Designing a Model for Puerto Rico: A Micro-Grid Case Study of Transmission following Hurricane Maria

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When Hurricane Maria struck Puerto Rico in 2017, disconnect between the Federal Emergency Management Agency (FEMA) relief team and local responders led to the disorganization of resources and loss of communication in the period following the hurricane. This proposal aims to explore "how micro-grid emergency infrastructure can relieve energy demand in disaster zones" by identifying renewable alternatives to generator installations. Specifically, this project will develop a model which may represent the national grid when all generation sources are solar and battery based. The developed model will evaluate the performance of solar micro-grid systems given the condition and resources available following Hurricane Maria. This study will propose energy systems alternatives available during a crisis so that response teams may have a more reliable, and sustainable power source when distributing and tracking resources, performing Critical Risk Assessments, and delivering messages to the affected population and coordinating responders.

1 Introduction

Following the September 2017 hurricanes, Hurricane Maria and Hurricane Irma in Puerto Rico, the country experienced a national level blackout as the entire grid was destroyed. Electricity was lost at every point on the island, plunging the 3.4 million residents into blackout (Mercy Corps, 2023). As shown in Figure 1, the path of the category five hurricane crossed most major transmission lines, and provided a disconnect from most major sources of generation with winds and rain strong enough to severely damage the national grid. Seen in Figure 2, the blackouts following Hurricane Maria included massive power outages, plunging 100% of the country into blackouts in the period immediately after the hurricane, and upwards of 80% of the country remained without power after months of repair efforts (Gay, 2019). Secure and safe shelter, food, and access to clean water became limited for many residents with billions in damage totalling across the island. With the extensive destruction of a costly national grid, Puerto Rico's prolonged troubles with power supply, power security, and grid resiliency require a redesign of the grid.

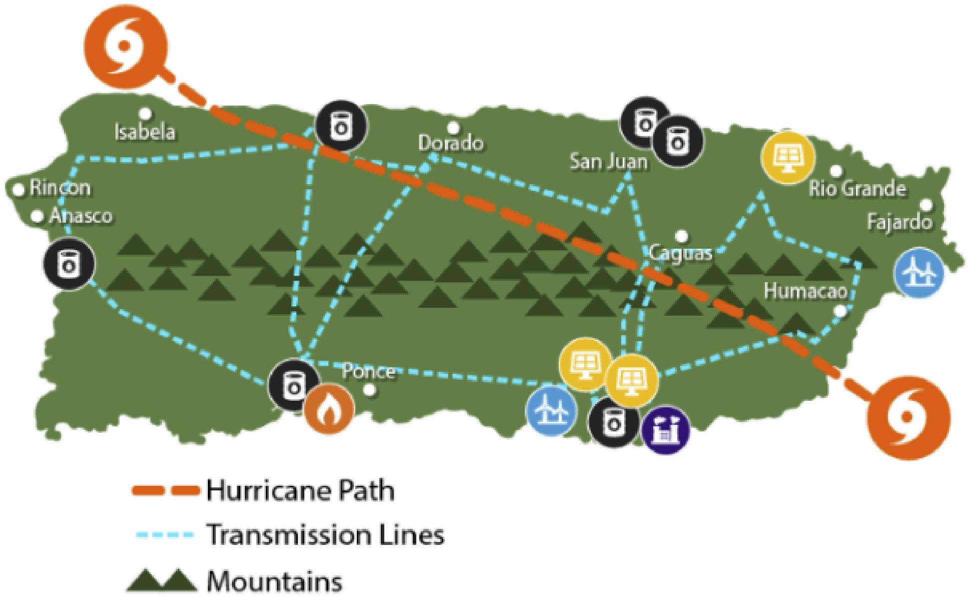

Figure 1: Hurricane Path with Major Power and Transmission Lines (Baggu, 2022)

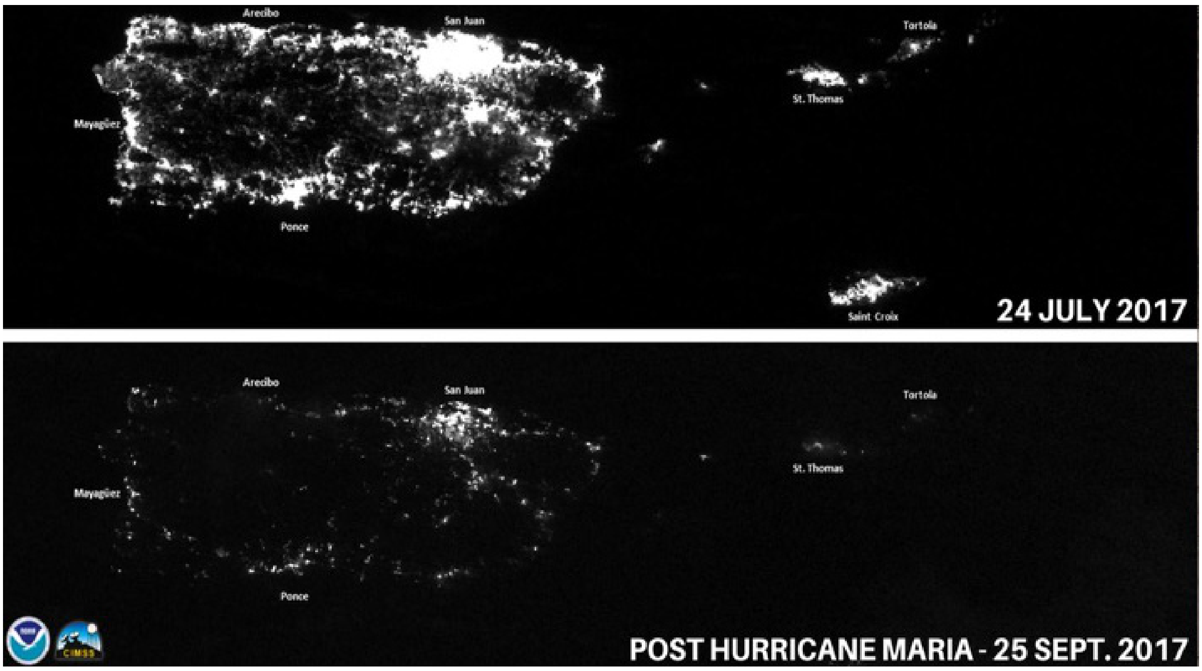

Figure 2: Satellite Images of Puerto Rico After Hurricane Maria (NOAA, 2017)

Without power across the country, Puerto Rico relied on international aid through the form of care packages, humanitarian support, and loaned diesel generators. These generators are within the standard response package for grid damage, but the extent of damage done to Puerto Rico persisted longer than the intended period of use. Hurricane Maria damaged power systems in every region, with 90 generators being provided to Puerto Rico in 2017 and upwards of 300 generators utilized to supplement regular power during the grid reparation phase (FEMA, 2021). According to the Puerto Rico Electric Power Authority (PREPA), it took nearly a year to reconnect the final customers to the grid following Hurricane Maria (Campbell, 2018). While challenging and unfortunate, the repaired grid remains vulnerable and this slow, costly, and centralized repair method will be a repetitive experience for the people of Puerto Rico without a grid redesign (Lopez-Cardala et al., 2018).

Having a form of localized power across Puerto Rico would reduce or eliminate the need for reliance upon diesel for electricity and on connectivity to other regions. Microgrids, and renewable based energy systems, are potential solutions to large centralized power plants. Solar based systems operate well under Puerto Rico's warm temperatures and consistently high irradiation throughout all seasons of the year. The average irradiance in Puerto Rico is somewhere between 1850 kWh/m^3 and 1950 kWh/m^3 with a high photovoltaic power potential of 1826 kWh/kWp annually (Solargis, n.d.). Puerto Rico experiences some seasonal variation over the course of the year but is overall bright with clearer skies and warm temperatures (WeatherSpark, n.d.). Given the potential of the region, several reports envision solar being part of, if not the major contributor to the national grid reconstruction(Smith-Nonini, 2020; Kwasinski et al., 2019). The Queremos Sol coalition of Puerto Rico specifically envisions rooftop, microgrid, and behind the meter storage as solutions to the reconstruction of the grid (Vila-Biaggi, 2021).

Creating a distributed grid with decentralized and varying power sources increases the resiliency of the nation's power supply. Puerto Rico's main power plants concentrated around the largest cities, with ~1400 MW capacity constructed in the San Juan area and ~2000 MW capacity installed near Guayama and ~1500 MW capacity in the Ponce area (Hartmann, 2021). Puerto Rico has around 6000 MW utility-scale electricity generating capacity, so within these three concentrations is 81.6% of Puerto Rico's capacity(EIA, 2023). The path of Hurricane Maria was able to destroy connection to these points, as have many hurricanes in the past, so a distributed system would avoid the reliance on these vulnerable connections. This case study aims to identify the capacity of solar and battery required for distributed micro-grids with minimal need for extensive transmission lines.

1.1 Research Question

The objective of this research is to develop and understand the feasibility of a renewable-based national grid for hurricane endangered regions, using Puerto Rico and Hurricane Maria as a case study. Studies such as this give insight to how resilient systems and locally generated power may resolve and aid in the recovery of hurricanes and similar disasters. This case study aims to demonstrate "how micro-grid emergency infrastructure can relieve energy demand in disaster zones." The developed model will be able to illustrate the capacity of solar and battery systems required to provide electricity during periods of crisis, specifically in cases when transmission is isolated, partially connected, or fully connected. The model will illustrate behaviour of the system during these scenarios, demonstrating when battery or solar is providing load, to what capacity, and to which region it is servicing.

Furthermore, the model is able to demonstrate shortages within generation when power supply is limited.

The recovery of Puerto Rico's national grid was and still is extremely costly and slowly being corrected, but the current design of the new national grid remains extremely vulnerable to future disasters. The need for resiliency and flexibility in Puerto Rico is high, as the country balances on the edge of total blackout once again. Understanding how distributed power supply and varied means of generation create security in a power grid must be taken into consideration when designing the electric profile of the future. The hope of this study is that Puerto Rico's national grid may begin to utilize micro-grid systems to satisfy the country's demand, if not for the entire load, for the remote regions which rely on extensive, heavy, and far-reaching transmission.

2 Methodology

This study utilizes the PyPSA package, which is a python-based plug in for Power System Analysis. The model was developed in three phases, firstly attempting to create a model which behaves as the existing system in Puerto Rico does, before a second phase introduces solar farms and a third phase introduces batteries with the sizing optimized for the complete elimination of fossil-fueled power plants. The model developed during this research is intended to illustrate basic transmission, connection, and generation scenarios, and is a highly simplified model. A map of the model can be seen in Figure 3, where the design utilizes demand and generation values which represent the total sum of values in the region, with respect to their hourly and monthly totals. The six regions described in this study represent the entire behaviour of energy across Puerto Rico, with each region having a sum of values for the cities and towns within the defined area.

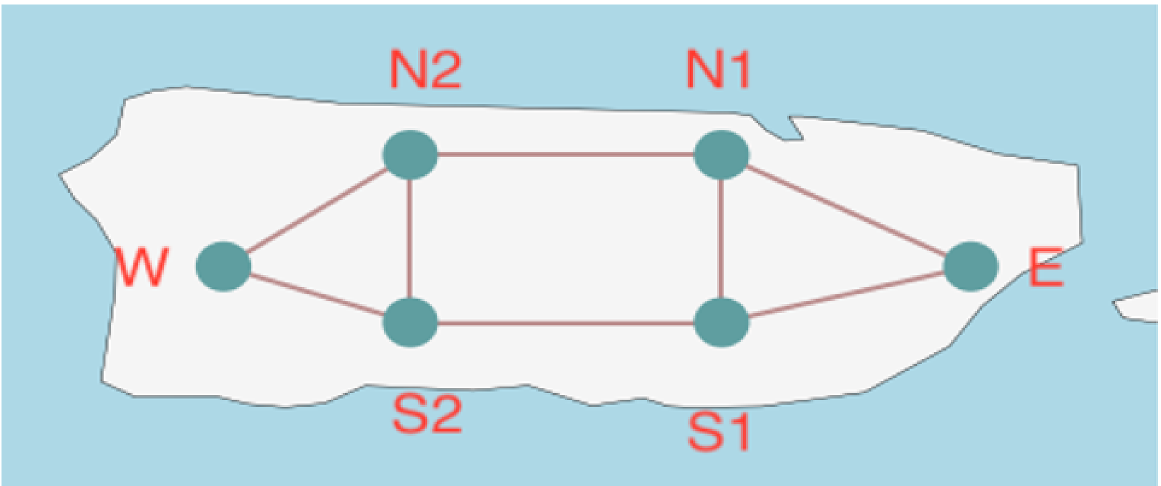

Figure 3: Model of Puerto Rico - The Six Nodes with Transmission Lines

2.1 The Simplified Model

The difficulty of this research was collecting accurate, open-source energy data for Puerto Rico. The annual and monthly consumption and generation of each region was known, but detailed daily and hourly data was incomplete. Due to this, a typical day or representative day was utilized for creating a year's worth of behaviour in the model. This typical day is designed after the known hourly demand of a weekday, where industry, commercial, and residential operations are in full use. With the monthly sum of demand and generation, the total sum of the month was divided by the number of days in the month and distributed based on the known load profiles of industry, commercial, and residential consumers. For generation, a solar yield-to-capacity ratio was found based on PV behaviour data and applied to the typical representative day.

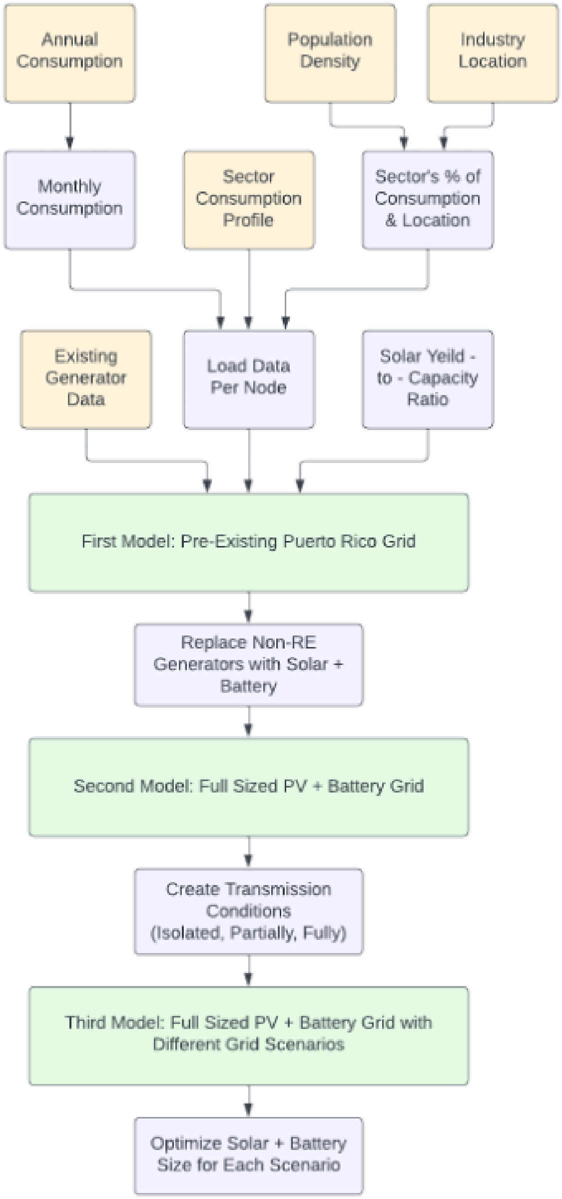

Figure 4: Methodology Flowchart for Building the Model

The development of the simple model utilizes many assumptions that create inaccuracies and lack necessary detail when compared to the actual system. However, the model, while extremely simplified, behaves in the same manner as an actual system, making the model responses an indicator of how the multitude of variables which would impact a grid of the national size were eliminated or given an assumed value which may not be wholly accurate to existing conditions. For example, transmission lines were given a capacity based on data found for the actual transmission lines between major cities. This line capacity had to be increased beyond the values found in literature, as the six nodes and the lines between them represent all the locations for generation and consumption in a region. The lines between nodes represent all lines crossing between regions, not just the one major line which data for was known.

2.2 Data Collection & Design

In order to build the model, there first needed to be a collection of pre-existing data for Puerto Rico. The annual consumption, population density and industry location, as well as demand data was needed. This data was utilized to create the profile of the 6 nodes which were used to represent a region in Puerto Rico. With a basic demand profile, data for the existing generators and generator types was collected so that the first model, pre-existing conditions, could be completed. This model had a small PV contribution, which required finding a solar yield-to-capacity ratio that suited the performance of PV in Puerto Rico. This yield-to-capacity ratio was able to be used in later models as well, which leads to the next step of replacing the pre-existing non-renewable generation sources with PV-Battery systems. This second model was sized so that in ideal conditions, there would be no non-renewable energy generation. Then, to create scenarios which may represent the conditions observed during and following Hurricane Maria, the model was given transmission cut-offs where the national grid either had no connectivity between nodes or partial connection. The model was then re-sized so that it ensured no non-renewable generation was required under these conditions.

As illustrated in Figure 4, the load data per node was calculated by utilizing data on the annual consumption of Puerto Rico and data on each region. The data of each region included population, industry, and energy consumption. Then, to create the typical day behaviour, the annual load was divided amongst the months by the average monthly consumption behaviour, and sector consumption profiles were applied to the data to illustrate data on the hourly basis. This simplified model utilizes a typical monthly day in order to find the hourly behaviour. Similarly, to create a baseline for the solar's behaviour, data for the yield to capacity ratio was found using data from the Global Solar Atlas. It was observed that the specific photovoltaic power output across the island was within a 200 kWh/kWp range. A year's worth of data was taken from a point near San Juan, and minimum and maximum behaviour days were found for each month, including an average type of day.

3 Results

3.1 Puerto Rico Electricity Demand

After collecting demand data, it has been observed that in Puerto Rico the daily demand data has a similar pattern all over the year, and in N1 is the highest demand amongst all other nodes. In Figure 5, the collective demands have been plotted monthly; whereas it has been shown that in the middle of the year like from May to October, the demand is almost the same; which varies from 2000 MWh to 2010 MWh. Over the course of the year, February has the lowest demand at 1,700 MWh.

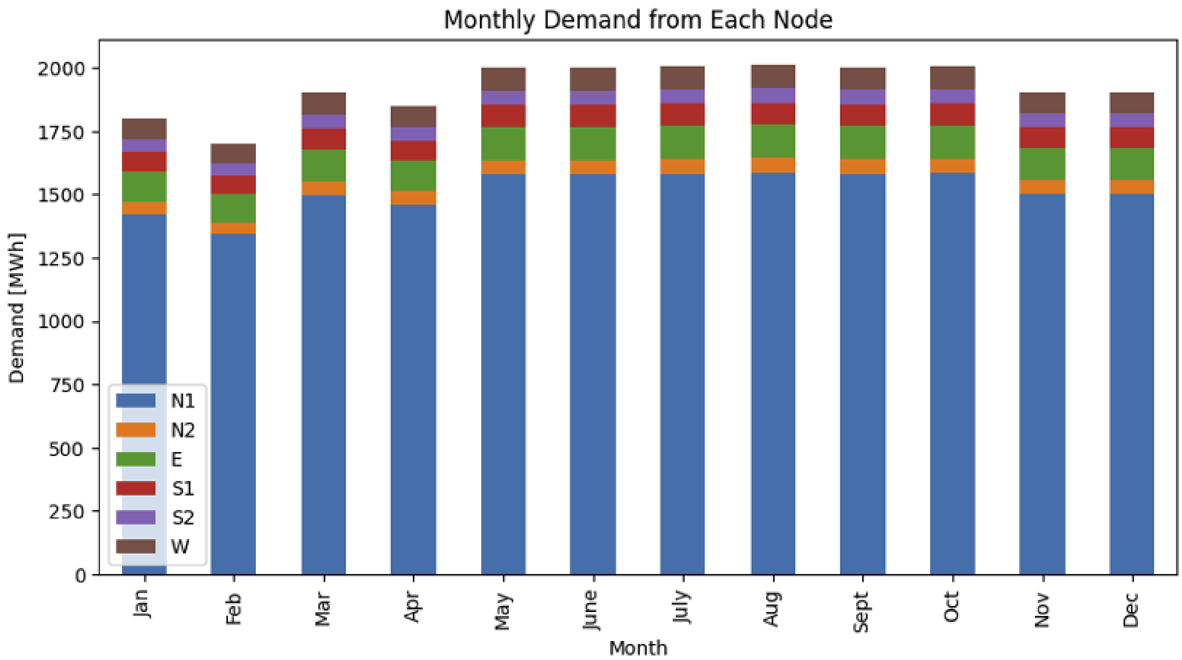

Figure 5: Monthly demand curve all over the year in all six nodes

After zooming in on hourly load, the total peak demand in a day is from 8:00 to 15:00, because of the commercial load. The peak demand for the residential is at 21:00. Industrial load is more or less constant over the entire day. Each day of a month represents that specific month. Whereas all over the month, the demand is the same. This hourly load demand has been pictured in Figure 6.

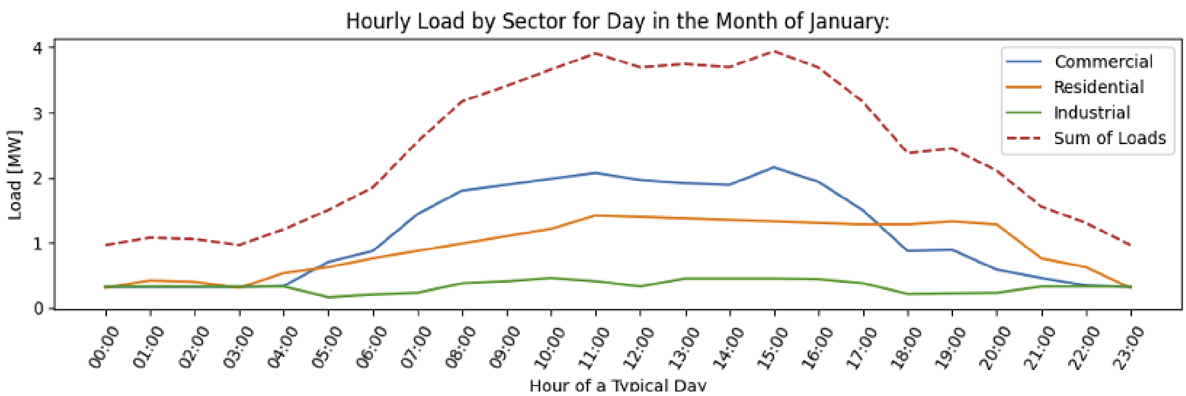

Figure 6: Hourly load demand in a day of three sectors

3.2 Solar Irradiation in Puerto Rico

With the data provided from the SolarGIS database, the behaviour for an ideal day in each month was found and can be seen in Figure 7. It is important to note that this plot is not over the course of each day in the month as the x-axis label may indicate, but is a plot of 12 days where the date is the month which the 24-hr period represents the ideal day behaviour of. The highest solar yield-to-capacity ratio found was in March for 0.79, and the lowest yield-to-capacity ratio was in June for 0.68.

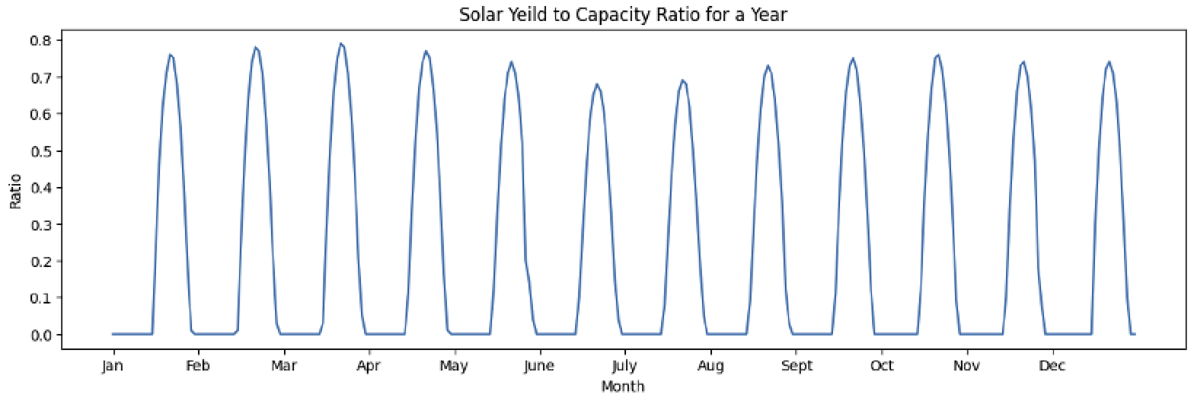

Figure 7: Yeild-to-Capacity Ratio for Representative Days of Each Month

3.3 Installed PV Capacity in the pre and post hurricane model

Before the hurricane, due to the major use of fossil fuels, PV was the smallest contributor to power generation. After the Hurricane in the model PV capacity has been increased 18 times more, due to the fossil fuels being replaced.

Table 1: PV plants Capacity before and after Hurricane

Before Hurricane	After Hurricane
31.5 MW	594 MW

In Figure 8, it has been shown that before and after the hurricane PV installed capacity is highest in node N1, because demand is high on that node. Before the hurricane, it was 17 MW and after the hurricane, it is 314 MW. 2nd biggest PV installed capacity in node N2. Before the hurricane there was no PV installed in Node S1, E and W. But after the hurricane in each node 40 MW PV plants have been installed to mitigate the demand.

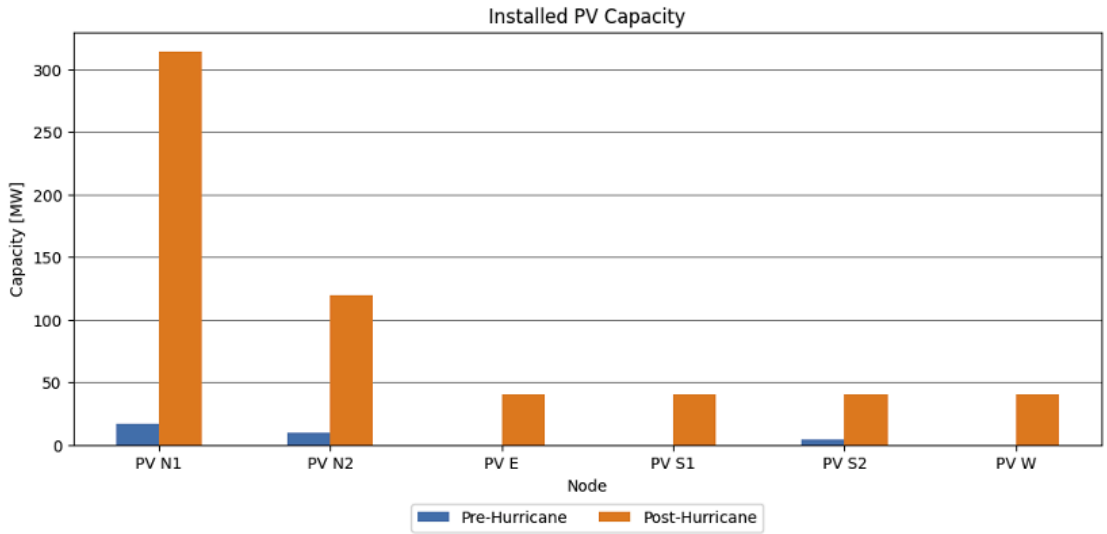

Figure 8: Installed PV Capacity Before & After Hurricane, Per Node

3.4 Six Nodes Modeling of Pre & Post Hurricane Electricity Generation

For the modeling, three scenarios have been created. These scenarios are fully connected, Partially connected, and fully isolated. And all scenarios have been modeled with PYPSA. In the 1st scenario- pre-hurricane, electricity generation mainly comes from fossil fuels. Petroleum power plants are the major contributor to this model. After that Gas and Coal are the 2nd and 3rd respectively. In January, February, and April, due to low electricity demand, Petroleum-3 has been completely shut down. After the hurricane, all fossil fuels have been replaced by PV. After the hurricane, N1 became the major electricity provider than other nodes. It is because N1 has the highest demand. In Figure 9, it has been observed that after the hurricane, electricity generation increased. It is because of the battery losses; The storage efficiency and the dispatch efficiency are 90%. Line efficiency is also the reason for high electricity generation. After the hurricane, the maximum generation of PV comes in March, because the highest solar irradiation has been achieved in this month.

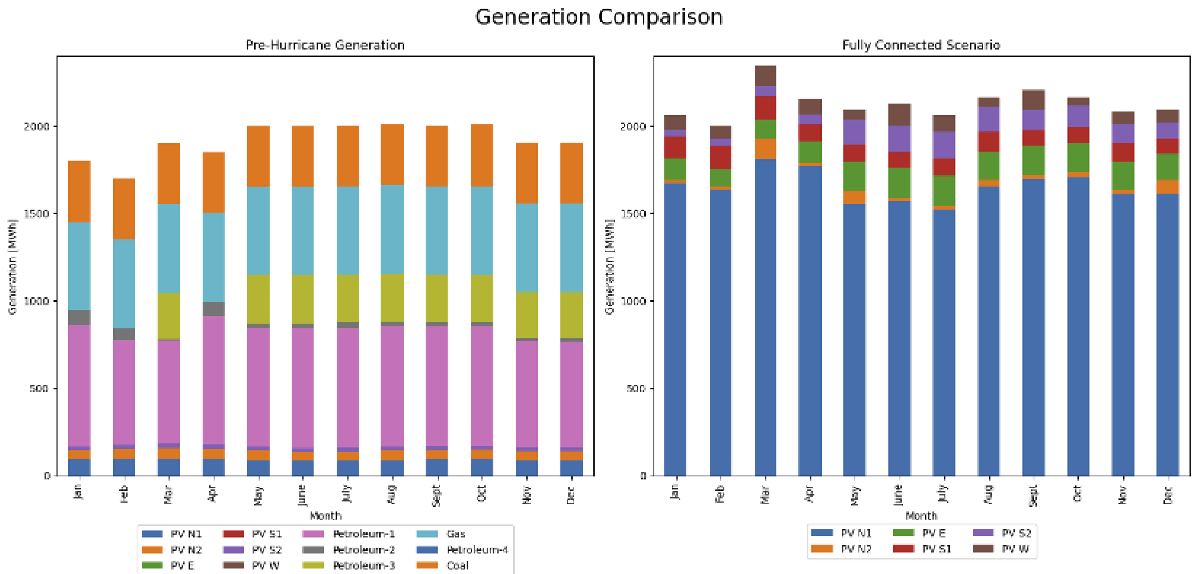

Figure 9: Monthly comparison pre and post hurricane in electricity generation

3.5 PV and Storage Comparison with two scenarios after hurricane

After the hurricane two scenarios have been considered. One is complete isolation and the other one is partially connected. Where lines are 0.05% disconnected in the partially connected. From the figure 10 It has been shown that the partially connected generate a bit more than complete isolation. In the complete Isolation PV generation only follows the demand based on the solar radiation; where at the mid of year PV generation is low because of solar irradiation also low. But during partial connection PV generation has been increased because of sharing with other Nodes and mainly the line losses. In both scenarios except N1, rest of the PV in other nodes remains the same.

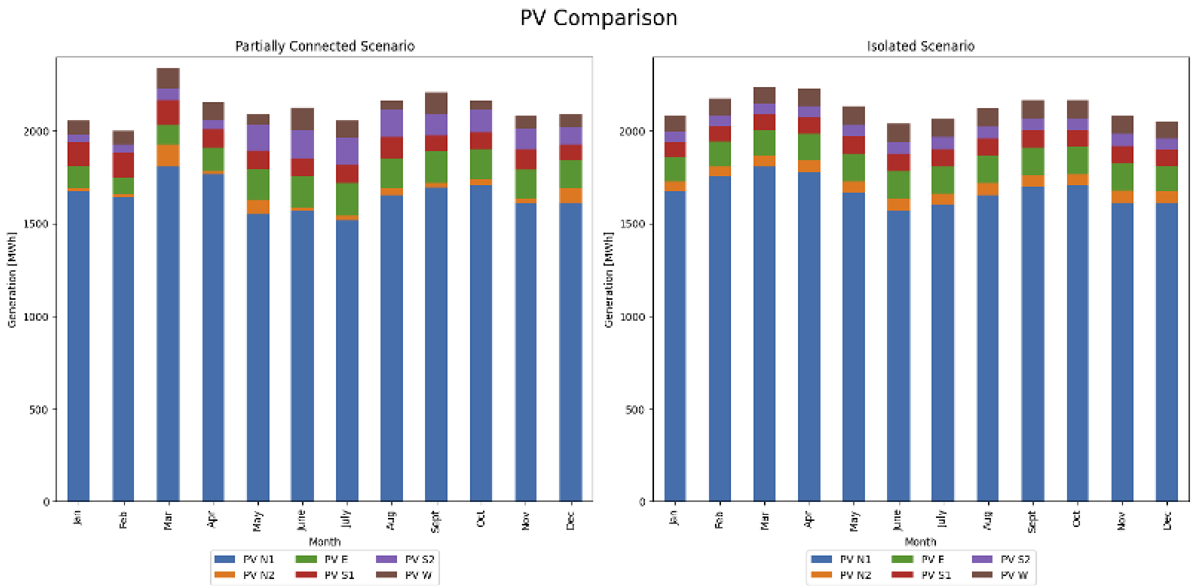

Figure 10: Monthly PV comparison between Complete Isolation and Partially connected

From the figure 11, it has been potrate the storage comparison between isolation and partially connected scenarios. The conversion from hourly storage data to monthly storage data has been done in two steps. In the 1st step for each month cumulative sum is calculated for each node. In the 2nd step stack all the results month wise and also node wise. The maximum discharge time of Battery is 09 hours. And battery efficiency is considered 90%.

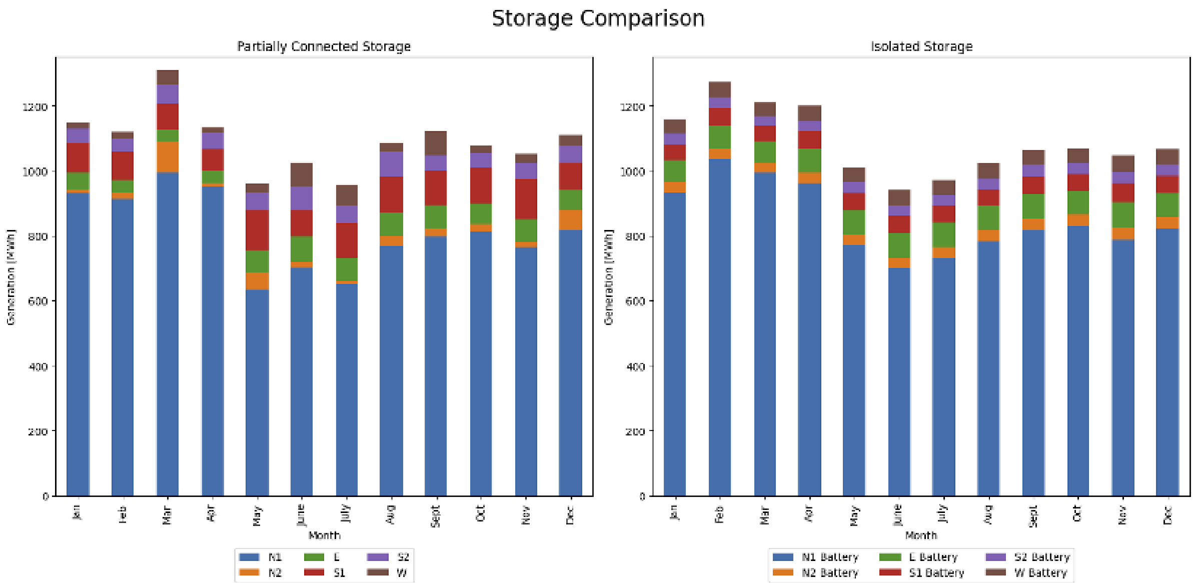

Figure 11: Monthly storage comparison between two scenarios

3.6 Annual and Hourly overview of a specific node

In the previous section it has been discussed that node N1 has the highest demand, so in this section node N1 will be taken a closer look with hourly resolution. Again in the two scenarios-fully connected and complete isolation have been considered for analysis. It has also been discussed that the demand is the same all over the year. So for this analysis, only January has been chosen. In the first scenario where all lines are fully connected, it has been portrayed in the Figure 11 that a random PV generation pattern. It is because of sharing with other nodes. In the Figure 12 It has been more clear that some time demand has been mitigated by the other nodes whereas the N1 has enough capacity to mitigate its own demand. That is why the overall PV and storage electricity supply has increased than isolated scenario.

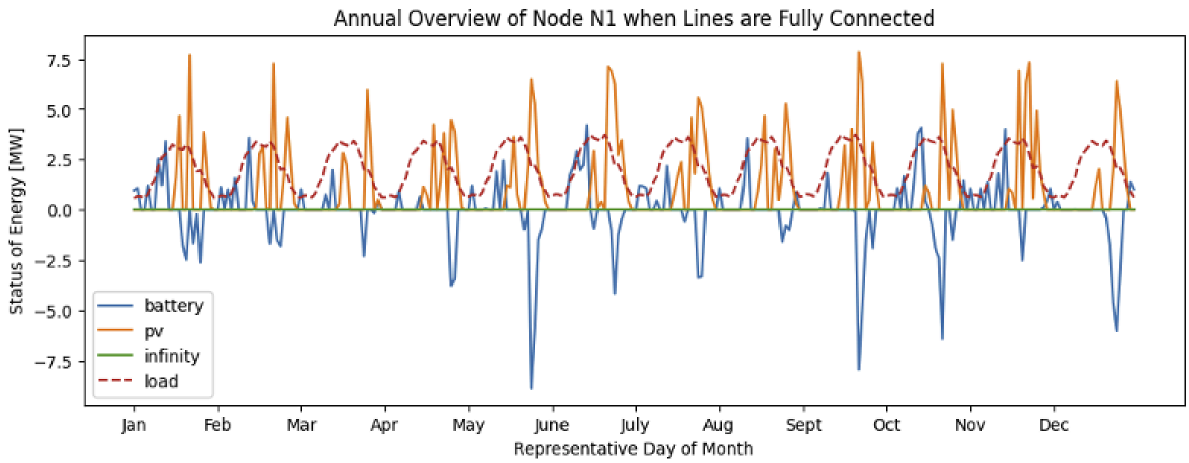

Figure 12 displays in N1 annual PV generation & storage when the lines are fully connected and mitigate the demand

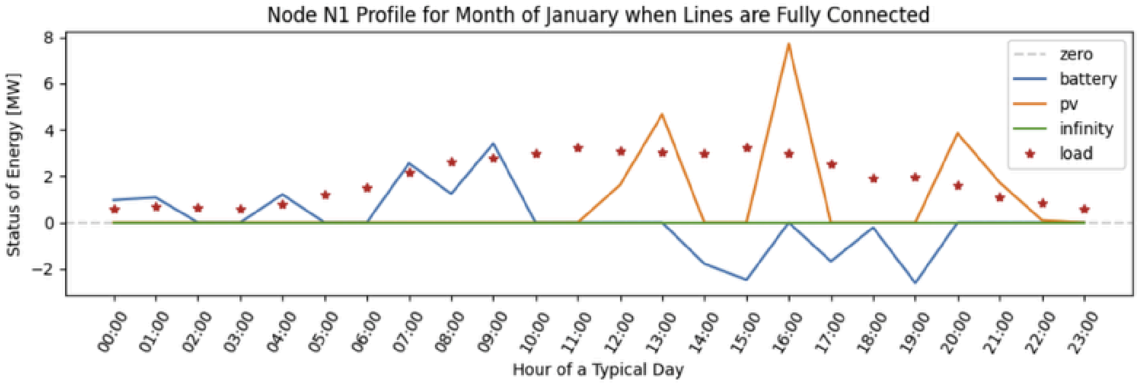

Figure 13 take a closer look with hourly resolution.

In the fully isolation scenario it has been a much more understandable picture portrayed. When all the lines are totally disconnected, then there is no way to sharing with neighboring nodes. All the generation will be consumed by its own demand and its own storage. Figure 13 shows that battery storage is following the PV generation and from Figure 14 it has been much more clear that how PV and battery react with the demand.

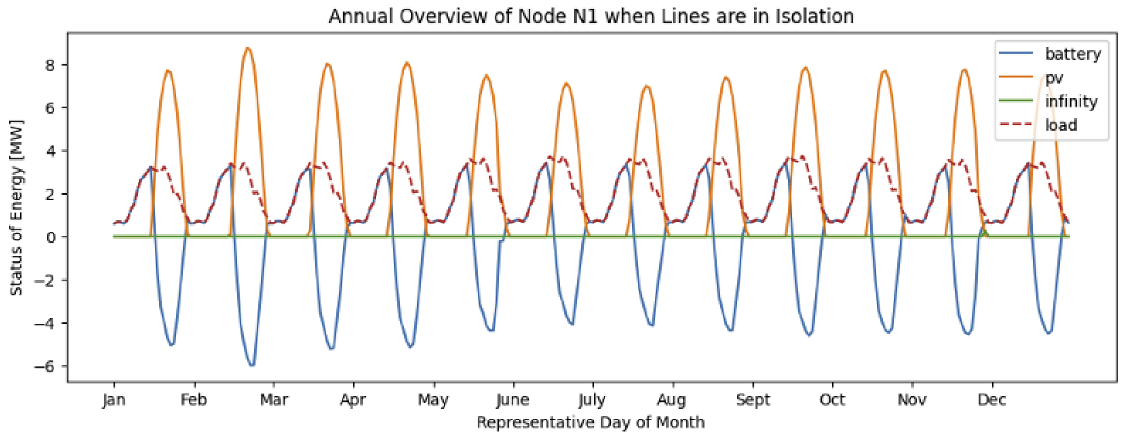

Figure 14: portraits in N1 annual PV generation and battery store and dispatch to meet the demand without fossil fuels

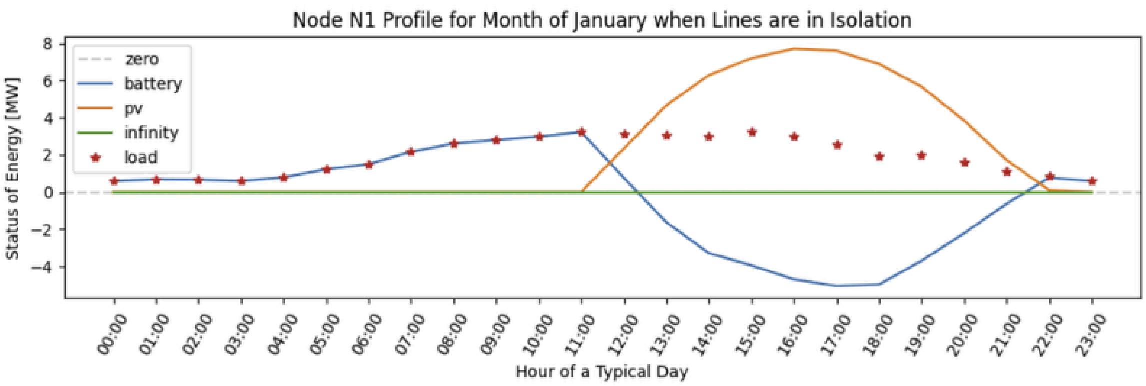

Figure 15: shows a closer look in hourly resolution.

3.7 Behaviour of the Transmission Line

When utilizing the model to observe the behaviour over the transmission lines, it becomes noteworthy the direction and volume of energy being transferred from one region to the other. In the two figures below, the x-axis month label is for the 24hr period of that month's representative day, so the cumulative value is of a 12 day period. These plots are utilized only to understand behavior, as the representative day is repeated within the month, the overall trend will be the same. In the isolated scenario, there is no transfer between lines so it is known that the modeled local size of solar and battery is sufficient.

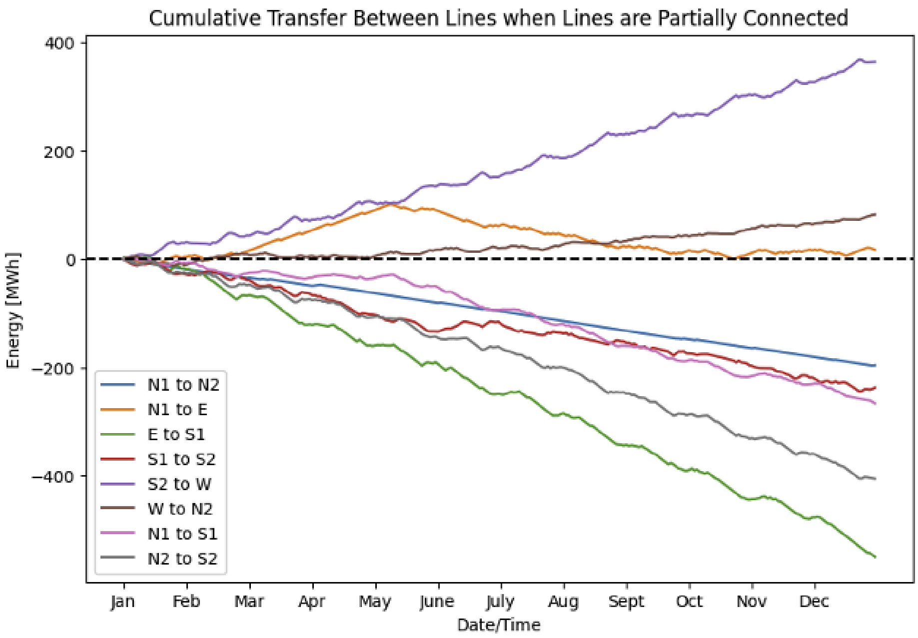

Figure 16: Cumulative Transfer Between Lines when Lines are Partially Connected

Within a partially connected scenario, it is noted that most energy transfer in the lines is mostly from Node N2 to Node N1. This is outside of expectations for model behaviour, as losses within the lines would ideally prevent the model optimization from occurring unnecessary losses. Similarly, it is during these periods where lines are being utilized that it can be seen batteries discharging during peak solar hours. Figure 16 demonstrates how most power is flowing through the model, with electricity from Node N2, S1, and S2 going towards Node N1.

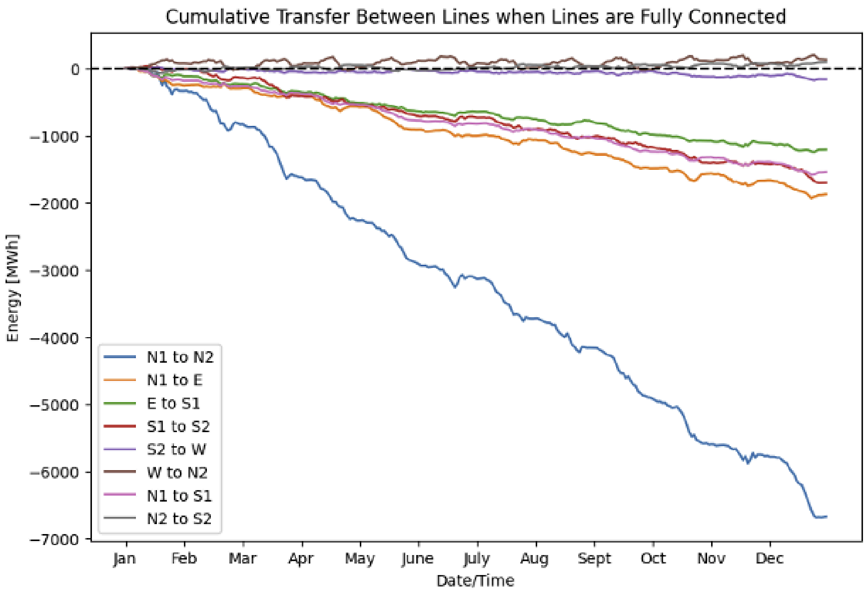

Figure 17: Cumulative Transfer Between Lines when Lines are Fully Connected

In a fully connected scenario, the observed behaviour in the partially connected scenario persists. Specifically, an immense amount of electricity is sent from Node N2 towards Node N1, while Node S1 and Node E provide a large amount of electricity to Node N1. Node N1 however begins to provide a slight amount of energy to Node S2. There are over 6,000 MWh of electricity transferred from one node to the other in these 12 representative days of the fully connected scenario, meaning much of the solar generation and battery discharge is not satisfying local demand but that of other nodes.

It has been theorized through the work of this project that the PyPSA optimizer likely does not consider losses but cost and CO2 emissions as factors for evaluation, so a future model iteration would require model optimization to consider transmission losses in order to prevent the scenario observed in the two connected scenarios.

4 Conclusions

The objective of this project was to create a model which would optimize the capacity of solar and battery systems needed to fully replace power plants in Puerto Rico. The behaviour of each node in the model was observed during each transmission scenario so that the optimum PV and battery size may be found. Contrary to the predicted results, the model yielded a larger capacity system required for connected scenarios than the isolated case. This was due to the unpredicted nature of the optimizer and the oversizing of nodes for power sharing. It is modeled that 594 MW capacity of installed solar with 670 MW capacity of battery systems would be able to provide power to the entirety of Puerto Rico, under the varying three transmission scenarios.

The model, while highly simplified, illustrated the behaviours of the national grid and furthered the understanding of obstacles surrounding emergency power for Hurricane Maria. The solar-battery system, while sized larger than what is practical, shows the capabilities of renewable energy in this region, and how micro-grids could be distributed.

Ideally, a larger profile of energy sources should be utilized to reduce battery-dependance and create resiliency in the national grid for resistance and flexibility in power generation.

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