile:	(703) 605-6900
E-Mail:	orders@ntis.gov
Online order:	https://classic.ntis.gov/help/order-methods/

ABSTRACT

In 2017, the island of Puerto Rico (PR) was devastated by the impacts of Hurricanes Maria and Irma. As a result, there was an island-wide blackout of the Puerto Rico Electric Power Authority (PREPA) system and it took several months to fully restore power to all the impacted customers. This led to a concerted effort in one of the mountain regions to plan a regional power subsystem, commonly known as microgrids. Microgrids have been and are being considered throughout the nation to mitigate the effects of extreme events such as hurricanes. In this work, a conceptual regional power subsystem or microgrid is considered to service a consortium of municipalities consisting of Barranquitas, Morovis, Ciales, Orocovis, and Villalba. These five municipalities experienced long-term blackouts in the wake of Hurricane Maria and have developed a five-municipality consortium, Consorcio Energetico de la Montana (CEM). The consortium plans to design and build a system that will serve the demand in each of the five municipalities This report considers the sizing and siting of solar and energy storage technologies to serve this microgrid utilizing an optimization model that minimizes the equipment costs of the solar and energy storage technologies. Additionally, critical loads have been identified within the CEM to create a critical system resilience in the occurrence of an extreme weather event. To provide a range of investment portfolios, several conceptual planning scenarios are implemented within the model. These scenarios vary based on the amount of load served and the operation of the ~11MW existing hydroelectric plants. Lastly, future work and recommendations are provided to assist with the next planning stages for the CEM.

==

La isla de Puerto Rico (PR) fue devastada por el impacto de los huracanes María e Irma en el 2017. Como resultado de estos fenómenos atmosféricos, la Autoridad de Energía Eléctrica de Puerto Rico (AEE) sufrió daños en su infraestructura causando que sus habitantes perdieran el servicio de energía eléctrica por varios meses. La región montañosa de la Isla fue la más afectada por la falta de energía eléctrica y esto intensifico el esfuerzo para planificar un subsistema de energía regional, comúnmente conocido como microrredes. Las microrredes han sido y están siendo consideradas en todo el país para mitigar los efectos de eventos extremos como los huracanes. En este trabajo, se considera un subsistema conceptual de energía regional o microrred para dar servicio al consorcio de municipios conformado por Barranquitas, Morovis, Ciales, Orocovis y Villalba. Estos cinco municipios experimentaron apagones a largo plazo a raíz del huracán María y por esta razón implementaron el Consorcio Energético de la Montaña (CEM). El consorcio planea diseñar y construir un sistema que cubrirá la demanda eléctrica en cada uno de los cinco municipios. En el presente informe se considera el tamaño y la ubicación de las tecnologías solares y de almacenamiento de energía para servir a esta microrred utilizando un modelo de optimización que reduce al mínimo los costos de equipo. Además, se han identificado las cargas críticas para crear resistencia del sistema en caso de un evento meteorológico extremo. Para proporcionar una variada cartera de inversiones, se implementaron varios escenarios de planificación conceptual dentro del modelo. Estos escenarios varían según la cantidad de carga servida y la operación de las plantas hidroeléctricas existentes (~ 11MW). Por último, se proporcionan recomendaciones y trabajos futuros para ayudar en las próximas etapas de planificación del CEM.

ACKNOWLEDGEMENTS

This work was funded by the Energy Storage Systems Program of the U.S. Department of Energy Dr. Imre Gyuk, Program Director. The authors would like to thank Josue Colon and Ruben Gonzalez of the Consorcio Energetico de la Montana in Puerto Rico.

TABLE OF CONTENTS

FIGURES

TABLES

This page left blank

1. EXECUTIVE SUMMARY

This report introduces the necessary components of this regional power system, provides a functional database that can be used in several stages of project planning, and describes a model framework for resource planning of the CEM. The process that was followed and key takeaways from this work are as follows:

1. **CEM Database Development:** In this work, the necessary data to perform an initial scoping of the required PV and ES technologies was gathered and analyzed. First, the CEM power system data was collected. This included developing a 23-bus representative model of the transmission and sub-transmission system. This also included acquiring SCADA data for hourly load data at various substations in the consortium. The only existing generation in the consortium area are the Toro Negro hydroelectric plants, with power ratings of 9 MW and 2 MW respectively. Investigation of these plants' performance and operation has been included in this study. Lastly, the substations, and interconnections within the CEM and the external buses have been mapped and the map is available for use in future work. To accurately model the performance of the PV technologies, hourly solar profiles, based upon data collected by the National Renewable Energy Laboratory [1], were developed at several substation locations within the consortium.

2. **Identification of Critical Infrastructure:** Using previous studies that located potential microgrids in PR, the consortium's critical infrastructure was identified [2]. With this data, the Department of Energy's commercial reference building database was used as a guideline to determine the annual consumption of the critical infrastructure. Furthermore, this critical infrastructure data was used in the planning model to provide the amount of PV and ES required to meet the critical loads.

3. **Regional Power System Planning Model Framework:** To determine the optimal mix of PV and ES necessary to meet the power demands of the consortium, an optimization model was developed. This model seeks to minimize the investment cost of the combined PV power system and energy storage system by optimizing the PV power output, Energy storage power output and stored energy capacity. The constraints to the model include the power balance constraint, the hourly PV performance, ES performance, hydro dispatch, curtailment limits, and, if desired, transmission constraints. This model can simulate an entire year (8760 hours) with hourly timesteps.

4. **Optimal Sizing and Siting of PV and ES Technologies:** The output of the planning model is the optimal sizing and siting of the PV and ES technologies at each bus, within each municipality, and for the entire consortium. Consequently, an estimated investment cost of the equipment can be provided. In this study, six planning scenarios are introduced that vary the hydro contributions and whether the load level is critical, intermediate, or completely standalone. In general, it has been found that to supply the critical loads at each CEM municipality the total PV power rating would be approximately 33 – 40 MW and the ES power size and stored energy capacity would be approximately 22 – 24 MW and 270-313 MWhr, respectively. An intermediate scenario, where 50% of the load is met, is also considered and would require 229 – 250 MW of PV, 144 – 154 MW of ES power size, and 1639 – 1718 MWhr of ES energy capacity. Furthermore, when considering a completely

standalone system, meaning 100% of the consortium's load will be met at all times of the year through renewables and energy storage, the PV power rating would be approximately 477 – 500 MW and the ES power size and energy capacity is to be between 297 – 308 MW and 3350 – 3435 MWhr. As an additional sensitivity, the planning scenarios were simulated with load conditions that reflected 5% load growth within the consortium.

5. **Future Work and Recommendations:** Future directions and recommendations for this work and project are also defined within this report. These include discussions about upgrading the Toro Negro hydroelectric facilities, transmission network considerations, and the reliability of the system. In this work, the hydroelectric plants , Toro Negro 1 &2 located near the municipalities of Villalba and Orocovis have been determined to be crucial in decreasing the amount of PV and ES need for the consortium. The assumptions regarding the Toro Negro hydro facilities' dispatch schedule and available dispatch capacity affect the required PV and ES required. Further studies regarding potential upgrades to the facilities should be performed to determine how the hydroelectric plants can be optimally dispatched to minimize the total investment costs. An initial mapping of the transmission network has been completed. It may be of interest to incorporate DC power flow transmission constraints into the model. Also, inspection of the PREPA system showed that the consortium municipalities are not totally interconnected. Therefore, the identification of additional transmission pathways should be considered. Furthermore, reviewing relevant regulations and interconnection standards should be included in the planning phases of this project.

   Due to the variable generation of the PV and the existing hydro plants, a reliability study should be performed. This could include, but is not limited to, defining a consortium-wide planning reserve margin and emergency capacity level. Likewise, a resilience study of the system under the influence of extreme events can be performed. This would allow for the insight into how the system could perform in the event of severe infrastructure damage. Additional analysis of the critical infrastructure and their respective energy consumption should be further evaluated.

   Lastly, the next steps of this project are outlined into the pre-planning and planning phases. These phases are presented as a high-level outline for the next steps. These phases include further refinements of the results from this study and future steps to be taken to enhance the engineering and design of the CEM infrastructure

2. RESUMEN

En este informe se presentan los componentes necesarios del sistema energético regional, se proporciona una base de datos funcional que puede utilizarse en varias etapas de la planificación del proyecto y se describe un marco modelo para la planificación de los recursos de la CEM. El proceso que se siguió y las principales conclusiones de este trabajo son las siguientes:

1. **<u>Desarrollo de la base de datos del CEM</u>**: En este trabajo, se recopilaron y analizaron los datos necesarios para realizar un estudio inicial de las tecnologías fotovoltaicas y de almacenamiento. Primero, se recopilaron los datos del sistema de energía del CEM. Esto incluyó el desarrollo de un modelo representativo de 23 buses del sistema de transmisión y subtransmisión. Esto también incluyó la adquisición de datos SCADA para datos de carga por hora en varias subestaciones del consorcio. La única generación existente en el área del consorcio son las centrales hidroeléctricas de Toro Negro, con potencias de 9 MW y 2 MW respectivamente. En este estudio se incluyó la investigación del rendimiento y la operación de estas centrales. Por último, se mapearon las subestaciones e interconexiones dentro del CEM y los buses externos. El mapa está disponible para su uso en trabajos futuros. Para modelar con precisión el rendimiento de las tecnologías fotovoltaicas, se desarrollaron perfiles solares por hora de varias subestaciones dentro del consorcio, usando datos recopilados por el Laboratorio Nacional de Energía Renovable [1],.

2. **<u>Identificación de la infraestructura crítica</u>**: La infraestructura crítica del consorcio se identificó utilizando estudios previos en los cuales se evaluaron localizaciones de microrredes en PR [2]. Con estos datos, el consumo anual de la infraestructura crítica fue determinado usando como guía la base de datos de edificios comerciales del Departamento de Energía. Además, estos datos de infraestructura crítica se utilizaron en el modelo de planificación para proporcionar la cantidad de energía fotovoltaica y energía de almacenamiento necesaria para satisfacer la demanda.

3. **<u>Modelo de planificación del sistema eléctrico regional</u>**: Para determinar la combinación óptima de energía fotovoltaica y energía de almacenamiento necesaria para satisfacer las demandas de energía del consorcio, se desarrolló un modelo de optimización. Este modelo busca minimizar el costo de inversión del sistema combinado de energía fotovoltaica y energía de almacenamiento mediante la optimización de la producción de energía fotovoltaica, la producción de energía de almacenamiento y la capacidad de energía almacenada. Las limitaciones del modelo incluyen la restricción de equilibrio de energía, el rendimiento fotovoltaico por hora, el rendimiento de la energía de almacenamiento, el despacho de energía hidroeléctrica, los límites de reducción y, si se desea, las restricciones de transmisión. Este modelo puede simular un año completo (8760 horas) con intervalos de tiempo por hora.

4. **<u>Tamaño y ubicación de las tecnologías PV y ES</u>**: El modelo de planificación determina el tamaño y la ubicación óptima de las tecnologías PV y ES en cada bus, dentro de cada municipio y para todo el consorcio. Por consiguiente, se puede proporcionar un costo de inversión estimado del equipo. En este estudio, se presentan seis escenarios de planificación variando las contribuciones hidroeléctricas y si el nivel de carga es crítico, intermedio o completamente autónomo. En general, se determinó que para suministrar las cargas críticas

en cada municipio del CEM, la potencia total fotovoltaica sería de aproximadamente 33-40 MW, la potencia y capacidad de energía almacenada serían aproximadamente 22-24 MW y 270-313 MWhr, respectivamente. También se considera un escenario intermedio, en el que se satisface el 50% de la carga. Este escenario requeriría 229 - 250 MW de potencia fotovoltaica, 144 - 154 MW potencia de energía de almacenamiento y 1639 - 1718 MWhr de capacidad de energía de almacenamiento. Al considerar un sistema completamente independiente, lo que significa que el 100% de la carga del consorcio se cubriría en todas las épocas del año a través de energías renovables y almacenamiento de energía, la potencia fotovoltaica sería de aproximadamente 477 - 500 MW, y la potencia y capacidad de energía almacenada debe estar entre 297 - 308 MW y 3350 - 3435 MWhr, respectivamente. Como sensibilidad adicional, los escenarios de planificación se simularon con condiciones de carga del 5% dentro del consorcio.

5. **Trabajos futuros y recomendaciones**: Las direcciones y recomendaciones futuras para este trabajo y proyecto también se definen en este informe. Estos incluyen discusiones sobre la mejora de las instalaciones hidroeléctricas de Toro Negro, consideraciones de la red de transmisión y la confiabilidad del sistema. En este trabajo, se determinó que las plantas hidroeléctricas Toro Negro 1 y 2 ubicadas cerca de los municipios de Villalba y Orocovis son cruciales para disminuir la cantidad de energía fotovoltaica y energía de almacenamiento que necesita el consorcio. Las suposiciones sobre el cronograma de despacho de las instalaciones hidroeléctricas de Toro Negro y la capacidad de despacho disponible afectan la energía fotovoltaica y la energía de almacenamiento requerida. Se deben realizar más estudios sobre posibles mejoras a las instalaciones para determinar cómo se pueden despachar las plantas hidroeléctricas de manera óptima para minimizar los costos totales de inversión. Puede ser de interés incorporar en el modelo las limitaciones de transmisión del flujo de energía de CC. Además, la inspección del sistema de la AEE mostró que los municipios del consorcio no están totalmente interconectados. Por lo tanto, debe considerarse la identificación de vías de transmisión alternas. La revisión de las regulaciones y estándares de interconexión debe incluirse en las fases de planificación de este proyecto.

   Debido a la generación variable de la energía fotovoltaica e hidroeléctricas existentes, se debe realizar un estudio de confiabilidad. Esto podría incluir, entre otros, el establecimiento de un margen de reserva para todo el consorcio y un nivel de capacidad de emergencia. Asimismo, se puede realizar un estudio de resiliencia del sistema ante la influencia de eventos extremos. Esto permitiría comprender cómo podría funcionar el sistema en caso de que se produjeran daños graves en la infraestructura. Análisis adicionales de la infraestructura crítica y su respectivo consumo de energía deberían evaluarse.

   Por último, los próximos pasos de este proyecto se describen en las fases de preplanificación y planificación. Estas fases se presentan como un esquema de alto nivel para los próximos pasos. Estas fases incluyen el perfeccionamiento de los resultados de este estudio y los futuros pasos a seguir para mejorar la ingeniería y el diseño de la infraestructura del CEM.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
CAIDI	Customer Average Interruption Duration Index
CEM	Consorcio Energetico de la Montana
DOE	Department of Energy
ES	Energy Storage
HI	Hybrid Intermediate Scenario
HR	Hybrid Resilient Scenario
HS	Hybrid Standalone Scenario
HUD	Housing and Urban Development
MTR	Minimum Technical Requirement
NREL	National Renewable Energy Laboratories
NSRDB	Nation Solar Radiation Database
Open-EI	Open Energy Information
PR	Puerto Rico
PREPA	Puerto Rico Electric Power Authority
PV	Photovoltaic (Solar)
RI	Renewable Intermediate Scenario
RR	Renewable Resilient Scenario
RS	Renewable Standalone Scenario
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control and Data Acquisition
SNL	Sandia National Laboratories
USGS	United States Geological Survey

3. INTRODUCTION

A regional power system, or microgrid, has been proposed in the mountainous region of Puerto Rico (PR). Five municipalities have agreed to form a consortium, Consorcio Energetico de la Montana (CEM), to design and construct a resilient, localized microgrid that will service the loads within the municipalities of Barranquitas, Ciales, Morovis, Orocovis, and Villalba.

In the wake of Hurricane Maria, the island of PR experienced long duration blackouts and severe infrastructure damage [3]. This provided a motivation for the CEM to plan a microgrid that will provide energy resilience in the event of another extreme disaster. Previous work has provided guidelines and recommendations for adopting community microgrids [4]. The authors of [4] provide motivation for building microgrids in PR. Furthermore, they discuss design and feasibility considerations that must be considered to adopt the community microgrids in PR. This previous work calls on the transformation of PR's grid system, such as the proposed CEM power system.

The power system in these municipalities was modelled in a linear program to determine the optimal mix of solar and energy storage for several planning scenarios. These planning scenarios are defined based on whether the transmission system and hydroelectric plants are included in the modelling framework. Furthermore, the scenarios differ in which load conditions are being modelled. In this paper, a critical load level based on the critical infrastructure located within each municipality is defined to design a resilient system. The standalone load conditions are defined as the entire load of each municipality. As a result, the model has the ability to determine the optimal mix of PV and ES to meet the critical and full demands of the consortium.

3.1. Puerto Rico Municipal Energy Consortium

The Consorcio Energetico de la Montana (CEM) consists of five municipalities: Barranquitas, Ciales, Morovis, Orocovis, and Villalba. The consortium lies within the mountainous region of PR. In total, the mountain consortium serves a population of nearly 150,000 people. This area of Puerto Rico is remote and experienced a long-term blackout due to Hurricane Maria in 2017. Due to the hardships encountered, the five municipalities decided to form a consortium that would design and construct an energy infrastructure to give them more flexibility and resiliency in the case of an extreme event such as a hurricane.

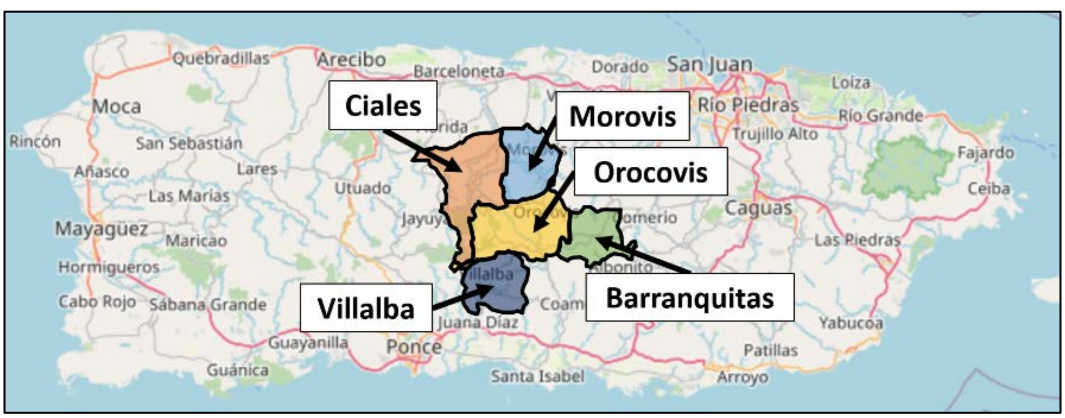

Figure 1: Municipalities in the CEM

Figure 1 displays the geographic location of the five municipalities on the main island of PR that formed the Consortium. CEM will engage in the design and construction of a mini-grid or regional power system to serve the load within the municipalities. In this report, several planning scenarios, where the load levels are varying to represent critical loads, are introduced to determine the optimal amount of PV and ES necessary

3.2. Impacts of Hurricane Maria

The CEM experienced long-term blackouts as a result from the damage to the Puerto Rico Electric Power Authority (PREPA) power system from Hurricane Maria. Specifically, the citizens of Orocovis and Barranquitas experienced an eight-month blackout that resulted in a collapse of their social and economic development, as well as greatly affecting the living conditions of the population.

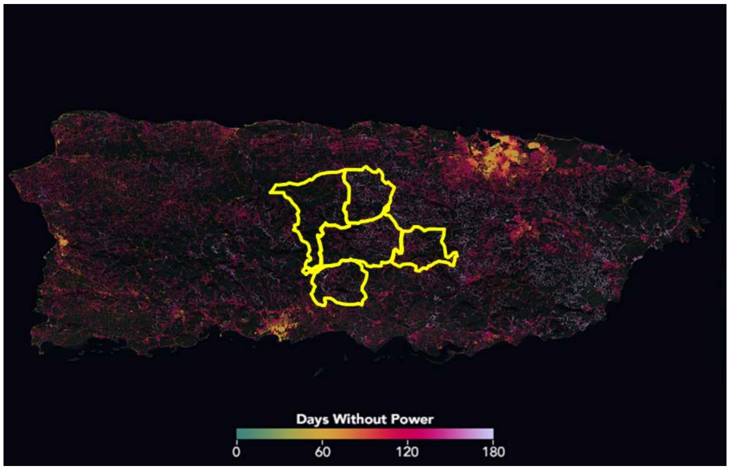

Figure 2: Satellite image representing the number of days without power in PR with the CEM highlighted

Figure 2 displays a satellite image developed by NASA that displays the amount of days without power by location in PR [5]. Note that the mountainous region where the CEM is located is highlighted as having a power outage of approximately 180 days or 6 months.

The members of the CEM have come together to design a resilient energy system that could meet the needs of the municipalities during extreme. Furthermore, establishing this system will provide the infrastructure that would allow more independence from the existing national grid, provide resiliency, lower energy costs, and provide the possibility to isolate from the existing grid in the event of an emergency. In the event of a hurricane, the base generation provided by PREPA via the transmission system may not be available. Therefore, designing a conceptual regional power system like the one that the CEM is proposing can mitigate the dependence of the main power system and decrease the amount of time blackouts occur.

4. PUERTO RICO MUNICIPAL ENERGY CONSORTIUM DATA

4.1. Network Topology

To evaluate the regional power system of the CEM, a network topology was developed for input in the planning model. Figure 3 provides a visualization of the substations located in each municipality. The transmission, sub-transmission, and distribution system has been omitted from the visualization in Figure 3. Furthermore, a 23-node network model has been developed for this study. This network is representative of the transmission (115 kV) and the sub-transmission (38 kV) systems of the area that comprises the entirety of the consortium area. Further database development is required to fully map out the distribution networks within the consortium.

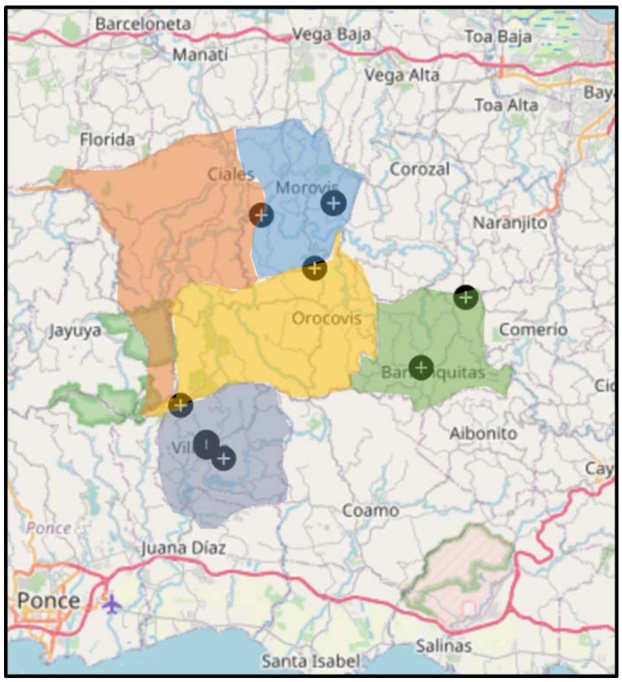

Figure 3: Locations of CEM substations

Within this network, nodes that contain load and hydroelectric generation have been identified. Table 1 provides a breakdown of the electrical buses along with their corresponding municipality, whether they include load, and whether they include hydroelectric generation.

Table 1: Breakdown of CEM buses

Bus #	Municipality	Load Bus	Hydro
1	Villalba	X	
2	Barranquitas	X	
3	Barranquitas	X	
4	Villalba		

Bus #	*Municipality*	*Load Bus*	*Hydro*
5	Villalba		
6	Villalba		
7	Ciales	X	
8	External		
9	External		
10	Orocovis	X	
11	External		
12	Villalba	X	
13	Morovis	X	
14	Orocovis		
15	Orocovis	X	
16	Barranquitas	X	
17	Orocovis		
18	Villalba	X	X
19	Villalba		
20	Orocovis		X
21	Villalba		
22	Villalba	X	
23	External		

This network also includes buses that are located outside of the consortium but have electrical connections with the buses of the consortium power system. The external buses are included in the initial mapping of the network to provide a framework for future studies including revenue potential for selling unused energy back to the main PREPA system.[1]

4.2. Toro Negro Hydroelectric Facilities

The CEM contains two existing hydroelectric facilities, Toro Negro I and Toro Negro II [6]. The Toro Negro I and Toro Negro II facilities have installed capacities of 9 MW and 2 MW, respectively. The entire Toro Negro hydroelectric system consists of several diversion dams, forebays, hydroelectric plants, and reservoirs located in the municipalities of Villalba, Ciales, and Orocovis. Specifically, the Toro Negro I plant is located in Villalba and the Toro Negro II is located in Orocovis. The hydroelectric plants are supplied with water from two major reservoirs: El Guineo

[1] During the pre-planning and planning phases it will be important to understand the loads on each bus, and if they will need to be isolated from the consortium microgrid.

and Matrullas. Figure 4 provides the approximate location of these facilities and these major reservoirs.

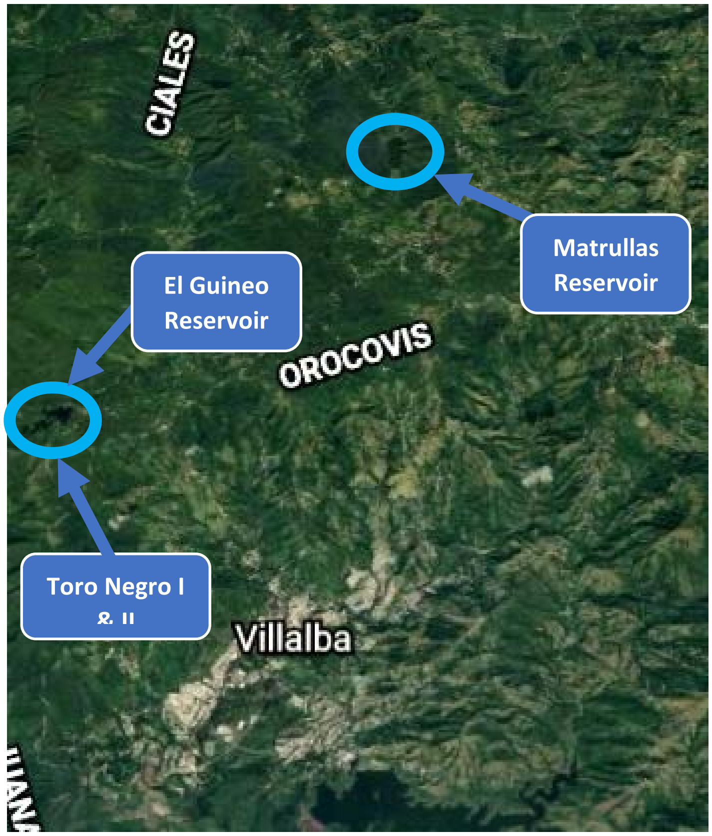

Figure 4: Approximate location of the Toro Negro hydroelectric facilities and major reservoirs

The Toro Negro facilities are owned and operated by PREPA. The system consists of several pipelines, canals, and penstocks that navigate water from the El Guineo and Matrullas reservoir. El Guineo is the sole source of water for the Toro Negro II plant. Water discharged from Toro Negro II and water from other pipelines and canals is fed into the Toro Negro I plant. The hydro plants have constraints such as water usage priority, sediment build-up, and aging infrastructure. It should be noted that in 2011 a study was done evaluating the hydro plant(s) and what would need to be done to increase their efficiency [6]. It would be beneficial for this study to be reviewed and the recommendations implemented in order to increase the hydro efficiency which would reduce the need for both PV and electrical energy storage

4.3. CEM Load Profiles

Power demand data were obtained from supervisory control and data acquisition (SCADA) data acquired from PREPA. Hourly load shapes were collected for 11 substations that lie within the mountain consortium. The annual energy consumption breakdown for each substation is displayed in Figure 5.

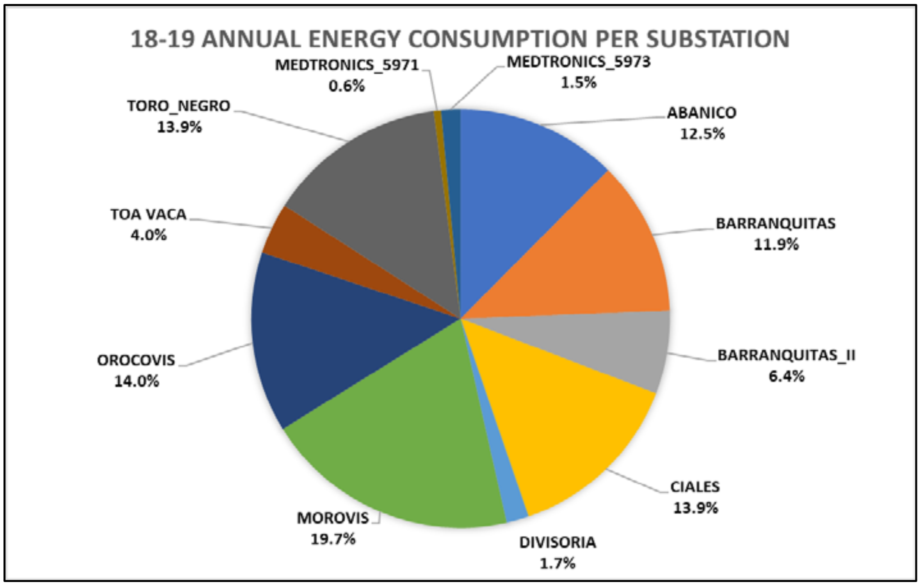

Figure 5: Annual energy consumption breakdown per substation

Table 2 displays the annual energy consumption and peak load for each municipality in the CEM. Figure 6 provides the annual energy consumption percentage breakdown of each municipality and Figure 7 provides the hourly load profiles for each municipality beginning on July 1, 2018 to June 30, 2019. The hourly load profiles for each substation in Figure 5 are summed together based on the corresponding municipality to obtain the data present in Figure 6 and Figure 7. As can be seen, the load is fairly consistent over the measured period. This is an advantage when sizing the PV and ES.

Table 2: Annual energy consumption and peak load for each CEM municipality

Municipality	Annual Energy Consumption (MWh)	Peak Load (MW)
Barranquitas	88,781.5	15.0
Ciales	40,243.3	6.5
Morovis	56,999.5	9.9
Orocovis	45,355.2	7.1
Villalba	65,113.8	10.3
Total	**296,493.3**	**48.8**

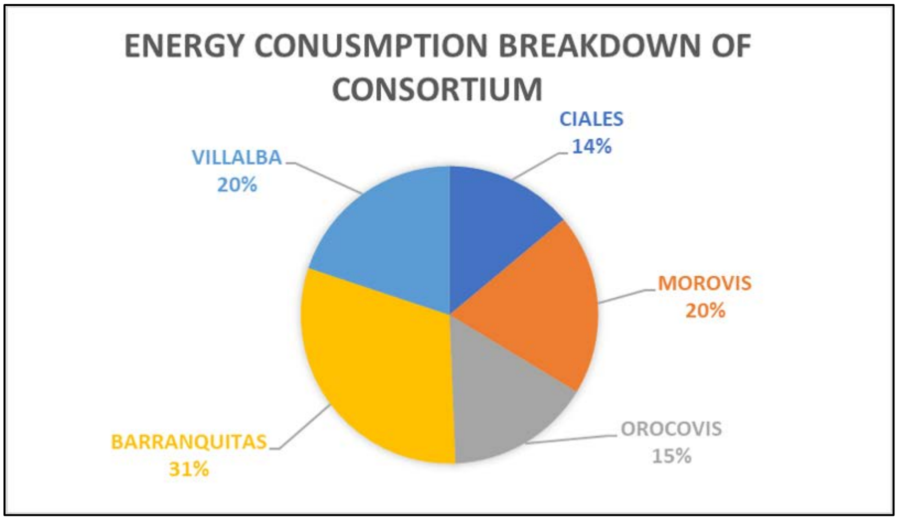

Figure 6: Load allocation per municipality

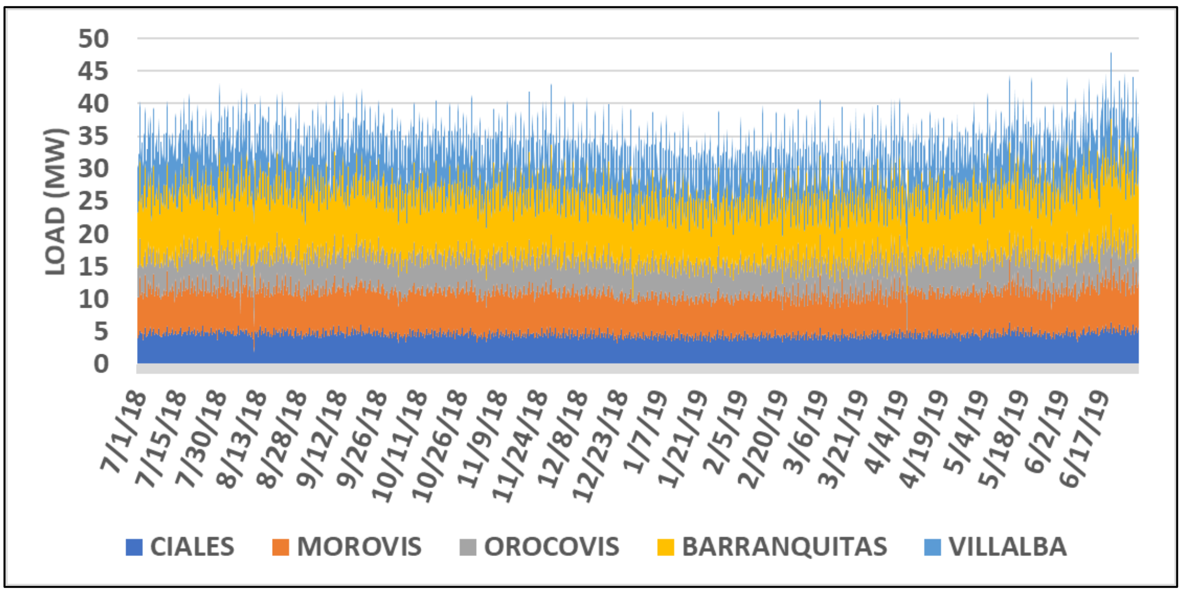

Figure 7: 8760 hourly load profiles per municipality

The peak demand of the entire CEM[2] occurs on June 20th at approximately 48MW. Figure 8 provides the average daily load profile for each substation in the CEM. A key takeaway is the presence of the nighttime peak. This is important to note when determining the optimal size of the PV and ES technologies.

---

[2] In this case the entire CEM includes all the loads on all of the 11 substations. In actuality, the total load may be less as some of the loads may be serving non-consortium areas.

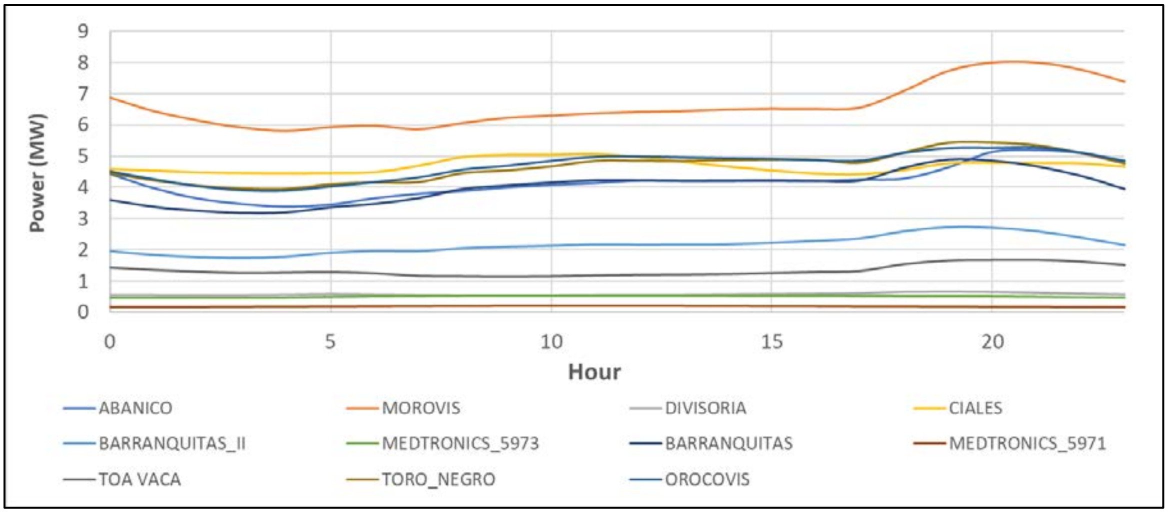

Figure 8: Average daily load profiles of substations in the consortium

The initial hourly data provided at the Medtronics substations were not for a complete year. For the load at the Medtronics substations to be modeled for a year, 8760 hourly profiles were constructed using the average weekly load profiles. Figure 9 provides these average weekly load profiles for the substations located at the Medtronics substations.

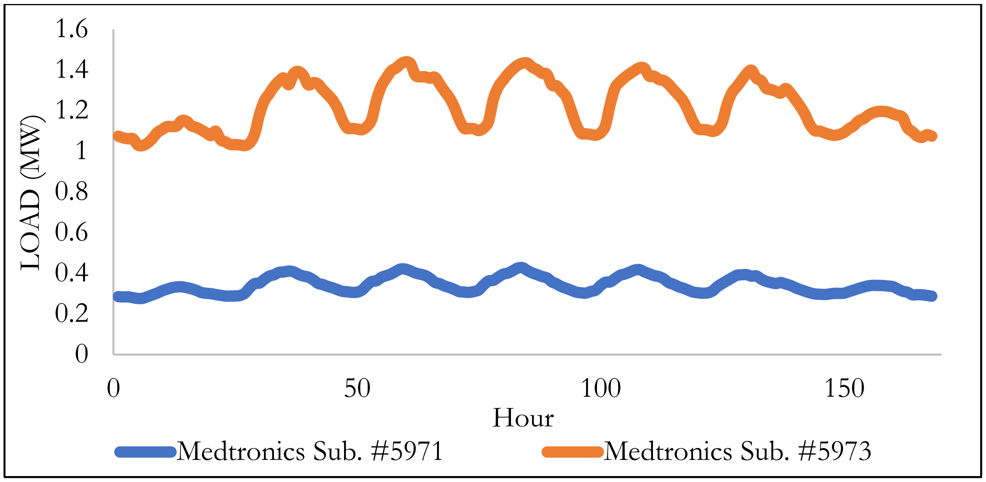

Figure 9: Average weekly load profiles for substations located at Medtronics

Since the Medtronics substations are considered to be industrial loads, the load diversity between the weekdays and weekends must be captured. The difference between the weekdays and weekends are present in the load profiles in Figure 9 and is assumed to be an adequate representation of typical load conditions at the Medtronics facilities.

4.4. Mountain Consortium Solar Potential

To properly capture the variability of the PV power output, the hourly per unit solar insolation was collected using the PVWATTS tool from NREL [1]. Figure 10 displays the solar irradiance for the islands of PR in W/m^2 extracted from the National Solar Radiation Database (NSRDB) from NREL [7]. The consortium municipalities are outlined as well.

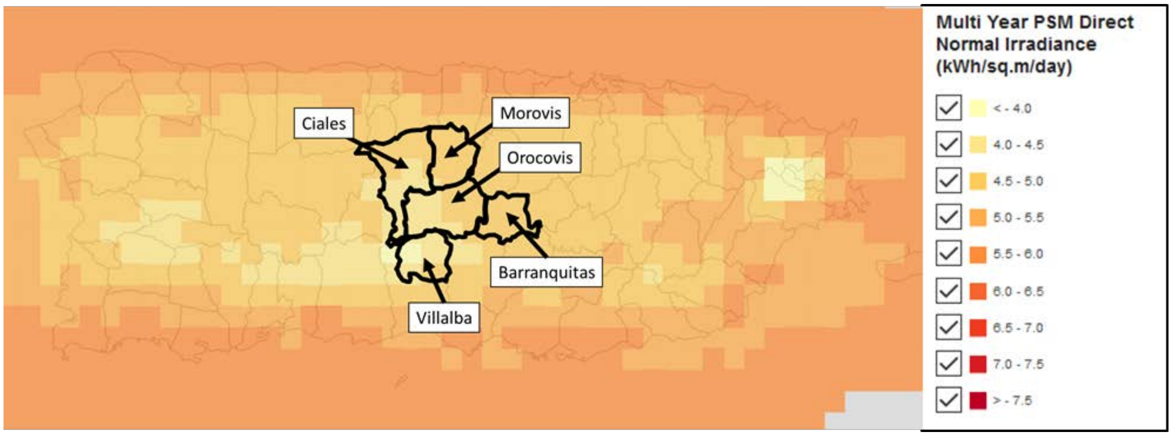

Figure 10: Solar irradiance map of PR with the CEM highlighted

The solar data collected from PVWATTS is assumed to be for a typical meteorological year for utility scale solar plants. The tilt angle was assumed to the latitude value of the substation's geographic coordinates. Figure 11 displays the average daily per unit insolation for selected substations in the CEM power system.

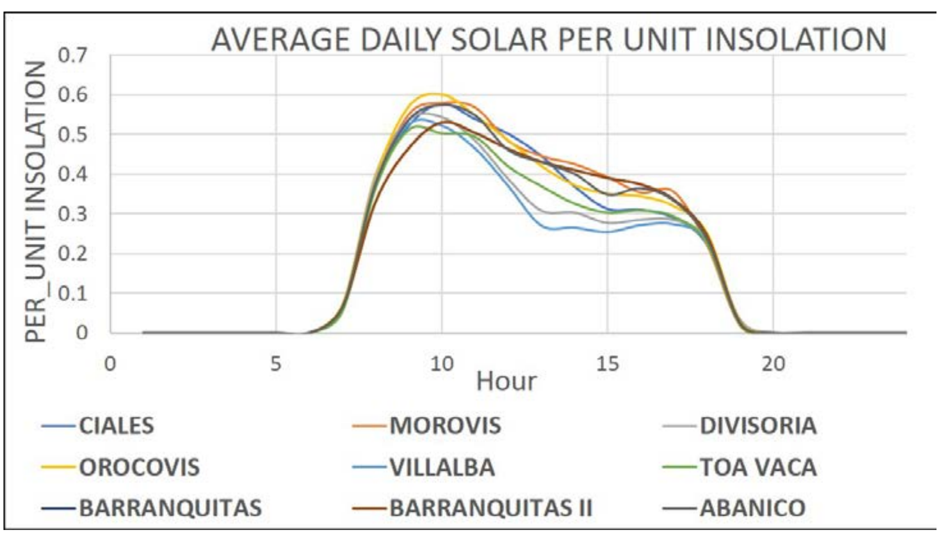

Figure 11: Average daily solar per unit insolation for selected substations

An important item to note is that the solar potential peaks in the mid-morning of the day. On average, the PV technologies can provide power for 10-12 hours a day. The afternoon decrease may be due to regular afternoon rain and cloud cover in the mountains. Also note that the substations located at the Medtronics location were assumed to have the same solar profile as the Villalba substation.

4.5. Mountain Consortium Critical Infrastructure

An initial study has been done to determine the different critical loads within the CEM. This effort is motivated by the need to design a resilient infrastructure in the consortium. Identifying the critical load types can provide an estimate for the amount of PV and ES needed to meet the critical demand. Furthermore, this information can assist with the construction of the multiple planning phases in this project. Table 3 provides a breakdown of the critical infrastructure categories considered in this study. This table and critical infrastructure data are derived from a previous study that analyzed microgrid potential throughout the islands of PR [2].

The authors of reference [2] provide detailed analysis of several categories of critical infrastructure for each municipality in PR. Each critical infrastructure category has been defined to follow the building classifications outlined by the DOE Open Energy Information (Open-EI) database and the National Renewable Energy Laboratory (NREL) [8]. Furthermore, the estimated square footage and energy usage data were gathered from the Open-EI commercial reference buildings database. Figure 12 shows the approximate locations of the critical infrastructure within the consortium.

Table 3: Critical infrastructure estimated data

Critical Infrastructure	DOE Open-EI Building	Estimated Square Feet	Energy Use (MWh/year)
Shelter	Primary School	73,960	924.1
Grocery Store	Supermarket	45,000	248.9
Hospital	Hospital	241,351 (1 floor)	8,499.8
Medical Center	Outpatient Health Care	40,946	869.7
Pharmacy	Stand-alone Retail	24,962	431.0
Bank	Small Office	5,500	99.3
Police, Fire, EMS	Small Office	5,500	93.1
Gas Station	Restaurant	2,500	23.6
Other Shelter	-	1,500	48.2

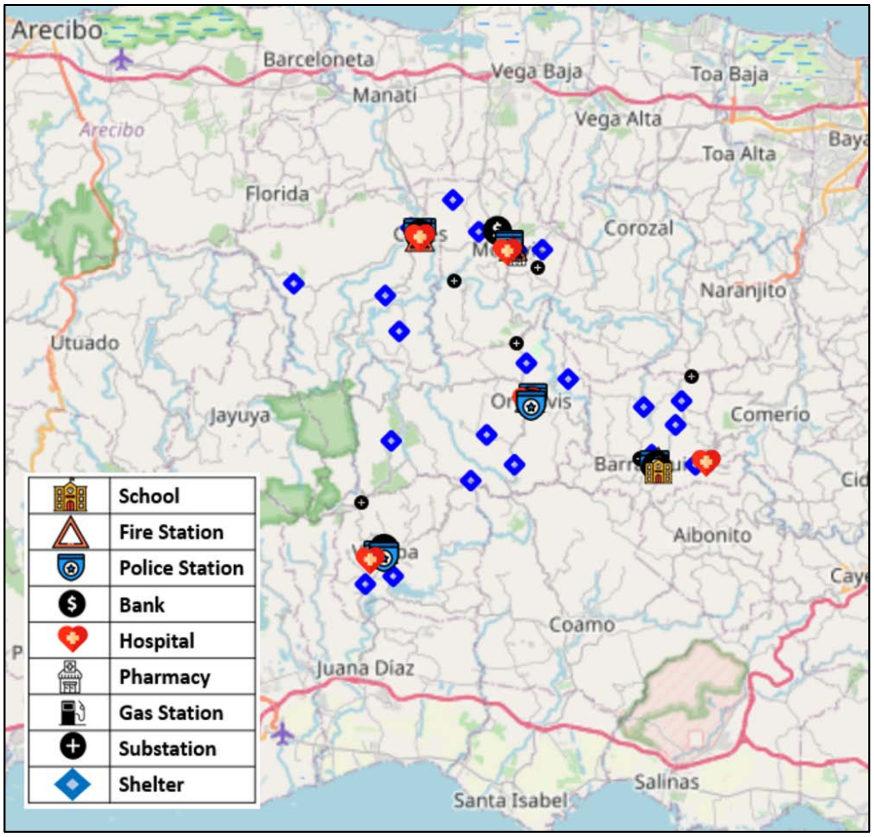

Figure 12: Map of critical infrastructure within the consortium

Using the critical infrastructure for each municipality and the estimated annual energy usage of each reference building from Table 3, the annual critical energy consumption is calculated for each municipality. Table 4 displays the annual energy consumption of the critical infrastructure and the critical load fraction, which is the percentage of each municipalities' annual energy consumption considered to be critical load.

Table 4: Breakdown of critical infrastructure energy consumption per municipality

Municipality	Annual Energy Consumption (MWh)	Annual Critical Energy Consumption (MWh)	Critical Load Fraction (%)
Barranquitas	88,781.5	6,986.4	7.9
Ciales	40,243.3	3,286.6	8.2
Morovis	56,999.5	3,717.6	6.5
Orocovis	45,355.2	13,300.9	29.3
Villalba	65,113.8	4,162.5	6.4

It has been estimated that the critical load in the CEM has approximately 19 GWh of annual consumed energy.[3] Also note that the municipality of Orocovis has a critical load fraction of 29% due to energy consumption of a local hospital with emergency services according to the data used in [2]. The critical load fraction is used in the planning model to scale the load of each municipality. This parameter is utilized when completing the simulation for the resilient scenarios. The estimation of this parameter provides the planner of critical load level that needs to be met in order to provide the necessities to the citizens of the consortium during an extreme event, such as a hurricane. Further evaluation and consulting with the CEM in identifying critical loads would result in a more accurate estimation of the critical load fraction.

[3] The evaluation of the CEM's entire critical load is based upon summing each municipalities' critical energy consumption from Table 4.

5. CASE STUDY & PRELIMINARY RESULTS

5.1. Model Description

For this case study, an optimization model was developed that minimizes the investment costs of PV and ES technologies needed to meet the power demands of the consortium. The model is a linear program that seeks to minimize the sum of the costs of the PV and ES equipment, as displayed in Equation 1.

$$\begin{aligned} &\boldsymbol{min} \quad \boldsymbol{I(x)} \\ &\boldsymbol{s.t.} \quad \boldsymbol{x} \in \boldsymbol{\Omega} \end{aligned} \tag{1}$$

Equation (**2)** defines the objective functions $\boldsymbol{I}(x)$ in terms of the decision variables, x. The decision variable vector can be defined as $x = [C_b^{PV}, C_b^{ES}, E_b^{ES}]$ and considers the PV power rating (C_b^{PV}), the ES power output rating (C_b^{ES}), and the stored energy capacity of the ES (E_b^{ES}). Additionally, these decision variables are weighted by the parameters μ, ω, and φ to reflect the unit cost of the PV ($/kW), ES power rating ($/kW), and the ES stored energy capacity ($/kWh) respectively. These weights (unit costs) were estimated using current investment costs derived from the NREL Annual Technology Baseline (ATB) database [9]. The energy storage for this study is assumed to be lithium-ion batteries, as in the ATB database. Assumed values of the unit costs can be found in the Appendix.

$$\boldsymbol{I(x) = \left(\mu * C_b^{PV} + \omega * C_b^{ES} + \phi * E_b^{ES}\right)} \tag{2}$$

Furthermore, the model's constraints are represented by the feasible set $\boldsymbol{\Omega}$. These include the power balance constraint to ensure that for each time step in the planning horizon the demand is met. Other constraints include the technology specific modeling for the power dispatch of the PV, ES, and hydroelectric dispatch. Additionally, if desired, transmission constraints can be included to account for the energy sharing capabilities within the municipalities of the CEM. The model simulates on hourly timesteps over an entire year for the planning horizon. Simulating an entire 8760 hours allows for the model to capture the variability of the PV performance throughout the seasons of the year. Consequently, the modeling of the ES technologies is able to be estimated accurately with a more refined PV model. The model also allows for the introduction of curtailment limits. This may be necessary in case of local regulations on interconnected renewable energy sources. Lastly, if the modeling of the Toro Negro hydroelectric plants is desired, the model allows for the dispatch of the plants with an assumed 40% capacity factor. The Toro Negro plants are also assumed to operate daily from 8 AM to 4 PM, based on information regarding the dispatch of the Toro Negro plants provided by PREPA [10].

A more detailed description of the planning model used in this study can be found in Appendix A. This includes key assumptions made regarding the parameters used and their assumed values. This model is written in a Python-based optimization software, Pyomo [11] [12]. The model is solved using the Gurobi 8.1.1 solver [13].

5.2. Planning Scenarios

To evaluate a range of generation and load conditions in the CEM four planning scenarios are developed. Table 5 provides these planning scenarios in terms of the modelling features. These modeling features include the dispatch of PV, ES, hydro, and the load served.

Table 5: Breakdown of planning scenarios

Scenario	PV	ES	Hydro	Load Served
Renewable Resilient (RR)	X	X	-	Critical
Renewable Intermediate (RI)	X	X	-	50%
Renewable Standalone (RS)	X	X	-	100%
Hybrid Resilient (HR)	X	X	X	Critical
Hybrid Intermediate (HI)	X	X	X	50%
Hybrid Standalone (HS)	X	X	X	100%

In the scenarios defined as "renewable", only the dispatch of the PV and ES technologies are modeled. The scenarios defined as "hybrid", introduce the hydro plants at Toro Negro along with the PV and ES technologies. Furthermore, the "resilient" scenarios are designed to meet the critical loads that were identified for each municipality in Section 4.5 while remaining grid tied. To provide more granular results, an "intermediate" scenario is defined. In the intermediate scenarios 50% of the load is met while the system remains grid-tied. The "stand-alone" scenarios are designed to meet the entire load (24/7) of the CEM for the entire planning horizon as a stand-alone (no grid tie) system.

These scenarios are designed to show a range of results for the CEM that provide insights to the amount of PV and ES required based upon the generation mix and load conditions.

5.3. Preliminary Results

To calculate the municipality-level results, the invested capacities of the PV and ES technologies at each bus are summed corresponding to the mapping displayed in and Figure 3 and Table 1. Furthermore, Figures 13 – 15 provide a breakdown of the installed capcities of the ES and PV technologies for each planning scenario. These results are provided in more detail in Table 7 and Table 8 found in Appendix B.

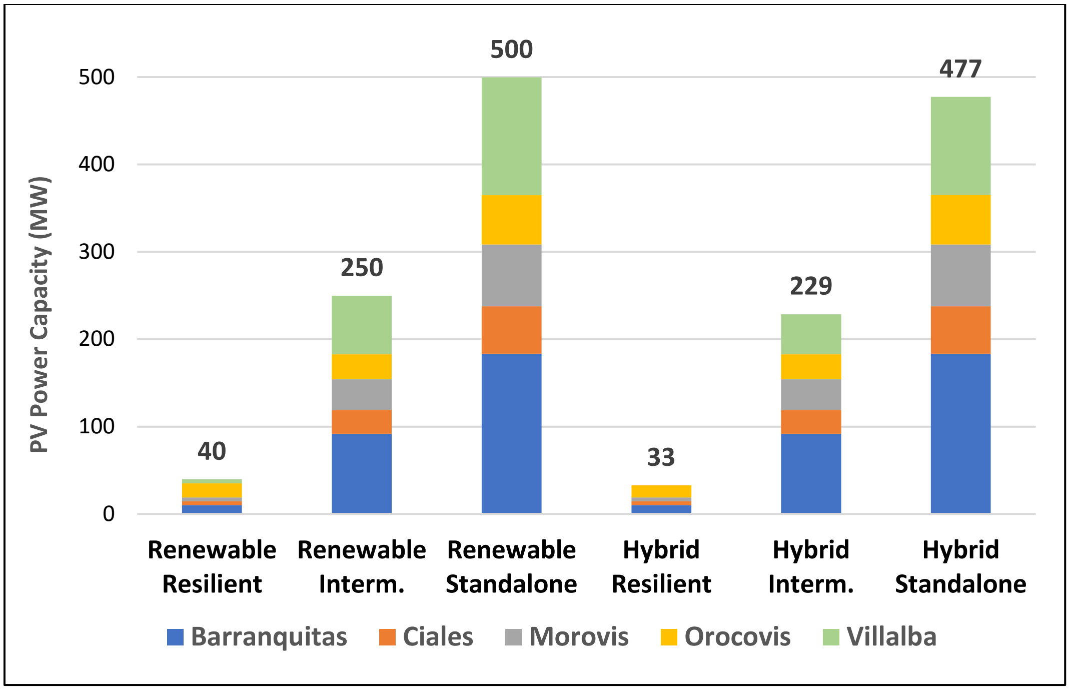

Figure 13: Breakdown of installed PV power capacity for each planning scenario

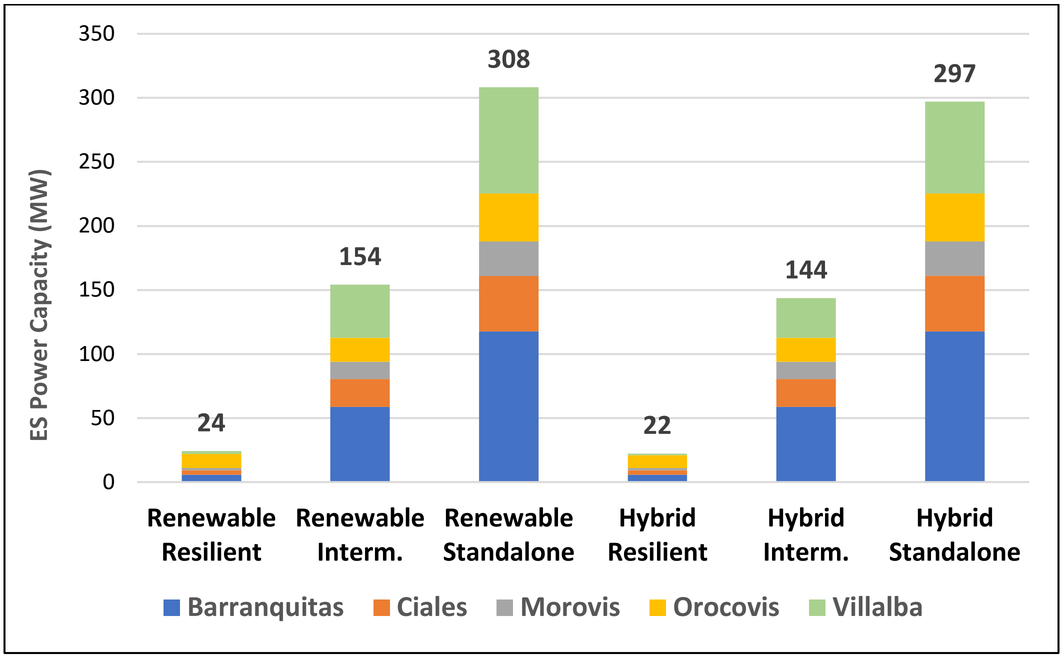

Figure 14: Breakdown of installed ES power capacity for each planning scenario

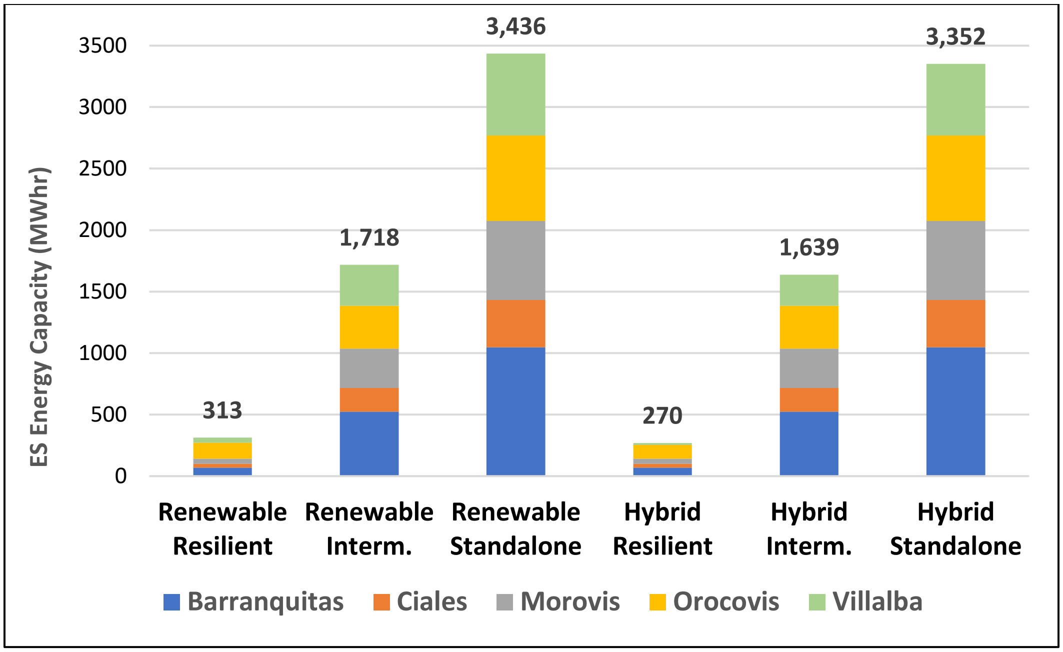

Figure 15: Breakdown of ES energy capacity for each planning scenario

Additionally, the results in Figures 13 – 15 display the differences in the PV and ES system sizes required to meet the critical, intermediate, and full load with the option of hydro contributions. A key takeaway is the influence that the hydro plants have on the PV and ES sizes required for the municipality of Villalba, where the hydro is located. Table 6 provides a breakdown of the percent differences in the PV and ES sizes when comparing the renewable and hydro scenarios.

Table 6: Percent differences of renewables compared to scenarios including hydro for Villalba

Scenario	% difference - PV (MW)	% difference - ES (MW)	% difference - ES (MWh)
Villalba Resilient	100 %	41.8 %	62.6 %
Villalba Intermediate	31.4 %	25.2 %	23.8 %
Villalba Standalone	16.7%	13.7 %	12.6%

The percent differences displayed in Table 6 represents the percent of the PV and ES technologies that would be required in Villalba when comparing the renewable and hybrid scenarios respectively. For example, in the renewable resilient scenario for Villalba the model chose to build 4.6 MW of PV. In the hybrid resilient scenario for Villalba, the model does not specify a PV size because the existing hydro is contributing to meeting the demand. Thus, there is a 100% savings in the PV costs when comparing the renewable and hybrid scenarios and the municipality of Villalba can meet its critical load with the existing hydroelectric generation coupled with the ES technology. A similar calculation is performed to determine the savings hydro can provide when sizing the ES technologies. Therefore, taking the hydroelectric contribution to supply power to Villalba into account can significantally decrease the sizes of the PV and ES systems needed, especially when meeting the critical demand in the resilient scenarios. Furthermore, the percent savings from the existing hydroelectric generation can be improved upon further investigation of the proper interconnection of the Toro Negro plants and increasing the plants' efficiencies.

Figure 16 provides the investment cost for the entire consortium for each planning scenario. The total optimal investment cost that the model provides can be broken down to identify the investment costs for the PV power generator, ES power equipment, and the ES stored energy component. Note that the stored energy component is the largest contribution to the cost.

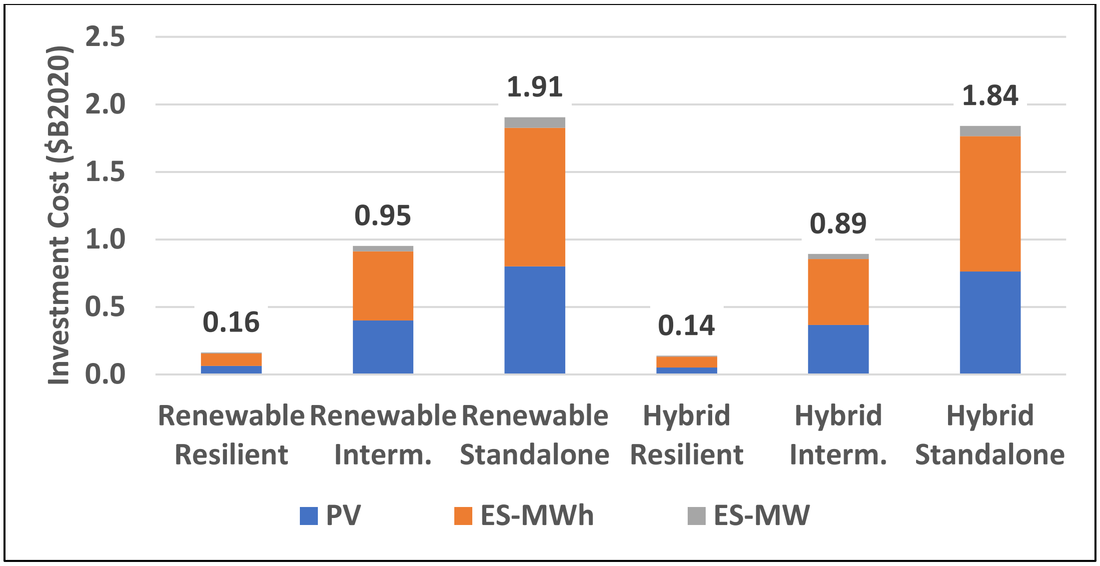

Figure 16: Investment cost per planning scenario for the entire consortium

The estimated investment costs are reflective of the present value ($B2020) and only include the cost of the equipment. The NREL Annual Technology Baseline (ATB) database was referenced for the investment costs of the PV and ES technologies [9]. The PV investment cost, represented by μ in Equation (**2)**, is assumed to be $1,600/kW. The ES power size cost, represented by ω, is assumed to be $260/kW. The ES energy capacity investment cost, represented by ϕ, is assumed to be $299/kWhr. Furthermore, the energy storage cost data is based on the medium cost scenario as found in the NREL ATB database. Lastly, incorporating the existing hydroelectric plants at Toro Negro decrease the overall investment costs for the resilience, intermediate, and standalone scenarios primarily in Villalba, as discussed above.

The renewable standalone (full coverage) scenario is the most expensive when comparing the total investment costs. When comparing the renewable scenarios with the hybrid scenarios, the renewable system is more costly. This sheds light on the value of the existing hydro system. Further analysis into the refurbishment of the hydroelectric plants needs to be performed to establish a cost-to-benefit ratio that could contribute to the decrease in the overall investment cost of the hybrid system. Lastly the resilient system cost ranges from 0.14 $B to 0.16 $B. This provides an initial equipment estimate of what the resilient system would cost to be able to serve the critical loads and meet the basic needs of the consortium during a natural disaster or loss of connection to the islands' primary grid system.

Figure 17 displays the generation dispatch for the hybrid standalone scenario for a week in June. This provides a typical dispatch for the entire consortium. To develop this figure, the dispatch of each technology is summed up for each bus at each hour. The plot in Figure 17 is a stack plot with the PV dispatch, ES charge, ES discharge, hydro dispatch, and curtailment is stacked on each other for each hour of the week.

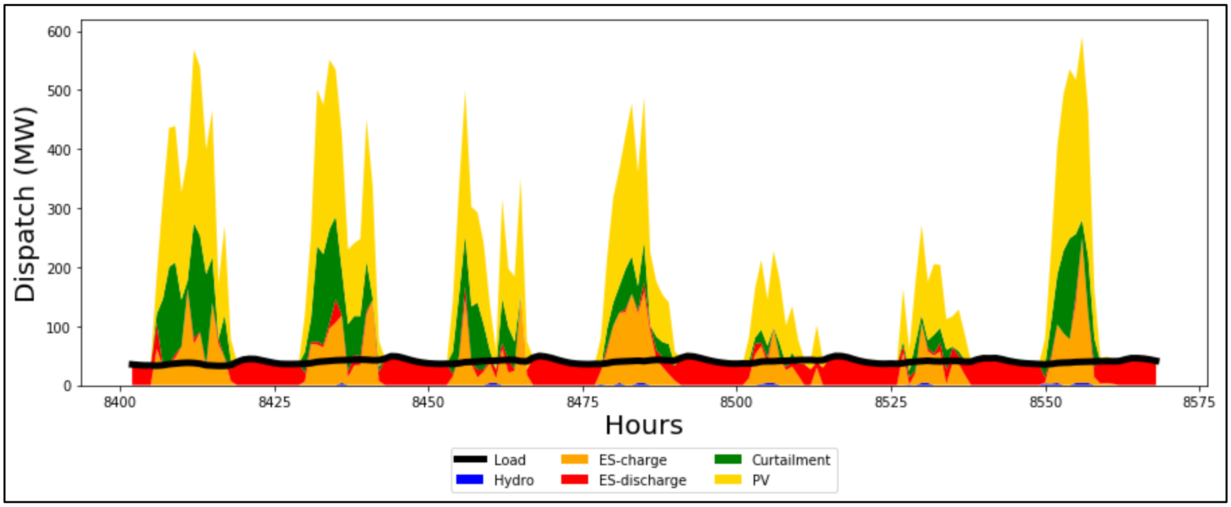

Figure 17: Stackplot of generation dispatch for a week in June in the hybrid standalone scenario for the entire consortium

The daily variability of the PV dispatch is captured in Figure 17. The consortium is located in a mountainous area where there is not the highest potential for solar dispatch compared to the coastal regions of PR. There may be several days or weeks throughout the year where cloud cover affects the PV dispatch. Therefore, it is crucial to model the entire year on an hourly timestep to ensure enough ES is built to meet the demand. The model is also allowing for curtailment, which is excess power due to the oversizing of the PV within the consortium. Future steps should involve investigating how this curtailed power could be used to generate a revenue stream for the consortium.

5.3.1. Additional Sensitivity – 5% Load Growth

An additional sensitivity analysis was performed to identify the proper size of the PV and ES technologies while assuming a 5% load growth. This sensitivity is performed in the anticipation of increased population and industries within the consortium. Figures 18 – 20 provide a breakdown of the installed capacities of the ES and PV technologies for each planning scenario. These results are provided in more detail in Table 9 and Table 10 found in Appendix B.

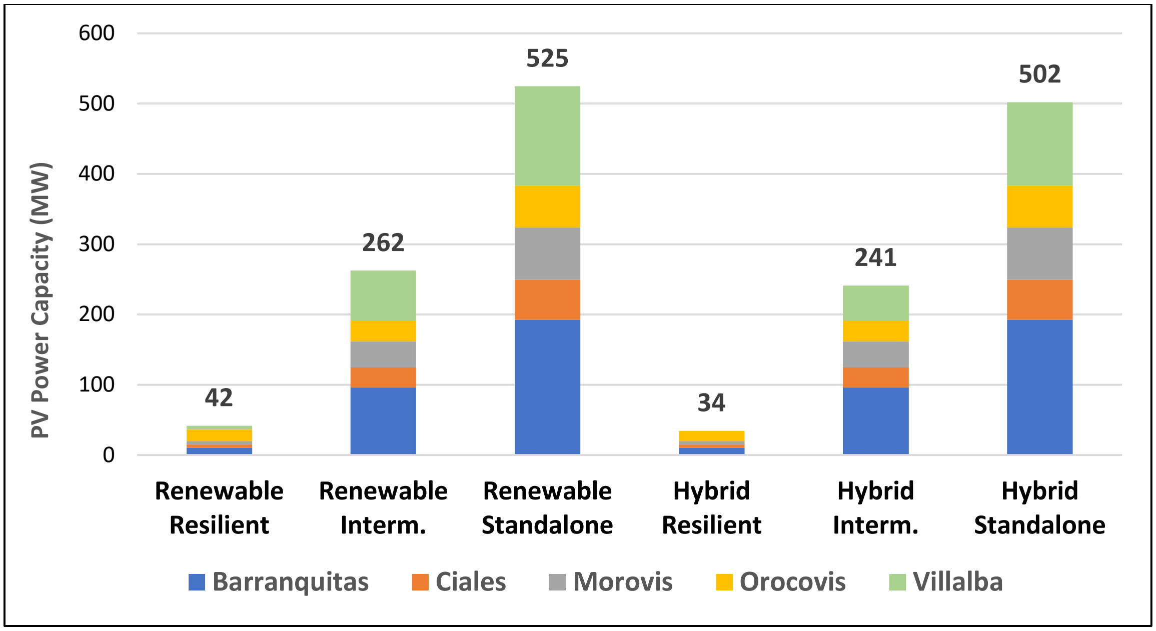

Figure 18: Breakdown of installed PV power capacity for each planning scenario with 5% load growth

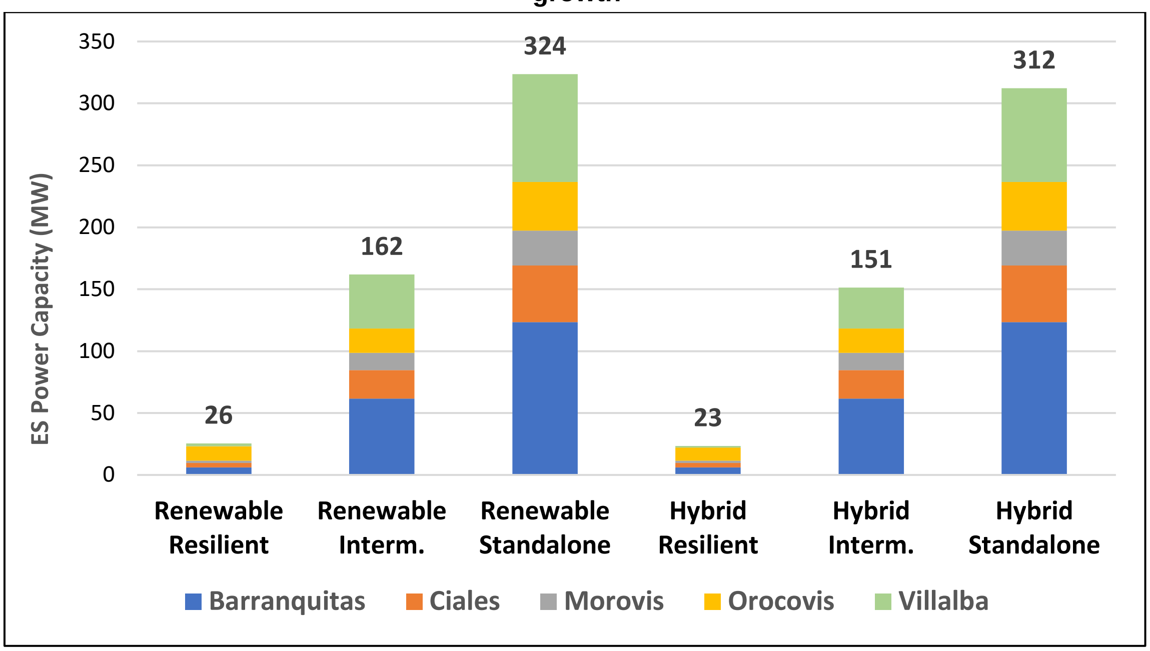

Figure 19: Breakdown of installed ES power capacity for each planning scenario with 5% load growth

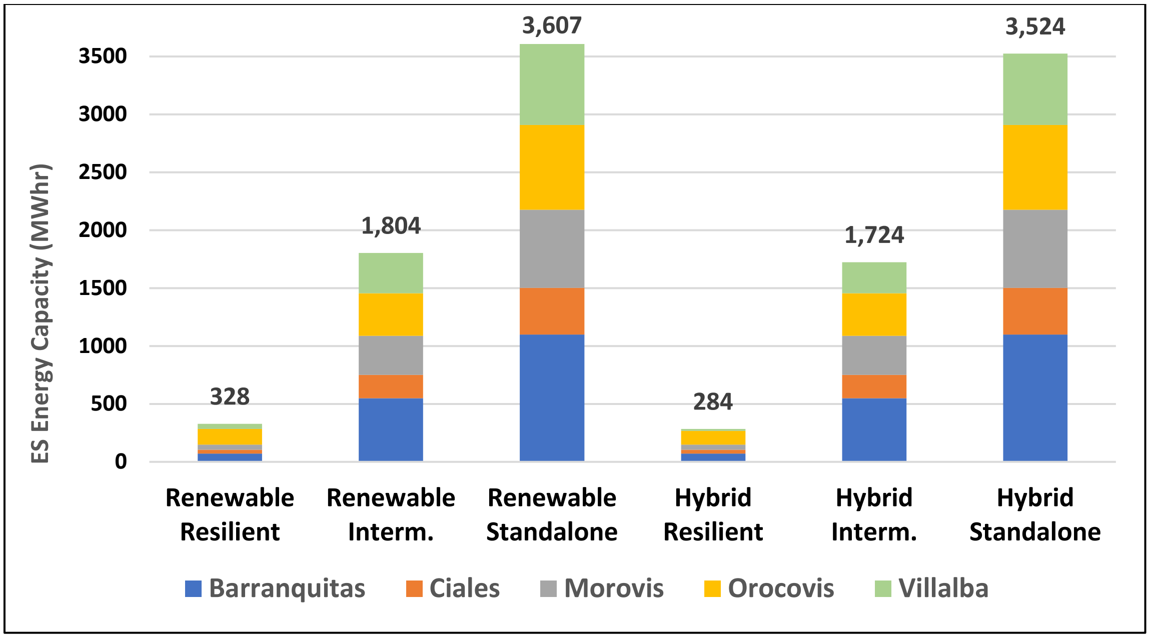

Figure 20: Breakdown of installed ES energy capacity for each planning scenario with 5% load growth

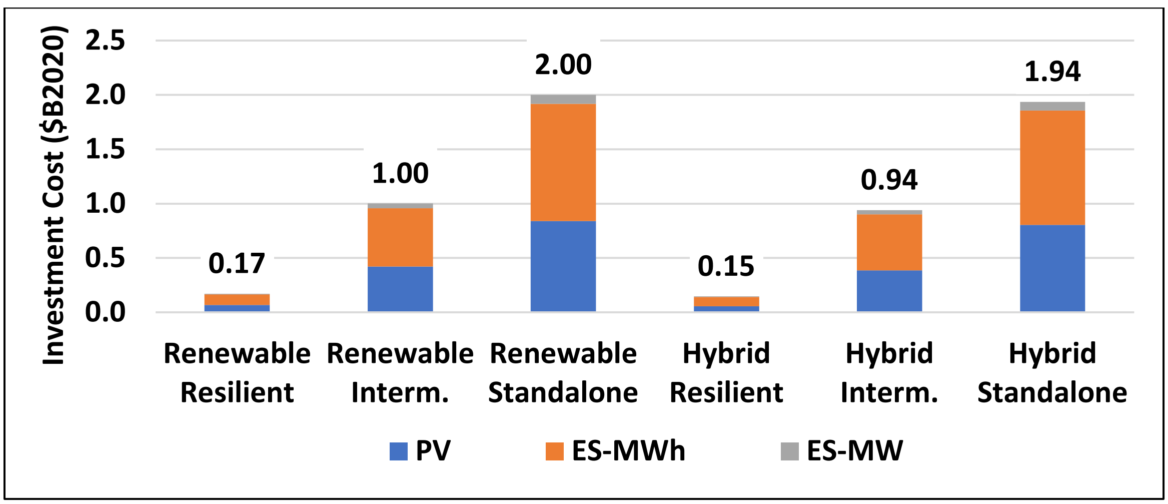

Figure 21: Investment cost per planning scenario for the entire consortium with 5% load growth

Figure 21 provides a cost breakdown of the PV and ES technologies for each of the planning scenarios under the assumption of 5% load growth. The investment costs reflect the present value ($B2020). These results provide a rough assumption of the necessary PV and ES technologies necessary within each planning scenarios given a 5% load growth. Furthermore, it provides insight into consortium's power system design and operation under the assumption that the 5% load growth reflects the introduction of new businesses and industries.

6. CONCLUSIONS & DISCUSSION

6.1. Conclusion & Key Takeaways

A conceptual design of a multi-municipality power subsystem has been introduced in this paper. The modeling framework developed for this study provides an initial scope of the amount of PV and ES needed given the planning scenario under study. Critical infrastructure within the municipalities of Barranquitas, Ciales, Morovis, Orocovis, and Villalba were identified and their approximate energy usage was used to develop the critical load levels. This enabled the appropriate sizing of the PV and ES technology for a resilient system where the critical loads are met and, in the case of a natural disaster, the consortium would be able to have its critical infrastructure available. Additionally, intermediate and stand-alone scenarios were evaluated to calculate the size of PV and ES to meet 50% and 100% of the CEM load, respectively. All scenarios were modeled with and without the contribution of two existing hydroelectric plants located at Toro Negro. Lastly, the planning scenarios were simulated with current load conditions and load conditions that reflected 5% load growth within the consortium.

In conclusion, a conceptual power system consisting of five municipalities in PR has been studied and an optimal mix of PV and ES sizes has been determined to serve various load levels within the CEM. These estimates of PV and ES equipment ratings can provide further insight for the consortium and assist with decision making in the future planning stages of the project.

6.2. Future Work

This work is part of an initial analysis stage with a goal of performing a scoping exercise to determine the sizing and siting of the PV and ES technologies within the consortium. This section of the report is designed to outline future work for this project that can be accomplished in the pre-planning and planning stage and provide general directions of how to further refine the results.

6.2.1. Transmission and Distribution Considerations

As mentioned previously, the transmission and distribution system have been simulated in this study. The modeling framework has been developed and is capable of providing results that are constrained by the transmission system[4]. To model the transmission system in the planning model, DC power flow constraints have been implemented. Since the model is a linear program, DC power flow approximations must be made and are sufficient for modeling the real power flow of the CEM network. The DC power flow constraint is detailed in Appendix A.

Additionally, one-line diagrams of the existing transmission, sub-transmission, and distribution systems have been reviewed. A key finding upon inspection is the lack of physical electrical connection between the municipalities. Figure 22 displays a high-level representation of the CEM transmission system.

[4] The results reflecting the transmission network has been neglected in this initial study due to the proprietary nature of the data.

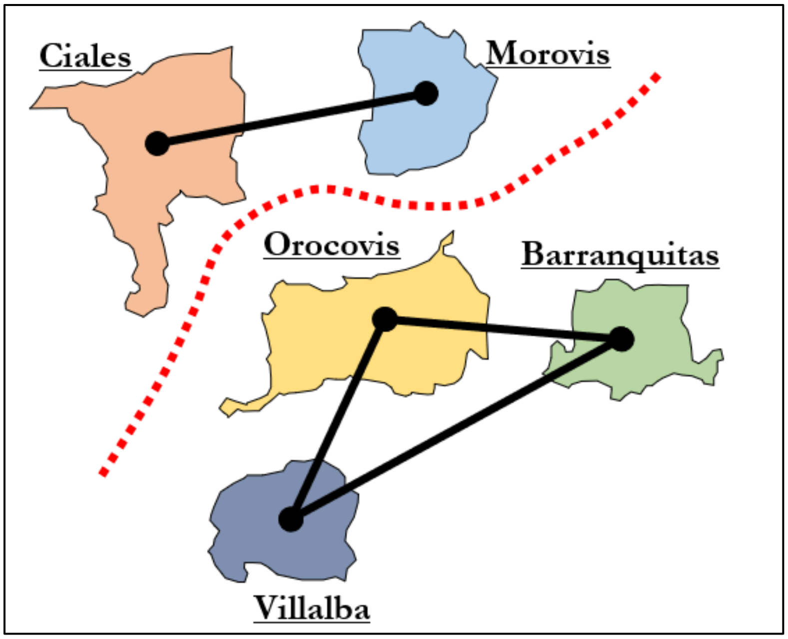

Figure 22: High-level visualization of the CEM transmission system

In Figure 22, it can be noted that there is no physical connection between the municipalities of Ciales and Morovis and the municipalities of Barranquitas, Orocovis, and Villalba. Future analysis of the transmission system can include optimizing the transmission investment within the developed planning model. A design should then be completed that evaluates transmission pathways to potentially form a connection from the southern municipalities (Barranquitas, Orocovis, and Villalba) to the northern municipalities (Ciales and Morovis). In addition, the design may need to include transferring non-municipality loads to other feeders and/or substations.

The cost of building transmission must also be taken into account to develop a cost-benefit ratio of building an interconnected consortium. The distribution system of the CEM power system at the 38 kV or less levels should also be considered. The distribution system is complex and may not be able to be modeled within the planning model. However, the distribution system and the existing feeder designs should be reviewed to establish hosting capacities of the existing infrastructure as seen in previous studies [14]. This information can be used for a more granular siting of the PV and ES technologies that the planning model provides. Lastly, consulting with local engineers to determine feasibility of transmission projects should be completed due to the mountainous terrain of the CEM.

6.2.2. Reliability & Resilience Considerations

With the potential investment in PV and ES technologies within the CEM, reliability and resilience analyses, while not part of this work, could be performed. For reliability studies, typical reliability indices such as system average interruption duration index (SAIDI), system average frequency index (SAIFI), and customer average interruption duration index (CAIDI) could be evaluated specifically for the consortium's power system. Performing these studies may provide a good indication of how the system will perform on average over a long period of time [2].

Additionally, reliability studies could provide information on how low impact and high frequency events affect the grid system [15]. The authors of [2] provide details for Puerto Rico-specific reliability metrics and attempt to locate the distribution feeders that experience high SAID, SAIFI, and CAIDI levels. While this information provides an indication of the overall reliability of the system, it does not provide information about how the system is vulnerable to high impact and low frequency events such as hurricanes. Figure 23 shows the historical path of hurricanes that have crossed the islands of PR [16]. This further motivates the need to study the reliability and resilience of the consortium.

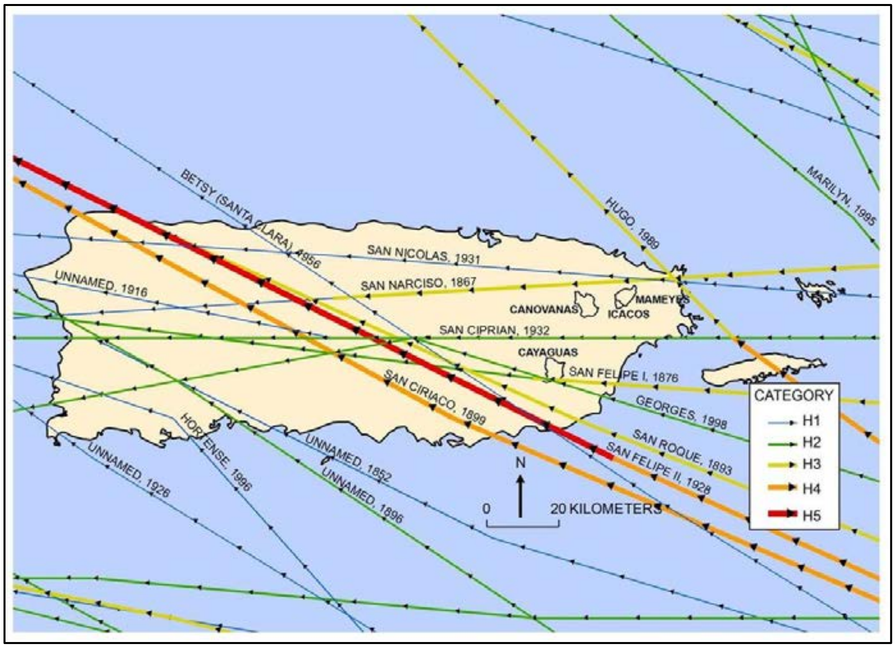

Figure 23: Historical hurricane paths across PR [16]

Resilience studies could be performed as well. While there are no industry-established metrics for resilience as there are for reliability, resilience analyses still may provide an insight into how the system will perform in the event of an extreme event. Resilience studies would include, but not be limited to, examining historical outages and damage reports from past extreme events. In the case of the CEM, it would be of interest to look back at the damages the consortium had from the hurricanes in 2017. From there, engineering judgments can be made on potential grid-hardening options. This analysis could also be incorporated into the planning model, to evaluate the interaction between the investment of the PV and ES technologies and the overall resilience of the system. Lastly, within the planning model that includes the transmission constraints, several contingency scenarios can be evaluated. Traditionally, single (n-1) and double (n-2) contingencies are evaluated for reliability studies. However, in the event of adverse weather there may be several contingencies occur at the same time. This multi-contingency study within the planning model could greatly affect the sizing and siting of the PV and ES technologies and could also provide insight into how the CEM should operate during and after the adverse weather event. Referring to Figure 23, it is evident that the CEM will experience another hurricane that will greatly affect its power system. Therefore, careful consideration in terms of the reliability and the resilience of the consortium should be considered for future stages of this project.

Lastly, to further increase the resilience of the consortium more accurate representation of the critical infrastructure can be developed. In Section 4.5, the critical infrastructure within the consortium is identified along with the estimation of the annual energy consumption for each infrastructure type. These critical load levels are generalized according to the data provided by the Open-EI database. Therefore, they may not completely represent the critical infrastructure power demands within the mountain consortium. To gather accurate critical load data, collaboration with the municipalities, various industries, and PREPA should be considered. Ideally having an 8760 load profile representing the CEM critical infrastructure would further provide insight into the PV and ES technologies required to build a resilient system.

6.2.3. Advanced Modeling of Toro Negro Hydroelectric Plants

In the preliminary results provided in this report, it was determined that taking advantage of the existing hydroelectric infrastructure decreases the total equipment investment cost for the hybrid planning scenarios. In this study, a capacity factor of 40% is assumed. This means that the Toro Negro I & II plants can only dispatch up to 40% of their installed capacities. It was also assumed that the hydro plants could only dispatch on daily basis between the hours of 8 AM to 4 PM. These modeling assumptions play a pivotal role in the sizing of the PV and ES in the municipality of Villalba. Therefore, future studies should include the investigation and validation of a "typical" dispatch schedule of the Toro Negro plants. Optional dispatch schedules should be considered as well. Notice in Figure 11 that PV potential peak in the middle of the day. This is also reflected in the weekly dispatch plotted in Figure 17. If the Toro Negro plants have the option to dispatch later in the day, perhaps 4 PM to 12 AM, or earlier in the day, 12 AM to 8 AM, this would decrease the power size and energy capacity of the ES technologies that would be need to satisfy the demand during the non-sunlight hours. Consequently, the total equipment investment cost would decrease because the most expensive cost component is the energy capacity of the ES, according to Figure 16. Additional engineering studies should be performed on how to increase the capacity factor of the hydroelectric facilities. This would include performing a cost-benefit study on refurbishing the older hydroelectric plants to increase the efficiencies and the power output. The facilities are almost a century old so major upgrades and renovations should be considered. Figure 24 displays a schematic of the Toro Negro hydroelectric system including the major components.

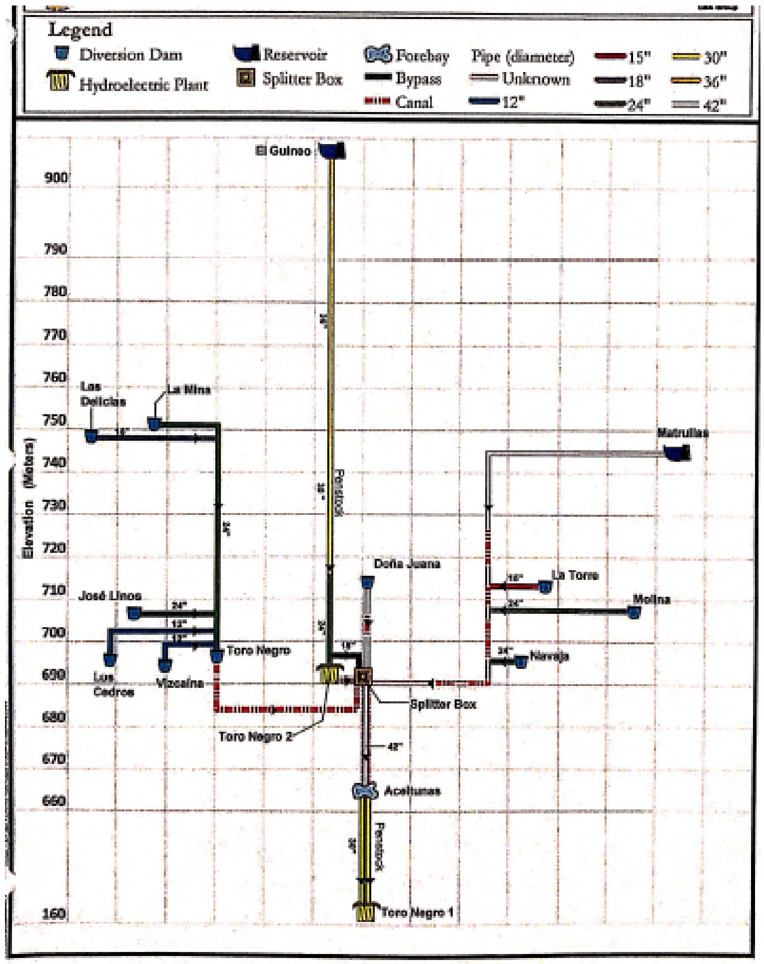

Figure 24: Toro Negro System Schematic [6]

Figure 24 also provides increased detail into how water is fed into the Toro Negro I & II plants for the El Guineo and Matrullas reservoirs. This provides the opportunity for incorporating a detailed water model into the already developed power system planning model. This could further refine the optimal dispatch of the Toro Negro plants. Furthermore, detailed water data can be collected from measurement stations operated by the United States Geological Survey (USGS) **[17]**. Figure 25 displays an example of the data that can be used to accurately model the hydroelectric power output. Figure 25 displays the annual reservoir elevation of the El Guineo reservoir. This information could be used to estimate the water input into the Toro Negro plants.

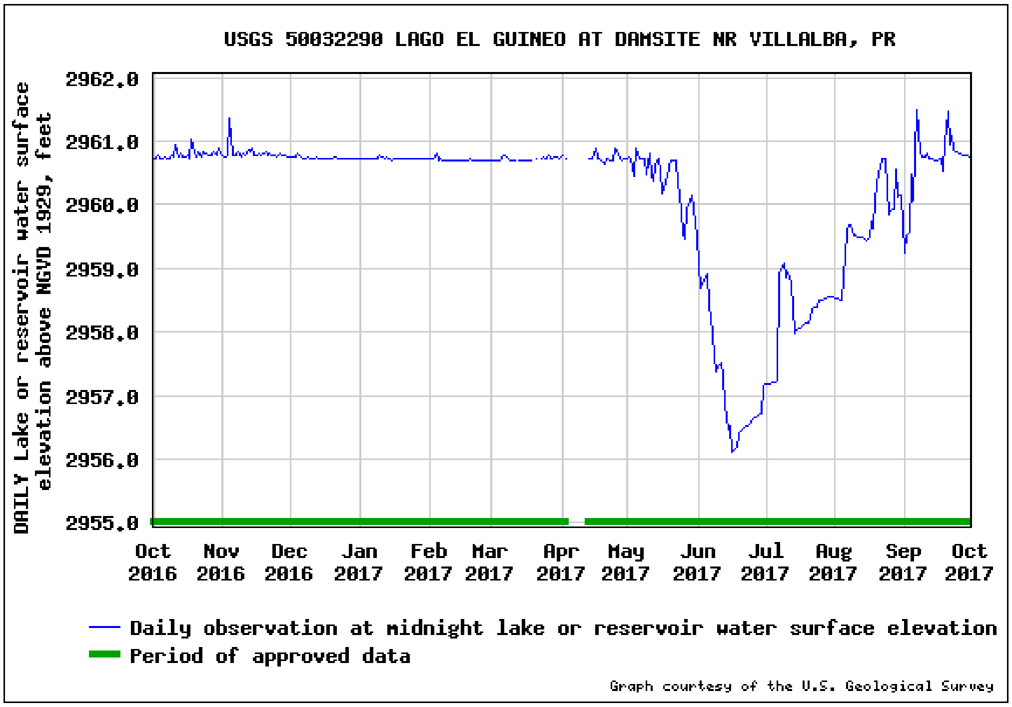

Figure 25: Plot of reservoir elevation of El Guineo reservoir

Similar data acquisition and analysis can be performed for the Matrullas reservoir. Performing this detailed analysis would provide a more accurate representation of the potential power dispatch from the Toro Negro hydroelectric plants. The Toro Negro plants have already been proven crucial to supplying the consortium with emergency power. In the wake of Hurricane Maria, the Toro Negro I plant was reinstated and used for emergency power and provided water to the municipality of Villalba **[18]**. With the assistance of Medtronics, the Toro Negro I plant was used to provide water to half of Villalba's population and electricity to a third of its population. Furthermore, the hydro facility was able to provide power to the local hospital, schools, and the police station. This proves that the Toro Negro hydro plants can play a pivotal role in the development of an autonomous system that the consortium desires to construct. The hydro plants should be further analyzed in order to determine the optimal amount of power given the budget limits and the energy potential of the Toro Negro water system. As a result, a hybrid regional power system consisting of hydro, PV, and ES technologies can be optimally placed within the consortium to form a resilient and efficient system the people located in the CEM.

6.2.4. Review of Regulations and Minimum Technical Requirements in Puerto Rico

A review of the minimum technical requirements (MTR) in PR should be completed as well as reviewing the microgrid regulations established by the Puerto Rico Energy Commission (PREC) [19] [20]. These regulations also provide guidance on developing rate structures for potential revenue streams that can be generated by the PV and ES technologies. The CEM network that has been mapped for this project includes the connections to external buses. This provides the opportunity to evaluate potential revenues generated by the overbuilt PV and ES technologies within the consortium. Recall, in Figure 17, curtailment of the PV occurs on a daily basis once the ES technologies are fully charged to cover the non-sunlight hours. Perhaps this curtailment could be sold back to the PREPA system under a future power purchase agreement. This additional revenue could alleviate the overall investment costs of the system.

In this study, the solar profiles are considered to be at the utility-level. Further analysis into distributed rooftop PV should be pursued. This analysis would consist of gathering additional solar profiles that are representative of the distributed PV arrays. Lastly, this should also involve consulting with the local municipalities regarding the feasibility of distributed rooftop solar.

6.2.5. Additional considerations during HUD program Pre-planning and planning phases

The Housing and Urban development (HUD) department has issued a solicitation to the help municipalities of Puerto Rico increase their resilience to future weather events. Part of this program includes funding for energy resiliency. CEM has submitted an application to the HUD for funding that includes the consortium microgrid. As part of this program there will be a pre-planning and a planning phase that will allow the CEM to develop plans and estimates to implement resiliency efforts, including a resilient microgrid. In addition to the future work outlined in sections 4.2.1 – 4.2.4, the following are other considerations that should be addressed during these two planning phases.

6.2.5.1. Pre-planning Phase

As the implementation of the overall microgrid work is a major undertaking, given time and funding limitation, the CEM should look to implement the project through a phased approach. To do this they should firm up the initial phase plan that has been developed. In addition, through the pre-planning engineering services provided by the HUD solicitation, the CEM may want to verify all the data and results of this study:

1. Compare calculated loads to original estimate.
2. Identify critical loads that will be connected to each municipality's resilient microgrid.
3. Determine load profile for each substation and/or proposed microgrid.
4. Verify PV(MW), and ES (MW/MWh) based on loads and load profile.
5. Identify which electrical buses CEM loads are connected to, and which substation the bus is connected to.
6. Identify non-CEM loads on CEM substations and design removal from CEM substation and refeed. Or decided to include.
7. Determine what loads are non-critical and how to isolate them from the critical loads (resilient microgrid).
8. Determine what upgrades PREPA is planning to do with Toro Negro 1 and 2.

6.2.5.2. Planning Phase

Upon completion of pre-planning phase, and once the funding is made available for the planning phase, the following are suggested steps that the CEM may want to perform. These steps include but are not limited to the following

1. Finalize phasing and what will be included in each phase.
2. Design PV installation.
   a. Power requirements per phase.
   b. Determine Location and infrastructure installation
   c. Vet components and installation process
3. Design ES installation
   a. Verify Power requirements per phase and per municipality.
   b. Verify Energy requirements per phase and per municipality.
   c. Determine location and infrastructure installation
   d. Vet components and installation process.
4. Redesign distribution system to separate critical loads from non-critical loads
   a. Provide design to move CEM critical and non-critical loads to appropriate distribution switchgear.
   b. Provide design to remove non-CEM loads to other substations or electrical bus.
   c. Design distribution switchgear needed
   d. Design transmission connection between northern municipalities with southern municipalities.

7. REFERENCES

[1] National Renewable Energy Laboratory (NREL), "PVWATTS," NREL, August 2017. [Online]. Available: https://pvwatts.nrel.gov/. [Accessed June 2020].

[2] R. F. Jeffers, M. J. Baca, A. M. Wachtel, S. DeRosa, A. Staid, W. Fogleman, A. Outkin and F. Currie, "Analysis of Microgrid Locations Benefitting Community Resilience for Puerto Rico," Sandia National Laboratories, Albuquerque, 2018.

[3] R. J. Pasch, A. B. Penny and R. Berg, "National Hurricane Center tropical Cyclone Report Hurricane Maria," NOAA, 2019.

[4] E. O'Neill-Carrillo, I. Jordan, A. Irizarry-Rivera and R. Clintron, "The Long Road to Community Microgrids," IEEE Electrification Magazine, 2018.

[5] NASA, "NASA Earth Observatory," March 2018. [Online]. Available: https://earthobservatory.nasa.gov/images/144371/night-lights-show-slow-recovery-from-maria.

[6] CSA Architects and Engineers, "Toro Negro Hydroelectric System Evaluation Report," CSA, San Juan, PR, 2011.

[7] National Renewable Energy Laboratory (NREL), "NSRDB: National Solar Radiation Database," NREL, 2020. [Online]. Available: https://nsrdb.nrel.gov/. [Accessed June 2020].

[8] M. Deru, K. Field, D. Studer, K. Benne, B. Griffith, P. Torcellini, B. Liu, M. Halverson, D. Winiarski, M. Rosenburg, M. Yazdanian, J. Huang and D. Crawley, "U.S. Department of Energy Commercial Reference Building Models of the National Building Stock," National Renewable Energy Laboratory, Golden, Colorado, 2011.

[9] National Renewable Energy Laboratory (NREL), "2020 Annual Technology Baseline," National Renewable Energy Laboratory, 2020. [Online]. Available: https://atb.nrel.gov/. [Accessed June 2020].

[10] Puerto Rico Power Authority (PREPA), "Operational Reports," PREPA, February 2016. [Online]. Available: https://aeepr.com/en-us/QuienesSomos/Pages/ley57/Operacionales.aspx. [Accessed May 2020].

[11] W. E. Hart, C. D. Laird, J.-P. Watson, D. L. Woodruff, G. A. Hackebeil, B. L. Nicholson and J. D. Siirola, Pyomo - Optimization Modeling in Python, Second ed., vol. 67, Springer, 2017.

[12] W. E. Hart, J.-P. Watson and D. L. Woodruff, "Pyomo: modeling and solving mathematical programs in Python," *Mathematical Programming Computation,* vol. 3, no. 3, pp. 219-260, 2011.

[13] L. Gurobi Optimization, *Gurobi Optimizer Reference Manual,* 2020.

[14] M. Lave, "Solar PV Design Considerations for Islanded Systems," Sandia National Laboraties, 7 December 2016. [Online]. Available: https://www.osti.gov/servlets/purl/1412087. [Accessed October 2020].

[15] E. Vugrin, A. Castillo and C. Silva-Monroy, "Resilience Metrics for the Electric Power System: A performance-Based Approach," Sandia National Laboratories, Albuquerque, New Mexico, 2017.

[16] United States Geological Survey (USGS), "Puerto Rico Hurricane Map," USGS, [Online]. Available: https://www.usgs.gov/media/images/puerto-rico-hurricanes-map. [Accessed September 2020].

[17] United States Geological Survey (USGS), "National Water Information System: Web Interface," USGS, 2017. [Online]. Available: https://waterdata.usgs.gov/nwis. [Accessed September 2020].

[18] Medtronic, "Teamwork: Medtronic Helps Villalba Resotre Power," Medtronic, February 2018. [Online]. Available: https://www.medtronic.com/us-en/about/news/villalba-power.html. [Accessed June 2020].

[19] V. Gevorgian and S. Booth, "Review of PREPA Technical Requirements for Interconnecting Wind and Solar Generation," National Renewable Energy Laboratory (NREL), Golden, CO, 2013.

[20] Puerto Rico Energy Commission (PREC), "Regulation on Microgrid Development," PREC, San Juan, PR, 2018.

[21] P. R. E. Bureau, "Review ofthe Puerto Rico Electric Power Authority Integrated Resource Plan," Puerto Rico Energy Bureau, San juan, PR, 2019.

[22] Siemens Power Technologies International, "Puerto Rico Integrated Resource Plan 2018-2019," Siemens Industry, Inc., Schenectady, NY, 2019.

[23] G. A. Carrion, R. A. Cintron, M. A. Rodriguez, W. E. Sanabria, R. Reyes and E. O'Neill-Carrillo, "Community Microgrids to Increase Local Resiliency," in *IEEE International Symposium on Technology in Society (ISTAS) Proceedings*, Washington, D.C., 2018.

APPENDIX A. MODEL FORMULATION

A.1. Nomenclature

A.1.1. Indices & Sets

$\boldsymbol{b/B}$	Bus / Set of buses
$\boldsymbol{m/M}$	Municipality / Set of municipalities
$\boldsymbol{l/L}$	Line / Set of lines
$\boldsymbol{t/T}$	Timestep / Planning horizon

A.1.2. Parameters

$\boldsymbol{\beta_{b,t}}$	Solar per unit insolation at bus b, time t
$\boldsymbol{\Delta t}$	Duration of timestep t
$\boldsymbol{\eta_c, \eta_d}$	Charge/discharge efficiency
$\boldsymbol{\eta_s}$	Energy storage efficiency
$\boldsymbol{\lambda_{min}, \lambda_{max}}$	Energy storage state of charge min / max
$\boldsymbol{k}$	Renewable curtailment rate
$\boldsymbol{\omega}$	Energy storage power size cost (\$/MW)
$\boldsymbol{\phi}$	Energy storage energy capacity cost (\$/MWh)
$\boldsymbol{P_{b,t}^{D}}$	Power demand at bus b, time t (MW)
$\boldsymbol{P_{ES}^{Max}}$	Maximum energy storage power size (MW)
$\boldsymbol{C_b^{hydro}}$	Existing capacity of the hydroelectric plant at bus b (MW)
$\boldsymbol{\epsilon_m}$	Critical load fraction for municipality m
$\boldsymbol{X_l}$	Reactance of line *l* (pu) (Optional)

A.1.3. Variables

$\boldsymbol{C_b^{PV}}$	Invested capacity of solar (MW)
$\boldsymbol{C_b^{ES}}$	Invested power size of ES (MW)
$\boldsymbol{E_b^{ES}}$	Invested energy size of ES (MWh)
$\boldsymbol{P_{b,t}^{PV}}$	Dispatch of solar PV (MW)

$P_{b,t}^{curt}$	Curtailed renewable power (MW)
$P_{b,t}^{cha}$	Energy storage charging power (MW)
$P_{b,t}^{dis}$	Energy storage discharging power (MW)
$P_{b,t}^{hydro}$	Dispatch of hydroelectric plants (MW)
$SOC_{b,t}$	Energy storage state of charge (MWh)
$P_{l,b,b',t}$	Real power flow of line l with receiving bus *b* and sending bus *b'* (MW) (optional)
θ_b	Phase angle of bus *b* (radians) (optional)

A.2. Model Formulation

The model is introduced in Section 5.1 and will further be defined in detail in this section. This model is a linear program that seeks to minimize the power size of the solar (PV) and the power an energy size of energy storage (ES) need to supply the load of the 5 municipalities within the mountain consortium.

A.2.1. Objective Function

The objective function $I(x)$ for the linear program is displayed in (3). The decision variable vector can be defined as $\boldsymbol{x} = [C_b^{PV}, C_b^{ES}, E_b^{ES}]$.

$$\min \quad I(x) = (\mu * C_b^{PV} + \omega * C_b^{ES} + \phi * E_b^{ES}) \tag{3}$$

The invested capacities of the PV and ES technologies are weighted to reflect their relative costs. The parameter μ is assumed to be $1,600/kW to represent the cost of solar investments. The ES power size cost, represented by ω, is assumed to be $260/kW. Lastly, the ES energy capacity cost, ϕ, is assumed to be $299/kWhr. These cost estimates were extracted from the 2020 Annual Technology Baseline (ATB) database constructed by the National Renewable Energy Laboratory (NREL) [9]. The energy storage cost data is based on the medium cost scenario as found in the NREL ATB database.

A.2.2. Photovoltaic Dispatch Constraint

The PV dispatch is calculated in (4) using the solar per unit insolation ($\boldsymbol{\beta}_{b,t}$) and the installed PV capacity (C_b^{PV}).

$$P_{b,t}^{PV} = \beta_{b,t} * C_b^{PV} \qquad \forall b \epsilon B, t \epsilon T \tag{4}$$

A.2.3. Energy Storage Constraints

Constraints (5)-(6) account for the behavior of the ES systems within the model for all of the timesteps within the model for all timesteps of the planning horizon. The state-of-charge, $SOC_{b,t}$, is calculated in (5). The charge and discharge efficiencies (η_c and η_d) are assumed to be 0.85 and 1.0 respectively. The storage efficiency (η_s) is assumed to be 1.0.

$$SOC_{b,t+1} = \eta_s * SOC_{b,t} + \Delta t * \left(\eta_c * P_{b,t}^{cha} - P_{b,t}^{dis}/\eta_d\right) \qquad \forall b \epsilon B, t \epsilon T \tag{5}$$

The constraint in (6) assumes that the state of charge remains within an appropriate operating level of the ES energy size, E_b^{ES}. The initial state of charge, $SOC_{b,0}$, is assumed to be 50% of the ES energy capacity. The minimum and maximum levels (λ_{min} and λ_{max}) are considered to be 0.2 and 0.8 respectively.

$$\lambda_{min} * \Delta t * E_b^{ES} \leq SOC_{b,t} \leq \lambda_{max} * \Delta t * E_b^{ES} \qquad \forall b \epsilon B, t \epsilon T \tag{6}$$

The constraint in (7) limits the charge and discharge to be within the limits of the installed ES power size, P_b^{ES}.

$$P_{b,t}^{cha} + P_{b,t}^{dis} \leq P_b^{ES} \qquad \forall b \epsilon B, t \epsilon T \tag{7}$$

It is common for the inclusion of binary variables in (7) to properly model the charge and discharge behavior of the ES technologies. However, for this case study these binary variables were neglected to relieve computational burden.

A.2.4. Curtailment

In the event where there is an overproduction from the installed PV and the ES is fully charge, the system has the option to curtail the excess power. The curtailment is constrained to be less than the PV generation ($P_{b,t}^{PV}$) as displayed in (8).

$$P_{b,t}^{curt} \leq P_{b,t}^{PV} \qquad \forall b \epsilon B, t \epsilon T \tag{8}$$

The constraint in (9) enforces the total annual curtailment to be limited by the curtailment rate k of the total solar generation in the planning horizon.

$$\sum_{b \epsilon B} \sum_{t \epsilon T} P_{b,t}^{curt} \leq k \sum_{b \epsilon B} \sum_{t \epsilon T} P_{b,t}^{PV} \tag{9}$$

In this study, the curtailment rate was assumed to be 1.0 and the optimizer determined the optimal amount to overbuild of the PV systems. For future studies, the planner has the opportunity to select a range of values for k as need be.

A.2.5. *Hydroelectric modeling*

The hydro dispatch ($P_{b,t}^{hydro}$) of the Toro Negro plants is calculated in (10). The parameter γ is assumed to be 0.4.

$$P_{b,t}^{hydro} = \gamma * C_b^{hydro} \qquad \forall b \epsilon B, t \epsilon T \tag{10}$$

The existing installed capacity of the hydro facilities is represented as $C_{b,t}^{hydro}$. The hydro plants are assumed to be able to dispatch only between 8 AM and 4 PM to reflect the actual operations of the Toro Negro hydroelectric plants.

A.2.6. *Transmission Constraints (optional)*

In constraint (11), the DC optimal power flow is calculated using the line's reactance, X_l, and the phase angle difference between the receiving bus (*b*) and the sending bus (*b'*) of line *l*.

$$P_{l,b,b',t} = \frac{1}{X_l} * (\theta_b - \theta_{b'}) \qquad \forall l \epsilon L, b \epsilon B, b' \epsilon B', t \epsilon T \tag{11}$$

It is important to note that this constraint is not enforced currently for this case study due to restrictions on the transmission data. However, this is a modeling feature that has been developed for future studies when the data becomes available.

A.2.7. *Power Balance*

To meet the hourly demand at each bus, the power balance constraint displayed in (12) is enforced for all timesteps.

$$\epsilon_m * P_{b,t}^{D} = P_{b,t}^{PV} - P_{b,t}^{dis} + P_{b,t}^{cha} - P_{b,t}^{curt} + P_{b,t}^{hydro} \qquad \forall b \epsilon B, m \epsilon M, t \epsilon T \tag{12}$$

When evaluating the resilient planning scenarios, the parameter ϵ_m is introduced to scale each municipality's hourly load to represent the critical load within the consortium. Each bus is assigned a value for ϵ_m based on the municipality the bus is located in, according to Table 1. If the DC power flow were to be enforced, the power balance constraint would also contain the real power flow variable, $P_{l,b,b',t}$.

APPENDIX B. EXTENDED PRELIMINARY RESULTS

Table 7 and Table 8 provide a breakdown of the PV and ES investment decisions for the no load growth conditions. The data provided in Table 7 and Table 8 reflects the data displayed in Figures 13-15 in Section 5.3.

Table 7: Results for the renewable planning scenarios under no load growth

Scenario	Municipality	PV (MW)	ES (MW)	ES (MWh)
Renewable Resilient (RR)	Barranquitas	10.0	5.7	67.4
	Ciales	4.4	3.5	31.4
	Morovis	4.6	1.7	41.8
	Orocovis	16.1	11.0	131.1
	Villalba	4.6	2.3	41.1
	Total	**39.7**	**24.3**	**312.9**
Renewable Intermediate (RI)	Barranquitas	91.7	58.8	523.8
	Ciales	27.1	21.7	192.2
	Morovis	35.4	13.4	320.8
	Orocovis	28.4	18.8	348.4
	Villalba	67.3	41.4	332.7
	Total	**249.8**	**154.1**	**1717.9**
Renewable Standalone (RS)	Barranquitas	183.3	117.6	1047.6
	Ciales	54.2	43.4	384.3
	Morovis	70.7	26.8	641.6
	Orocovis	56.7	37.5	696.8

Scenario	Municipality	PV (MW)	ES (MW)	ES (MWh)
	Villalba	134.6	82.9	665.4
	Total	**499.6**	**308.28**	**3435.7**

Table 8: Results for the hybrid planning scenarios under no load growth

Scenario	Municipality	PV (MW)	ES (MW)	ES (MWh)
Hybrid Resilient (HR)	Barranquitas	10.0	5.7	67.4
	Ciales	4.4	3.5	31.4
	Morovis	4.6	1.7	41.8
	Orocovis	13.7	10.0	113.8
	Villalba	-	1.3	15.4
	Total	**32.7**	**22.3**	**269.8**
Hybrid Intermediate (HI)	Barranquitas	91.7	58.8	523.8
	Ciales	27.1	21.7	192.2
	Morovis	35.4	13.4	320.8
	Orocovis	28.4	18.8	348.4
	Villalba	46.2	31.0	253.5
	Total	**228.7**	**143.7**	**1638.7**
Hybrid Standalone (HS)	Barranquitas	183.3	117.6	1047.6
	Ciales	54.2	43.4	384.3
	Morovis	70.7	26.8	641.6

Scenario	Municipality	PV (MW)	ES (MW)	ES (MWh)
	Orocovis	56.7	37.5	696.8
	Villalba	112.1	71,6	581.7
	Total	**477.2**	**297.0**	**3352.0**

Table 9 and Table 10 provide a breakdown of the PV and ES investment decisions for the no load growth conditions. The data provided in Table 9 and Table 10 reflects the data displayed in Figures 13-15 in Section 5.3.1.

Table 9: Results for the renewable planning scenarios under 5% load growth

Scenario	Municipality	PV (MW)	ES (MW)	ES (MWh)
Renewable Resilient (RR)	Barranquitas	10.5	6.0	70.8
	Ciales	4.7	3.7	33.0
	Morovis	4.8	1.8	43.9
	Orocovis	16.9	11.6	137.7
	Villalba	4.8	2.4	43.1
	Total	**41.6**	**25.6**	**328.5**
Renewable Intermediate (RI)	Barranquitas	96.3	61.8	550.0
	Ciales	28.5	22.8	201.8
	Morovis	37.1	14.1	336.9
	Orocovis	29.8	19.7	365.8
	Villalba	70.7	43.5	349.3
	Total	**262.3**	**161.8**	**1803.7**

Scenario	Municipality	PV (MW)	ES (MW)	ES (MWh)
Renewable Standalone (RS)	Barranquitas	192.5	123.5	1100.0
	Ciales	57.0	45.6	403.6
	Morovis	74.3	28.1	673.7
	Orocovis	59.5	39.4	731.6
	Villalba	141.3	87.0	698.6
	Total	**524.6**	**323.7**	**3607.5**

Table 10: Results for the hybrid planning scenarios under 5% load growth

Scenario	Municipality	PV (MW)	ES (MW)	ES (MWh)
Hybrid Resilient (HR)	Barranquitas	10.5	6.0	70.8
	Ciales	4.7	3.7	33.0
	Morovis	4.8	1.8	43.9
	Orocovis	14.5	10.5	120.3
	Villalba	0.0	1.4	16.1
	Total	**34.5**	**23.5**	**284.1**
Hybrid Intermediate (HI)	Barranquitas	96.3	61.8	550.0
	Ciales	28.5	22.8	201.8
	Morovis	37.1	14.1	336.9
	Orocovis	29.8	19.7	365.8
	Villalba	49.5	33.0	269.6

Scenario	Municipality	PV (MW)	ES (MW)	ES (MWh)
	Total	**241.1**	**151.4**	**1724.0**
Hybrid Standalone (HS)	Barranquitas	192.5	123.5	1100.0
	Ciales	57.0	45.6	403.6
	Morovis	74.3	28.1	673.7
	Orocovis	59.5	39.4	731.6
	Villalba	118.8	75.7	615.2
	Total	**502.1**	**312.3**	**3524.1**

DISTRIBUTION

Email—Internal

Name	Org.	Sandia Email Address
Technical Library	01911	sanddocs@sandia.gov

This page left blank

Sandia National Laboratories

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.